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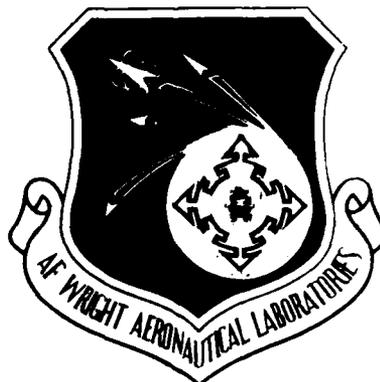
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Volume II

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BENEFITS ANALYSIS OF PAST PROJECTS

Volume II: Individual Project Assessments

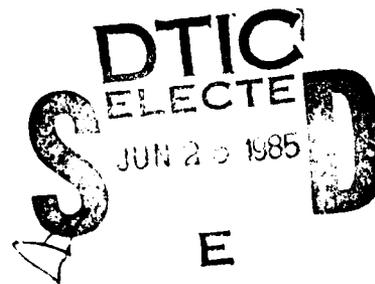


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November 1984

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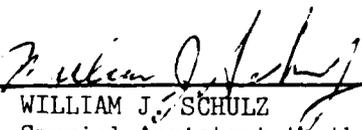
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This technical report has been reviewed and is approved for publication.



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FOR THE COMMANDER:



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<p>A program was conducted to assess the technical results, degree of implementation, and resulting benefits from 75 past Air Force MANTECH projects. The projects encompassed nineteen divisions of eight major aerospace contractors, and most types of USAF end items.</p> <p>Almost one-half (47%) of all projects led to production implementation, yielding over \$992 million (in 1982 dollars) in projected manufacturing cost savings through 1992, under a peacetime scenario. The savings figures are conservative in that they reflect only actual or definitely programmed cases of implementation, for implementation only at the contractor that performed the project, and reflect manufacturing cost only, exclusive of IR&D, G&A, and profit loadings.</p> <p>Approximately \$593 million (60%) was in savings on military items, and \$399 million (40%) was in production of commercial items. The Air Force portion of the military savings</p>			
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was approximately \$522 million (88%). The bulk of the commercial savings resulted from employment of MANTECH-developed technologies by General Electric and Pratt & Whitney Aircraft for production of commercial aircraft engines.

The savings-to-cost ratio for all projects and all economic benefits was found to be 19:1. Considering savings only to the military, the savings-to-cost ratio was 11:1, and from the perspective of the Air Force alone, 10:1. The savings figures and ratios do not include numerous non-economic benefits which were identified. Many of these were product quality improvements which resulted in more mission-effective end items.

Several recommendations were made for enhancing the likelihood that MANTECH projects will lead to implementation and generate economic and other benefits.

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FOREWORD

This is Volume II of the final, comprehensive technical report on work performed under Contract F33615-81-C-5145, "Benefits Analysis of Past Projects." It contains the results of the individual project assessments. A summary analysis of all projects is presented under separate cover in Volume II.

The work reported herein was performed by Applied Concepts Corporation of Woodstock, Virginia and Berthoud, Colorado for the Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. Mr. William Schultz was the Project Engineer for the Manufacturing Technology Division. Mr. James A. Simpson, Applied Concepts' Program Manager, and Mr. Robert L. Uphoff were the authors of this report. Mr. Stanley L. Pond and Mr. J. Scott Hauger contributed to the technical work.

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General Electric Company

COST-EFFECTIVE ENGINE REPAIR TECHNIQUES

(F33615-76-C-5094; May 1976 - February 1979; \$267,550)

Background

Turbine blades and vanes are subjected to an extremely hostile environment in the engine. Even with advanced designs for cooling and the use of high strength, high temperature resistant nickel or cobalt base superalloys, degradation and damage still occur which limit their useful service lives. Repair, generally through welding, is particularly difficult and only feasible in certain areas of the components. Scrap-out rates of both blades and vanes are high. Furthermore, these parts are numerous and extremely expensive (\$700 to \$1,000 each, and up). Thus, low cost techniques which could be used to repair damaged blades and vanes and extend their service lives would yield very large economic benefits.

Project Objectives

Establish cost-effective techniques for repairing conventionally cast turbine airfoils.

Project Description

First, the types of blades and vanes, and the repair processes and applications with highest generic payoff potential for the Air Force ALCs were determined. With Air Logistics Center (ALC) input and coordination, it was determined that the most suitable components for developing generic repairs were TF39 Stage 1 HPT blades (Rene' 80) and stages 1 and 2 HPT nozzle vanes (X-40 and Rene' 80, respectively). Repair applications with the highest potential payoff were identified as blade tip replacement and cleaning and healing cracks in vanes.

Three repair techniques were selected for testing. G.E.'s previously developed mini-bonding process was selected for blade tip replacement. For the vanes, fluoride ion cleaning was selected for oxide removal and Activated Diffusion Healing (ADH) for crack filling.

Specific repair procedures were developed for:

1. ADH of TF39 Stage 1 HPT nozzle vane (X-40); especially its leading edges (preceded by H₂ cleaning).
2. ADH of TF39 Stage 2 HPT vanes (Rene' 80) (preceded by fluoride ion cleaning).
3. Mini-bonding of replacement tip caps for TF39 Stage 1 HPT blade.

After the repair processes were developed, 40 pieces of each component were processed through a pilot repair process to demonstrate manufacturing control and repeatability, and to estimate costs. The integrity of the repairs was checked by NDE of coupon specimens and metallographic examination.

A number of successfully repaired components (12 Stage 1 and 15 Stage 2 vanes) were engine tested. The mini-bond process on the blades had low yields due to inadequate process controllability, so a furnace bonding approach was tried.

Project Results

Repaired Stage 2 vanes (Rene' 80) indicated performance better than a weld-repaired part. Repaired Stage 1 vanes, however, exhibited severe cracking and were unsatisfactory. Changing the repair alloy corrected the problem.

As mentioned above, the mini-bond process had low yields due to inadequate process controllability, so a furnace bonding approach was tried. This proved technically feasible but not economical.

For vanes, ADH showed a slight cost savings over the current method of repair and a marked cost savings over part replacement. The mini-bond blade repair was found to be slightly more expensive than weld repair.

For both blades and vanes, scrap-out rates are relatively high because a number of common defect types cannot be repaired. Improved repair processes would mean that more areas and thus more blades and vanes could be repaired. A decrease in the scrap-out rate was the main economic "carrot" for developing a better repair technology. The Filion/ADH repair process was found to increase the number of repairable vanes by approximately 50%. The mini-bond blade repair did not increase the percentage of repairable blades.

Repairs generally restore about 80% of the rupture life and 60% of the low cycle fatigue life. G.E. estimates that each initial repair saves, net overall, approximately 50% of the cost of a new part.

Extension of these components' utilization lifetime would also yield savings in material utilization.

The following equations exhibit the cost reduction potential of component repair. They were developed from equations presented in the project final report.

PRC = Part Replacement Cost

Y = # Components requiring replacement or repair at overhaul.

A = % of components judged non-repairable and initially scrapped.

B = % of components on which repair was attempted and was successful.

C = % of components on which repair was attempted and was unsuccessful.

$$A+B+C = 100\%$$

$$\text{PRC} = [Y] [(A) (\text{new part cost}) + (B)(\text{repair cost}) + (C)(\text{new part cost}) + (C)(\text{accumulated repair cost when scrapped})]$$

-or-

$$\text{PRC} = [Y][(A + C)(\text{new part cost}) + (B)(\text{repair cost}) + (C)(\text{accumulated repair cost when scrapped})]$$

The above equations illustrate the importance of developing reliable, low cost repair processes which enable a larger percentage of parts to be repaired. Repair opportunity, cost, and yield all affect overhaul cost. Money spent to process parts ultimately scrapped can substantially increase the overall average (successful) repair cost per part.

It should be noted that these equations are illustrative only. They do not encompass overall cost savings since repaired replacement parts typically have lower remaining service lives than new parts. Thus, true overall savings from repair would be somewhat less than might be inferred from these equations.

An analysis in this project of a large sample of CF6-6 Stage 1 and

drilling acceptable small diameter holes with large depth-to-diameter ratios in superalloy components.

Project Description

First, eight types of laser systems were evaluated based upon performance criteria, acquisition cost, and operational costs. A select-grade ruby rod and a Nd:YAG rod laser were selected. The focussing optics of the lasers were optimized and a method was demonstrated for automatic position sensing of the drill target. Beam splitting optics were tested for simultaneous multiple hole drilling. A low-cost solution was found for protecting the drilling and position sensing optics from expelled metal particles. Process and work-material variables were optimized for drilling holes with greater penetration depth and improved geometrical integrity in Rene' 125, MAR-M-509, and Hastelloy X. Rene' 125 is an investment cast nickel base superalloy used for turbine blades and vanes. MAR-M-509 is an investment cast cobalt base superalloy with potential application as HPT vane material. Hastelloy X is a nickel-chromium superalloy used in high temperature sheet metal applications, such as combustion liners and turbine blade and vane impingement baffles.

Abrasive flow machining was investigated as a technique for recast removal. Fluorescent penetrant inspection was investigated as a NDE method for verifying removal of recast and damaged substrate. A mechanical testing program (HCF, SETS, and stress rupture tests) was conducted on Rene' 125 to determine the effects of laser drilled holes on its critical properties.

The optimized drilling process was demonstrated on a production-line Hastelloy X combustion liner and two different Rene' 125 turbine blades-- one prototype and one production line.

LASER DRILLING

(F33615-73-C-5006, April 1973 - April 1975, \$285,701)

Background

G.E.'s large turbine aircraft engines contain many thousands of small air cooling holes. The CF6-50/-80 family of engines require approximately 70,000 cooling holes each; some advanced technology development engines require up to 100,000 cooling holes. Most air cooling holes are located in turbine nozzle components and shrouds, turbine rotor blades, and combustor components. Hole diameters in turbine airfoils and shrouds range from about 7 to 30 mils, up to 3/4" deep, have depth-to-diameter ratios of up to 50, and many are drilled at sharp entrance angles. Due to the small hole sizes, the drilling angles, and the hardness of the materials, unconventional drilling processes such as electrochemical drilling (ECD) and electrical discharge machining (EDM) must be used.

In the late 1960's, G.E. began looking for lower cost hole drilling processes to replace the unconventional processes then being used. Around 1970, G.E. developed internally a laser drilling process, but it had limited penetration capability and was confined to drilling sheet metal components. Holes from .007 inches to .030 inches in diameter, in material thicknesses to .050 inches, were drilled in impingement cooling tubes and turbine blade tip covers (or tip caps) for production line engines. Solid state lasers with standard grade ruby rods were used. Although this early laser system had only a limited application potential, the enormous potential of an improved laser drilling system became evident. In April 1973, G.E. was awarded this MANTECH contract to develop an improved laser drilling process.

Project Objective

Develop and demonstrate a cost-effective laser drilling process for

Technology Transfer

Cast-plus-HIP is a widely used process in the aerospace sector. It is commonly accepted throughout the industry that titanium castings would hardly be feasible without a technique like HIP to eliminate internal flaws. New cast-plus-HIP parts exhibit significantly improved tensile and fatigue strength over as-cast materials, and HIP is being used by some firms to "rejuvenate" used parts. Technology transfer will be explored more fully over the course of the project and reported in the final report.

All dollars in Figure 1 are in 1982 dollars. Savings are assumed to begin in the year following process introduction. The estimate of total savings is based upon company forecasts of engine and spare parts sales. More detailed breakdowns are not presented to prevent disclosure of this proprietary information. Some of the cost savings estimates are based upon vendor quotes, others on internal G.E. cost analyses. In both cases, savings represent the cost differences between a prior forge-plus-machine or fabrication process and HIPed castings, using reduced material volumes and lower cost material. Most savings are in material costs, with some parts showing machining cost savings.

The 10 applications in Figure 1 represent approximately 7% (10/137) of the 137 cast-plus-HIP applications that were identified. The percentage of the total cost savings represented by these 10 applications is unknown. Nevertheless, it is clear that the overall cost savings would greatly exceed the \$56.6 million presented in Figure 1.

Figure 1 includes one atypical but extremely important cast-plus-HIP application. HIP densification was used to correct a high cycle fatigue problem in Rene' 80 CF6-6 stage 1 and 2 HPT blades. Three HCF failures on American Airlines DC-10s had cost G.E. approximately \$500,000 each to repair. New cast-plus-HIP blades (same alloy and design) were installed to solve the problem. The alternative was a costly (\$3 million-plus in 1977 dollars) and time consuming (2 years) redesign and recertification process. Cast-plus-HIP technology for this application clearly saved G.E. millions of dollars.

Another benefit of the cast-plus-HIP process not included above is improved weldability of the components. Shop savings of \$250 per component in welding costs have been cited. Also in addition to the savings discussed so far, there will probably be new applications of cast-plus-HIP to both existing and new engines. An example of a potential new application for an existing engine is the TF39 fan frame. Savings of \$20,000-\$40,000 per engine are expected if the current forging can be replaced by a cast-plus-HIP part.

PART	ALLOY	ENGINE	PIECES/ ENGINE	INTRO. YEAR	SAVINGS/ ENGINE, 1982\$
Front Compressor Casing	Ti-6Al-4V	F101	1	1982	\$ 7,600
Rear Compressor Casing	IN718	F101	1	1982	\$ 2,400
HPT Blade Retainers	MARAGE 250	F101	88	1975	\$ 3,344
Actuator System Casings	Ti-6Al-4V 17-4PH	F101	6 Actuator Systems	1982	\$ 2,143
Compressor Extension Casings	IN907	F101 & CFM56	1	1982	\$ 2,000
Forward Compressor Casings	Ti-6Al-2Sn- 4Zr-2Mo	F101 & CFM56	1	1982	\$ 1,800
Fan Frame Castings	Ti-6Al-4V	CF6-80C	1 Set	1983	\$ 26,850
Stage 1 & 2 HPT Blades	Rene' 80	CF6-6	100	1977	\$4,500,000 (one-time savings)
Power Turbine AFT Adapter	17-4PH	LM2500	1	1977	\$ 4,498
Power Turbine Damper Diaphragm	17-4PH	LM2500	1	1977	\$ 2,999

ENGINE PRODUCTION SAVINGS (IMPL. YR+1 THRU 1992) = \$55,420,000
 SPARE PARTS PRODUCTION SAVINGS (IMPL. YR+1 THRU 1992) = 1,215,000
 TOTAL SAVINGS (IMPL. YR+1 THRU 1992) = \$56,635,000

FIGURE 1:

SAMPLE OF 10 CAST-PLUS-HIP APPLICATIONS (OF 137 COMPANY-WIDE)

It should be possible to process different parts and alloys together. Also, commitment of an autoclave to a single range of parameters would decrease change-over and maintenance costs, and thus decrease total processing costs.

It was found that HIP densification could have a high payoff, if used selectively in high payoff applications, such as on complex castings suffering a poor yield in the casting process. Another high payoff application was thought to be where subsurface porosities are found during machining late in the manufacturing process, after a considerable processing investment has been made in the part.

The highest payoff for this technology, however, would be in replacing wrought structural components with castings, particularly for intricate parts or others requiring extensive machining. In addition to processing cost savings, significant material savings would also be realized.

It should be mentioned that there was a follow-on MANTECH program at G.E., entitled "Manufacturing Methods for Production of Premium Quality Castings At Lower Cost" (F33615-76-C-5076), which explored HIP densification further and with other alloys.

Implementation

Since the MANTECH projects on HIP densification, cast-plus-HIP processes have received wide implementation at G.E. A computer inquiry revealed 137 different applications for the process, encompassing a wide range of different types of components (both rotating and non-rotating), and a wide range of alloy types. Estimating the cost savings from all 137 applications was beyond the scope of the effort of this project. However, estimates of cost savings per engine were developed for a sample of 10 of the 137 applications. These are presented in Figure 1.

and to encourage implementation of the densification process were identified. The main area was the development of improved autoclave procedures and component specifications based upon vendor and G.E. statistical data. Also recommended was an effort to identify fabricated wrought parts which could be replaced with densified castings.

Preliminary manufacturing process specifications and quality assurance procedures were prepared.

The two major cost factors in HIP densification of castings were found to be the autoclaving cycle and bridging technique required. Autoclaving cost per unit is highly dependent on the number of parts which can be HIP-ed together. This in turn, is dependent upon the size of the autoclave, the size of the part, and the confidence in the equipment and process in relation to the possible economic loss from an overtemperature HIP run. The cost comparison below is based upon the results of this project.

Cost Comparison of Autoclave Sizes (1974 dollars)

	<u>6" Diameter</u> <u>8" Hot Zone</u>	<u>8" Diameter</u> <u>24" Hot Zone</u>	<u>17" Diameter</u> <u>48" Hot Zone</u>
Cost/Run	\$700	\$850	\$2200
Cost/Vol	\$1.38/in ³	\$.70/in ³	\$.20/in ³
Approx. # of Blades	60	165	1600
Processing Cost per Blade	\$11.67	\$5.15	\$1.38

Typical bridging costs for Rene' 80 would run approximately \$2/blade. For Ti-6Al-4V mounting brackets, bridging would be approximately \$.60/in² for the area requiring bridging, which would usually be less than \$2/casting.

Phase II: Densification of Full-Scale Complex Castings

Phase III: Process Verification and Economics.

Project Results

Manufacturing processes, based on HIP, were established for successfully densifying both Rene' 80 and Ti-6Al-4V castings. HIP effectively sealed shrinkage porosity in the castings, producing a metallurgical bond. Bridging was found to be necessary only in special cases because the as-cast surface was generally sound and free of porosity. The need for bridging was principally in the gating area after gate removal, in that porosity was exposed to the surface during cutting. CVD nickel plating and TIG welding were found to be the most effective surface bridging techniques for Rene' 80 and Ti-6Al-4V castings, respectively.

Improved properties of cast-plus-HIP parts were most noticeable for titanium parts. The elimination of nominal as-cast porosity considerably improved the fatigue endurance limit of these castings (by up to 30%) and produced fatigue endurance limits approximately 75% of those of forgings. However, stress rupture tests indicated that HIP may degrade the stress rupture properties of as-cast components with large porosity.

No significant difference in fatigue strength was found between the as-cast and densified Rene' 80 blades, due to the low degree of porosity in the as-cast blades. The densified Rene' 80 blades performed slightly worse than the as-cast blades in extremely rigorous Simulated Engine Thermal Shock (SETS) tests. This was due to alloy depletion, which was probably caused by autoclave gas impurities. Improved autoclave gas purity would result in less alloy depletion and reduced cleaning requirements on all densified castings.

Follow-on efforts required to resolve some of the problems encountered

2. Establish bridging methods for closing surface connected porosity.
3. Determine the process parameters for densifying each alloy.

Work on meeting these first three objectives entailed working with cast slabs only. The following three objectives involved work with actual engine components.

4. Refine the process using actual cast components (Rene' 80 LPT blade and Ti-6Al-4V engine mounting bracket).
5. Demonstrate pilot production-size runs of actual components, to demonstrate process reproducibility and economics.
6. Develop preliminary material and process specifications, and quality control and NDE procedures.

Project Description

Rene' 80 casting was performed by Howmet/Misco, and for Ti-6Al-4V by Titanium Technologies International. The titanium was centrifugally cast in a consumable electrode, skull crucible, vacuum furnace, using a rammed graphite mold material. This kept surface connected porosity to a minimum and reduced bridging requirements. Problems experienced included autoclave gas contamination, improper use of surface bridging, and determining the proper autoclave temperature cycle. All were found capable of degrading properties in the densification process.

The project had 3 phases:

Phase I: Determine Preliminary Process Parameters for Densifying Castings

PROCESS FOR HIGH INTEGRITY CASTINGS

(F33615-72-C-1381; May 1972 - June 1974; \$299,000)

Background

Casting is a moderately low cost process which provides great flexibility in the size, shape, and composition of the components that can be made. However, castings often have subsurface porosities which tend to seriously impair their fatigue properties. Large porosities can be detected by X-ray, and high rejection rates are not uncommon. Small undetectable porosities, whose presence is known on the basis of past experience, require that cast components often be used at conditions below the capability of the alloy.

Hot Isostatic Pressing (HIP) is a process which can be used to densify castings. This entails subjecting a casting, which can be NNS or NS, to simultaneous application of temperature and pressure in an autoclave. Before this MANTECH project, laboratory work had shown that HIP could produce fully dense material with uniform mechanical properties, and that already dense zones are little affected by densification. It thus offered opportunities for reducing scrap costs, improving material properties (especially fatigue strength) and, ultimately, replacing wrought or fabricated components with lower cost NS or NNS castings. There was also hope that HIP could be used to rejuvenate used components.

Project Objectives

The overall objective of this MANTECH project was to establish and demonstrate a manufacturing process to repair the inherent defects in castings of Rene' 80 and Ti-6Al-4V on a reliable, production basis.

There were 6 specific project objectives:

1. Define NDE techniques for detecting shrinkage.

Technology Transfer

G.E. has licensed the F1 ion/ADH repair technology to Motorturbine Union (MTU), a German turbine manufacturer. Like G.E., MTU is using a F1 ion/ADH repair process for CF6-50 stage 2 HPT vanes, and a H₂/ADH repair process for stage 1 HPT vanes. Chromalloy is currently exploring licensing with G.E. Technology transfer will be explored more fully over the course of the project and reported in the final report.

of Air Force engines, particularly those with turbine vanes of Rene' 80-- e.g., TF39, TF34, and F101. Rene' 41 turbine vanes in TF39 and J79 engines, and Rene' 77 turbine vanes in TF39, TF34, and F101 engines are also potential future application candidates. Of course, implementation of the processes for USAF repair is an Air Force decision.

There are also potential applications for the F404 engine, other HPT and LPT airfoils, and combustor components.

Benefits

G.E. estimates that the total cost savings from Fl-ion/ADH repair of CF6-6 and CF6-50 stage 2 HPT vanes is 13¢-20¢ per vane flight hour, or \$4.45-\$6.53 per (33 piece set) flight hour, in 1982 dollars. The CF6 family of engines has been logging about 4 million hours per year for the last 3 years (ref. G.E.'s magazine, "Commercial Engines," Summer, 1982). The lower bound estimate of \$4.45 per engine hour converts to \$17,800,000 per CF6 fleet year. Using these assumptions, savings for 1982 through 1992 (11 years) would amount to \$195.8 million, in 1982 dollars. Savings from H₂/ADH repair of CF6 stage 1 vanes were not estimated. These savings would be less than for the stage 2 vanes, since some welding is still required, but they would still be substantial. Although the MANTECH projects concentrated on developing the Fl-ion/ADH process for Rene' 80 components (i.e., the CF6 stage 2 HPTN vane), considerable process development work was also accomplished for X-40 (i.e., CF6 stage 1 HPTN vane) materials. Thus, the MANTECH program should be allocated at least some credit for the unmonetized but substantial savings from H₂/ADH repair of stage 1 HPTN vanes.

As discussed in an earlier section, the bulk of the repair cost savings from these ADH processes result from decreased scrap-out rates, since more vanes can be successfully repaired. There are also some savings in direct repair costs, especially for stage 2 vanes.

with F1-ion; both prior to an ADH process. The F1-ion/ADH process is a G.E. patented, improved process. The installation cost of the ADH processes at the Tennessee Avenue facility was approximately \$500K. To date, over 15,000 vanes have been processed with this technique. Turbine blades are still repaired by TIG welding.

It should be noted that there was a successful follow-on USAF MANTECH project at G.E.--F33615-78-C-5134--which scaled up the fluoride ion/ADH process from the first program, investigated other fluoride ion sources, and investigated the feasibility of cleaning several different alloys.

For new implementations, G.E. recommends a slightly different approach from the one they are now using. This new approach, developed during the follow-on project, entails using hydrogen fluoride gas alone and controlling the process by temperature. This would allow the use of lower temperatures, but involves using cylinders of hydrogen fluoride gas, a safety concern.

Discussions with both technical and management staff at G.E. indicated that this MANTECH project was indeed a significant contributing factor to implementation of the ADH processes.

Projected

Other than for the expanding application base of CF6-80A (A310, 767) and CF6-80C (A300, 767, 747) engines, no other applications are projected at this time. .

Potential

The F1-ion/ADH and H₂/ADH processes have potential for a large number

2 HPT blades and vanes (which are identical to those in the TF39) yielded the following results regarding repairability and costs:

Repairability Summary

<u>Component</u>	<u>% Repairable by Welding</u>	<u>% Repairable by ADH</u>	<u>% Increase in No. Repairable</u>
Stage 1 HPTV	67%	95%	42%
Stage 2 HPTV	63%	95%	51%
Stage 1 HPTB	48%	48%	-0-

Repair Cost Summary (Ratios)

<u>Component</u>	<u>New Part Cost</u>	<u>ADH Repair Costs</u>	<u>Weld Repair Cost</u>
Stage 1 HPTV	1.0	.33	.37
Stage 2 HPTV	1.0	.32	.39
Stage 1 HPTB	1.0	.45	.37

Implementation

Actual

An ADH process has been implemented recently by G.E. for CF6-6 and CF6-50 HPTN vanes at its Tennessee Avenue Component Repair Facility in Cincinnati and at its Singapore, Malaysia repair facility. The Stage 1 X-40 vane is H₂ cleaned, and the Stage 2 Rene' 80 vane is cleaned

Project Results

This project demonstrated that laser drilling can successfully drill small holes from .007 to .050 inches in diameter with depths of .250 inches and .100 inches, respectively, in nickel and cobalt base engine alloys, at entrance angles down to 15°. The select-grade ruby rod laser was found to be optimum for holes .007 inches to .035 inches in diameter, and the Nd: YAG rod had advantages for holes from .035 to .055 inches in diameter. The laser drilling process was found to leave a surface recast around the holes. For Rene' 125, HCF properties of flat specimens were found to be unaffected in holes \leq .018 inches in diameter (this is about the maximum diameter for turbine blades). Larger diameter laser drilled holes (\geq .050 inches in diameter) showed reduced HCF properties over non-laser-drilled holes. Intermediate-size holes were not tested, but other G.E. studies had indicated a threshold diameter of approximately .028 inches. Endurance limits were restored when the recast layer of laser drilled holes was removed by abrasive flow machining (AFM). AFM was found to be effective for removing recast in holes \geq .015 inches in diameter. SETS tests of Rene' 125 vane segments revealed superior performance for laser drilled holes (both coated and uncoated) and particularly for laser drilled/abrasive flow machined holes. Stress rupture tests showed that laser drilled holes yield stress rupture properties roughly equal to parent metal and superior to electrochemically drilled samples.

Process capability for drilling an advanced air-cooling design was demonstrated by drilling eleven advanced technology turbine blades. HCF tests confirmed properties equal to electrochemically drilled blades.

Equipment criteria, including maintenance and safety requirements, were established. Fluorescent penetrant inspection was found capable of detecting surface defects in holes \geq .025 inches in diameter when L/D ratios were 4:1 or less. Beam splitting optics for simultaneous drilling of multiple holes were successfully demonstrated.

Implementation, Benefits

The implementation and benefits from laser drilling are discussed in the following report on Adaptive Controlled Laser Drill Inspection, contract F33615-76-C-5135. The implementation and benefits from both MANTECH laser drilling projects are discussed together since they were part of the same development process. The Adaptive Controlled Laser Drill Inspection project followed the Laser Drilling project by nine months.

ADAPTIVE CONTROLLED LASER DRILL INSPECTION
(F33615-76-C-5135; January 1976 - September 1979; \$345,000)

Background

A previous Air Force MANTECH project (Laser Drilling, F33615-73-C-5006) had demonstrated the technical feasibility and economic attractiveness of laser drilling for a broad range of potential applications. However, there were still two areas in need of further development before laser drilling's full application potential could be realized. Greater penetration depth was needed; and opportunities for reducing drilling and inspection costs by using on-line inspection and adaptive control methods warranted pursuit.

Prior to this program, laser drilling had been proven capable of producing holes from 7 to 50 mils in diameter, to depths of 250 to 100 mils, respectively. Hole inspection was performed manually with "go/no go" pin gages. Cooling circuits were airflow inspected on "flow stands", and magnifying lenses and fiber optics light probes were used to detect hole defects.

Project Objective

Develop and demonstrate increased laser drilling penetration capability, an on-line hole measurement method, and adaptive process control.

Project Description

The project was performed in two phases. In Phase I, a development phase, work was conducted to increase laser drill penetration capability and to develop optimum parameters for drilling engine components. An adaptive controlled laser drill inspection method was also established and refined in this phase. In Phase II, a demonstration and evaluation phase,

a production prototype adaptive controlled laser drill inspection machine was constructed based upon the design criteria established in Phase I, and then tested. The machine was used to drill and inspect two different types of air cooled components--20 cast Rene' 80 prototype turbine blades and 2 Hastelloy X air nozzle guides. One-half of each type were drilled with adaptive control, and one-half were drilled with the adaptive control feature turned off. Detailed cost estimates and a process specification were then prepared.

Project Results

Efforts were successful in increasing laser drill penetration capability. Penetration capability was increased by a factor of almost 3 across hole diameters from 7 to 50 mils. This yielded a laser drill capability approaching the hole diameters and depths of other nonconventional processes, and encompassing hole size requirements for the vast majority of air cooled turbine components.

A remote lens positioning system was developed which permits the use of a Nd:YAG laser medium for drilling holes from 7 to 35 mils, to depths of .68" and .48", respectively. This method requires 40% fewer pulses for penetration, is less expensive, and can produce the majority of holes in air cooled turbine components. A large data base and a computer optimization program for minimizing hole taper were developed in the project.

Daily system calibrations of the electro-optical inspection system were required when the prototype system was operated in an on-line drilling and inspection mode. The inspection system was found to be generally effective for on-line adaptive control of the drilling process. Air-flow predictions were within $\pm 14\%$ of actual readings.

For advanced technology turbine blades, the cost savings of moving from standard laser drilling to adaptive controlled laser drilling were found to be quite small, approximately \$3.52 per blade or \$332 per engine.

The cost saving of standard laser drilling compared with electrochemical drilling of blade holes was confirmed at \$22.82 per blade, or approximately \$2,145 per engine.

Standard and adaptive controlled laser drilling costs for the air nozzle guides appear to have been equivalent. Savings over conventional EDM was estimated at \$19.50 per part, or 26% of total part cost.

Laser Drilling Implementation

Substantial implementation of laser drilling has occurred since the MANTECH laser drilling projects and more is in process. Six G.E. production engines now either utilize laser drilled components or are expected to do so in the near future. Applications include Stage 1 turbine vanes, shrouds, and blades. The materials are nickel and cobalt-base superalloy castings, mostly Rene' 80 but also including Rene' 125, MA754, and X-40. AFM is not being used for recast removal. If AFM had been required for product performance reasons--such as cyclic life--the economic attractiveness of the laser drill process would have been greatly reduced.

Adaptive control technology worked but was not found to be economically justifiable, the major factor being high equipment cost (based upon price quotes from vendors). Another problem is the time delay in on-line hole measurement. Since the MANTECH projects, drilling technology has advanced rapidly and drilling speed has substantially increased. The time delays required for on-line hole measurement are still substantial, and would negate the benefits from the enhanced drilling equipment capabilities. There were also some concerns regarding the difficulties in calibrating the hole measurement/adaptive control system. G.E. staff doubt that this problem can be resolved in the near-term. There is currently no feedback or real-time response capability on G.E.'s laser drilling production machines.

Implementation efforts at G.E. began in earnest in 1974 with the application of the laser process for drilling some of the CF6-50 Stage 1 HPT blade airfoil cooling holes. There was some difficulty in qualifying the laser drilling process internally at G.E. for other applications. Some reductions in tolerance limits had to be negotiated, and premature failures of laser-drilled F101 test engine turbine blades in 1975 had been attributed erroneously to the laser drilling process. Failure analysis later identified other factors as the cause.

Production implementation of laser drilling accelerated in 1978, with turbine nozzle vanes for the T700, a helicopter engine. By the beginning of 1978, G.E. had 3 laser drilling machines, drilling approximately 3 million holes per year. Since then, laser drilling has continued to expand. G.E. currently has 9 production laser drilling machines in Evendale, Ohio, 5 in Madisonville, Kentucky, and one in Albuquerque, New Mexico. Two more will be delivered soon. The machines cost \$240K-\$300K each and have a useful service life of approximately 10 years. By the end of 1982, G.E. will be laser drilling approximately 22 million cooling holes per year, or about 40%-45% of all holes. G.E. expects the use of laser drilling to continue to expand and to level off in the future with approximately 60%-65% of all holes laser drilled.

Figure 2 is an overview of G.E.'s laser drilling development and implementation processes. Note the two MANTECH programs in the shaded zones. Figure 3 relates laser drilling capabilities to capabilities of other nonconventional processes and to hole size requirements in G.E. engines. Figure 4 summarizes current and planned laser drilling implementation at G.E., and the resulting cost savings. Figures 2 and 3 were provided by G.E.

The laser drilling process is now the production process of first choice for turbine airfoil cooling holes. Figure 4 presents all current and planned laser drill applications, but it is reasonable to expect that over the next decade at least some of G.E.'s current advanced development engines will enter full-scale production using the laser drilling process. The extent of laser drill utilization and the production volume of these are unknown

Laser Drill Technology Roadmap

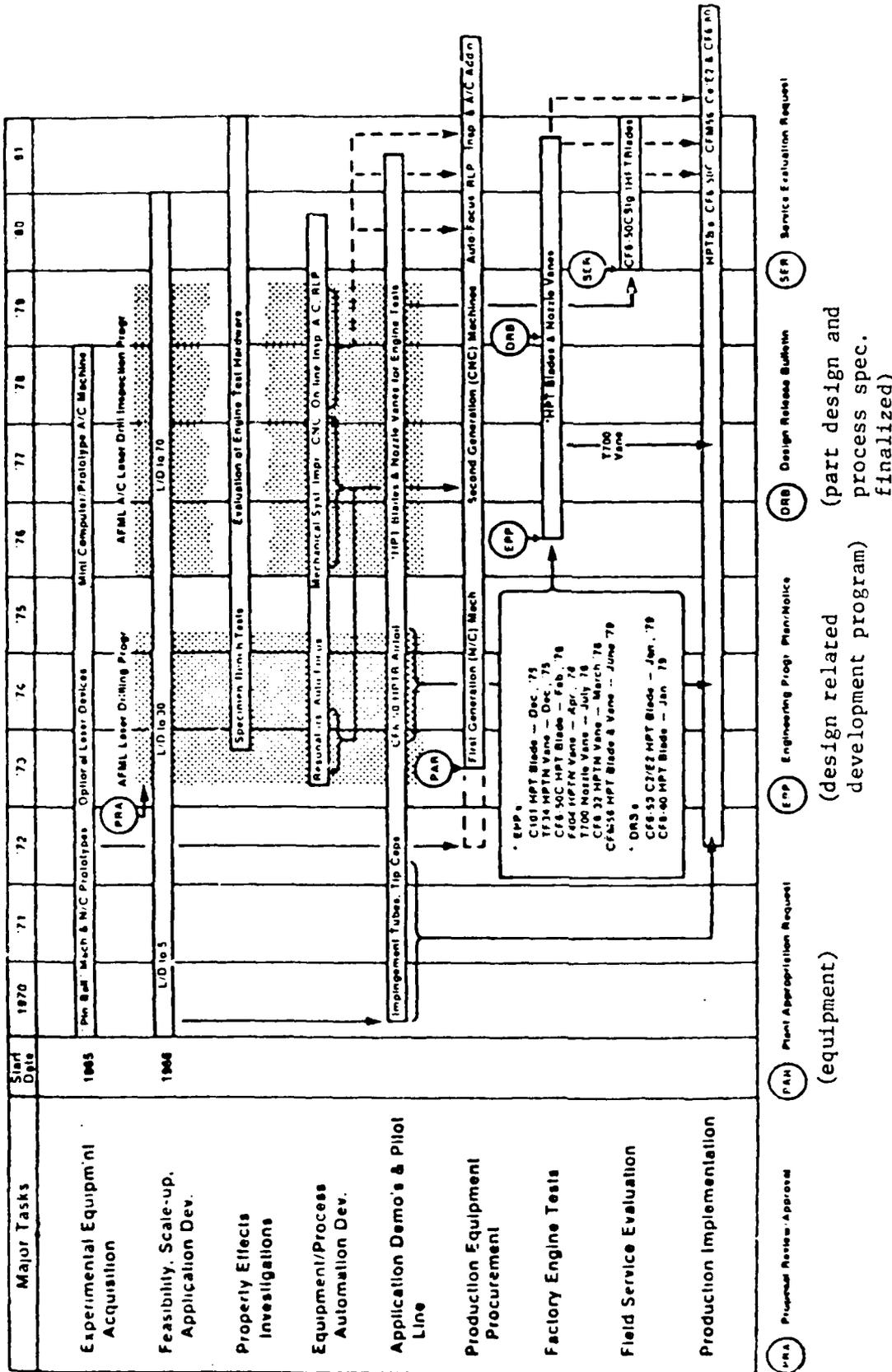


FIGURE 2:

LASER DRILL TECHNOLOGY ROADMAP

Expanded Penetration Capabilities of Laser Drill Process

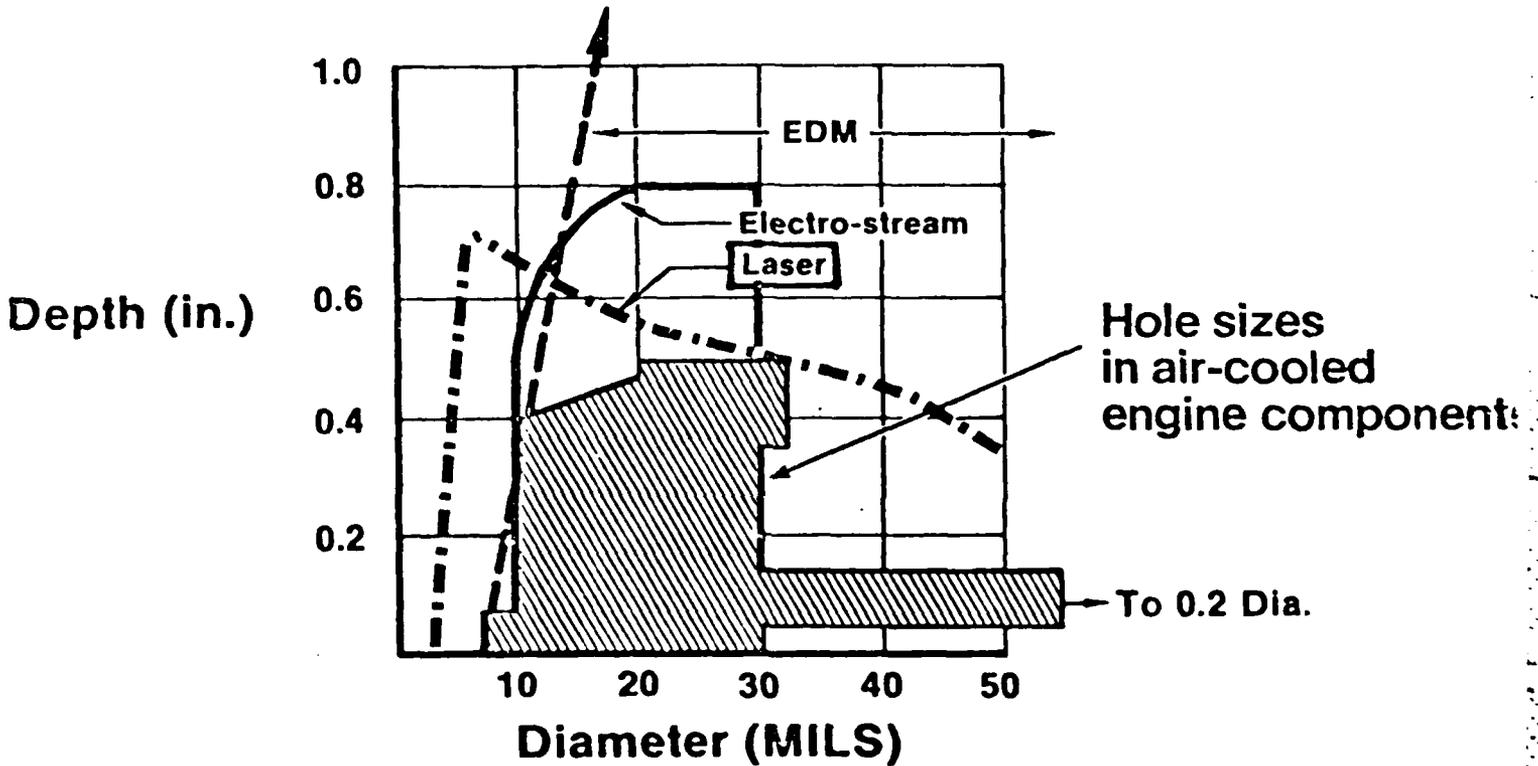


FIGURE 3:

EXPANDED PENETRATION CAPABILITIES OF LASER DRILL PROCESS

Line	Part	Parts/ Engine	Savings/Part (1982\$)	Savings/Engine (1982\$)	Implementation Year
F700	Stg. 1 Nozzle Vane	12	41.65	500	1978
CF6-50 CEE2	Stg. 1 HPT Blade	80	14.77	1182	1981
CF6-50 CEE2	Stg. 1 HPTN Vane	44	39.05	1718	1983
CF6-80	Stage 1 HPT Blade	80	14.77	1182	1981
CF6-80	Stage 1 HPTN Vane	44	39.05	1718	1983
CF6-80	HPT Shroud	24	41.67	1000	1982
CFM56	Stg. 1 HPT Blade	72	22.22	1600	1983
CFM56	Stg. 1 HPTN Vane	23	56.52	1300	1981
CFM56	HPT Shroud	27	48.15	1300	1982
F101	Stg. 1 HPT Blade	72	25.63	1845	1983
F101	Stg. 1 HPT Vane	23	78.26	1800	1983
F404	Stg. 1 HPT Blade	64	31.25	2000	1983
F404	Stg. 1 HPTN Vane	22	22.73	500	1983

ENGINE PRODUCTION SAVINGS (IMPL. YR+1 THRU 1992) = \$31,891,000

SPARE PARTS PRODUCTION SAVINGS (IMPL. YR+1 THRU 1992) = 14,253,000

TOTAL SAVINGS (IMPL. YR+1 THRU 1992) = \$46,144,000

FIGURE 4:

LASER DRILLING COST SAVINGS SUMMARY

at this time, and thus are not included in Figure III-4. The feasibility of the laser drill process for advanced turbine materials, such as DS Rene' 80 and monocrystal N4, has recently been established.

Benefits

The estimated total production cost savings from the first year after implementation through 1992 for current and near-term projected laser drill applications amounts to \$46,144,000, in 1982 dollars. Almost all savings are in direct labor costs of the drilling operations. The figures were obtained from internal G.E. cost analyses comparing laser drilling costs with either electrostream or electrical discharge machining on a part by part basis. As mentioned above, these hefty savings do not reflect any expansion of laser drill applications over the coming years, which is likely but unquantifiable at this time.

Technology Transfer

It appears that laser drilling is becoming increasingly cost-effective and increasingly utilized in American industry. Solar employs laser drilling for cooling holes in combustion chamber housings, and laser cutting has apparently been employed by airframe manufacturers and ship building firms. Technology transfer will be explored in detail over the course of the remainder of the project and reported in more detail in the final project report.

NEAR NET SHAPE DISK
INSPECTION SYSTEM
(F33615-78-C-5085, Sept. 1977-December 1979, \$497,000)

Background

Powder metallurgy (P/M) technology can be used for the production of NNS superalloy components, thus offering opportunities for large savings in material and machining costs. However, before critical, rotating components manufactured by P/M-NNS technology can be used in aircraft, reliable, high quality ultrasonic (U/S) inspection is essential to identify flaws, particularly near-surface flaws. At the time of this MANTECH project, conventional U/S inspection systems could inspect only blocky shapes and material envelopes greater than 1/8". Radii under 6" could not be reliably inspected without special procedures and calibration. Thus, while the use of P/M technology in itself provides considerable savings, the ability to fully realize the benefits of P/M technology requires an inspection system with superior capabilities to conventional systems.

In addition to their inadequate technical capability for near net shapes, conventional U/S inspection systems require extensive operator control and involvement. G.E. was using six conventional U/S inspection systems in production at the time of this MANTECH project. Before this project, G.E. had developed internally a laboratory prototype NNS-U/S inspection system. This MANTECH project built upon G.E.'s prototype system.

Project Objective

There were two main objectives in this project:

1. Develop a higher quality U/S inspection system, acceptable for P/M-NNS components.

2. Automate the inspection process, to make it more reliable and to increase productivity.

Project Description

The project was performed in three phases. Phase I identified the improvements needed in G.E.'s prototype system, and defined and procured the components of the production system. The hardware was purchased with G.E. funds, at a cost (in 1978-79) of approximately \$320,000. Phase II dealt with characterization technique investigation and system verification. Phase III demonstrated the system on an F404 blade retainer and an outer balance piston seal. These components were Rene' 95, and had been modified to provide (.5") curved contours and near surface (.05") fabricated flaws. F101 hardware had been planned but was not available. These representative P/M specimens, with small radius contours and fabricated near surface flaws, thoroughly tested the inspection capability of the NNS-U/S inspection system.

Project Results

The system had precise contour following, good adaption to unexpected deviations from nominal part shape, good resolution of near surface defects, and corrected for ultrasonic signal distortion caused by curved surfaces. The NNS-U/S inspection system could reliably inspect superalloy material envelopes down to .05" - .06" (as opposed to .125" before) and radii as small as .5" (as opposed to 6" before).

The following improvements/benefits were found, as compared to the conventional system:

1. Inspection scan rates were 2 to 3 times faster.
2. Operator influences were almost completely removed from the inspection process, improving reliability and repeatability. All phases were automated: set-up, calibration, testing, evaluation, and reporting.

3. Estimated 25-30% reduction in inspection costs.
4. Enabled procurement of lighter and therefore cheaper forgings.
5. Overall productivity (throughput) increased by 30-50%, depending on the component.

Implementation

Actual

G.E. has installed two production NNS-U/S inspection stations at its Evendale, Ohio plant and one at its Wilmington, North Carolina plant. The systems are used to inspect a wide range of different sizes and configurations of hardware, including disks, seals, blade retainers, spools, and engine mounts. Parts are inspected at envelopes down to .06". G.E. has developed and implemented software, which was developed outside the scope of the MANTECH project (called WIPP--Wrenn's Interactive Part Programming), which uses the graphics terminal linked to the electronic part definition in the CAD/CAM system. This allows the part geometry definition to be acquired directly from the CAD/CAM system.

Projected

The NNS-U/S inspection system developed in the MANTECH project has remained in the laboratory since development. It has been used to develop and improve NNS-U/S inspection methods. Current plans are to transition this system to normal production in early 1983. The original G.E. prototype system has been updated and modified to the same configuration as the MANTECH-developed production system. Current plans are to continue to use this system for G.E. manufacturing laboratory development programs.

Potential

Although there is no requirement now for inspection of envelopes less than .06", the new U/S inspection systems could be used to inspect down to finished configurations.

Benefits

All dollars referenced below are stated in terms of 1982 dollars.

From Actual Implementation

The primary elements in U/S inspection are set-up, calibration, inspection, and evaluation. The new NNS-U/S inspection systems improve the latter three elements of the process, but not the first. Since so many different sizes and configurations of hardware are inspected, making realistic part-by-part estimates of savings would be a monumental task. Therefore, the benefits have been analyzed in terms of overall savings across all parts--that is, on a functional work station basis.

For 1983, G.L. shop personnel estimate direct labor savings of 20% from use of the new NNS-U/S inspection equipment. Assuming a two shift, 6 day per week operation, this yields direct labor savings of approximately 1000 hours per machine. At an average rate of \$45 per hour for this work station, this amounts to \$45,000 per year per machine. With three machines, this yields \$135,000 in savings for 1983. Due to a learning curve effect, labor savings in 1984 and beyond are estimated to be 30%. Thus, from 1984 on, the annual savings per machine will be approximately \$68,000, or \$204,000 for the three machines. These figures do not include savings from reduced material envelopes or reduced machining requirements.

From Projected Implementation

If the system developed in the MANTECH project is transitioned to

molds at the midpanel locations. G.E. built a TRW-designed precision alignment and gaging fixture for cementing the mold segments together. An eight-piece segmented mold casting was also made--with a hub, ring, and 6 struts.

Project activities focussed upon process refinement and development, encompassing mold preparation, joining, and pouring. Technical and cost comparisons were made between the one-piece cast fan frame and the one fabricated from eight individual cast components. Studies were made to determine the effect of HIP on heat treatment, chemical milling, and welding. The eight piece fan frame was component tested, but not engine tested.

Project Results

The program successfully demonstrated the technical feasibility of using segmented molds and HIP densification for large castings. The HIP-densified Inconel 718 castings showed improvements in mechanical properties (particularly ductility), were able to be chem-milled, and had outstanding weldability. The basic concepts for a material and process specification were produced.

Dimensional accuracy of ± 0.02 inch per inch was achieved, although the number of castings was too small to gather data on repeatability of the process dimensions. The segmented mold was found to have the capability to adjust dimensions without expensive tool rework. The process has a potential for reducing mold inclusions since the mold surfaces in contact with the metal can be inspected before assembly of the mold segments. The segmented mold process was found to be particularly useful for producing large symmetrical parts, that can be divided equally into a number of parts of a size that enables the mold segments to be assembled and dipped by hand.

MANUFACTURING METHODS FOR LOW COST TURBINE ENGINE
COMPONENTS OF CAST SUPERALLOYS
(F33615-75-C-5084, Feb 1975-Nov 1979; \$1,229,286)

Background

Large, complex, non-rotating superalloy engine components, such as engine frames, have traditionally been fabricated by welding together a large number of small castings, sheet metal panels, and forgings. This process suffers from poor material utilization and substantial labor costs in subcomponent production, metal removal, assembly, welding, and inspection.

Even with those drawbacks, however, the difficulties in producing good quality large castings with the dimensional repeatability required for weld assembly, coupled with a high cost, had made the use of larger castings less attractive than the current practice.

USAF cost reduction studies and seminars in the early 1970's identified the need to develop improved methods of obtaining large castings as a high priority.

Project Objective

The objective of this project was to establish reliable, lower cost manufacturing methods for the production of large, complex superalloy castings, using advanced methods of mold making, melting and pouring, and Hot Isostatic Pressing (HIP) densification.

Project Description

A TRW-patented segmented mold process, combined with HIP densification, was used to produce a F101 fan frame (Inconel 718). The F101 integral fan frame consists of an inner hub, an outer ring, and six struts. For the one-piece casting, the hub and ring were segmented into six sections using the strut as the center line for each segment, because of the ease of joining

Due to the newness of the implementations and the lack of production experience, realistic estimates of cost savings could not be made to meet the deadline for this report.

Technology Transfer

Materials and coating requirements vary greatly across industries and firms, and typically each firm has its own internally developed processes and techniques for applying coatings. These factors tend to inhibit rapid transfer of coating technology. Each firm must recognize the potential benefits of the technology and then work to develop it and to apply it in its particular production environment. The level of industry interest in this technology, however, appears to be rather high. At least three (and maybe up to five) vendors now market automated thermal spray control systems (there were none before the project). Contacts with equipment vendors will identify more precisely the extent of technology transfer.

G.E.'s Gas Turbine Department in Schenectady, New York has installed and is presently qualifying for production an automated vacuum plasma system to apply corrosion resistant coatings to MS5000 and MS7000 turbine blades. G.E.'s Aircraft Engine Business Group's Albuquerque, New Mexico plant is in the process of installing an automated vacuum plasma unit to coat CF6, CFM56, F101, and F101-DFE high pressure turbine shrouds. The systems at Schenectady and Albuquerque are not yet qualified for production, but both are expected to be qualified in early 1983.

G.E. also has a prototype vacuum plasma unit at its facility in Evendale, Ohio, which is used for pilot line operations on new processes and coatings. G.E. is installing an air-plasma and combustion spray system at its Evendale manufacturing technology laboratory, in an attempt to develop a system which is more flexible and which enables control of a larger number of process variables. G.E. is also now evaluating a method to produce rapid solidification by plasma deposition. This is being supported through a MANTECH project (contract number F33615-81-C-5156).

Benefits

The objective of this MANTECH project was primarily technical--the need for a consistent, reproducible, high-quality finish in the spraying process rejection rates. Potential cost savings result from: increased successful throughput per unit of time; decreased material requirements; reduced direct labor requirements; and avoided facilities costs. Given the high equipment cost (currently running \$200,000-plus per system) it is unclear whether or not substantial net cost savings will be realized. Since high-quality coatings are essential for acceptable engine performance and, in many cases, acceptable component reliability and durability, their pursuit is thought to be worthwhile even at a higher cost. However, it is reasonable to expect that over time automation will drive costs down, and will ultimately lead to net overall savings compared with the manual approach.

feasibility of automating the process through computerization and remote controlled hands-off system operation. It demonstrated the capability of producing graduated coatings, and both combustion gas and plasma arc operation. It successfully removed the operator from the processing environment.

Implementation

In 1982, G.E. implemented an automated microprocessor controlled combustion spray process at Cincinnati Flame Spray (a G.E. subsidiary). The system, obtained through Plasma Technik, AG, Switzerland, was based upon the results of the USAF MANTECH program as well as internally funded development work. The design of the new system reflects advances in robotics and automated control technology which have occurred since the MANTECH project. Since, the project, G.E. has concentrated on improving manipulation and process control subsystems, and on using state-of-the-art commercially available industrial robotics equipment which will provide equal or better capability at lower cost. A key functional difference in the new system is that the spray process control is separated from the mechanical manipulation control system.

The system at Cincinnati Flame Spray was used to apply abrasible seal coatings to CFM56, F101, and F101-DPE compressor liner segments. The close property tolerances that were required could not be met using manual spray techniques. After production qualification and debugging, 101 runs were made. The process appeared highly effective and reduced re-work rates from 20% to 3%.

However, recent field operation of CFM56 engines has indicated that erosion of the coatings has been excessive. Therefore, a more erosion-resistant coating will be applied, by plasma spray methods. The automated combustion spray equipment will no longer be used for the applications previously mentioned. G.E. expects, however, to employ the system in the future for other abrasible seal coatings. These applications cannot be defined at this time.

uncontrollable within the actual conduct of the process. Uncontrollable variables were explained and suggestions were made on how to deal with them to maintain reproducible spraying properties. Effective ranges for variables were determined. Application techniques and materials were selected and a study made of their particular parametric variables and control categories, through controlled experiments.

Phase II evaluated control techniques and established methods suitable for real-time adaptive control. A basic system was conceived; a survey of computer and control hardware and software was conducted; and procurement recommendations were made.

In Phase III, a demonstration thermal spray unit was assembled and integrated. It was then tested, calibrated, and evaluated on its performance in thermal spraying (both combustion gas spraying and plasma arc spraying) simulated engine components. Evaluation of the spray runs included testing for erosivity, abrasability, adhesion, and micro-structure. Combustion spraying met or exceeded all minimum requirements. Plasma arc spraying met or exceeded all minimum requirements except tensile strength.

Phase IV was a process demonstration and verification phase. Ten TF39 stage 2 HPT blades, five F101 stage 4 HPC stator liners, and five J85 HPC rotor spools were coated, each with their required coating. The TF39 turbine blades were plasma arc sprayed with a graduated coating of a NiCr alloy and a refractory oxide, Al_2O_3 . The J85 rotor spools were combustion gas sprayed with an abrasable coating of a NiC composite over a layer of NiAl composite. The F101 stator liners were plasma arc sprayed with pure Al overlaid onto a NiAl composite bond coat.

Project Results

The system demonstrated a capability to apply coatings of an acceptable, reproducible quality and consistency. It thus demonstrated the technical

MANUFACTURING METHODS PROGRAM FOR AUTOMATION OF THE
THERMAL SPRAY PROCESS

(F33615-76-C-5188, July 1976-March 1979, \$450,000)

Background

Thermal spraying is a process widely used by gas turbine engine manufacturers and military repair centers for providing an abradable seal between blade tips and the engine casing. It is also sometimes used to deposit hard surfaces on such components as mid-span shrouds, shafts, and seal teeth. A coating is built up by propelling a coating material in a high temperature flame or plasma and depositing it upon a target surface in the activated state. There are a great many variables involved, including raw material properties, flow rate of the material, heat source properties, work piece characteristics, gun distance, impingement angle, gun traverse speed, and others.

In the past, an operator set a number of input variables and an automatic start-up system brought each of the parameters to the pre-assigned levels. However, there was no system to monitor and regulate these parameters as the process progressed. The quality of the coatings was highly operator dependent. A real-time monitoring and controlling function was determined to be essential for reproducible, high-quality coatings.

Projective Objective

The objective of this project was to develop and demonstrate a fully automated thermal spraying process, controlled in real time, which would produce high quality, reproducible coatings, with the operator removed from the process environment.

Project Description

The project was performed in four phases. Phase I identified, classified, and tabulated process parameters, and evaluated their individual and combined effects on the quality and characteristics of the resultant sprayed material. Variables were then identified as potentially controllable or

<u>Engine</u>	<u>Part</u>	<u>Implementation Date</u>	<u>Savings Per Engine</u>
F101	Stage 1 HPT Vane	1983	\$1,500
F101DFE	Stage 1 LPT Vane	1983	\$9,000
F404	Stage 1 HPT Vane	1983	\$1,500
F101	HPT Nozzle Band	1983	\$2,000
F101	HPT Nozzle Band Contoured Ring	1986	\$1,000 add'l
ENGINE PRODUCTION SAVINGS (IMPL. YR+1 THRU 1992) =			\$21,264,000
SPARE PARTS PRODUCTION SAVINGS (IMPL. YR+1 THRU 1992) =			4,443,000
TOTAL SAVINGS (IMPL. YR+1 THRU 1992) =			\$25,707,000

FIGURE 5:

ODS VANES
SUMMARY OF COST SAVINGS
(in 1982\$)

feasible. Savings for F101-DFE stage 1 LPT vanes are estimated at \$9000 per engine. The savings are summarized in Figure 5. They are based upon internal G.E. cost analyses. Materials cost savings account for approximately two-thirds of the total, the rest being due to reduced machining requirements.

Technology Transfer

None has been identified to date. This will be explored more fully over the course of the project and reported in the final report.

Implementation

Implementation of the NNS processes has been hindered by low production schedules for the F101 and F404 engines. Low engine quantities have meant that the cost and effort to replace heavily-machined extrusions with the new processes are more difficult to justify.

G.E. is now developing detailed NNS manufacturing processes, based upon the work in this project, for F404 stage 1 HPT vanes and F101-DFE stage 1 LPT vanes. Engine testing of the NNS-produced F101-DFE LPT vanes is planned for CY83. If engine testing is successful, production implementation will be considered. The F404 HPT vane will not require engine testing. The final decision on production implementation for both will probably be made in CY83. If implementation occurs, G.E. will probably produce the HPT vanes. Two qualified vendors have been identified for the LPT vanes. A decision on production implementation of a NNS-process for F101 stage 1 HPT vanes will follow the F404 program. G.E. staff indicated that the likelihood of implementation of these processes is very high.

A rolled ring process is now being considered for implementation, for F101 stage 1 HPT inner and outer nozzle bands. Implementation could occur in 1983. G.E. is also contemplating a contour rolled ring approach for production of these components. Implementation of the contour ring approach, if it is successful, would be anticipated for 1986. While this MANTECH project did not explore rolled ring NNS processes, it laid important groundwork for them.

Benefits

Savings for F404 and F101 stage 1 HPT vanes are estimated to be approximately \$1500 per engine. Savings for F101 nozzle bands are estimated to be \$2000 per engine, or \$3000 if the contour rolled ring process proves

test of NNS-produced F101 LPT vanes substantiated this. Although only LPT vanes were engine tested, the data indicated that both LPT and HPT nozzle components produced by these NNS processes would perform as well as conventionally produced components.

The EDM removal and braze replacement method which was used in the project to install the vanes in the bands for engine testing showed promise as an ODS nozzle repair process.

At the time of this project, the vanes were MA754, uncooled, and were produced by the conventional method, that is, by machining rectangular bar extrusions down to net shape. The final report covered the tests and development work in great detail, but did not present manufacturing process specifications.

Materials cost savings of 50-60% and machining cost savings of 20-30% were projected for the NNS process as compared with the conventional process for producing MA754 turbine nozzle components.

The EDM removal/braze repair process used in the project was found to be a cost-effective turbine nozzle repair method for MA754.

The cost comparison below is based upon the results of the project.

	<u>HPT Vane</u>		<u>LPT Vane</u>		<u>HPT Band</u>	
	Current Method	NNS Method	Current Method	NNS Method	Current Method	NNS Method
Material (lbs)	3.48#	1.51#	2.25#	.9#	5.4#	2.52#
Material (%)	80%	35%	75%	30%	85%	40%
NNS Processing	N/A	8%	N/A	9%	N/A	5%
Machining Cost to finish contour only)	20%	14%	25%	20%	15%	11%
TOTAL	100%	57%	100%	50%	100%	56%

and 8077. However, other testing of these alloys which was occurring at G.E. concurrently with the project showed MA754 to be the superior material. Therefore, the other 2 alloys were dropped from further consideration. Directional forging was selected for processing F101 HPT vanes, and plate rolling, followed by forge bending, was selected for F101 LPT vanes and F101 HPTN bands. Considerable experimentation and development work was performed in preform design, and forging and bending processes. Several attempts to forge to NS were attempted, but were not successful. Isothermal rolling did not produce acceptable results. Extensive testing of various preform shapes was conducted. 15 NNS-produced HPT vanes, 8 NNS-produced LPT vanes, and 7 NNS-produced HPT bands were final machined, and preliminary manufacturing process and product specifications were prepared.

Four LPT vanes were engine tested with satisfactory results. The HPT nozzle components were not engine tested because of a design change in the F101 HPT nozzle, rendering the fabricated parts obsolete.

Project Results

NNS processes were established for secondary working of ODS MA754 for turbine nozzle components. These processes were shown to be capable of maintaining required microstructures and properties for both the vane and band applications. Directional forging for HPT vanes, and plate bending for LPT vanes and HPT bands, were found to be the most cost-effective processes.

It was shown that commercially available bar stock can be used for forging stock and hot rolled plate for bending stock. Extruded kidney shapes with suitable microstructures could not be produced for use as preforms. Currently available equipment for isothermal shape rolling lacked the width and squeeze force necessary for HPT vanes.

Extensive testing showed that microstructures and textures equivalent to conventionally processed MA754 can be obtained by NNS processes. An engine

LOW COST PROCESS FOR MANUFACTURE OF OXIDE DISPERSION STRENGTHENED (ODS)

TURBINE NOZZLE COMPONENTS

(F33615-76-C-5235, June 1976-December 1979, \$398,250)

Background

ODS alloys are attractive for use as turbine nozzle materials because, although somewhat weaker at low temperatures than superalloys, they offer greater strength and creep resistance at high temperatures. They have higher melting points and are microstructurally stable nearly to their melting points. In some applications they can operate without protective coatings. The main attractiveness of the ODS alloys in application is that they reduce cooling air requirements and thus offer opportunities for improving engine efficiency. However, ODS alloys are very expensive, commonly costing \$60.00+ per pound. This high materials cost is compounded by the low utilization factor (8-10%) of the conventional process, which entails machining rectangular bar extrusions down to net shape. Furthermore, the machined chips are not directly recyclable.

Project Objective

The project's objective was to develop lower cost processes for manufacturing ODS turbine nozzle components. Processes analyzed included: large unit, high yield processes for primary preforms; near-net-shape (NNS) secondary working (directional forging and forge bending); and machining processes. A major unknown was the extent to which the process could move away from extruded rectangular bar and preserve the microstructure of the materials, which is critical. In addition to the question of technical feasibility, another major unknown was the cost of getting to NNS with acceptable material properties. The project was also to explore the feasibility of cheaper and more oxidation resistant ODS alloys.

Project Description

Originally, it had been planned to test 3 ODS alloys--YDNiCrAl, MA754,

production in early 1983 as planned, total savings in 1983 would be approximately \$180,000, and total savings per year in 1984 and beyond will be approximately \$272,000 per year. Savings from 1984-1992 would be \$2,448,000.

From Potential Implementation

As an enabling technology, the NNS-U/S inspection system enables the procurement of near-net-shape hardware with thinner envelopes, with consequent savings in materials and machining costs. Although this is happening to some extent now and is likely to occur even more in the future, meaningful estimates of the resulting savings cannot be made at this time. Also, additional NNS-U/S inspection machines are likely to be procured in the future, which would increase savings, but the numbers and timeframe for implementation are unknown at this time.

Technology Transfer

This MANTECH project contributed to the enhancement of equipment vendors' understanding and capability to produce NNS capable equipment. These testing stations are not commercially available except under contract per user specifications. Although vendors generally are not totally skilled in all areas of NNS-U/S inspection technology, the commercially available equipment is becoming more compatible with NNS intent. A number of other companies, including Pratt & Whitney Aircraft and a number of forging vendors, are also utilizing NNS inspection technology. Technology transfer will be explored more fully over the course of the project and reported in the final report.

The eight piece Inconel 718 fan frame showed a 29% overall cost savings over a similar Inconel frame produced by the conventional process. The one piece cast frame was estimated to save 26% of the standard process cost. The major unique costs of the one piece frame are 1) mold assembly, 2) added x-ray inspection, finishing, and straightening efforts due to the large, more cumbersome casting and its more extensive gating and 3) potentially higher repair and salvage costs.

Production F101 fan frames were, and still are, fabricated of 17-4PH materials, and not Inconel 718. 17-4PH is a ferrochrome alloy with material properties generally inferior to Inconel 718. Inconel 718 was selected for investigation because it is much more widely used for engine frames and castings than 17-4PH, which is used primarily in the front, cooler areas of the engine. The eight piece Inconel 718 casting was approximately 9% more expensive to produce than the fabricated 17-4PH fan frame; the one-piece casting was approximately 14% more expensive. 17-4PH's cost advantages in machinability and weldability could not be overcome.

Implementation

Components produced by the segmented mold process are not currently being used in G.E. production engines. T.R.W. continued development of the process, and G.E. subsequently explored the use of the segmented mold process under a NASA Energy Efficient Engine (E³) program contract. The process has been proven fully technically acceptable. However, based upon T.R.W. price quotes on a number of engine components, the process is judged to be not cost-effective at this time.

It should also be realized that recent advances in integral casting of large structures, many of which were supported by MANTECH, have tended to lessen the relative attractiveness of the segmented mold process.

Benefits

A potential, perhaps long-term, benefit of this process is that it would

enable smaller foundries to produce large structural castings with a minimum of new facilities. Such capability increases the number of competitors and yields cost and delivery advantages.

HOT ISOSTATIC PRESSING OF Ti-6Al-4V
POWDER FORGING PREFORMS
(F33615-72-C-1449; July 1972 - December 1974; \$285,740)

Background

In the early 1970's, powder metallurgy (P/M) surfaced as a manufacturing technology which offered significant potential cost savings for production of titanium alloy components. The use of titanium alloys in aircraft engines had expanded dramatically during the previous decade. Their costs were high, however. Titanium was very expensive and becoming more so, and material utilization in conventional forging of Ti billets was poor. Direct consolidation of Ti prealloyed powder into NNS preforms or NS components offered a way to reduce material inputs as well as machining costs. There were also other potential advantages of Ti P/M--more homogeneous microstructure, improved mechanical properties, improved machineability, and the capability of producing alloys that cannot be produced via conventional arc melting due to segregation problems.

Previous development efforts at G.E. and Battelle Columbus Laboratories (BCL), much of which had been supported by AFWAL/MLT, had demonstrated:

1) that what at that time was considered satisfactory quality titanium prealloyed powder could be economically produced if the oxygen content of the input material was kept below .13%; and 2) that cold-press plus sinter plus forge techniques could not achieve satisfactorily high density to prevent surface connected porosity. Only 90-92% theoretical densities could be attained.

G.E. and Battelle believed that hot isostatic pressing (HIP) could solve the densification problem. This was the approach investigated in this contract.

Project Objective

The objective of this project was to demonstrate that shaped Ti

preforms could be economically produced by HIP, which could be forged into engine disks with acceptable properties.

Project Description

In summary, the project entailed determining the best combination of powder type, HIP parameters, and forging parameters to produce a usable Ti part. The program was divided into the following three phases and tasks:

I. Process Selection

- A. Characterization of Powder
- B. Selection of Powder Size and Outgassing Techniques
- C. Selection of Preferred HIP Parameters & Powder Type
- D. Selection of Preferred Forging Temperature and Production Parameters

II. Process Refinement

III. Preliminary Specification and Q.C. Procedures

Battelle Columbus Laboratories was a major subcontractor on the project, and performed the HIP work and much of the powder analyses. Wyman-Gordon was also a subcontractor and performed the forging of the preforms.

Two powder lots were procured from each of two vendors, and one lot from a third vendor. All powder came from a common, low oxygen (600 ppm) in lot. Lots were screened to yield three screen fractions: coarse, fine and as-received. Characterization analyses were then conducted for particle size, distribution, microstructure, surface characteristics, tap and vibrated

density, and chemistry. Using HIP parameters that were known to yield fully dense compacts, a series of evaluations were conducted to determine the preferred outgassing temperature (room temperature or 100°F) and preferred screen (particle) size for each of the lots and groupings of powders. A series of 13* sets of HIP parameters--that is, variations of temperature, pressure, and time--were used to consolidate the preferred size of the powders, outgassed at the preferred temperature. One powder type and one set of HIP parameters were then selected as preferred, based upon the best combination of strength, ductility and fracture toughness of the as-HIPed compacts. Next, a number of subscale forging preforms of various sizes and shapes were compacted from the selected powder at the selected HIP parameters. These were forged at BCL on an instrumented forge press. Several variations of temperature and height reductions were evaluated to establish the preferred forging schedule. Two pieces of the original input material were forged along with the powder preforms for comparison purposes.

In Phase II, four shaped forging preforms for J79 first stage compressor disks were consolidated from the preferred powder, using the preferred HIP parameters developed in Phase I. Two NNS disks were also HIPed. The preforms were forged (at Wyman-Gordon) using two different forging schedules established in the subscale forging evaluation. The parts were machined to an ultrasonic configuration, non-destructively tested by ultrasonic and fluorescent penetrant inspection, and cut up for evaluation of mechanical properties. A piece of the as-HIPed material was evaluated for comparison purposes.

In Phase III, preliminary specifications were prepared for the powder and process. Quality control procedures were also established. Lastly an economic evaluation was performed which compared the costs of: forging powder preforms to NNS; the as-HIP to NNS process, and the conventional forging process.

*14 including baseline conditions

Project Results

The spherical powder, produced by Nuclear Metals, Inc. by a rotating electrode process (REP), was selected as the preferred powder. Its oxygen level increased less, it could be HIPed directly without a preparatory cold press, and most importantly, it could be outgassed at room temperature. The hydride and a hydride-dehydride (HDH) powder required cold compaction to prevent metal container wrinkling. The HDH required a hot (1000°F) outgas. The minimal differences in results in using the three powder sizes indicated that the costs of selective screening are not warranted, and therefore run of mill (ROM) or "full cut" could be used. The presence of tungsten inclusions in the REP powder, from its manufacturing process, showed no harmful effects on any of the properties tested, including fatigue properties. The presence of these inclusions was determined by radiography and metallography. Although these did not affect the properties of annealed Ti-6Al-4V as tested, an inclusion in an area of high stress could result in premature component failure in a high strength alloy system such as Ti-6Al-2Sn-4Zr-6Mo.

The final HIP powder preform for the J79 first stage compressor disk was designed to impart an average panel reduction of about 50%. Conventional beta forging required two blows in the finish die. Alpha plus beta forging imparted the full 50% panel reduction in a single blow. Both forged materials, as well as the as-HIP material, exhibited excellent material properties. The forged material exceeded specifications in all properties tested. The as-HIP material's tensile strength (ultimate and 0.2% offset yield) was about 2-4 ksi below specification. However, this low strength was attributed to the low oxygen content of about 600 ppm. Its fatigue properties were approximately equal to the forged materials.

Several sets of HIP parameters (time-temperature-pressure) yielded 99.9-100% theoretical densities. However, for production of material to be used in an as-HIP condition, the 1750°F-10,000psi-3hr HIP cycle was found to yield superior fracture toughness qualities. The forgeability of HIP powder preforms was found to be equal to or slightly better than conventional billets

An economic analysis was conducted for a typical flat engine disk, based upon the following key assumptions:

- 1) production run of 250 parts
- 2) new dies
- 3) \$6.00 per pound powder cost
- 4) use of latest technologies in the production process
- 5) all costs in 1974 dollars
- 6) as-HIP to NNS defined as the finish machined part with a nominal .100 inch thick envelope
- 7) HIP and forging performed by outside vendors

It was found that forging HIP powder preforms offered potential savings of approximately 12% over the conventional process. HIP to NNS offered a greater potential savings--approximately 39%.

The (12%) estimated cost savings from forging HIP Ti-6Al-4V powder preforms results primarily from 1) reduced forging costs, due to new dies and a smaller finish preform, 2) decreased material requirement from using smaller, closer envelope dies, and 3) decreased rough machining due to decreased material input (closer envelope). The problem of die draft angles (approximately 6°) in the conventional forging process which was used, and the fact that two different subcontractors were required for HIP and forging, which compounded indirect and profit charges, tended to depress the potential savings.

The larger cost reductions (39%) for HIP to NNS are due to several

factors. There are no forging costs, and since the forging draft angles do not have to be considered, material requirements are considerably reduced. Since the material envelope is so drastically reduced, machining requirements are also substantially reduced.

An added advantage of HIP-NNS technology is that it reduces the cost of design changes. Changes in component design do not require expensive sinking of new dies or modifications in forging procedures or equipment.

Even with the promising findings from the particular conditions tested in this project, it was fully realized that the inclusions in the powder were a major limiting factor, and that this problem would have to be resolved before widespread implementation was possible. There have been a number of follow-on MANTECH programs with powder vendors to improve the powder. G.E. staff state that verification of an acceptable powder, made by a plasma rotating electrode process, may soon be obtained.

Implementation

In addition to powder contamination, Ti powder's high cost has also been a major barrier to its use. Even in large quantities, Ti powder now costs significantly more than Ti barstock. G.E. is not currently using Ti powder processes for production, nor does it have any plans for doing so in the near-term.

Benefits

Due to lack of implementation, no monetary benefits were identified.

Technology Transfer

Northrop is now working on qualifying an F404 engine mount support on the F-18 made as-HIP to NNS from Ti powder. Thirty will be produced and

tested. DoD, the Navy, and Northrop have all agreed that if the test results are acceptable, that is, if the technical and economic feasibility are demonstrated, the as-HIP process will be used in production. The target for a decision on the qualification is 1985. Colt Crucible is the contractor performing the HIP, with Northrup serving as the mechanical property evaluation subcontractor.

A currently ongoing MANTECH project at Williams International is exploring the technical and economic feasibility of using an as-HIP Ti compressor impeller in the F107 cruise missile engine. Colt Crucible is the HIP contractor in this project with Williams International the evaluation subcontractor. They have produced 8 impellers and have begun to static test them. Engine testing will follow. Preliminary estimates of savings are \$1200-1300 in machining costs per engine plus material savings of approximately 9 pounds of Ti alloy per engine. The powder being used is made by NMI's plasma rotating electrode process.

MANUFACTURING METHODS FOR SHROUDED BLADE AND VANE FABRICATION
(F33615-75-C-5053, January 1975-January 1979, \$491,000)

Background

Shrouds on the mid-spans and tips of blades and vanes have become extensively used in recent years to produce required rigidity with minimum thickness and width. This yields improved efficiency and thrust. Shrouds also provide a marginal increase in FOD protection. The high stresses present require that the shroud be an integral part of the blade.

The conventional method of producing shrouded blades involves forging from large preforms followed by extensive machining and hand benching. G.E. cost analyses have shown that conventionally produced shrouded blades cost 2 to 8 times as much to produce as unshrouded blades. The high cost of producing shrouded blades and vanes drove G.E. to look for new and better technology for their production.

Pressure bonding, (now called pressure welding) appeared to be an attractive approach, for both titanium as well as some high temperature superalloys. Using this technique, separately produced shrouds are joined to conventionally produced airfoils. The joint interfaces are induction heated and joined under high pressure. The induction heating is localized, leaving the bulk of each unaffected. The high energy rate plastic upsetting could produce a joint with mechanical properties equal or nearly equal to the parent metal. The joining process had the potential for rapid throughput and could join a wide range of irregular cross-sections, thus offering many potential applications. Pressure welding also showed promise as a repair technique.

Project Objective

The MANTECH project's objective was to establish a manufacturing process for producing shrouded titanium fan and compressor blades and vanes at lower cost, by employing pressure welding to join inexpensive shroud and airfoil subcomponents.

Project Description and Results

The F101 Stage 2 fan blade (tip-shrouded), F101 Stage 2 fan vane (shrouded at both ends), and the TF39 Stage 1 compressor blade (mid-span shrouded) were selected as representative shrouded airfoils for demonstration. Just prior to the project, G.E. installed a first generation pressure welding facility (equipment cost was approximately \$45,000) which was used in this project.

In addition to welding numerous simulated airfoils in process investigation, welding of the following 3 types of components was attempted:

F101 Stage 2 fan blade:

Ten welds were attempted, but they were all too questionable for component or engine testing.

F101 Stage 2 fan vane:

There were many problems encountered in pressure welding the F101 vanes. Of the 24 vanes welded, only 4 resulted as candidates for testing after all machining and inspection had been performed. The welds in all the vanes were judged too questionable to engine test. Component testing showed impact resistance and HCF properties essentially equal to conventionally produced vanes.

TF39 Stage 1 compressor blade:

An approximate 90% yield was obtained in welding, with dimensional accuracy of $\pm .005$ ". A total of 26 pressure welded blades were finish machined, heat treated, surface peeled, and wear coated. Six bonded blades were bench HCF tested and showed no difference in HCF life from conventionally produced blades. The six blades were then engine

tested. The blades were acceptable in all respects. The mid-span shroud was easier to bond and most successful due to the larger bonding area. All components were titanium alloys.

Savings on the TF39 Stage 1 compressor blade were estimated to be 10.6% of the finished part cost. The main reason the savings were not higher was that a finished part could not be pressure welded, due to the dimensional criticality of the shrouds.

Implementation

The modest potential cost savings realizable from pressure welding have not been judged sufficient to warrant implementation of the process. The economically attractive and technically feasible application of this technology is limited to the bonding of finish machined subcomponents where dimensional tolerances are rather loose. Since this kind of application base is small, to date other implementation also has not occurred.

Although pressure welding has not been implemented to date, it is a leading candidate process for production of fan blisks (these combine the hub and fan blades into one unit) for future engines. G.E. is currently evaluating pressure welding technology for blisk production as part of its JTDE work, with Navy support. Potential applications would be in the JTDE and F404B engines. Blisks yield large weight savings and thus substantially improved fuel consumption. If successful, introduction of pressure welding technology at G.E. could occur in the 1987-88 timeframe.

Technology Transfer

None was identified. The Navy and the American Welding Society will be contacted for leads.

MANUFACTURING METHODS FOR
STANDARD PROCESS SCALE-UP OF FINEWEAVE
CARBON-CARBON COMPOSITE BILLETS
(F33615-75-C-5254, Sept 1975-Sept 1977, \$526,018)

Background

In the late 1960's, the Air Force and industry began looking for improved materials for re-entry vehicle (RV) nosetips. During this period, RV nosetips were being made of carbon matrix materials which were less than 100% carbon. They had less than acceptable thermal stress properties at high temperatures, and their reliability was unsatisfactory. Their ablation upon re-entry was rather severe and variable, thus degrading the accuracy of the RV. They also imposed certain design constraints on the RV.

By the early 1970's, G.E. and other industry researchers, with USAF and Navy research and development support, had made significant breakthroughs in producing pure carbon materials suitable for use in RV nosetips. The process for production of this material consisted essentially of densifying woven carbon preforms. This was accomplished in a three stage process entailing 1) production of a fineweave carbon preform, 2) carbon infiltration by chemical vapor deposition (CVD), and 3) densification through an impregnation-carbonization graphitization process (see Figure III-6). The final carbon-carbon billet which was produced could be machined to size and shape using conventional machining equipment and processes.

This process was called the "2-2-3 Standard Process". The "2-2-3" refers to the 3-D orthogonal construction of the preform, using T-50 fibers in all three directions, with 2 plies of fibers in 2 directions ("X" and "Y") and 3 plies in the third direction ("Z"). Fiber Materials, Inc. (FMI) made the preforms, Union Carbide performed the densification (at Oak Ridge in government owned facilities), and G.E. performed the NDE, CVD, and machining.

Since G.E. was USAF's major producer of RV's, it would be the user of the carbon-carbon product.

The attractiveness of the 2-2-3 carbon-carbon composite stems primarily from its material properties. Its thermal stress properties are excellent, and it yields extremely reliable nosetips for RV protection. It has low, predictable ablation, resulting in low, predictable shape change during re-entry, and thus improved RV accuracy.

The "2-2-3 Standard Process" had been developed and used to produce 4"x4"x8" carbon-carbon composite billets. However, USAF was moving to bigger nosetips and RV designs (i.e., cone angles) which required larger billets for their production. USAF was also interested in using these larger sizes in certain rocket nozzle applications. But before this was possible a manufacturing process was needed for the larger sizes.

Project Objective

The objective of the project was to use the same basic CVD and densification processes which had previously been developed for 4"x4"x8" nosetip billets to produce larger billets (4"x4"x11", 6"x6"x8", and 8"x8"x12") of equal quality. This included preparing complete material and process specifications.

A secondary objective was to determine if the 2-2-3 densification process could be used to produce carbon-carbon composites from a different kind of preform. The alternative preform was AVCO's Fineweave Pieced Fabric preform (FWPF). These are made of a graphite woven fabric lay-up which has been reinforced in the third direction ("Z") with close packed graphite fiber bundles. These do not require CVD since they are rigidized during fabrication.

Several significant problems remained to transition the laboratory model concept into an operationally acceptable configuration. The size, weight and technical uniqueness of system components in the laboratory model were of major concern. Manufacturing technology and producibility became a key element in the transition of the HIRD concept into a production-ready display system. Areas identified for a manufacturing technology study were: 1) relaxation of the necessity for custom design and manufacture of key components, 2) establishment of tooling for production prototypes, and 3) system verification of the manufacturing process by producing and evaluating a prototype of the HIRD system from a pilot production manufacture sample.

Project Objective

The primary objective of this effort was to develop a simplified manufacturing process for economical production of a multi-tube display and multi-sensor processor unit capable of meeting USAF HIRD requirements.

Project Description

The program was divided into three phases:

- Phase I. The development of manufacturing methods for display optics, memory components and display tubes.
- Phase II. The construction of one complete display and processor engineering model using the manufacturing methods developed in Phase I.
- Phase III. The construction of two display and processor units on a manufacturing sample basis to verify product performance and manufacturing reproducibility.

A biocular lens had previously been developed by G.E. under Air Force contract for use in a multi-tube display. This display provided image magnification, low distortion, and fatigue-free viewing for use with a number of USAF guided weapons delivery systems. Phase I tasks were defined to reduce the number of required optical elements

MANUFACTURING METHODS FOR HIGH INFORMATION RATE
COCKPIT DISPLAY
(F33615-75-C-5203, July 1975-May 1978, \$1,754,000)

Background

In the early 1970's, with the development of new sophisticated weaponry and target acquisition and designation sensors, it became apparent that the use of these technologies was extremely problematic. As the number of sensors grew to include radar, forward looking infrared (FLIR), and television, two problems became apparent:

- 1) Aircraft cockpits could not accomodate all the necessary displays and controls.
- 2) Simplification of the display and sensor operation was required for a weapons officer to fully use the sensors' high data rates.

Operators concluded that a cluster of cathode ray tubes that could sort and display the high information rates would minimize handover time from one sensor to another. In addition, the ability to switch rapidly from sensor to sensor on a single display would enhance target identification and tracking. A laboratory display system had been fabricated by G.E. to evaluate alternative solutions to solve these problems. The High Information Rate Cockpit Display (HIRD) system concept evolved from these early investigations.

PAVE TACK was an ongoing USAF development program during this time period. A requirement existed in the PAVE TACK program for a cockpit display system that could handle TV, IR, and radar imagery with high information rate display. The development of G.E.'s laboratory model system had been funded by other USAF programs ongoing at this time that had a requirement for integrated weapon system cockpit displays. The AGM-65 and GBU-15 "smart bombs" (laser and TV guided) were two of these.

from \$12,500 each in 1975-1976, to \$7,500 in 1977, to less than \$2,000 today, where they are batch processed in groups of 36.

Technology Transfer

The previously mentioned application of carbon-carbon material for protective shells for space motors can be considered a case of technology transfer. Also, G.E. is investigating the use of carbon-carbon materials for combustion chamber liners in jet engines. Technology transfer will be explored in more detail during the course of the project and reported in the final project report.

Battelle estimated the total cost for equipment and facilities for EISP to be \$1,611,500. IISP equipment and facilities cost would be almost identical. Since equipment and facilities costs represent only 7% of total processing cost, a 50% increase in throughput would reduce the per unit fixed costs by only 13.5%. However, there would also be a considerable savings of consumables (esp. gas), which accounts for approximately 13% of all costs. The major unknown is the labor cost saving. Labor costs were estimated to be 60% of the total processing cost for the EISP. The IISP percentage should be similar. What is not known is the degree of fixed versus variable labor cost. At least some modest portion of the labor requirement is fixed, and would lead to some labor cost savings using IISP.

Based upon all the evidence available, G.E. staff now believe IISP will save somewhere between 34%-50% of the total processing cost. These percentages are somewhat higher than would be inferred from the Battelle cost analysis. However, Battelle amortized all equipment over a 10 year period while analyzing production runs for 2.1 and 5.6 year periods. Since equipment was to be totally dedicated, the 10 year amortization period appears unrealistically long. A 5.6 year amortization period, which might even be optimistic, would almost double the equipment cost per processed billet, and thus almost double the savings from IISP's higher throughput. Therefore, it is not unreasonable to anticipate a 50% overall cost saving from the IISP, per billet processed.

Another benefit of the EISP and IISP development work is that it laid important groundwork for establishing the reliability and feasibility of concentrated batch processing for nosetips. The potential for enhanced batch processing was explored more fully in a USAF (non-MANTECH) supported project subsequent to this project called Pan Pilot Plant Production (P⁴) Program which batch processed 18 billets. Increased batch processing has been largely responsible for the steady and significant cost reductions which have been made in nosetip billet production. For example, the selling price of G.E.-produced nosetip billets has fallen

Benefits

The primary benefit of the EISP effort was that it established an approved process for a contractor to supply the material to meet Air Force needs. Since G.E. was the major producer of RVs for the Air Force, the project not only got the process ready for production but, in doing so provided the impetus for the contractor to prepare for production as well.

The manufacture of carbon-carbon composites involves two major operations, and two major cost factors. One is the manufacture of the preform. The other is the densification of this preform to convert it to a carbon-carbon composite. All preforms in this project were supplied to G.E. as GFM. Their manufacturing cost, as well as machining and other final part preparation costs, are not considered in the analysis of potential cost savings. Thus, the percentage cost savings from the IISP, which are presented below, are not in terms of finished part cost but, rather, in terms of the processing cost to convert a preform into an acceptable carbon-carbon composite. It should be noted that unlike 2-2-3 preforms, FWPf rigidization is performed as part of the preform manufacturing process.

A brief cost analysis was conducted by G.E. for the IISP. Under a G.E. subcontract, Battelle Columbus Laboratories conducted a detailed cost analysis of the EISP. All estimates are in 1977 dollars. Based upon reasonable baseline assumptions regarding production volumes, production rates, preform sizes, equipment utilization and indirect costs, IISP savings in CVD infiltration were estimated at approximately \$71 per preform (from approximately \$209 to \$138), a saving of approximately 34% (of CVD infiltration costs). The major saving, however, is the reduced autoclaving time in densification, which enables greater throughput--approximately 50% greater. With many costs fixed, the densification cost per processed billet is reduced.

nosetips. However, some of the findings from the IISP effort were incorporated into the EISP. The use of thermocouples in the autoclave, inside and on the cans, has been adopted for better process monitoring and control. Also, a 230°C 11 hour autoclave hold cycle was reduced to 3-6 hours.

G.E. used the results of the IISP to develop processing specifications for carbon-carbon composites for rocket nozzles. Since 1978, over 100 rocket nozzle billets have been produced for the Air Force by the IISP method. USAF procurement of these is expected to increase sharply in the near future. There are no MIL-specs for these components.

G.E. has also used the IISP to produce protective shells for RTG's containing radioactive material (esp. space motors).

During the development work on IISP, BMO was moving aggressively to flight test and develop specifications for advanced RVs with EISP-produced nosetips. By the time IISP was ready, BMO had already completed its testing program with satisfactory results, and had already committed to EISP. Part of the anticipated cost savings from IISP--the CVD infiltration savings--would not have been realized anyway since BMO selected FWPF, which does not require CVD infiltration. Nevertheless, G.E. staff believe that if for any reason USAF went to 2-2-3 preforms significant savings could be made.

G.E.'s capability to produce carbon-carbon composites extends to billet sizes up to 16" in diameter. There are some other attractive MX rocket nozzle applications that require billets larger than this. However, based upon the uncertainties in procurement volumes to date, G.E. has not committed to facilitate for their production. Facility costs are estimated at \$1-2 million.

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G.E. has also used the IISP to produce protective shells for RTG's containing radioactive material (esp. space motors).

During the development work on IISP, BMO was moving aggressively to flight test and develop specifications for advanced RVs with EISP-produced nosetips. By the time IISP was ready, BMO had already completed its testing program with satisfactory results, and had already committed to EISP. Part of the anticipated cost savings from IISP--the CVD infiltration savings--would not have been realized anyway since BMO selected FWPF, which does not require CVD infiltration. Nevertheless, G.E. staff believe that if for any reason USAF went to 2-2-3 preforms significant savings could be made.

G.E.'s capability to produce carbon-carbon composites extends to billet sizes up to 16" in diameter. There are some other attractive MX rocket nozzle applications that require billets larger than this. However, based upon the uncertainties in procurement volumes to date, G.E. has not committed to facilitate for their production. Facility costs are estimated at \$1-2 million.

Detailed IISP process specifications were prepared. Flight tests of IISP-produced nosetips have not been conducted.

This program demonstrated the reproducibility of the carbon composite production process within small batches, between batches, and between two types of preforms. This yielded a high degree of confidence in the process. All results indicated that the EISP and IISP were both ready for production. No additional equipment or facilities were required for nosetip production.

Implementation

EISP

As a result of this project, G.E. was established as an industrial source for manufacturing carbon-carbon composites, using the EISP. MIL-specs were issued based upon the project findings. The first application of the EISP was at G.E. in 1977 for ICBM RV nosetips. The process has been used continuously since this time to produce RV nosetip materials for newer generation RVs. Currently, nosetips for all USAF ICBM RVs are being produced by G.E., using this process. Nosetips for projected future Air Force ICBM RVs, including advanced models now under development, are also expected to be produced by G.E. as another source using the EISP. To date over 1400 billets have been produced at G.E. by this process. 500 more are on order, and more are anticipated after that.

Based upon vendor price quotes in 1976-1977, the FWPF preform was found to result in lower overall cost than the 2-2-3 preform, and was selected by USAF.

It should be noted that McDonnell-Douglas is an Air Force approved second source for nosetips.

IISP

Officially, IISP has never been adopted as a process for advanced

liquid pitch impregnation process, reducing autoclave hold times, reducing the number of process cycles required, improving process control through use of thermocouples in the autoclave and reducing graphitization temperatures. After the IISP was established, two AVCO FWPF billets were densified.

Note:

All equipment used for CVD infiltration, impregnation, pressure carbonization, graphitization, and (in-process) NDE was purchased and installed by G.E. with internal resources.

Project Results

EISP

Detailed characterization tests by SoRI and USAF showed the EISP billets to be of equal or superior quality to those previously produced using a combination of an industrial source for CVD infiltration and a government source for matrix densification. One of the two billets was subsequently machined into a RV nosetip and was successfully flight tested.

IISP

Combining the 1500° heat cleaning and the two CVD processes into a single operation was successful. The standard 2-2-3 infiltration process of a 35 hour cycle followed by a separate 45 hour cycle was reduced to a single 60 hour infiltration. The liquid pitch impregnation process was successful and autoclave time was cut from 34 hours to 16.5 hours. All of this was accomplished without adversely affecting the quality of the product. Reductions in graphitization temperatures (from 2750°C to 1800°C) were found to be inefficient. The IISP was found to be applicable to FWPF billets, and to be more efficient in densifying both types of material. Four-cycle IISP densification of FWPF preforms yielded bulk densities greater than 1.94 g/cm³. Four cycle IISP densification of standard 2-2-3 preforms yielded bulk densities of 1.858 g/cm³. The EISP required 5 densification cycles to meet minimum specification requirements of 1.840 g/cm³.

Thus, the first objective primarily involved process demonstration, while the second objective entailed process development and demonstration.

Project Description

EISP

Two 4"x4"x11" 2-2-3 preforms were supplied to G.E. as GFM by Fiber Materials, Inc. (FMI). All processing, including NDE, CVD, and densification, was performed by G.E. staff using G.E. equipment and facilities. NDE, mechanical, and thermal characterization of the final billets were conducted by SoRI. The Air Force conducted ablation tests.

Several slight modifications to the CVD process were made involving NDE procedures and adjusting for the 11" long preform as compared to the 8" preform (for which the process had been established). Some design deficiencies were found in the autoclave, and a heater malfunction in the final densification cycle caused a slight deviation from process specifications. However, the problems were minor and manageable, and all were corrected after the EISP billets were processed.

IISP

Each manufacturing, testing, and evaluation operation was reviewed to identify where economies in the standard 2-2-3 process could be made without sacrificing quality.

In the CVD process, efforts focussed on combining the two-cycle process into a shorter, single cycle. Four FMI preforms were used to establish optimum single-cycle processing conditions, and four more FMI preforms were used to demonstrate the reproducibility of the single-cycle process. The graphite support frame was modified to improve gas infiltration.

In the densification process, efforts focussed on developing a

MANUFACTURING METHODS FOR PROCESSING
FINEWEAVE CARBON PREFORMS
(F33615-76-C-5016, Dec 1975-Nov 1977, \$389,800)

Background

A previous MANTECH project (F33615-75-C-5254) was successful in demonstrating the feasibility of producing larger carbon-carbon billets, up to 8"x8"x12" in size. However, densification had been performed in government-owned facilities. What was needed now was an approved industry source and process for large-scale production of these critically needed billets.

G.E. staff had been actively involved in the densification efforts at Oak Ridge. They also had learned a great deal about CVD and NDE procedures in the earlier contract. G.E. staff believed a number of efficiencies could be made in the standard process, which would reduce costs without sacrificing product quality.

Project Objective

This project had two objectives. One objective was to establish an industrial source to manufacture 2-2-3 carbon-carbon composites using the standard process. Given the previous work, this primarily involved transfer of the densification process from government facilities to industrial (G.E.) facilities. This phase of the project was to result in the establishment of an Equivalent Industrial Standard Process (EISP).

The second project objective was to develop a less expensive manufacturing process for producing 2-2-3 and FWPF carbon-carbon composites, without degrading performance characteristics. This was to result in the establishment of an Improved Industrial Standard Process (IISP).

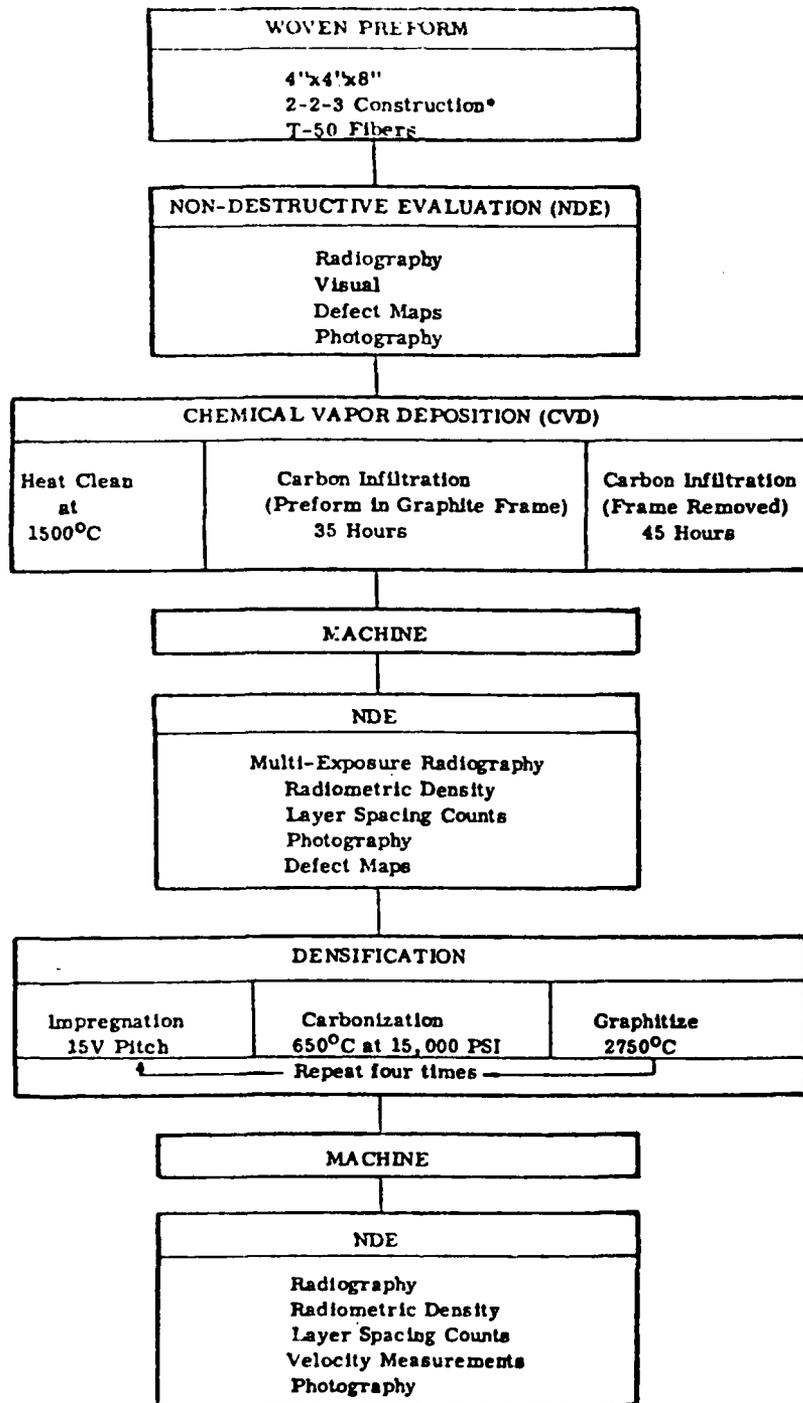


FIGURE 6:
SIMPLIFIED PROCESS FLOW DIAGRAM FOR 2-2-3 DENSIFICATION PROCESS*

*This chart was obtained from G.E.'s Final Project Report

The reproducibility obtained in the scale-up billets strongly indicated that the scale-up process was ready for manufacturing with little risk and minimum start-up/shake-down problems.

Two important reasons given by G.E. staff for the technical success of this project were 1) USAF allowance of detailed testing and microstructural work in the development of process parameters and, 2) the program was well planned, with detailed testing (including destructive testing) and evaluation after each phase.

The objective of this project was technical as opposed to cost. The objective--to develop a process for manufacturing larger billets--was accomplished.

Another benefit of this project was that it provided the groundwork for developing the Equivalent Industrial Standard Process (EISP) in a subsequent MANTECH project. This is the only Air Force qualified densification process for RV nosetips.

Implementation, Technology Transfer

See these sections in the following report on "Manufacturing Technology for Processing Fineweave Carbon Preforms", contract F33615-76-C-5016. Implementation and technology transfer for these two contracts are addressed together, since the process was not ready for industry implementation until after this subsequent work.

Other Note

A very strong interest in the progress and results of this project on the part of the Air Force and the aerospace community gave the project a high visibility and emphasis which helped to maintain the schedule through the many organizations which were involved (USAF, G.E., AVCO, FMI, Union Carbide and SoRI). The strong interest was due to the fact that the product, and thus the manufacturing process to make it, was needed immediately by USAF.

Project Description

The following FMI-supplied 2-2-3 preforms were processed:

<u>Number</u>	<u>Size</u>
5	4"x4"x11"
5	6"x6"x8"
2	8"x8"x12"

AVCO supplied 3 4"x4"x8" FWPF rigidized preforms. All preforms were supplied to G.E. as GFM, under separate USAF contracts with FMI and AVCO. G.E. provided all equipment for CVD, microstructural study, and NDE. Densification was performed (as GFM) by Union Carbide at Oak Ridge facilities, and testing of mechanical and thermal properties was conducted as (GFM) by Southern Research Institute (SoRI) in Birmingham, Alabama.

The major problem and challenge turned out to be the development of CVD infiltration process parameters for the larger size preforms. Many process adjustments, particularly in gas flows, gas mixtures, and infiltration times had to be made. Changes were also made in the preform frame. Much detailed microstructural analysis work had to be performed to establish the required CVD process parameters. The densification process was found to be rather insensitive to preform size. A few modifications were made in the impregnation stage, and a few changes in NDE were needed.

Project Results

Acceptable processes were developed for 2-2-3 billets up to 8"x8"x12" with mechanical and thermal properties comparable to 4"x4"x8" billets. Detailed material and process specifications and testing procedures were formulated. The densification process was found to be applicable to the FWPF preforms, yielding billets with acceptable mechanical and thermal properties.

and to simplify and reduce the expense of the lens manufacture. The lens form factor was changed from circular to a less conventional rectangular shape. Lens alignment and dimensional tolerances were met by modifying standard circular edging equipment. Four complete sample lenses were produced and evaluated.

Additional Phase I tasks were to establish the configuration of cathode-ray tubes most suitable for use in the multi-tube display unit and to upgrade the multi-sensor memory using currently available technology to reduce part count, size, and manufacturing complexity. A dual evaluation program was conducted with a standard metal oxide semiconductor 4K random access memory (MOS RAM) and a new hybrid semiconductor memory containing up to 24K memory bits. Samples of each were evaluated to verify functional, environmental, and system lifetime characteristics.

Phase II and III tasks were to demonstrate that the Phase I display and memory units could be integrated and that the manufacturing processes developed would result in the fabrication of an acceptable product. In Phase II, the integrated system was built to engineering sketches and laboratory tested to verify the compatibility of the key display system components with the balance of the processor system.

Two systems were fabricated in Phase III using production tooling and were tested with Air-Force-approved test procedures, demonstrating the producibility of the design and key components. These two systems were then tested by General Electric in a 1450 hour reliability demonstration test--not specifically part of this MANTECH contract--sponsored by the PAVE TACK System Project Office.

Project Results

The objectives established for this MANTECH effort were achieved. The program resulted in significant improvements in optics producibility, a reduction in weight and glass cost, and assembly and sealing techniques that ensure a high-yield lens system.

Implementation

The HIRD display and sensor processing concept is now being implemented in production retrofit of a number of inventory aircraft. Seventy-nine F111F's in the PAVE TACT program stationed at RAF Lakenheath, England are in the process of being retrofitted with the system. G.E. has proposed a retrofit to the existing F111 fleet to convert the standard radar display to a TV format similar to that used in the HIRD system. General Electric is under contract to convert the Royal Australian Air Force's F111C aircraft to the PAVE TACK configuration. A number of F-4E's and RF-4C's were retrofitted with the lens (magnifier) part of the HIRD system. However, the Air Force Weapons Test Center at Nellis AFB has decided that the HIRD system is not desirable for the F-4 aircraft and is having them removed. The radar-to-TV scan converter and display was flown in the B-1 prototypes, but will not be in production models.

Benefits

The benefits realized from this project are mainly technical, as opposed to cost. The project enabled the production of a system which would substantially enhance mission capability. A weapons officer could use the full capability of sophisticated target acquisition and designation systems in the strict confines of the cockpit of a high performance aircraft. The development of the HIRD system provides a means to retrofit inventory aircraft with state-of-the art weapon-delivery systems at reasonable cost.

In addition to improvements in mission performance, this program lowered the cost and improved the producibility of the HIRD optical display and sensor data processor. The optical system achieved a 3:1 reduction in glass cost (\$975 to \$306, in 1978 dollars) mostly through a redesign that reduced the number of optical elements required. G.E. estimated a 60 percent reduction in overall system assembly cost was achieved, mostly through the use of machines to generate lens shape

Design refinements were made that enabled identical electron guns and yokes to be used in the two different CRT's.

At the start of this effort, conventional memory systems used 1K static random access memories (RAM) as the memory element. The HIRD system required approximately 3/4 million bits of memory or 750 standard RAM modules, which would have made the electronics subsystem a bulky, high power unit. A militarized version of a 4K static RAM was developed and has become a standard stock item. A 16K dynamic RAM (total of 64 modules, with 1 million bits of memory) is actually being used now in production versions of the HIRD system.

The engineering model units of Phase II were integrated into an APQ-144 radar and electro-optic test system at G.E. Live-radar video was properly scan converted in the processor and displayed in television format on the multi-tube display unit along with live TV video from an operational TV camera.

Phase III units were completely constructed and assembled by production personnel. Despite the fact that only two systems were built, a full manufacturing drawing release was used and work was accomplished through formal manufacturing procedure routines. The manufacturing cycle was continually monitored by the G.E. Reliability and Quality Assurance Group. These units verified that consistent performance was attained and that manufacturing processes were capable of repeated performance. For example, 16 of 17 multi-tube display parameters were within specification. In the multi-sensor processor, 10 of 13 test parameters were within specification.

This equipment was subjected to a 1450 hour Reliability Demonstration Test Program under the F111F PAVE TACK contract. The observed mean time between failure was in excess of the 250 hours specified for the HIRD system.

(instead of hand grinding), and simplified lens alignment. A six-fold increase in throughput was achieved in the areas of aspheric lens surface generation, cropping, and lens assembly.

The cathode ray tube development resulted in an improved, integrated CRT/yoke/shield assembly that uses a common electron gun for both a 4-inch and 6-inch CRT with an overall reduction in packaging length of 30 percent.

The memory device developed became a standard DoD stock item and was used in a number of applications until technology advances improved memory device capability.

As anticipated, the monetary benefits from this project are overshadowed by the performance benefits achieved with the HIRD system, especially when it is incorporated into the PAVE TACK weapon delivery system now entering the Air Force inventory. At most, only a few hundred HIRD systems will be built, even in the unlikely circumstance that all inventory fighter/bomber aircraft are retrofitted. The monetary savings of HIRD if all these retrofits occurred would barely cover the \$1.7M cost of the contract. The improvement in ordnance delivery accuracy is the most significant benefit of the HIRD development. The Air Force has documented a 25 percent increase in bombing accuracy with the use of the HIRD scan converter (the dual CRT display that converts radar imagery to a television format to improve visual placement of crosshairs on a target). When the HIRD system is used in the PAVE TACK target-acquisition, designation, and weapon-delivery system, it is estimated that a force improvement of 4:1 is achieved.

Since PAVE TACK would not work without some sort of HIRD-type display, HIRD can be considered a "necessary but not sufficient" condition for PAVE TACK and its resulting force improvement. This MANTECH project appears to have been key to the development of HIRD.

Due to its benefits being primarily mission-related, monetization of benefits from the HIRD technology is not particularly meaningful under a peace-time scenario. Using a "willingness to pay" approach, it would be reasonable to estimate that the peace-time deterrence value to the Air Force is at least equal to the total life cycle cost of the systems.

Under a war-time scenario, the benefits could become extremely large. The 25% increase in bombing accuracy with the HIRD means that fewer bombs per target are required for an equivalent level of damage. The 4:1 average force improvement means that one plane equipped with the HIRD/PAVE TACK System can do the job of four comparable aircraft not equipped with the system. A reduced number of sorties would result in a lower attrition of attacking aircraft, and reduction in loss of pilots. Thus, under a war-time scenario, this system, and the manufacturing process to produce it, would yield enormous savings in costs, and more importantly for this scenario, pilots and aircraft.

Technology Transfer

No other military applications of the HIRD technology, other than the applications mentioned above, have been found. Commercial applications will be explored over the course of the program.

MANUFACTURING METHODS FOR MNOS MEMORY ARRAYS
(F33615-72-C-1706, Dec 1972-Oct 1976, \$254,820)

Background

Integrated microcircuit fabrication developed along several different lines during the 1960's. In 1958, Kilby of Texas Instruments had discovered how to produce in a tiny chip of silicon an interconnected network of resistors and transistors by diffusion of various gases at high temperatures. Thus was born the monolithic silicon integrated circuit (SIC).

In the 1960's and 1970's, manufacturers produced many commercially available standard monolithic SICs for both analogue and digital applications. These standard SICs used two main device types: bipolar (ordinary) transistors and unipolar MOS (metal oxide semiconductor) field effect transistors. The popularity since that time of MOS technology is based on characteristics of low power consumption, high noise immunity, operation over a wide power-supply range, and speed.

At the time of this contract, nonvolatile memory was available only if power was continually applied to memory arrays or in non-semiconductor form such as tapes or disk storage. This effort was one of the first to investigate the manufacturing processes of an electrically alterable, nonvolatile (permanent) memory array that would exhibit the desirable characteristics of solid-state memory arrays. These characteristics include a large memory storage in a small volume, increased hardness to radiation, no requirement for warm up before operation, high reliability and the potential for lower cost in production quantities. These devices have application to airborne or missile weapons systems where these characteristics significantly enhance mission performance and reduce costs through lower failure rates.

MOS technology has improved steadily over the last 5 years as ways have been found to increase output drive capabilities and decrease sensitivity to input and output patterns. Improved performance over that achieved during this effort has resulted from MOS device manufacturers' use of isolation techniques with silicon substrates silicon-on-sapphire (SOS) fabrication methods, and silicon-gate and ion-implant processes to achieve improved speeds, lowered thresholds, and increased circuit densities. Standard products using these processes are now available.

Project Objectives

The objectives of this project were to develop manufacturing and control processes and to identify required materials for cost-effective production of metal nitride oxide semiconductor (MNOS) non-volatile memory arrays. The MNOS arrays would retain memory without external power, would be electronically alterable and would have all the advantages of a semi-conductor type memory (high reliability, low power requirements, long life, radiation resistance, etc).

Project Description

The project was divided into two phases. Phase I was to optimize the process-control technology to achieve increased yield in the manufacture of large bit size MNOS memory arrays and to provide an early circuit design and layout to verify the proposed 2048-bit memory array. Phase II was to demonstrate on a pilot production line the processes and design established in Phase I.

A number of process-control goals were established to focus Phase I efforts. These goals bounded production-yield percentages, memory-retention time, radiation hardness, surface cleanliness limits, and various voltage thresholds. The insulator structure of the memory was fabricated to attain a 24,000 hour retention while achieving a 10^6 Rad sensitivity to total ionizing dose. To eliminate the need

for bipolar interface circuitry, the correct voltage at the gate of the memory transistor was designed to be less than 30 volts. A one-volt threshold for MNOS transistors was established to minimize threshold losses thereby allowing for reduced chip interface voltages.

A modified version of the Phase I test chip was designed for use in Phase II. This test chip was used for process monitoring, memory, and stable-device characterization and radiation testing. The test program began at the silicon wafer fabrication level with the verification of electrical characteristics. The total integrated chip circuitry was tested to determine its degree of operation. Finally, a portable memory exerciser was designed to provide a self-contained, minimum complexity unit to demonstrate the non-volatile characteristics of a working memory.

Project Results

This project was only a partial technical success. It achieved the project objective as broadly stated previously. However, some specific technical objectives were relaxed to accomplish the final results. For example, the memory capacity was reduced from 2048 bits to 1024 bits. This and other technical problems encountered are discussed below.

A number of tradeoff studies were performed in the areas of work and bit organization, speed, power requirement, endurance, read disturb, and memory retention. A set of MNOS Design Guides was developed in the critical areas of read cycle time and writing and retention characteristics to assist in the above tradeoff analyses. Based on the results of the tradeoff analyses and a yield/cost analysis for various array configurations, a modified version of the Phase I test chip was recommended, built, and used as the demonstration device for pilot production in Phase II. The major change was a reduction in memory capacity from 512 words by 4 bits (2048 bits) to 256 words by 4 bits (1024 bits). The power requirement

was increased from 500 milliwatts to a 600 milliwatt average. Additional modifications were made to the prototype memory array in signal routing. This resulted in the need for four timing sequences in the final design versus three for the preliminary G.E. design, with the added benefit of longer read and store pulses.

During verification tests on the Phase II memory array, a write problem, in which voltage levels were too high, was corrected by including additional isolation regions within the array. In addition, a problem with low breakdown voltages between the isolation and ground was resolved by increasing the isolation diffusion linewidth.

Approximately 20 packaged memory arrays using this final Phase II design were tested. These devices showed some read action 80 percent of the time and some write action 50 percent of the time. At the time, this was considered fairly good performance considering the stringent design specifications. Today of course they would be totally unacceptable.

Implementation

General Electric has not implemented the specific MNOS technology and manufacturing processes developed during this effort. There were no follow-on efforts at G.E. to continue this specific work. G.E. bid on a contract to essentially implement the manufacturing process and produce MNOS counter memory arrays for the Army's Harry Diamond Laboratories (HDL). They were unsuccessful in this bid and subsequently the company did not pursue MNOS work any further.

Benefits

Although General Electric did not pursue MNOS technology, a number of direct benefits were realized from this effort, both for the company and for others pursuing integrated circuit semiconductor development.

The MNOS Design Guide developed during this effort to direct performance tradeoff activity served as an early catalyst for the development of industry-wide standards for performance and manufacturing process definition. An appreciation was gained of the importance of subcircuit level sensitivity to array performance and of the requirement for material purity and assembly cleanliness.

General Electric designed and built a semiconductor circuit manufacturing facility shortly after the end of this contract. Although this facility was not for MNOS manufacture, the "lessons learned" were applied to help determine the level of equipment sophistication required for acceptable process controllability and product reproducibility. Critical steps in the generic manufacturing process identified in the MNOS effort were monitored as a standard procedure in the design and construction of the new facility.

Technology Transfer

General Electric produced some internal posters and conducted some demonstrations of the results of this effort. At the time of this contract however, technology transfer was not emphasized as much as it is now.

Counter-memory array work at HDL could be considered a "spin-off" of this effort. The HDL effort took the fabrication process and process control used by G.E. in this MANTECH effort and applied them to the production of a counter-memory array for some Army electronic equipment. These counters were not manufactured to the tolerance levels that G.E. attempted to achieve, nor were the specifications for input/output voltage levels, memory capacity, etc., as stringent. HDL used the G.E. manufacturing technology developed in this effort to produce a more simplified and somewhat less capable memory array.

Other Notes

This was a high risk project. The product specifications in the contractual statement of work were known to be well beyond the state-of-the-art. During the course of the work, they were found to be unattainable and were relaxed. Unfortunately, but necessarily, a large portion of project resources had to be spent on re-designing the circuits and the production process. In the area of SIC memories, circuit design and manufacturing are necessarily very closely related functions.

In spite of all the problems, the project was a limited technical success. However, not long after the project, the technology was eclipsed by other major breakthroughs in SIC manufacturing.

Pratt & Whitney Aircraft

Pratt and Whitney Aircraft
QUALITY STANDARDS FOR PRODUCTION OF TITANIUM ALLOY CASTINGS
F33615-73-C-5039
May 1973 - May 1976
\$385,170

Background

Up until this project, little effort had been directed toward the development of new materials and manufacturing processes to reduce the cost and weight of metallic static components used in airframes and gas turbine engines, although these components had been increasing in size and complexity. One of the most attractive ways to reduce the cost and input weight of static components was through expanded use of titanium alloy castings. However, the cost-effective use of cast titanium alloy for larger and more critical components, as well as for more cost-effective production of existing titanium alloy castings, required the development of new, more realistic standards and specifications for cast titanium alloy components.

Project Objective

The primary objective of this program was to establish more realistic standards and specifications for titanium alloy castings based on the properties of titanium alloy castings themselves rather than on the more stringent existing standards based on nickel-base superalloy casting technology. This would ensure component integrity in the use of titanium alloy castings. It would also provide the technical base needed to extend the use of titanium alloy castings to more critical and larger engine and airframe components.

Project Description

This project was a coordinated effort between engine (P&WA) and airframe (Grumman) manufacturers, and casting firms. It was performed in three phases.

In Phase I, six different bill-of-material Ti-6Al-4V castings were selected for nondestructive inspection (NDI) and cut-up evaluation to provide the necessary data for developing new, more realistic NDI standards and specifications for Ti-6Al-4V castings.

Two of the castings were for F100 engine components, and the other four castings were for F-14A airframe components. The selected engine components were the compressor synchronizer arm and a nozzle hinge beam; the selected airframe components included the airframe hinge beam, a missile fairing, and two heat exchanger fittings. These components were selected because they were representative of thin wall state-of-the-art titanium castings. One of the program objectives was to evaluate the effects of defects which occur in thin-wall casting sections.

To provide an adequate data base for developing new standards, a total of 254 of these castings were purchased from the following four casting sources: Howmet, REM, PCC, and TiTech. Each source used current production procedures, except that weld repairs were not permitted. Some reject castings were requested so that large defects could be evaluated.

Radiographic, fluorescent penetrant, and visual NDI of the castings allowed the exact location and classification of defect-free areas and areas with internal and surface defects for subsequent mechanical property testing. Internal shrinkage and gas-porosity defects were detected by radiographic inspection, and surface pitting and linear defects were detected by fluorescent penetrant and visual inspection.

Test specimens were machined from both defect-free and defective areas of the castings. The appropriate specimens were subjected to tensile, creep-rupture, high-cycle fatigue, and impact tests.

Weld repair by the casting sources was omitted to permit complete surface defect characterization. After defect mapping through NDI, necessary weld repair was done by P&WA and Grumman on their respective castings. Test specimens containing weld repairs were then machined and included in the mechanical properties testing program.

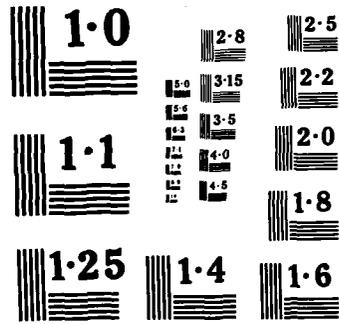
Under a program modification explained below in the Phase II description, additional castings were hot isotatically pressed (HIP) to close and bond internal defects. Test specimens machined from these HIPed castings were also included in the mechanical properties testing program.

Mechanical property test results for defect-free material were evaluated through regression analysis to establish baseline mean and minimum design curves. Then mechanical property improvement or degradation above or below the baseline curves were determined for defective, weld-repaired, and HIPed materials.

The original intent of the Phase II effort was to select, produce, and evaluate modified masterheat chemistries for improved strength, ductility, and castability. However, a computer analysis of chemistry and mechanical property data from a large number of masterheats showed that no significant improvements could be obtained through chemistry modifications. For this reason, the production and evaluation of alternate masterheat chemistries were deleted from the program.

In place of the deleted effort, evaluations of HIPed castings were added to the original Phase I and Phase III efforts, and the casting and evaluation of engine and airframe components not then being produced as castings were added to the Phase III effort.

In Phase III, the defect problem areas found in the Phase I castings were reviewed with the casting sources. Casting process variable modifications were mutually selected with the goal of decreasing the severity of internal shrinkage and surface flow lines, two major casting



NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

problem areas. Modifications in gating, mold preheat, mold composition, and g-force were investigated.

A total of 126 castings of four of the Phase I components were cast with the selected process modifications. These castings were subjected to the same NDI and mechanical properties testing procedures as the Phase I castings. Additionally, as a result of the Phase II modification, 66 castings of five previously non-cast components were produced by PCC, Howmet, and TiTech to demonstrate state-of-the-art advancement in titanium casting. The five new components were: the number 1 bearing housing, number 1 bearing housing seal ring holder, and 4th stage compressor blade for the F100 engine; the canopy support fitting for the F-14 airframe; and the rail support for the F-15 airframe. These castings were also subjected to the same inspection and testing procedures as the Phase I castings.

Project Results

Except for the originally proposed Phase II evaluation of modified masterheat chemistries, the objectives of this project were successfully achieved. The overall objective was met by the establishment of new, more realistic standards and specifications for Ti-6Al-4V castings based on the project's extensive NDI and mechanical properties testing results. These new standards and specifications permit a more cost-effective utilization of cast titanium engine and airframe components.

The casting and testing of previously non-cast components showed that significant cost savings can be realized by using titanium castings for larger, more critical engine and airframe components.

Implementation

There have been a number of Air Force MANTECH projects at P&WA on titanium castings since this project. These projects, combined with IR&D at P&WA and casting vendors, have substantially pushed the state of the art in titanium casting technology. This early project was just the starting point of a major and widespread effort to expand the capability and utility of titanium casting technology. Although this particular project played an important contributing role in the technology development process, it is impossible to factor out the implementation and benefits directly attributable to it alone. Thus, the substantial implementation and resulting benefits discussed below are a result of the total development effort.

Military Engines

1. Cast #1 bearing housing and cover (two pieces) for PW1120 and PW1128 engines. The casting replaces (from the F100 baseline) complex wrought components. Production implementation is programmed for 1986. The parts will be supplied by vendors. They have already undergone engine testing. Savings, based on vendor quotes, are estimated to be \$390 per component set.

2. Integrally cast intermediate case for Improved Life Core for F100(3) engines. For the F-16 aircraft model (an 8 strut, proximate splitter configuration), savings are estimated at \$20,000 per engine, based on the average of two vendor quotes. Engine weight savings (which were not monetized) are also realized. Implementation is programmed for 1985. For the F-15 aircraft model (an 8 strut, remote splitter configuration), savings are estimated at \$13,000 per engine. Savings are based on the average of two vendor quotes. Engine weight is increased by 3.5 pounds. Implementation is also programmed for 1985. For both engine models, the cost savings are primarily due to reductions in material input and machining requirements.

3. Integrally cast intermediate case for PW1120 and PW1128 engines. Savings (based on vendor quotes) are estimated to be \$20,000 per engine. Implementation is programmed for 1986.

4. Integrally cast intermediate case for TF30-P-100 and TF30-P-414A engines. Savings (based on vendor quotes) are estimated at \$20,000 per engine. All such engines in the inventory will be retrofitted in a durability improvement program, to begin in early 1985.

5. Cast F100(3) augmentor A-frame brackets (approximately 30 pieces per engine). These replace wrought components. Savings per engine are estimated to be approximately \$4,770. This is a "ballpark" estimate based upon known overall part cost and minimum acceptable corporate investment criteria. Implementation occurred in 1976.

6. Cast #2 bearing front support and #3 bearing rear support for F100(3), PW1120, and PW1128 engines. These replace wrought components. Production implementation is programmed for 1984. The savings for the #2 bearing front support is estimated at \$650 each (one per engine), based upon vendor quotes. The #3 bearing rear support has been redesigned for improved bearing durability. The cost of the cast component is higher, but the substantially improved bearing durability is of far greater worth. The net benefits were not quantified. The new design would not have been practical without a casting.

Commercial Engines

1. Cast intermediate case for PW2037 engine. Savings are conservatively estimated at \$27,000 per engine (based on vendor quotes) but may in fact be twice that amount if an integral bulkhead proves feasible. FAA certification is expected by the end of 1983. Production implementation is now ongoing.

2. Cast intermediate case struts (8) for JT9D-7R4 engines. Based upon vendor quotes, savings are estimated at \$2,000 per engine. This was the baseline production process for this engine, which has already been in production for several years.

3. Cast intermediate case bulkhead for JT9D-7R4 engines. Savings are estimated to be \$2,900, based upon vendor quotes. This is the baseline design for this engine, which has been in production for several years.

4. Cast fan exit case rear strut segments for JT9D-7R4 engines. Savings are estimated at \$2,000 per engine, based on vendor quotes. Again, this is the baseline design for this engine.

5. Cast HPC front case for PW2037 engines. This is a two part casting. Savings are estimated at \$5,000, based upon vendor quotes. Production implementation occurred in 1982.

Potential Implementation

It should be noted that vendors recently have been aggressively upgrading their already substantial capabilities to cast large, complex titanium alloy components. Many of these efforts have been supported by the Air Force MANTECH program. Howmet is installing a casting furnace with an 8 ft. diameter mold chamber, and will be capable of pouring two large intermediate cases at once. They are also expected soon to have in production a new 41 in. diameter by 100 in. long HIP vessel with fast cooling capability. Precision Casting Corporation (PCC) has also been a leader in pushing titanium casting technology. With the processes proven and improved casting facilities coming on-line in the industry, integral casting is now being considered for a large number of new applications in both military and commercial engines. P&WA's next generation of military engines, such as the Joint Fighter Engine, will probably incorporate many of the applications mentioned above. Also, derivatives of existing engines can be expected to incorporate this technology. New commercial engines, such as the PW4000 series and the multinational collaboration engine, are also expected to exploit the recent advances in titanium casting technology. Thus, the long-term economic payoff of this technology development should be many times greater than the amounts presented in this report.

As a final note, P&WA staff strongly believe that the USAF MANTECH program deserves major credit for the advances in titanium casting technology. The USAF MANTECH program is perceived to have been the driving force, particularly in the early period, in bringing this technology to production readiness.

Benefits Summary

Figures 7 and 8 summarize the savings from titanium castings, by engine type. Based upon P&WA engine sales forecasts, the total manufacturing cost savings through 1992 totals to approximately \$161.3 million. Of this, approximately \$85.9 million is in military engines, and \$75.4 million is in commercial engine production. Of the thirteen projects reviewed, this project has the greatest amount of identified manufacturing cost savings.

<u>Application</u>	<u>MC Savings/Engine (in 1982 \$)</u>	<u>Implementation Year</u>
<u>F100(3)</u>		
Cast Ti I/C (in ILC)	\$20,000 (for F-16)	1985
	\$13,000 (for F-15)	1985
Augmentor A-frame brackets (30 pieces)	\$ 4,770	1976
Cast Ti #2 bearing front support	\$ 650	1984
<u>PW1120</u>		
Cast Ti I/C	\$20,000	1986
Cast Ti #1 bearing housing	\$ 390	1986
Cast Ti #2 bearing front support	\$ 650	1984
<u>PW1128</u>		
Cast Ti I/C	\$20,000	1986
Cast Ti #1 bearing housing	\$ 390	1986
Cast Ti #2 bearing front support	\$ 650	1984
<u>TF30-P-100</u>		
Cast Ti I/C	\$20,000	1985 retrofit all in inventory
<u>TF30-P-414A</u>		
Cast Ti I/C	\$20,000	1985 retrofit all in inventory
TOTAL MC SAVINGS AT P&WA IN MILITARY ENGINES, THROUGH 1992 = \$85.9 MILLION		

FIGURE 7
Titanium Castings - Summary of
Implementation and Manufacturing Cost (MC) Savings for Military Engines

<u>Application</u>	<u>MC Savings/Engine (in 1982 \$)</u>	<u>Implementation Year</u>
<u>PW2037</u>		
Cast Ti I/C	\$27,000	1982
Cast Ti HPC front case	\$ 5,000	1982
<u>JT9D-7R4</u>		
Cast Ti I/C Struts (8)	\$ 2,000	1980
Cast Ti I/C Bulkhead	\$ 2,900	1980
Cast fan exit case rear strut segments	\$ 2,000	1982
TOTAL MC SAVINGS AT P&WA IN COMMERCIAL ENGINES, THROUGH 1992 = \$75.4 MILLION		

FIGURE 8
Titanium Castings - Summary of
Implementation and Manufacturing Cost (MC) Savings for Commercial Engines

Pratt and Whitney Aircraft
PRODUCTION OF NNS SUPERALLOY DISK SHAPES BY ISOTHERMAL FORGING
F33615-75-C-5184
May 1975 - March 1977
\$412,200

Background

When this project was initiated, powder metallurgy and hot isothermal forging techniques were being used to produce gas turbine engine components from advanced superalloy materials. A P&WA heat treatment and hot isothermal forging process, called Gatorizing, maintained superalloy materials in a superplastic state during forging. This allowed the forging of complex-shaped components to extremely close tolerances without surface cracking. A component could be forged to a near finished shape which required minimal machining to obtain the desired final shape.

Although these newer forging techniques had already reduced input weights and machining for IN100 parts used in F100 engines, their full potential had not been realized because of limitations imposed by ultrasonic inspection requirements. Existing ultrasonic equipment required the forging to have a blocky shape with an overstock of up to 0.25 in. beyond its finished shape at all points to ensure an adequate inspection. It was determined, however, that feasible improvements in ultrasonic inspection technology could provide adequate inspection for complex near-net shape (NNS) forgings with overstock envelopes of 0.05 in.

A complementary project to improve ultrasonic inspection components and integrate them into a computerized inspection system made it possible to utilize isothermal forging techniques in this project to establish manufacturing methods for producing NNS F100 components with substantial input material and cost savings.

Project Objective

The overall objective of this project was to develop near-net shape forging techniques for incorporation into production of IN100 components for F100 engines. Specific program objectives were:

- 1) Reduce the cost of manufacturing IN100 components for F100 engines by forging closer to finish shape to reduce input material and machining requirements.
- 2) Establish a reproducible process for manufacturing NNS components by advanced isothermal forging techniques.
- 3) Demonstrate the developed process and fully qualify forgings in the laboratory through mechanical property testing and metallographic examination.
- 4) Develop improved sonic inspection equipment and techniques, as

required, to ensure full inspection of NNS components.

- 5) Determine the economics of the NNS manufacturing process.

Project Description

The two-step forging process used throughout this project involved either machining or forging flat, pancake-like preforms from IN100 billet and then isothermally forging these preforms into near-net shape components.

The project was conducted in three phases. Phase I was concerned with subscale forging studies involving die design, preform geometry, and the metallographic examination of forgings for six different F100 parts. Phase II was concerned with scaling up Phase I results to produce full-scale forgings of one part, the 1st-stage turbine disk, for laboratory testing and engine testing. Phase III was concerned with improving ultrasonic inspection equipment and techniques to ensure adequate non-destructive inspection of NNS forgings.

During Phase I, subscale forging studies were carried out for the following six different IN100 parts for the F100 engine: 1st through 4th stage turbine disks, 1-2 turbine rim spacer, and 13th-stage compressor cone seal. The full-scale dimensions of all parts were scaled down to one-third for subscale die designs. The design for each part minimized forging input weight by using, whenever possible, a NNS forging envelope of 0.05 in. For this subscale phase, preforms were machined rather than forged to allow for variations in preform geometry during iterative forging studies, without high tooling costs.

The iterative forging procedure for each part started with a determination of the volume of material needed to fill the die during forging. A preform was machined with this volume and a reasonable diameter, and then forged in the subscale die. The resulting part was inspected and another preform was machined with the same volume, but a different diameter, to improve die fill and to eliminate laps. This procedure was repeated with preforms of constant volume and different diameters until an optimum preform geometry was obtained. For three of the six components, it was found necessary, after initial preform and forging iterations, to improve material flow during forging by slightly enlarging certain die contours. In these cases, preform volumes were correspondingly increased, and the iterative forging procedure was resumed with the new preform volume to obtain the optimum preform geometry.

After the subscale preform and final-forging configurations were optimized, several additional forgings of each part were produced for metallurgical examination and a study of dimensional stability during heat treatment.

Phase II involved a scale-up of the optimum subscale 1st-stage turbine disk forging configuration. For the full-scale die design, a NNS forging

envelope of 0.05 in. was also used, whenever possible, to minimize forging input weight. IN100 billets of appropriate volume were machined from 6.2 in. diameter stock. Each billet was ultrasonically and metallographically inspected before forging. The billet was isothermally forged on a flat die to a pancake-like preform that was lightly machined to ensure symmetry. The preform was ultrasonically inspected and then isothermally forged to NNS.

After the first two full-scale iterations, it was found necessary to considerably enlarge the die contour of the integral arm and increase preform volume in order to completely fill the integral arm flange during forging. Because of the resulting volume increase, the preform configuration was reoptimized through a new set of subscale forging iterations using the new die configuration. Finally, after two more full-scale iterations, an excellent, well-filled NNS part was obtained.

A study of the dimensional stability of the full-scale forgings showed that they were shrinking, both radially and axially. Radial shrinkage, which was much greater than axial shrinkage, was approximately 0.05 in. at the outer diameter of each forging. To compensate for this shrinkage, several diameters of the die cavity were increased by 0.05 in. and corresponding punch diameters were increased with an overthick plasma-sprayed molybdenum coating that was machined to the desired punch-die tolerance.

After the full-scale 1st-stage turbine disk forging configuration was finalized, five forgings were produced and heat treated with no problems. One forging was cut up for mechanical properties testing. Other ones were used for ultrasonic inspection studies in the next phase of the project.

In Phase III, an initial attempt to use improved commercially available components for NNS ultrasonic inspection was not successful due to continual component failures in new systems from two manufacturers. Consequently, all billets, preforms, and final forgings were inspected with equipment designed and produced by P&WA. The P&WA equipment included a high-rise time pulser and broadband receiver coupled with a new commercially available, highly damped metaniobate transducer. This equipment met the basic requirements for ultrasonic inspection of full-scale NNS parts: near surface and far-surface resolution to 0.05 in. through 3-1/4 in. of material.

Phase III also included an economic analysis to determine the potential cost savings from incorporating the two-step NNS forging process into the production of all IN100 rotating parts for the F100 engine.

Project Results

The NNS isothermal forging program met all of its main objectives. The subscale phase of this program demonstrated the ability of the two-step forging process to adapt to a variety of forging configurations. The process repeatedly yielded full-scale NNS forgings in a manner suitable for production. At each step, metallographic examinations verified

microstructural integrity. The results from mechanical properties testing showed that NNS properties are as good as, and generally much better than, those under current forging procedures. The ultrasonic inspection phase of the program demonstrated the inspectability of full-scale NNS forgings. The economic analysis in Phase III of this program showed a potential for major cost reductions in production parts.

Implementation

Implementation of NNS isothermal forging has been extensive at P&WA, and is expanding. There has been a large amount of internally and externally funded follow-on development work in this area, some of which has been to extend NNS isothermal forging technology to titanium alloy components. Implementation resulting from this important but single project cannot be separately identified. The implementation discussed below is a result of the culmination of all of the development efforts. It is a snapshot of the steady improvements in NNS isothermal forging technology which have occurred and are still occurring at both P&WA and vendors.

Military Engines

1. NNS isothermal forging of IN100 turbine and compressor disks, and related components, for F100(3), PW1120, and PW1128 engines. For the F100(3) and PW1128 engines the components are stages 1, 2, 3, and 4 turbine disks, stage 1-2 turbine rim spacers, stages 9, 11, and 13 compressor disks, and stage 13 compressor spacer. The PW1120 implementation includes all these components, except the stage 4 LPT disk, which it does not have. Implementation of the process represents a movement from conventional isothermal forging to NNS isothermal forging. P&WA is making a major investment in new facilities and equipment for isothermal forging at a new plant in Georgia, and will be capable of producing all these components in-house at this facility. The in-house versus vendor production split will be based upon vendor price quotes on a component by component basis. While a few of the components are already being produced by the NNS process, all are programmed for implementation by the end of 1984. With full implementation, savings per engine (in 1982 \$) for the F100(3) and PW1128 are estimated at \$20,000. Savings for the PW1120 are estimated at \$17,800 per engine.

The \$20,000 per engine savings figure was estimated based upon internal P&WA and vendor studies of input material savings. These show that approximately 400 pounds of input material will be saved. At \$30 per pound for IN100 billet, and \$20 per pound for rough machining, total savings per engine amounts to \$20,000.

2. NNS isothermal forging of titanium alloy components for F100(3), PW1128, and PW1120 engines. The implemented components are the stages 1, 2, and 3 fan disks, and stages 4 and 5 compressor disks. In the early 1970s, these components were conventionally forged and machined to large sonic shapes (approximately 250 mil envelopes). Over 350 pounds of

material were machined from the forgings. In 1976, largely as a result of information developed in this project, coupled with P&WA work with vendors, reduced sonic shape envelopes were introduced. Vendor quotes reveal an approximate savings of \$660 (in 1982 \$) for the five disks. A conventional forging process was still used.

Conventional isothermal forging was introduced for the 5 disks during the 1978-80 timeframe. Subsequent savings were realized, but these cannot be attributed to the MANTECH project.

An intermediate NNS isothermal forging process was implemented in the 1979-80 time period. Savings for the set, as compared to conventionally isothermal forged components, were \$885 (again, based on vendor quotes). Thus, savings from moving to more NNS processes and more precise sonic shapes totalled to \$1,545 (that is, \$660 + \$885) for the set of five titanium alloy disks, for the F100(3) engine. The savings for the PW1128 and PW1120 engines is approximately the same.

It is now planned that a fully NNS isothermal forging capability for the 3 fan disks will be implemented in 1984 at P&WA's new Georgia facility. This will yield additional savings of \$900 for the F100(3) and PW1128 engines, and \$2400 for the PW1120 engine.

3. NNS isothermal forging of TF30-P-414A stage 1 turbine disks. In this case, a NNS isothermal forged IN100 disk replaced a conventional forge-plus-machine process using Waspaloy. Production implementation began in April 1982. These are part of the Longer Life Turbine kits to be retrofitted in all Navy F-14s.

Dollar benefits are estimated based on the assumption that the disk would have been changed to IN100 even if the NNS process had not been available. Thus, the cost savings represent the differences in costs between using NNS isothermal forging, with precise sonic shape (approximately 50 mil envelope), versus conventional isothermal forging with standard sonic shape (approximately 250 mil envelope).

Savings are made in input material and machining costs. Compared with conventional isothermal forging, NNS isothermal forging of the disk requires 66 fewer pounds of input material. At \$30 per pound for IN100 billet, this yields \$1,980 in material savings per disk. Machining savings are primarily from avoided rough turning of the forging to sonic and then final shape. At a \$20 per pound manufacturing cost for rough turning of IN100, and approximately 66 fewer pounds to be removed, this yields \$1,320 in machining savings. Final, finish machining costs (including hole drilling, polishing, etc.) would be roughly equivalent for the two processes. Total savings per disk are approximately \$3,300.

Disk life more than doubled and disk weight decreased by 12 pounds. However, these benefits cannot be attributed to the NNS process, since most of these also would have been realized with conventional isothermal forging, albeit at a higher cost. Since it does not respond as well to

heat treatment, a conventionally isothermal forged disk might have to be several pounds heavier than the NNS isothermal forged disk, to get the same properties.

Commercial Engines

1. NNS isothermal forging of stage 1 and 2 HPT disks (IN100) for PW2037 engines. Production implementation is programmed for 1984. Savings are estimated at \$15,000 (in 1982 \$). Savings are primarily in input material costs (approximately 150 lbs. saved per disk at \$30 per pound) and machining costs (150 pounds less to machine at \$20 per pound).

2. NNS isothermal forging of stages 1,2,3,5, and 6 disks (titanium alloys) for JT8-D engines. Production implementation is scheduled for 1984. Savings are estimated to be \$1,600 (in 1982 \$). Savings are in input material costs (approximately 133 pounds saved at \$10 per pound) and machining (133 pounds less to machine at approximately \$2 per pound).

3. NNS isothermal forged stages 5,9, and 11 compressor disks (titanium alloys) for JT9D and JT9D-7R4 engines. Production implementation is scheduled for 1984. Savings are estimated at \$1,440. Savings are in the cost of input material (approximately 120 pounds saved at \$10 per pound) and machining (120 pounds less to machine at \$2 per pound).

In addition to the savings identified and documented above, it is likely that the PW4000 series engine will incorporate NNS isothermal forging. Although implementation decisions have not been made at this time, stages 1, 1.5, 2, 3, 4, and 5 disks (titanium) will probably be NNS isothermally forged, as well as any disks of IN100. Also, the multinational collaboration engine, the Joint Fighter Engine, and new derivatives and new engines in the 1990s will all probably utilize the technology to some extent. Savings from the above cannot be estimated at this time, but are likely to be substantial.

Benefits Summary

Extrapolating the savings per part and per engine in the previous section across forecast engine sales through 1992 yields a total savings of \$117.5 million for this technology. Of this, \$77.5 million is in production of military engines, and \$40 million is in production of commercial engines. Figures 9 and 10 summarize the implementation and manufacturing cost savings from this technology, by engine type.

<u>Application</u>	<u>MC Savings/Engine (in 1982 \$)</u>	<u>Implementation Year</u>
<u>F100(3)</u>		
NNS isothermal forge: Stages 1,2,3,4 HPT disks Stage 1-2 turbine rim spacers	\$20,000	1984
Stages 9,11,13 compressor disks Stage 13 compressor spacer		
Intermediate NNS isothermal forge: Stages 1,2,3 fan disks	\$ 1,545	1980
Stages 4,5 compressor disks		
NNS isothermal forge: Stages 1,2,3 fan disks	\$ 900 (additional to above)	1984
<u>PW1128</u>		
NNS isothermal forge: Stages 1,2,3,4 HPT disks Stage 1-2 turbine rim spacers	\$20,000	1984
Stages 9,11,13 compressor disks Stage 13 compressor spacer		
Intermediate NNS isothermal forge: Stages 1,2,3 fan disks	\$ 1,545	1980
Stages 4,5 compressor disks		
NNS isothermal forge: Stages 1,2,3 fan disks	\$ 900 (additional to above)	1984

FIGURE 9
NNS Isothermal Forging - Summary of
Implementation and Manufacturing Cost (MC) Savings for Military Engines

This was thought to be correctable through better repair procedures and heat treatments.

A subscale rotor was successfully EB welded. No defects were found and properties were good.

Airframe Program

Ti-8-8-2-3 and Beta C were successfully welded by each technique. However, a substantially lower efficiency in fatigue strength was observed in both welded beta alloys. As in the alpha-beta alloys, there was a trend toward lower tensile ductility. Also, repair welds in the beta alloys were substantially inferior to the original welds.

The 0.5 in. Ti-8-8-2-3 material was clearly superior to the 0.5 in. Beta C alloy with respect to overall weldability, weldment properties, and base metal machinability. Results on 0.1 in. thick Beta C sheet were generally better than on 0.5 and 1.0 in. Beta C plate.

PAW and EBW were found to be the preferred methods on both technical and cost bases. EBW was found to be more generally applicable since PAW was less capable of welding thick sections and was more prone to inducing distortion.

Ti-8-8-2-3 alloy was selected as the preferred alloy due to its superior weldability and the mechanical properties of the welds. Ti-8-8-2-3 alloy was used in fabrication of the subscale component, for both EBW and PAW. Both processes resulted in substantial distortion, and were found to require additional fixturing or straightening after welding if they were to be used as production processes.

Overall Findings

Processes were most successful for EBW of alpha-beta alloys. Ti-6-2-4-2 EB welds were superior to Ti-6-2-4-6, since the Ti-6-4 filler metal limited weld properties. It was believed, however, that an improved filler wire could resolve this problem. Model specifications were developed for both alpha-beta alloys.

Beta C was found to require much more work before specifications could be established for reliably producing high quality welds. Model specifications were developed for Ti-8-8-2-3.

Implementation

P&WA has implemented EBW for production of rotors for both military and commercial engines.

1. Electron beam (EB) welded fan rotor in PW1120 and PW1128 engines. These rotors were designed from the beginning for welded joints, as opposed to bolting. Ti-6-4 is used, instead of Ti-6-2-4-6 as in the F100(3), to ensure slow crack growth rate properties. Production facilities have already been established. Use of the technology will accelerate as

Since neither of the two alloys in the engine portion of the program had been widely welded in the past, there was no readily available parent metal filler wire. Ti-6-2-4-2 wire was successfully produced and used in diameters of 20, 45 and 62 mils. However, severe cracking and fracture were encountered in drawing Ti-6-2-4-6 wire. Only 65 mil diameter wire could be produced, and this did not feed evenly in the automatic weld wire feeding equipment. Therefore, Ti-6Al-4V alloy filler wire was used for welding Ti-6-2-4-6.

Acceptance criteria were developed for both .1 in. and .5 in. thicknesses, based upon likely component applications and expected subsequent machining. Considerable process work was required to identify optimum heat treatments for the two alloys. Weld repair techniques were developed for EBW and PAW.

Following the establishment of welding parameters and characterization of properties, a 3-stage subscale compressor rotor was constructed. Three Ti-6-2-4-6 alloy rings with 13 in. outside diameters and .5 in. thick walls were joined by two circumferential electron beam welds. The rotor was heat treated and dimensionally inspected, and subjected to the full range of NDE and material properties tests.

Airframe Program

The approach to this portion of the program was similar to that of the engine-related program. Welding parameters and heat treatment procedures were established for 1 in. thick Ti-3Al-8V-6Cr-6Mo-6Zr (Beta C) plate and 0.5 in. thick Beta C and Ti-8Mo-8V-2Fe-3Al plate, which are representative of current weldments such as wing and tail structures. Procedures were established for 0.1 in. thick Beta C sheet in anticipation of fuselage skin construction for advanced aircraft.

After process development work and properties evaluation were completed, EBW and PAW were used to construct two Ti-8-8-2-3 alloy components which simulated a Grumman F-14 lower wing cover splice joint.

Project Results

Engine Program

Methods were established for welding Ti-6-2-4-6 and Ti-6-2-4-2 by all processes. The two alloys were basically similar with respect to weldability and weldment properties. It was easier to consistently achieve good properties in Ti-6-2-4-6 welds, but the data developed in this program was insufficient to form a general conclusion. In general, the alloys were found to be no more sensitive to weld preparation and process parameters than the more conventional titanium alloys. However, they did require considerably more attention to the choice of heat treatment. Both alloys exhibited slightly low ductility in the tensile properties of the welds. Repair welding was successful, but resulted in reduced tensile strength.

Pratt and Whitney Aircraft
MANUFACTURING TECHNOLOGY FOR JOINING TITANIUM ALLOYS
F33615-72-C-1624
February 1973 - February 1975
\$305,207

Background

For large aircraft engines, the conventional process for joining fan and compressor disks into rotors has traditionally been by bolting. In the early 1970s, welding was being explored as a potential low cost joining method for rotors, offering benefits of decreased weight and increased stiffness. However, more complex titanium alloys (e.g., Ti-6Al-2Sn-4Zr-6Mo and Ti-6Al-2Sn-4Zr-2Mo) were beginning to be used for these components to obtain higher strength and temperature resistance. While welding processes for simpler titanium alloys (e.g., Ti-6Al-4V, Ti-3Al-2.5V) were reasonably well established, a number of studies in the academic community and industry suggested that the more complex alloys would be more difficult to weld. Consequently, there was an evident need to establish the necessary welding technology so that full advantage could be taken of the new alloys, not only for engines, but for airframes as well.

Project Objective

The objective of the project was to establish optimum welding and heat treatment process parameters for 3 thicknesses of 4 titanium alloys, for 4 welding processes--plasma arc welding (PAW), electron beam welding (EBW), gas tungsten arc welding (GTAW), and inertia welding (IW)--and to demonstrate preferred welding processes on subscale components.

Two alpha-beta alloys, Ti-6Al-2Sn-4Zr-6Mo and Ti-6Al-2Sn-4Zr-2Mo, were selected for engine applications. Two beta alloys, Ti-3Al-8V-6Cr-4Mo-4Zr and Ti-8Mo-8V-2Fe-3Al (Beta C), were selected for airframe applications. P&WA performed the engine-related work and Grumman Aerospace Corporation undertook the airframe-related work as a subcontractor.

Project Description

Engine Program

Parametric evaluation was conducted by making welds which joined 0.1 and 0.5 in. thick flat plates three inches wide along a 24 in. length. For inertia welding, 8 in. outside diameter by 0.5 in. thick wall cylinders were used. Metallurgical processes were developed in conjunction with the establishment of welding parameters. The practicalities of production manufacturing operations were considered in parameter selection. Thus, the "optimum" processing parameters which were developed were those believed to be best suited for production use, that is, they were realistically controllable in the production environment and took into consideration operator discomfort and dexterity.

<u>Application</u>	<u>MC Savings/Engine (in 1982 \$)</u>	<u>Implementation Year</u>
Reclamation of IN100 for F100(3)	\$1,530	1978
Reclamation of IN100 for PW1128	\$1,530	1984
Reclamation of IN100 for PW1120	\$1,326	1984
Reclamation of IN100 for TF30-P-100	\$ 408	1978
Reclamation of IN100 for TF30-P-414A	\$ 408	1978
Reclamation of IN100 for PW2037	\$2,550	1978

TOTAL SAVINGS THROUGH 1992 = \$17.8 MILLION

FIGURE 11
Strategic Materials Reclamation - Summary of
Implementation and Manufacturing Cost (MC) Savings, Military & Commercial
Engines

Project Results

The Strategic Materials Reclamation Seminar and the scrap survey showed very little previous concern about scrap problems. Aerospace scrap handling techniques developed for the Model Scrap Handling System could significantly improve the quality and thus the reclamation of both titanium alloy and nickel base superalloy scrap materials.

The two density separation methods were both found to be inadequate for removing high density contaminants. An evaluation of fan disks forged from reclaimed Ti-6Al-4V demonstrated the potential of the Teledyne nonconsumable skull melting process for producing material with acceptable quality and mechanical properties. The production scale processing of nickel base superalloy sludge by conventional drying and electric-arc air melting operations showed that reclamation of this sludge was profitable.

Implementation

P&WA implemented a scrap management system for titanium alloy and isothermal forged IN100 at the Manufacturing Division (MD) in Hartford, Connecticut in 1978-79. All chips and turnings from isothermal forged IN100 are recovered. Scrap IN100 is collected and crushed, magnetic pieces are removed, and volatile materials are burned off. All this is done in-house at MD. The material is then shipped to a melter to melt it into ingot. The ingot is shipped to Homogeneous Metals Inc. (a P&WA subsidiary) which makes the powder. The powder is used by P&WA for all IN100 parts except those in the HPT. Titanium is sold to scrap dealers at prevailing market prices for scrap. Approximately 70% of the IN100 and titanium is successfully reclaimed.

Benefits

Based on vendor quotes for virgin powder, and compared with HMI's average price for all powder, P&WA estimates it saves \$3.00 per pound for all IN100 powder--virgin and non-virgin--it buys from HMI. Since company-wide approximately 85% of IN100 used is procured from HMI, savings average \$2.55 for every pound of IN100 used.

The savings per engine are presented in Figure 11. These are conservative estimates because they are based upon the number of pounds of IN100 in the engine as produced, and not upon the amount of required input material (data on this was not available). Total savings through 1992 are estimated to be \$17.8 million, \$11.2 million of which is in military engine production, and \$6.6 million is in production of commercial engines. Savings from titanium reclamation are not included because they cannot be directly attributed to this project.

A number of scrap reclamation technologies were investigated during Phase I. These included two variable apparent density separation methods. One was the AVCO ferrofluid method, and the other was the Frankel fluidized-bed method. The ability of these processes to cost-effectively separate contaminants from scrap was assessed through a series of tests using scrap with a known contamination. The Frankel fluidized-bed separation method was selected for scale-up in Phase II. For removing high density contaminants by melt-skull entrapment, two nonconsumable melt processes were investigated: the Teledyne-Schlienger rotating electrode system and the AIRCO-Temesal electron beam cold hearth melting system. The Teledyne-Schlienger system was selected for Phase II scale-up. A molten salt bath process developed by the Frankel Company was evaluated for its potential to purify nickel base superalloy grindings and sludges for subsequent separation and remelting processing. Materials subjected to this process come out as dry particles of metal and their inorganic substances, such as carborundum and aluminum oxide used in grinding compounds. The process had not previously been evaluated for full-scale industrial conditions. Materials reclaimed during Phase I were chemically analyzed, non-destructively inspected, and tested for selected mechanical properties.

During Phase II, the Model Scrap Handling System was implemented and refined at a forging company with extensive, affiliated machining requirements. For the Phase II scrap reclamation technology effort, the Frankel fluidized-bed separation process and the Teledyne non-consumable melting process were established on a production scale basis to provide a complete titanium reclamation system. The system was evaluated by procuring two 5000 lb lots of Ti-6Al-4V chips and turnings and processing them through the system to obtain two 5000 lb ingots. This reclaimed material was chemically analyzed, non-destructively inspected, and tested for selected mechanical properties. The ingots were converted to forging billets which were cut to appropriate barstock lengths for forging. Four TF33 Stage 2 fan disks were successfully forged from this reclaimed titanium alloy bar stock. For the Phase II intermediate scale-up of the molten-salt bath purification process, two 800 lb lots of commercially generated nickel base superalloy sludge were processed. Because of operational problems, the molten salt process was replaced by a conventional drying process. The dried sludge was then melted to produce ingots. These ingots were chemically analyzed.

In Phase III, the Model Scrap Handling System was evaluated by comparing the amount of scrap that was recyclable back into aerospace materials before and after the system was implemented. The Phase III scrap reclamation technology effort included testing the mechanical properties of the fan disks forged during Phase II from reclaimed Ti-6Al-4V alloy and comparing them with P&WA specifications. It also included the processing of a production scale 6000 pound lot of nickel base superalloy sludge by conventional drying and electric arc melting methods.

Pratt and Whitney Aircraft
STRATEGIC MATERIALS RECLAMATION
F33615-74-C-5019
March 1974 - May 1979
\$700,000

Background

The cost of raw-material input is a significant part of the overall cost of producing components for gas turbine engines. This is particularly so for those components made of scarce and expensive materials such as nickel base superalloys and titanium alloys. Because of high quality requirements, over 50% of these input materials typically becomes scrap during component fabrication. This scrap had been sold cheaply for recycling by non-aerospace specialty users with much lower quality requirements. The failure to recycle this scrap back into the aerospace industry represented a large cost burden, as well as an inappropriate use of scarce strategic materials. Thus, there were strong incentives for reclaiming these scrap materials by establishing appropriate scrap management procedures and reclamation technologies.

Project Objectives

The objectives of this project were to identify possible scrap management and processing methods for reclaiming titanium-alloy and nickel base superalloy scrap and then to select, establish, and verify the most promising one.

Project Description

This project was conducted in three phases. Phase I was concerned with selecting the most promising management and processing methods for reclaiming titanium alloy and nickel base superalloy scrap. Phase II was concerned with implementing and refining a model scrap management system. It was also concerned with implementing and evaluating selected scrap reclamation technologies on a production-scale basis. In Phase III, the previously established scrap management system was further evaluated, with mechanical property testing of titanium alloy components forged from reclaimed material. An economic analysis of large-scale reclamation of nickel base superalloy grinding sludge was also performed.

In Phase I, a Strategic Materials Reclamation Seminar was held by P&WA to provide an overview of the then current titanium and superalloy scrap situation and to identify new concepts for increased utilization of these scrap materials in aerospace applications. Also, a survey was conducted to determine the quality, quantity, and disposition of titanium and nickel base superalloy scrap generated by the aerospace industry. On the basis of both the seminar and the survey, a Model Scrap Handling System was defined.

of work station throughput, by reducing average disk inspection time from 1.5 hours to .5 hours. Equipment costs of the NNS Systems are approximately the same as for the previous systems. In determining savings from implementation, equipment costs are assumed to be zero, because new ultrasonic systems are required for the Georgia facility anyway, and most of the testing over the 1984-1992 timeframe will be performed there. At \$50 per hour loaded labor cost for this work station, approximately \$50 is saved per disk. Total savings through 1992 are estimated at \$3.3 million (in 1982 \$).

The contour sensing and following subsystem in CAUS-1 permits the inspection of non-regular near-net disk shapes without prior machining. It has its own ultrasonic signals and computer controls for continually sensing the shape of a part and adjusting the direction of the inspection transducer so that the ultrasonic inspection beam is always normal to the inspection surface. Contour sensing provided an entirely new capability for inspection systems, that is, dimensional measurement of shapes. CAUS-1 accurately measures a shape (± 0.01 in. absolute, ± 0.003 in. relative) with the same data used for contour following. Dimensional data are computer analyzed to determine if and how a final disk can be machined from a NNS forging.

With CAUS-1, near-net shapes could be inspected for both material defects and dimensional tolerances in one-fourth of the time it takes to inspect sonic shapes for material defects alone using baseline inspection methods.

Implementation

The major benefit of this technology is as an "enabling" technology. Most of its resulting dollar benefits are included in the findings for NNS isothermal forging, which it enables. A brief discussion of implementation is presented below, along with a brief description of direct manufacturing cost savings.

Two NNS ultrasonic inspection systems are now in operation at P&WA's Manufacturing Division (MD) in Hartford, Connecticut and one at its Government Products Division (GPD) in West Palm Beach, Florida. Implementation has been taking place since 1975-76, as improvements to existing equipment have gradually been made. All three systems are semi-automated, have contour following capability, and operate with 50 mil material envelopes. They perform a more sensitive internal inspection than previous equipment, detecting flaws down to 1/64" in size.

Engine disks are the main components tested on these systems. Except for some thin compressor disks that do not require ultrasonic inspection, all engine disks produced in-house, for both commercial and military engines, are inspected on this equipment. Also, vendors have installed similar NNS ultrasonic inspection systems and inspect on their system disks which they produce. Much of the company-wide NNS ultrasonic inspection function will be transferred to P&WA's new Georgia facility in 1984. In addition to much of the ultrasonic inspection for military engines, commercial nickel disks and titanium fan disks will also be inspected at Georgia.

Benefits

P&WA estimates the NNS ultrasonic inspection system enables a tripling

transducer were provided to other manufacturers, and new transducers were purchased periodically. Two manufacturers (Harisonics and Panametrics) repeatedly delivered transducers that met performance requirements. The ultrasonic pulser and receiver were of conventional design except for modifications necessary to allow them to be computer controlled. To ensure the detection of all indications of interest, the defect gate used in this subsystem was designed to evaluate for and record the amplitude and position of the two largest indications between the front-face reflection and the farthest expected back-face reflection. This allowed for the possible occurrence of two back-face reflections at a point where there is a step change in the thickness of the part being inspected. If any indications larger than a preset level were found, a computer interrupt signal would be sent at the end of the gate time to tell the computer to store the data recorded by the gate.

The software system was a large computer program which controlled CAUS-1 activities. It was divided into program segments that correspond to major CAUS-1 functions such as: learning an inspection procedure, inspecting a part, and reporting inspection results. Specifications for an entirely new inspection procedure could be entered into the system in about one hour for a typical part. A given inspection procedure needed to be specified only once, since each procedure was named and stored on a system disk and could be recalled quickly by name. An editing feature allowed an existing procedure to be modified to meet changed requirements.

The capability of the CAUS-1 system to meet NNS inspection requirements was verified by using it to inspect simple pancakes of isothermally forged IN100 as well as three demonstration disks. The disks included one TF30 turbine disk and two F100 turbine disks. The TF30 disk was machined to NNS from a HIPed compact of low-carbon Astroloy. This disk shape was chosen because it had all the shape variations, such as overhangs, tapers, and thin sections, that might ultimately be found in a NNS disk. Both F100 disks were forged to NNS by isothermally forging IN100 preforms. One was inspected as-forged, and the other was machined to shape before inspection. For reference, #1 and #2 flat-bottomed holes were drilled at selected locations in both disks.

Project Results

A new computer-aided ultrasonic inspection system for near-net shape (NNS) turbine disks was successfully developed during this project. This inspection system, called CAUS-1, made it possible to implement NNS production techniques that greatly reduce material overstock and machining requirements. It also reduced inspection time.

Improved ultrasonic instrumentation and transducers developed for CAUS-1 reduced overstock requirements from 1/4 inch to 5/64 inch. The sensitivity of the new ultrasonic equipment was four times better than existing inspection equipment.

3) Increase inspection sensitivity from #2 FBH (flat bottomed hole) to #1 FBH.

4) Demonstrate that machining of NNS forgings is not required for ultrasonic inspection.

5) Computerize the measurement of NNS forging dimensions to aid in machining disks to final shapes.

6) Reduce the cost of inspection.

7) Demonstrate how inspection information can aid in the control of disk manufacturing processes.

8) Stimulate the development of inspection technology.

9) Transfer inspection technology to commercial suppliers of inspection equipment.

Project Description

To meet the objectives of this project, contour following and ultrasonic inspection subsystems were developed and interfaced with a PDP 11/40 minicomputer through the computer's data bus. Operation of the subsystems and data acquisition, storage, and analysis were controlled by a software package designed to run under the PDP 11 Disk Operating System. This computer-aided ultrasonic inspection system was called CAUS-1.

The contour following subsystem was assembled mostly from commercially available components in order to minimize cost and simplify maintenance. This subsystem kept the ultrasonic beam positioned normal (within 0.2°) to the inspection surface by monitoring the front-surface reflection amplitude and keeping it at a maximum by appropriate motions of a manipulator that held the ultrasonic transducer. The distance between an inspection surface and the transducer was determined to within .0025 in. through time-of-flight measurements of reflected ultrasonic pulses. Transducer positioning and inspection scanning were accomplished through ten highly accurate motorized axes that could be controlled either manually or by the computer. The positions of all axes and the transducer-to-surface distance were sent to the computer and stored at a predetermined rate to provide data on the dimensions of the part being inspected. These data could later be used as input to a computer-aided dimension inspection software system called CADI.

For the ultrasonic subsystem, there were no commercially available transducers that could meet the project's sensitivity and near-surface resolution requirements. Two manufacturers undertook development programs, and one of them (Harisonics) provided a transducer that substantially met the project requirements. General specifications for the Harisonics

Pratt and Whitney Aircraft
PRODUCTION INSPECTION OF NEAR NET TURBINE DISK SHAPES
F33615-75-C-5193 and F33615-76-C-5432
June 1975 - December 1977
\$439,116

Background

At the time this project was initiated, the standard production process for engine disks involved forging with large amounts of overstock. Forging weights were much greater than the weight of the finished disk, resulting in high input material and machining costs. Recent advances in hot isostatic pressing and isothermal forging techniques had made it possible to forge disks into shapes that were very close to their final shapes. These near-net shape (NNS) forging techniques promised considerable cost savings. However, the benefits from implementing NNS production techniques could be fully realized only by overcoming shape and size constraints imposed by existing ultrasonic inspection requirements.

Existing ultrasonic inspection practices required the machining of rough-forged disk shapes into blocky shapes with smooth flat surfaces before inspection. Such shapes were needed so that the ultrasonic inspection beam could easily be kept perpendicular to the inspection surface for maximum sensitivity. Existing ultrasonic equipment also had poor sensitivity for defects near surfaces. This required a sonic shape to have an overstock of up to 0.25 in. beyond the finished disk shape to ensure adequate inspection of the finished disk.

Because of the limitations of existing ultrasonic inspection equipment as described above, the successful implementation of NNS disk manufacturing processes developed under another contract (F33615-75-C-5184) required the complementary development of an entirely new ultrasonic inspection system. The requirements for the new system were: 1) it must automatically maintain the inspection beam normal to unmachined NNS surfaces, 2) it had to adequately detect near-surface defects, and 3) it must measure a near-net shape forging to verify that a finished disk could be machined from it.

Project Objective

The overall objective of this project was to develop a new computerized ultrasonic inspection system for NNS superalloy disks that complemented NNS disk production methods and enabled them to be implemented. Specific program objectives were:

- 1) Eliminate the need for blocky sonic shapes.
- 2) Reduce overstock inspection requirements to 0.050 inch.

<u>Application</u>	<u>MC Savings/Engine (in 1982 \$)</u>	<u>Implementation Year</u>
<u>PW2037</u>		
NNS isothermal forge stages 1 & 2 HPT disks	\$15,000	1984
<u>JT8-D</u>		
NNS isothermal forge stages 1,2,3,5,6 disks	\$ 1,600	1984
<u>JT9-D</u>		
NNS isothermal forge stages 5,9, & 11 compressor disks	\$ 1,440	1984
<u>JT9D-7R4</u>		
NNS isothermal forge stages 5,9, & 11 compressor disks	\$ 1,440	1984

TOTAL MC SAVINGS AT P&WA IN
COMMERCIAL ENGINES, THROUGH 1992 = \$40 MILLION

Figure 10
NNS Isothermal Forging - Summary of
Implementation and Manufacturing Cost (MC) Savings for Commercial Engines

<u>Application</u>	<u>MC Savings/Engine (in 1982 \$)</u>	<u>Implementation Year</u>
<u>PW1120</u>		
NNS isothermal forge: Stages 1,2,3 HPT disks Stages 1-2 turbine rim spacers	\$17,800	1984
Stages 9,11,13 compressor disks Stage 13 compressor spacer		
Intermediate NNS isothermal forge: Stages 1,2,3 fan disks	\$ 1,545	1980
Stage 4,5 compressor disks		
NNS isothermal forge: Stages 1,2,3 fan disks	\$ 2,400 (additional to above)	1984
<u>TF30-P-414A</u>		
NNS isothermal forge: Stage 1 turbine disk	\$ 3,300	1982

TOTAL MC SAVINGS AT P&WA IN
MILITARY ENGINES, THROUGH 1992 = \$117.5 MILLION

Figure 9(Cont'd)
NNS Isothermal Forging - Summary of
Implementation and Manufacturing Cost (MC) Savings for Military Engines

full-scale production of PW1120 and PW1128 engines begins, probably in 1984.

2. EB welded compressor rotor for the PW2037 engine. The alloys are Ti-6-4 and Ti-6-2-4-2. This rotor was designed from the beginning for welded joints. Production implementation occurred in 1982.

3. P&WA is now actively investigating the use of EB and inertial welding on a range of titanium alloys. Either EB or inertial welding will probably be used for drum rotor production for the Joint Fighter Engine and all new and derivative engines in the 1990s.

Benefits

1. The total savings from EB welding the PW1120 and PW1128 fan rotors is difficult to estimate. There are numerous factors affecting savings, each of which is difficult to quantify and monetize, particularly since they were both initially designed for EB welding. P&WA provided a "benchmark" estimate of net manufacturing cost savings of \$10,000 per rotor. This figure is based upon analyses of comparable substitutions of EB welding for bolting of rotors. Construction of the rotor is less difficult (esp. machining, assembly, and hole drilling), and the forgings are simpler and less expensive.

There is also an engine weight savings benefit of 30 pounds. Weight is saved by eliminating bolts, spacers, stiffening blocks, and flanges. Also, elimination of stresses around the bolts and spacers enables the use of somewhat thinner, lighter disks. Most importantly, EB welding yields a more rigid rotor, yielding payoffs in enhanced rotor durability and efficiency. There are also failure avoidance benefits, from elimination of stresses around the bolts. Weight, durability, efficiency, and failure avoidance benefits could not be readily monetized.

2. Manufacturing cost savings for the EB welded compressor rotor for the PW2037 engine are estimated at \$10,000 per engine, based upon the same approach as in #1 above. The other benefits of improved durability, efficiency, and failure avoidance are also realized. There are also major weight savings in the rotor, but required design changes in the case make it heavier, offsetting most of the weight savings.

Total manufacturing cost savings from #1 and #2 above through 1992 at P&WA are estimated to be \$35.2 million. Of this, \$24 million is in PW2037 production, and \$11.2 million is in production of PW1120 and PW1128 engines.

Pratt and Whitney Aircraft
HIP REJUVENATION OF CREEP-DAMAGED TURBINE BLADES
F33615-77-C-5219
August 1977 - October 1979
\$280,000

Background

The high operating temperatures of advanced gas turbine engines have led to complex turbine blade designs with intricate cooling passages to maintain blade temperatures at acceptable levels. Even with these sophisticated designs, blade overtemperature has continued to be a major cause of premature blade scrappage. Engine overtemperature results in reduced creep resistance. Blades which have accumulated a large amount of engine time experience a similar reduction in creep resistance.

Excessive creep (blade growth) is due to microstructural degradation of superalloy precipitated phases. This type of degradation can, in most cases, be eliminated by thermal rejuvenation. Mechanical discontinuities, such as microporosity and microcracks, constitute another type of internal blade damage. Discontinuities are due largely to stress and can be closed by the reapplication of stress during a HIP cycle. It was believed that the temperature and stress conditions applied during HIP should be able to rejuvenate both the internal microstructures and the mechanical properties of damaged blades in one HIP operation.

After HIP rejuvenation, normal refurbishment operations, such as welding, grinding, and blending can be used to restore damaged blades to engine-service condition.

The most obvious benefit from the development of a successful turbine blade rejuvenation/repair program is the economic advantage of returning scrapped parts to engine service. Other benefits are increased spare parts support, enhanced production surge capability, and conservation of strategic material.

Two other MANTECH projects at P&WA (F33615-76-C-5151 and F33615-76-C-5208) also contributed to the establishment of HIP rejuvenation and repair procedures.

Project Objective

The purpose of this process was to define and demonstrate a HIP repair process for rejuvenating the internal microstructure and mechanical properties of scrapped turbine blades and restoring them to engine-service condition.

Project Description

To represent the two types of turbine blade investment casting

processes in general use, two bill-of-material turbine blade alloys were selected for this project: directionally solidified (DS) MAR-M200+Hf (PWA1422) and conventionally cast (CC) IN100. All initial property evaluations were made with test specimens machined from cast bars.

First, optimum HIP and post-HIP heat treatment conditions were determined for each alloy. Next, baseline data were obtained by testing standard heat-treated machined bar specimens for each alloy in three ways: as machined, after HIP treatment only, and after both HIP and post-HIP heat treatment. Specimens of each alloy were then prepared for rejuvenation studies by creep testing them to partial life. These specimens were split into three groups. One group was retested directly to failure to assess the amount of rupture life lost due to prestrain, another group was HIP treated only before retesting, and the last group was both HIP and post-HIP treated before retesting.

Test results demonstrated the ability of HIP plus post-HIP treatment to eliminate the damaging effects of prior creep strain for DS MAR-M200+Hf test bars. Further tests to determine whether or not such property recovery could be extended to several strain/HIP cycles were not successful. For IN100 test bars, HIP plus post-HIP treatment did not overcome prior creep-strain damage. It also degraded the properties of non-prestrained specimens. For these reasons, work with IN100 was discontinued.

All further project work was devoted to developing HIP plus post-HIP rejuvenation procedures for F100 stage 1 turbine blades cast in DS MAR-M200+Hf. HIP trials with new blades showed that the aluminide blade coatings could be retained during HIP to prevent oxidation of the blade surface by high pressure gaseous contaminants. Blades stripped of their coating after HIP could be heat treated in a protective atmosphere. These new blade trials also showed that the effects of HIP on surface recrystallization and dimensional stability were insignificant.

Creep test specimens were machined from new blades and blades that had been HIPed after having been scrapped due to engine overtemperature. Creep-stress rupture test results for HIP rejuvenated scrapped blade specimens were statistically indistinguishable from those for new blade specimens.

The previously developed HIP, aluminide coating removal, and solution heat treatment procedure was scaled up to process scrapped blades with varying degrees of observable surface damage. Blade refurbishment operations were added to restore the scrapped blades to engine service condition. Refurbishment operations included weld repair of worn and cracked blade tips, rework of impingement tubes, blending of eroded areas, and replacement of aluminide coatings.

Eighty HIP-rejuvenated blades were submitted for refurbishment. Two of these were damaged by mishandling before any appreciable work had been done and were discarded. Two other exhibited weld defects but were successfully rewelded. During quality control inspection, eleven blades were found to have inadequate minimum air flow capability. The tips of

four of these were plugged with removable foreign material. Thus, 71 out of 78 blades were repaired successfully—a 91% yield.

Project Results

Early test results during this project demonstrated that HIP rejuvenation of CC IN100 components was not feasible and work on this alloy was stopped. Later information has indicated that the slow cooling rate of the HIP system is responsible for degradation of CC IN100 mechanical properties.

HIP rejuvenation and repair of DS MAR-M200+Hf F100 1st-stage turbine blades were successfully demonstrated during this project. The rejuvenation process fully restored the rupture life of scrapped overtemperature blades to new blade specifications.

An unforeseen result of this project was a pronounced improvement in the weldability of rejuvenated over non-rejuvenated DS MAR-M200+Hf. Previous weld repairs of non-rejuvenated turbine blade tips had a rejection rate in postweld fluorescent penetrant inspection of nearly 75%. In many cases it was possible to reweld these rejected blades. Rewelding, however, is time consuming and adds to the repair cost. Only two, or 2.6%, of the 78 rejuvenated blades were rejected for weld defects. These two blades were rewelded successfully. A drop from 75% to 2.6% in the initial weld rejection rate significantly affects blade refurbishment costs.

Based on the documented project costs for restoring 78 scrapped blades, rejuvenation and refurbishment costs were determined to be 45% of new blade costs. HIP and heat treatment represented only 5.6% of the total restoration cost. Previous repair methods could restore blades only to partial life and encountered severe welding problems. Since HIP rejuvenation was shown to restore blades to full life and to greatly improve weldability during refurbishment, it appeared to be a very financially attractive process.

Implementation

HIP rejuvenation has still not been successfully developed for IN100. However, HIP rejuvenation and repair was implemented in 1982 at P&WA's Southington, Connecticut repair facility for F100(3) stage 1 turbine vanes. The material is DS MAR-M200+Hf, the same alloy that was successfully demonstrated in the MANTECH project.

Chromalloy is also now qualified as a vane repair facility.

P&WA is now beginning work on a Navy MANTECH project to develop a HIP repair process for stage 1 and 3 turbine blades in TF30 engines. If successful, the process will probably be implemented at the TF30 Naval Air Re-work Facility.

Benefits

The main benefits are decreased scrappage and life extension. The process that has been implemented restores more than 100% of new part life. Service life of repaired parts is approximately 1800 Tactical Air Command Performance Cycles (TACs), versus 1200 for the original part. The service life improvement is obtained by closing the original cooling holes and re-drilling holes in a different, better location. The weldability improvement from the HIP process makes this possible.

The repair cost per part averages \$330 compared to a new part cost of \$1,100, a savings of \$770 per part. Although new vanes that are produced incorporate the new hole configuration from the beginning (and are HIPed), the benefits will accrue for many years to come, due to the large volume of F100(3) stage 1 turbine vanes already in service and the fact that the vanes can be repaired several times. Based on average annual throughput and the life extension obtained, P&WA estimates average annual savings of \$9.96 million. This is based upon an internal P&WA study. Total savings, beginning in the year after implementation, through 1992, are \$99.6 million.

In addition to the above dollar savings, the enhanced repair capability has significant beneficial impacts upon the capability of the Air Force to maintain high operations tempos, such as in times of mobilization or combat. Also, there are savings in strategically important materials.

Pratt and Whitney Aircraft
PRODUCTION OF POWDER METALLURGY NICKEL-BASE SUPERALLOY TURBINE DISKS
F33615-74-C-5108
December 1973 - January 1976
\$293,081

Background

There were two separate development efforts in this project. Both were concerned with the use of nickel base superalloy powder metallurgy techniques for the production of turbine disks.

One portion of the project was concerned with the production of full-size F100 1st-stage and 3rd-stage turbine disks from AF2-1DA alloy powder. The motive for this portion of the project was the occurrence in F100s of creep growth in IN100 disks, due to overtemperature. This effort was a follow-on to an earlier project (contract F33615-70-C-1387) in which three advanced nickel base superalloys were evaluated, using both conventional ingot and powder metallurgy techniques, to determine the feasibility of producing turbine disks with a temperature advantage of approximately 100^oF over existing disks. Subscale evaluation during the earlier project resulted in the selection of AF2-1DA powder metallurgy for further development. AF2-1DA powder consolidation and processing techniques were then optimized and used to produce full-scale billet stock. Although the results of this previous work were encouraging, there was still a need to manufacture full-size turbine disks from AF2-1DA powder for evaluation and testing and to establish the reproducibility of the manufacturing process.

The other portion of the project investigated the use of powder metallurgy, in place of conventional casting and multi-step forging, for producing TF30-P-100 1st-stage Astroloy turbine disks. The main motive for this effort was cost reduction. Astroloy powder could be HIPed to preform shape that required only a final, single forging step. Prior experience had also shown that powder metallurgy processing of Astroloy would improve its forgability, mechanical properties, and machinability.

Project Objective

AF2-1DA Powder for F100 Disks

The objective of this portion of the project was to utilize previously established subscale procedures to produce full-size F100 turbine disks from AF2-1DA alloy powder for material properties evaluation, potential engine qualification, and to establish the reproducibility of the manufacturing process. The use of AF2-1DA was expected to provide an increase of approximately 100^oF in operating temperature capability over the current bill-of-material IN100 alloy.

Astroloy Powder for TF30-P-100 Disks

The objective of the other portion of the program was to establish processes and specifications for producing TF30-P-100 1st-stage turbine disks from low-carbon Astroloy powder. This would demonstrate the cost and material savings from replacing the conventional multi-stage forging process with final-stage forging of annular preforms that had been HIPed from powder.

Project Description

AF2-1DA Powder for F100 Disks

This portion of the program was performed in two phases. In Phase I, acceptable AF2-1DA powder was hot compacted and extruded into billets. Forging bars were machined from the billets and isothermally forged to subscale disks which were then solution heat treated. Subscale disk properties were evaluated for various combinations of forging and heat-treatment temperatures to establish process parameters for producing full-scale turbine disks during Phase II.

In Phase II, full-scale F100 turbine disks were produced by isothermal forging segments machined from the billet stock prepared during Phase I. Two preliminary full-scale 3rd-stage disks were forged, cut up, and evaluated to verify and adjust for full-scale production the process parameters established in Phase I. Finally, three 1st-stage and three 3rd-stage disks were forged. These disks were non-destructively tested, and center slugs machined from them were evaluated for microstructural and mechanical properties. Further testing included fatigue testing of one 1st-stage disk to failure, hot spin burst testing of one 3rd-stage disk, and cut-up evaluation of one disk of each type. The two remaining disks were finish machined.

Astroloy Powder for TF30-P-100 Disks

This portion of the project focussed on producing TF30-P-100 1st-stage turbine disks from low-carbon Astroloy powder. The Astroloy powder was HIPed into annular preforms which were then forged into disks in a single conventional forging step. The program included an evaluation of two different HIP pressures—750 psi and 15,000 psi.

Three low-pressure (750 psi) HIP preforms, supplied by Kelsey-Hayes Co., were impact forged by Ladish Co. into disks using existing final stage production dies. After heat treatment, one disk was selected for cut-up evaluation, and a second one was machined to sonic shape. The second disk met existing NDI requirements, and was finish machined and engine tested.

Two sets of high-pressure (15,000 psi) preforms were obtained successively from two different suppliers. Because of high oxygen problems associated with powder handling and preform container filling, all of these preforms were rejected. Finally, two satisfactory high pressure HIP

preforms were obtained from a third supplier, Udimet. The preforms were impact forged into disks by Ladish Co. using existing final stage production dies. One of the disks was cut into quarters for heat treatment studies. The other disk was heat treated on the basis of results from these studies and then cut up for testing.

Project Results

AF2-1DA Powder for F100 Disks

The temperature advantage of AF2-1DA over IN100 disks was found to be 60°F to 70°F rather than the approximately 100°F that was expected. Also, cut-up evaluations revealed low tensile strength for AF2-1DA disks.

Astroloy Powder for TF30-P-100 Disks

This portion of the program was fully successful. The manufacturing process was fully demonstrated and material properties were good. Reduced manufacturing cost was verified.

Implementation

The AF2-1DA powder process was not implemented for disks. The overtemperature problem with IN100 disks was overcome, with a weight penalty, by using a cover plate to direct additional cooling air over the disk rim. This was a less costly solution, which also ensured maintenance of required material properties.

The AF2-1DA powder process, however, has been implemented for J-58 engine components. AF2-1DA stage 9 compressor tie bolts were installed in J-58 engines for evaluation, replacing Astroloy bolts. The evaluation results are positive, and it now appears that the entire J-58 fleet will be retrofit, at the time of scheduled engine overhaul. Production qualification of the bolts was completed in August 1980, with initial production beginning soon thereafter. The bolts are produced by a hot compact-plus-extrude-plus-isothermal forge process. Except for finish machining, the bolts are produced in-house at P&WA.

Benefits

There is an approximate \$25 per bolt manufacturing cost savings which, with 36 bolts per engine, yields per engine savings of \$900. Astroloy bolts are scrapped at overhaul, while AF2-1DA bolts are not. Also, there is a major reduction in production leadtime for these components. Total manufacturing cost savings through 1992 are estimated to be \$45,000.

Pratt and Whitney Aircraft
ADVANCED COMPOSITE ENGINE STATIC STRUCTURES
F33615-77-C-5032
July 1977 - January 1979
\$284,930

Background

Advances in the quality and consistency of high-performance composite materials had made it feasible to consider them as alternatives to metals for the fabrication of major static structures used in advanced gas turbine engines. Because of their high specific strength and stiffness, it appeared possible for advanced composites to meet structural and performance requirements while providing significant weight and cost benefits.

Project Objective

The objective of this project was to test F100 augmentor ducts fabricated from graphite/polyimide (Gr/PI) composite materials in order to assess the suitability of the materials and manufacturing methods that were used. The augmentor ducts to be tested were fabricated under separate contracts by Rohr Industries (contract F33615-76-C-5429) and Composites Horizons (contract F33615-76-C-5333), according to design requirements established by P&WA.

Project Description

The F100 augmentor duct was selected as a substantial, yet average-risk, demonstration article for this program. As a major engine structure, it was suitable for validating available materials, fabrication methods, and projected weight and cost advantages. It contained most of the features found in other major static structures, such as flanges, cylindrical and conical shells, instrumentation holes, bosses, and attachments.

The F100 augmentor duct must maintain its structural integrity at temperatures above 550^oF for short intervals. This dictated the use of polyimide resin matrices, since other classes of resins have inadequate oxidative stability at these temperatures.

Before this P&WA project began, P&WA prepared a preliminary layout which defined the F100 augmentor duct configuration, loads, temperatures, and acoustic environment. Two fabricators, Rohr Industries (RI) and Composites Horizons (CH), were separately contracted by the AFWAL/MLT to design and fabricate composite augmentor ducts according to these P&WA specifications. During the fabricators' design phases, P&WA obtained more realistic temperature data from an instrumented augmentor duct test which showed local hot-streak effects that increased maximum temperature requirements from 550^oF to 700^oF. The fabrication experience indicated that the 700^oF requirement was still within the maximum

temperature limits for the composite materials they had selected and their basic duct designs were not changed.

For its Gr/PI composite system, RI initially selected Hercules Type AS graphite fiber and Monsanto Skybond resin matrix. Composites fabricated with Skybond 703 had shown more than adequate long-term thermal stability at 550° F. Although the maximum short-term temperature specification was raised to 700° F, RI continued with Skybond 703, since previous RI data had shown it to have acceptable properties after 100 hours at 650° F. To improve oxidation resistance at the higher temperature limit, the inside of the composite duct was coated with a layer of DuPont NR150-B2 polyimide resin.

CH initially selected Celanese Celion 6000 (C6000) graphite fiber and PMR-15 polyimide resin for its composite system. Although PMR-15 was thought to have excellent mechanical properties at 700° F, the CH duct was fabricated with an inner shell of C6000/NR150-B2 composite to provide additional oxidative stability at the higher temperature limit.

P&WA reviewed the duct designs and found the overall design approaches of the two fabrications to be essentially the same, with a forward titanium flange, rear titanium cone assembly, and two side-port bosses, all riveted and bonded to a composite barrel. Both designs met F100 engine requirements and provided weight savings of 10%-15%.

The P&WA portion of the composite duct program was performed in three distinct phases. In Phase I, Gr/PI composite test panels were procured from the fabricators. The panels represented, as closely as possible, the materials and fabrication processes used for full-scale ducts. They were ultrasonically inspected and then mechanically tested at ambient and elevated temperatures and pressures to verify data used in the duct designs and to establish standards for later subelement and full-scale duct testing.

For Phase II, subelements were designed and fabricated to simulate the highly stressed front flange and rear cone attachments and bosses on the full-scale ducts. These subelements were tested to evaluate the fabricators' methods for composite-to-metal attachment and reinforcement. The composite materials were ultrasonically inspected, and the attachments were x-rayed for possible rivet cracking. Subelement tensile strengths and low-cycle fatigue strengths were measured and found to be excellent. Data from these tests were used to locate instrumentation for full-scale duct testing.

In Phase III, the two full-scale composite augmentor ducts received from the fabricators were weighed and then subjected to visual, dimensional, x-ray, and ultrasonic inspections. The expected weight savings were verified, and the various inspection results were all satisfactory. For structural testing, a composite augmentor duct was attached to other engine ducts, and a tubular air pressurization fixture was installed inside the augmentor duct. The resulting assembly was mounted on an F100 Structural

Conformance Test Frame, with mounting points identical to those used for an F-15 aircraft installation. Test loads, simulating a flight condition (designated LDG-70), were applied through the engine mounts as well as through the attached ducts. A series of test runs were made with each duct for both the flight and the landing conditions. Test data was obtained from 58 strain-gauge rosettes, 44 deflection indicators, and a pair of acoustic emission probes attached to each duct during testing.

The maximum detected stresses for both composite ducts were significantly lower than those measured previously for a titanium sheet-and-stringer duct. Compared to the titanium duct, radial deflections were slightly higher for the composite ducts, and axial deflections were significantly lower. Ovalization was within design tolerance for both composite ducts.

Project Results

Two Gr/PI composite augmentor ducts were received and tested by P&WA. Although both ducts provided the expected weight savings and met the structural requirements for F100 engine installation, they were both found to be unsuitable for actual engine testing because of PI resin matrix problems. The Skybond 703 resin used for the Rohr Industries duct could not withstand the thermal environment, even though the inside surface of the duct was coated with a layer of DuPont NR150-B2 polyimide resin to improve oxidation resistance. The coating peeled off during thermal cycling. There was excessive air leakage through the composite material of the Composites Horizons duct. In an engine, this leakage, attributed to resin microcracking, would result in insufficient cooling for the augmentor liner and nozzle structure.

Implementation

Follow-on work at P&WA, supported by the Air Force MANTECH program (contract F33615-78-C-5099) demonstrated Gr/PI composites as feasible and attractive for external nozzle flaps. Since these two projects, continued advances have been made in Gr/PI technology.

The only implementation at P&WA certain at this time are Gr/PI external exhaust nozzle flaps for the PW1120 engine. Full-scale production implementation is expected in mid-1986. The part will be supplied by vendors. It should be noted that the external exhaust nozzle flap on the PW1128 engine is of a different configuration. The flap on the PW1120 is a structural part. On the PW1128, it is a fairing, and weight savings are not as great as for the PW1120. Improvements (mainly durability) to the PW1128 flaps were obtained at lower cost through use of an aluminum braze process.

The process is a leading candidate for production of augmentor and fan ducts, and external nozzle flaps for the Joint Fighter Engine (JFE). Gr/PI would replace (from the F100) titanium honeycomb in forward and aft fan ducts, titanium sheet-and-stringer in the augmentor duct, and titanium in the flaps. Work is ongoing now at P&WA to develop production techniques

for integral flanges, which are needed. Any implementation would occur in the early 1990s.

Benefits

The main benefits of Gr/PI technology for all of the above applications are lower weight and improved durability. Cost savings may be realized, but could not be estimated at this time. The Gr/PI external nozzle flaps for the PW1120 will save approximately 7 pounds per engine.

Pratt and Whitney Aircraft
MANUFACTURING METHODS FOR ADVANCED SANDWICH PANEL CONSTRUCTION
F33615-72-C-2151
October 1972 - July 1975
\$772,145

Background

In the late 1960s and early 1970s P&WA IR&D efforts had investigated structural sandwich panel concepts in an attempt to identify lower cost alternatives, with equivalent strength-to-weight ratios, to commercially available honeycomb. Test results indicated favorable properties and production costs for a type of sandwich panel composed of thin face sheets bonded to a low density core formed at elevated temperature from a single sheet of superplastic material. This sandwich structure was capable of carrying compressive loads normal to the plane of the sandwich while stabilizing the face sheets, which in turn carry loads parallel to the plane of the sandwich. What was needed was to extend P&WA's work by developing and demonstrating the manufacturing process for a strong, economical sandwich material suitable for use in an advanced engine.

Objective

The objective of this program was to establish the manufacturing process for the core and for its attachment to face sheets to produce sandwich panels for full-scale engine components. The process was to be demonstrated by fabrication and testing of actual engine hardware. Project objectives also included the establishment of optimum NDI techniques, determination of the effects of alternative core geometries on the mechanical properties of the sandwich panels, and the establishment of optimum methods for attaching edge members and panel inserts.

Project Description

The project was organized into four phases. Phase I was to establish processing parameters for the core and for attaching face sheets. Three nickel base alloys, Astroloy, WASPALOY, and AF2-1DA, and two titanium base alloys, Ti-8Al-1Mo-1V and Ti-11.5Mo-6Zr-4.5Sn (Beta III), were evaluated. Properties of as-received sheet were analyzed for processing feasibility and tooling studies were conducted. Dies, fixtures, and retorts were fabricated and core forming studies conducted on subscale and then full-scale (22" by 36") components to determine the optimum combination of processing time, temperature, and pressure for core production. Brazing, welding, and diffusion bonding techniques were investigated for attaching the face sheets, and NDI techniques were evaluated for use in determining the integrity of the joints. A wide range of mechanical tests were conducted on the test sandwich panels. Three F100 sandwich panel divergent augmentor flaps were constructed of Astroloy, utilizing WASPALOY for details. They were inspected, engine tested, and a production cost analysis was conducted. The baseline F100(3) divergent augmentor flap was

constructed of WASPALOY facesheet, WASPALOY flap details, and IN718 honeycomb.

Phase II evaluated the effects of various core geometries, core sheet thicknesses, and facesheet thicknesses on sandwich panel mechanical properties. This involved the design and fabrication of two additional sets of forming dies, and the performance of core fabrication trials with Astroloy and Ti-8Al-1Mo-1V. Facesheets were attached and mechanical properties tested. Approximately 40 Astroloy and 40 Ti-8Al-1Mo-1V sandwich panel test specimens were produced and tested.

Phase III evaluated the mechanical properties of joints between sandwich panels and solid end members. Brazing, resistance welding, fusion welding, and riveting attachment methods were explored. The effect of core and panel splices on mechanical properties were also evaluated.

The objective of Phase IV was originally to design, develop, and proof test a Ti-8Al-1Mo-1V sandwich panel F100 rear fan duct segment, which upon successful completion of NDI and static proof testing would be made available for engine testing. Phase IV had progressed to the point that advanced sandwich panels had been produced, using a process involving creep forming to a 120° configuration (i.e. three to a duct) and brazing in a single cycle. At this point, the project was modified to use a Rockwell International superplastic forming/diffusion bonding (SPF/DB) process, which had recently been shown to be cost-effective in airframe applications, for fabrication of the sandwich panel. The material was changed from Ti-8Al-1Mo-1V to Ti-6Al-4V, for which Rockwells' SPF/DB process had been developed. A (flat) test panel was produced and a short testing program was conducted. A preliminary cost estimate was made which compared SPF/DB construction with Stressskin honeycomb construction for the F100 rear fan duct.

An effort was begun to 1) design and manufacture tooling for 120° curved sandwich panels, 2) to fabricate by SPF/DB and inspect a number of duct panels, 3) to assemble three panels into a F100 rear fan duct aft barrel section, 4) to attach the aft subassembly to an existing F100 rear fan duct, 5) to conduct NDI and static proof tests of the aft duct, and 6) to perform a final cost analysis. However, severe tool distortion occurred in step 1 and acceptable parts could not be produced without a major addition to project funding, which was not provided.

Project Results

It was found that neither WASPALOY nor Beta III exhibited sufficient superplastic behavior for the fabrication of sound cores. These alloys were dropped from further consideration. AF2-1DA, Astroloy, and Ti-8Al-1Mo-1V sheet material proved suitable for production of advanced sandwich panel cores. Hot forming with a vacuum hot press was found to be the most attractive production process for the cores, especially for full

Commercial Engines

JT8-D

An axial flow, dual compressor turbofan. Thrust ratings of the various models range from 14,500 to 17,400 pounds. It powers 727, 737, DC-9, and Caravelle transports. More than 8000 have been sold, exceeding sales of any other commercial engine.

JT9-D

An axial flow, dual compressor, high bypass ratio turbofan, with models developing 43,000 to 56,000 pounds of thrust. It powers 747 and DC-10 transports.

JT9D-7R4

A more efficient version of the JT9-D, with thrust ranging from 48,000 to 56,000 pounds. It powers A310, 767, and 747-300 transports.

PW2037

An all new, 25,000-pound thrust engine, for two-engine and three-engine transports. It was designed for low operating costs and low noise, for short, medium, and long range transports of 150 to 200 passengers. It currently powers 757 aircraft.

PW4000 series

An advanced version of the JT9-D, designed to be of lower cost and to have one-half the number of parts. Thrust will probably be approximately 58,000 pounds.

Description of P&WA Engines Discussed in This Project

Military Engines

F100(3)

A high performance, afterburning turbofan in the 25,000-pound thrust class. It powers Air Force F-15 and F-16 aircraft. Newer models may contain an improved life core (ILC), digital electronic engine control (DEEC), and an improved fuel pump system.

PW1128

An up-sized F100 with a larger fan and LPT, which operates at higher temperatures for improved performance, for application in advanced F-15 and F-16 aircraft. It utilizes the F100 ILC, DEEC, and improved fuel pump system.

PW1120

A turbojet version of the F100 with the ILC, DEEC, and improved fuel pump system. It has a shorter afterburner and a lighter, simpler exhaust nozzle. Israel's Lavi fighter will use this engine. Thrust is in the 20,000-pound class range.

TF33

The first military turbofan engine, with versions rated between 17,000 and 21,000 pounds of thrust. It powers B-52, C-141, and E-3A aircraft.

J58

A 30,000 thrust class turbojet engine. It powers SR-71 aircraft.

TF30

A 25,000-pound thrust class turbofan. It powers Air Force F-111 aircraft (TF30-P-100), Navy F-14 aircraft (TF30-P-414A), and Navy and Air Force A-7 aircraft.

Joint Fighter Engine (JFE)

An all new advanced technology engine, targeted to the USAF/Navy Advanced Tactical Fighter aircraft in the late 1980s and early 1990s.

in high strength titanium alloys. Vacuum hot pressing was found to be a reliable method for detecting gross powder contamination. However, radiography or forging and testing a small compact is necessary to determine the presence and/or effect of small inclusions in consolidated powder. Tensile ductility of extrusions reflected microstructural differences as well as contamination present in the materials. Tensile strengths were not significantly affected by either forging temperature or inclusion level. Direct extrusion of powder resulted in more uniform structural response than HIP, although both resulted in fully compacted material.

The project was plagued by difficulties in detecting small inclusions. It was noted that techniques needed to be developed for detecting these small inclusions (i.e., ≤ 25 mils).

In summary, clean Ti-6-2-4-6 powder was found to be unprocurable, and cleaning methods not fully effective. A clean powder needed to be developed before a production forging process could be optimized or parts tested in an engine.

Implementation

No P&WA rotating titanium parts are currently produced using powder metallurgy techniques, nor are there specific plans to do so in the near future. Technical problems remain with this process, especially regarding powder quality. In addition to powder quality problems, a fact that also tends to inhibit the development and use of this technology is that there have been major advances in competing titanium technologies, especially isothermal forging and, for other applications, casting. Thus, there is presently no pressing need for titanium powder processes for engine applications.

Task II Results

Both as-extruded and extrusions that had been forged and heat treated showed low ductilities, which were found to be caused by nickel and phosphorus inclusions. The HIPed billets had porosities and interstitial contamination. An additional extrusion and two HIPed billets were produced using a different canning procedure and were evaluated to test whether the canning procedure (especially the brazing) was the cause of the contamination. All still showed unacceptable properties. Numerous inclusions were found on the surfaces of the failed tensile specimens, and thus contamination of the powder itself was suspected. A detailed study conducted with a scanning electron microscope equipped with an energy X-ray spectrometer found inclusions in all the material. Most were tungsten, although there were some nickel and some others that could not be positively identified--possibly iron or chromium. Erosion of the tungsten stinger electrode was believed to be the source of the tungsten inclusions. Nickel inclusions were believed to have resulted from prior processing of nickel in the powder rig. Even extremely rigid cleaning procedures had not removed all the nickel particles. The other inclusions were thought to have been caused by erosion of the viewing port on the powder rig or perhaps mishandling of the powder after production.

Task III Description

Task III evaluated AVCO's ferrofluid separation technique for cleaning the REP powder. Approximately 470 pounds of additional Ti-6-2-4-6 powder were cleaned in two runs. However, both batches were found to contain small iron oxide contaminants. A full scale extrusion using this powder suffered press stall, and salt contamination occurred from a leaky weld in the repaired can, which was used in the re-run. The billet was unsuitable for further evaluation.

Several chemical solutions were used to try to remove the iron contamination from the remaining unused powder. The most effective cleaning technique utilized a PS140 solution, which is a neutral cleaning and descaling solution containing a minimum 36% by weight cleaning agent. A billet was extruded using the resulting powder, and subscale disks were forged. Tensile specimens, however, failed to meet specifications due to a low amount of primary alpha and the presence of inclusions. Although the PS140 cleaning technique was effective in removing iron from contaminated powder, analysis revealed inclusions similar to those found earlier.

Task III Results

Ferrofluid and/or chemical cleaning of contaminated powder did not appear to offer a solution to the powder contamination problem.

Overall Project Results

This project showed the dramatically detrimental effects of inclusions

conducted to identify the inclusions, their causes, and how they might be prevented or removed. Task III evaluated the use of a ferrofluid cleaning technique for cleaning contaminated T1-6-2-4-6 powder. Detailed descriptions of Tasks I-III follow.

Task I Description

Hydride-dehydride powders were obtained from Titanium Metals Corporation of America (TMCA) and Nuclear Metals and Equipment Corporation (NUMEC), and rotating electrode process (REP) powder from Nuclear Metals Corporation. Characterization analyses were performed on all powders. Each billet was analyzed to determine macrostructure and microstructure interstitial chemistry, and mechanical properties, and each was ultrasonically inspected.

Task I Results

As mentioned previously, each of the powders was found to have unacceptable inclusions. Although the extent and nature of these inclusions varied among the sources, their presence in the material resulted in equally catastrophic effects on material properties, especially ductility. Inclusions containing nickel and chromium were found in the REP powder. The TMCA hydride-dehydride showed evidence of iron, cobalt, chromium, and another unknown inclusion. Silicon inclusions, as well as an unknown inclusion, were found in the NUMEC hydride-dehydride. The inclusions were thought to be preventable by more stringent handling and processing procedures. On the positive side, both HIP and extrusion were demonstrated to be viable means of consolidating titanium powder alloy to theoretical density.

NMI's REP powder was selected as the preferred powder material due to 1) its significantly lower interstitial levels (lower percentage of fine particles, lower specific surface, all inert handling), 2) the nature of its inclusions (i.e., the problem probably could be readily solved by a dedicated production facility or more stringent cleaning procedures), 3) its higher bulk density (resulting in higher yields and lower costs in the production of forging billet), 4) its higher ductility, and 5) its structural uniformity, which consistently yielded fine grain structures.

Task II Description

Three new 100 pound lots of powder were provided by Nuclear Metals. A number of special precautions were taken during production to ensure high quality powder, based upon the Task I results and other recommendations from Nuclear Metals. Three cans of the powder were extruded at RMI and three cans were HIPed at Industrial Materials Testing Laboratories. Each of the three extrusions and HIP processes varied slightly, based upon the results of Task I. The billets were then evaluated as to structure, chemistry, and mechanical properties.

Pratt and Whitney Aircraft
MANUFACTURING METHODS FOR PRODUCTION OF TITANIUM ALLOY COMPRESSOR DISKS
FROM POWDER BILLET
F33615-72-C-1390
May 1972 - October 1976
\$262,500

Background

In the development of the F100 engine, P&WA moved from Ti-6Al-4V to Ti-6Al-2Sn-4Zr-6Mo for a number of fan disk and HPC disk, blade, and vane applications. Ti-6-2-4-6 has a higher strength-to-weight ratio and higher operating temperature capability than Ti-6-4, the workhorse aerospace alloy which previously had been used in these applications. Before selecting Ti-6-2-4-6 over Ti-6-4, P&WA had conducted extensive microstructural analysis, property testing, and process development work. Two MANTECH projects (F33615-68-C-1226 and F33615-71-C-1569) had played an important supporting role in this effort.

A potential problem in the use of the more heavily alloyed Ti-6-2-4-6 is that it is prone to macrosegregation, especially when produced in ingot sizes large enough to make components such as disks. Powder metallurgy offered a way to prevent macrosegregation and to produce a more homogeneous product, with superior properties. Microsegregation could occur, but in pure powder would be confined to individual powder particles.

Objective

The objective of the project was to establish the process for producing F100 compressor disks from Ti-6-2-4-6 powder. The entire process was to be explored in detail, including powder preparation, consolidation, forging, heat treatment, and testing. The reproducibility of the process would be demonstrated and a comprehensive cost analysis conducted. The project was to result in preliminary material specifications, process specifications, and quality control procedures.

However, powder contamination problems surfaced early in the project which necessitated a re-direction of the effort. The modified project focussed on identifying the causes of the powder contamination, developing procedures for preventing contamination, and evaluating methods for cleaning contaminated powder.

Project Description

The project (as modified) was organized into three tasks. In Task I, two types of powder from three vendors were evaluated and a preferred powder selected for use in later tasks. In Task II, various consolidation techniques and processing parameters were explored, and an analysis

Benefits

Although implementation of DS Eutectics has not occurred at P&WA, a great deal of the knowledge developed in this program, particularly regarding computerized DS process control, has been applied by P&WA and vendors in casting regular DS and single crystal turbine blades and other components. No monetary estimates could be developed.

Process parameters for this alloy were nominally the same as for the other alloy except for a lower casting immersion rate and an argon rather than a vacuum environment. Again, other types of blades were cast in one-blade and three-blade molds. The hollow JTDE blades were cast in both root-up and root-down gating configurations. The solid F100 blades were all cast with root-down gating. The overall quality of blades from these final casting trials for both alloys was assessed through standard non-destructive and destructive testing procedures.

Results

Master melting procedures established in Phases I and II of this project were used as guidelines by Special Metals Corporation to prepare two 300-pound commercial scale master heats of $\gamma/\gamma' + \delta$ eutectic alloy using commercial grade elements. Both heats were qualified by P&WA in terms of cleanliness and creep-rupture properties. One of the two heats exhibited acceptable chemistry and was used for melt charges in the final casting trials. This part of the project was successful in that it demonstrated the feasibility of commercially produced master heats of $\gamma/\gamma' + \delta$ eutectic alloy in cost-effective 300-pound sizes. Previous work with this alloy had been limited to the use of laboratory-produced heats of under 10 pounds.

Another successful aspect of this project was the development of a computer controlled directional solidification (DS) casting process which employed a low melting point liquid-metal immersion bath to obtain the necessary higher temperature gradients. Computer monitoring and control accurately and reproducibly kept the extreme thermal conditions and the slow immersion rate required for DS casting within very tight limits.

The primary objective of this project, reliably producing eutectic turbine blades, was not successfully achieved. Throughout the project, there were core problems with hollow JTDE blades cast in the $\gamma/\gamma' + \delta$ alloy. Inadequate core strength resulted in core shift and core distortion during casting. For the solid F100 blades, there were problems associated with detachment of blade surfaces from molds during casting. The same core and surface attachment problems were encountered with blades cast in the NiTaC-13 alloy. For both alloys, poor creep-rupture properties were generally found in the root portions of the blades. Of the blades cast in the $\gamma/\gamma' + \delta$ alloy during the final casting trials, 81% of the hollow JTDE blades were rejected, and 94% of the solid F100 blades were rejected. All blades cast in the NiTaC-13 alloy were rejected.

Implementation

The pursuit of DS Eutectic technology has been dropped at P&WA due to technical problems and the attractiveness of competing processes, e.g. single crystal casting and RSR powder. No implementation of DS Eutectic technology has occurred or is anticipated.

the high temperature gradients required for directional solidification of eutectic turbine blades. This process involves pouring the eutectic alloy into an investment casting mold attached to the top of a chill plate and then lowering the mold at a controlled rate into a molten bath of low melting point metal. The displaced coolant metal spills over into a reservoir. As the mold is lowered, coolant metal around the solid portion of the casting provides a near constant length heat conduction path from the solidification front which permits steady-state heat transfer conditions to be approached. Molten tin was selected for the cooling medium because of its relatively low melting point (450°F), low vapor pressure characteristics, good thermal properties, and low cost. Its low vapor pressure allows vacuum processing at elevated temperatures. The molten tin bath was stirred to improve both temperature control and heat transfer.

This project was performed in three phases. The first task in Phase I established the procedures required for producing acceptable 50-lb master heats of $\gamma/\gamma' + \delta$ eutectic alloy from laboratory grade elements. A series of casting trials was performed during the second task to optimize the directional solidification process parameters in terms of microstructural, chemical, and non-destructive inspection quality of the cast blades. Cored JTDE 1st-stage turbine blades were cast for most of these trials. At the end of this task, solid F100 3rd-stage turbine blades were cast from both $\gamma/\gamma' + \delta$ and NiTaC-13 alloys to investigate the adaptability of this casting process in terms of blade geometry and alloy characteristics.

The initial task in Phase II established procedures for reducing material costs for the $\gamma/\gamma' + \delta$ eutectic alloy. This involved: 1) the use of commercial grade starting materials, 2) recycling scrap from Phase I, and 3) scaling up procedures established in Phase I to produce 300-pound small scale commercial heats of this alloy. The second task during Phase II involved the design and implementation of a computerized process control system. This system automatically monitored and controlled the following casting process parameters that were established in Phase I: alloy pour temperature, mold hot-zone temperature, tin bath temperature, and casting immersion rate. The operation of the system was evaluated through a series of casting trials. Hollow JTDE 1st-stage and solid F100 3rd-stage turbine blades were both cast in $\gamma/\gamma' + \delta$ eutectic alloy. The system's effectiveness in controlling process parameters was verified. The cast blades were tested for microstructural, chemical and non-destructive inspection quality.

In Phase III, the optimized casting process parameters established in Phase I, a 300-pound master heat fabricated in Phase II, and the computerized process-control system implemented in Phase II were combined to cast directionally solidified hollow JTDE 1st-stage and solid F100 3rd-stage turbine blades from the $\gamma/\gamma' + \delta$ eutectic alloy. Both types of blades were cast in one-blade and three-blade molds. The casting trials were followed by similar ones using NiTaC-13 eutectic alloy.

Pratt and Whitney Aircraft
REDUCED COST PROCESSING FOR DIRECTIONALLY SOLIDIFIED EUTECTIC AIRFOILS
F33615-74-C-5018
February 1974 - April 1976
\$743,100

Background

At the time of this project superalloys used in turbine blades were limited to temperatures around 1800°F. At the higher temperatures proposed for advanced engines, these superalloys would require excessive amounts of cooling air in order to maintain component temperatures at levels compatible with good durability. The more complex internal air-cooling schemes needed to meet such requirements would significantly increase manufacturing costs. An alternative to more complex and costly designs would be the use of other alloys which had higher temperature capabilities than the baseline superalloys.

Directionally solidified (DS) eutectic alloys offered the potential for significantly higher temperature capabilities. Eutectic alloys, reinforced with the intermetallic compound δ -Ni₃Cb, possessed many of the properties needed for advanced gas turbine applications. In terms of their creep behavior, they offered a 100°F - 150°F temperature advantage over the currently used superalloys, such as MAR-M-200. This higher temperature capability could be exploited to improve thrust, engine efficiency and component durability.

The solidification behavior of eutectics requires them to be directionally solidified under closely controlled thermal conditions to obtain the desired oriented eutectic microstructure. To sustain the plane growth conditions required for developing the desired microstructure, a sufficiently high G/R ratio (where G is the temperature gradient in the liquids at the solidifying interface and R is the solidification rate) is needed to suppress constitutional supercooling and to promote lamellar growth. Thus, stringent control of a relatively slow solidification system would be required in order to establish a reliable process for manufacturing eutectic turbine blades and vanes.

Project Objective

The objective of this program was to establish reliable, reproducible, and cost-effective manufacturing methods for producing directionally solidified eutectic airfoil castings. This would help to ensure the availability of this class of alloys for use in advanced gas turbine engines.

Project Description

For this project, a liquid metal cooling process was used to obtain

Implementation

This technology is essentially proven but the small dollar savings (albeit a high percentage savings) to be realized have not induced change. There is a material specification on the process and it is awaiting an attractive application. However, the lack of weldability seriously limits its application potential within the engine. There is also some reduction in fatigue properties. The process was a candidate for F100 ILC compressor stator connecting links. It was not implemented because a design change was made which changed the alignment of the link, which would require machining, and eliminated the cost savings. The process is still a candidate for the F100 and is being assessed again in a new cost reduction program.

Benefits

Due to lack of implementation, no benefits were identified.

effects of chloride on weldability. Specially processed powder, procured from Nonferrous International Corporation (NFI), was required for this. NFI, metallographic examination, tensile tests, microprobe analysis, and weldability tests were conducted and inclusions were found. There were areas of segregation, low density inclusions, and other indications of incomplete diffusing of the master alloy during sintering. Welding properties were poor, and only one of 40 tensile specimens met P&WA standards. A number of inconsistencies surfaced in the evaluation of microstructure and tensile properties. Density of sintered compacts ranged from 80.3% to 97.2%, and ultrasonic inspection revealed indications which needed further investigation. Due to these reasons, the project was revised to conduct additional process evaluation work.

Additional sodium-reduced Titanium sponge fines were obtained from NFI, RMI, and TIMET. A new round of process evaluation was conducted. Gould was the subcontractor in the revised effort. Mechanical and microstructural evaluation of the sintered specimens showed that RMI powder pressed at 44.49 TSI and sintered at 2275^oF produced the most acceptable results. The large indications in earlier compacts were not observed in the pressed and sintered compacts produced by Gould. The revisions in sintering time and temperature were thought to have successfully diffused the master alloy particles into the matrix. Weldability, however, was still not satisfactory, regardless of the powder's chloride content level.

The second part of Phase I entailed evaluating shape making characteristics of the powders. The shape making effort was highly successful, yielding good dimensional uniformity from part to part. Mechanical properties of both convex and concave configurations were comparable to those measured on specimens earlier. It was found that relative complex geometries could be reproducibly manufactured by the technique.

F100 compressor rigid stator links were produced by the process parameters. Some of the links were produced from the same powder lot used in the critical part of Phase I, and some from the improved powder lot. Subjected to identical process parameters, the links made from the improved powder were clearly superior. The links produced from the improved powder showed properties equal or superior to those of wrought links.

An economic analysis revealed that, at \$3.00 per pound for blended Ti-6-4 powder, a cost reduction of 71% was realizable for pressed and sintered components over conventional machining from barstock. Decreased material and machining costs accounted for the bulk of the savings.

Project Findings

An acceptable press and sinter process for manufacture of Ti-6Al-4V engine components was successfully developed and demonstrated. Both the technical feasibility and economic attractiveness of the process were established.

Pratt and Whitney Aircraft
CONSOLIDATION OF BLENDED ELEMENTAL Ti-6Al-4V POWDER TO NEAR-NET SHAPES
F33615-74-C-5028
December 1973 - December 1978
\$252,828

Background

In the early 1970s, there was great interest in titanium powder metallurgy as a way of reducing the production cost of titanium components and conserving what at that time was considered to be extremely scarce and strategically critical material. Direct consolidation of titanium powder to net shape or near-net shape had been proven cost-effective and technically acceptable for a number of small, non-critical components such as brackets, bosses, hinges, and bushings. Before the application base for this production technique could be expanded to more critical components, the capability of the production process to produce components with acceptable structural and mechanical properties and good weldability had to be demonstrated.

Project Objective

The objective of this project was to establish a manufacturing process for producing titanium alloy engine parts by cold press-plus-sinter of titanium alloy powder to near-net shape. The project was to establish process parameters, and then to demonstrate the reliability and cost effectiveness of the process by producing a static engine component of sufficiently complex configuration to be representative of the potential application base for the process. The F100 compressor stator connecting link was selected. This is a static structural component requiring good material properties. The link connects the synchronizing arm to the 4th and 5th stage compressor guide vanes. It is made of Ti-6Al-4V and in the conventional process is machined from barstock.

Project Description

The project was organized into two phases. Phase I was to evaluate process parameters, select optimum parameters, and then to use these to produce test shapes to determine shape making capability. Phase II was to produce F100 compressor rigid stator connecting links using the process parameters established in Phase I. This was to verify the capability of the process to produce acceptable parts and to provide detailed information on potential cost savings.

Elemental Titanium sponge fines with four different (low) chloride levels were blended with 10wt% 60Al-40V master alloy powder, cold pressed, and then sintered in vacuum. REM Metals Corporation (REM) was a major subcontractor, performing the pressing and sintering. Various pressing pressures and sintering temperatures were evaluated, in a two-hour sinter cycle. The different chloride levels were to enable an assessment of the

scale production of multiple cores. A large data base was developed on the formability and mechanical properties of alternative core geometries.

Brazing was found to be the most suitable facesheet attachment method. Ti-15Cu-15Ni and Omdry 914 (Ni-20Co-3B-4Si) were the most attractive braze fillers for Ti-8-1-1 and Astroloy, respectively. Diffusion bonding and resistance welding were rejected as face sheet attachment methods, primarily because the core nodes could not support the loads required to obtain sound joints. Ultrasonic and X-ray radiography were both found to be suitable NDI methods for evaluating the integrity of sandwich panel brazements.

Three F100 sandwich panel divergent augmentor flaps were produced and successfully engine tested. Their overall performance in the engine test was superior to bill-of-material honeycomb. Strength-to-weight ratios of the sandwich panels were found to be roughly equivalent to conventional honeycomb.

In summary, this program successfully demonstrated the production of superplastically formed flat sandwich panels for engine applications. It provided evidence that advanced sandwich panels could probably be utilized for production of curved components, although this was not conclusively demonstrated. It showed that it may be possible to creep form and braze curved sandwich panels in a single operation, with resulting large cost savings.

Implementation

Although the technology has been shown to be technically feasible for engine applications, at least for panels, its cost-effectiveness has not warranted implementation. The divergent augmentor flap investigated in this project was changed to titanium sheet-and-stringer. Sandwich panel processes are under consideration for producing inlet struts for JT8-D, PW2037, PW1128, and PW4000 series engines. Also, P&WA is exploring the use of sandwich panel processes for production of hollow fan blades, though NASA's Energy Efficient Engine program.

Benefits

Due to lack of implementation at P&WA, no monetary benefits were identified.

General Dynamics Corporation

General Dynamics Corporation/Ft. Worth Division
COMPOSITES PRODUCTION INTEGRATION
F33615-77-C-5018
Jan. 1977 - Jan. 1980
\$503,700

Background

Hand layup and cutting had been the traditional method of manufacturing for graphite/epoxy (Gr/Ep) composite structures, even as late as the early 1970s. The manual process is extremely labor intensive with major, inherent quality control problems. General Dynamics began as early as the mid-1960s to develop automated and semi-automated tape-laying equipment for Gr/Ep composites based on the expectation that future aircraft would extensively utilize these materials. By the early 1970s, it had become evident that the F-16 (General Dynamics' YF-16) would utilize Gr/Ep skins for vertical and horizontal stabilizers, to reduce weight and improve aircraft performance.

Company IRAD programs in the mid-1960s resulted in the development of a prototype tape laying machine, called GDTL-1, which proved the basic feasibility of automation. An Air Force MANTECH program was initiated in 1967, entitled "Development of Composite Tape-Laying Process for Advanced Fibrous Reinforced Composite Structures" (F33615-67-C-1271), and developed an improved machine, called CONRAC TLM-100. It was developed under a General Dynamics subcontract to the Machine Tool Division of CONRAC Corporation. It employed 3-in. wide prepreg on a 4-in. wide carrier, and had a traveling NC controller, three-axis movement, 720 in. per min. lay down rate, and capability of cutting angles of ± 60 degrees, and 9.75-in minimum lengths. The machine was basically sound and usable for production, but needed more accurate layup positioning and monitoring for full cost and technical effectiveness. Another Air Force MANTECH program, F33615-72-C-1652, was initiated in 1972, in which General Dynamics successfully developed an improved tape laying head with automatic centerline positioning adjustment.

When the F-16 production program began in 1976, the CONRAC machine, with the improved TLM-100 head, was scheduled for lay-up of vertical stabilizer skins. However, the machine still had many limitations, resulting in a great deal of hand work. The maximum angle of cut was 60 degrees; it used 3-in. tape on 4-in. paper, which was difficult to control; it could not cut lengths less than 9.75 in.; and there were many interruptions required in the lay-up process. What was needed was a more automated system for laying high quality composite laminates, that did not have the TLM-100's limitations. The benefits would be reduced production costs and reduced material scrappage.

Project Objective

The objective of this project was to develop and demonstrate a new computer-controlled tape laying head for the CONRAC machine which would more fully automate layup of Gr/Ep composite laminates for F-16 aircraft applications.

Project Description

The project consisted of two phases - a concept development phase and a demonstration phase. In Phase I, the existing machine and production methods were analyzed, needed changes were identified, an initial demonstration of machine modifications was performed, costs were estimated, and an ICAM interface analysis performed. Phase II demonstrated the machine modifications by laying up two complete F-16 horizontal stabilizer skins, and verifying costs and laminate quality. General Dynamics provided between \$100,000-\$200,000 of company funds to support this project.

Project Results

The new tape-laying head was successful, and the project demonstrated the repeatability of the process. Some of the attempts to push the technology to total automation made the system too complex and created problems, and the final head that was later implemented was somewhat simplified. This project essentially proved the technical and economic feasibility of highly automated layup.

Implementation

A follow-on MANTECH program, entitled Composites Manufacturing Operations Production Integration (F33615-78-C-5217) continued the development of a number of composites manufacturing concepts and their integration into a high volume composites laminating center. CONRAC was updated with the advanced tape-laying head; a 1-inch tape laying head was developed to lay small parts; an automatic tape loading and threading system was developed; a 6-inch Ingersoll tape laying machine and a 1-inch/6-inch combination tape laying machine were added; and a computer controlled automated material handling system was developed and integrated.

The Air Force MANTECH Division also has supported the development of an in-process control and inspection system which integrates all of the functions of General Dynamics' Laminating Center, by providing quality control and traceability of laminates from receipt of raw material to delivery of the finished part. Automated, integrated systems have been developed for prepreg analysis, on-line tape-laying inspection, module cutting and coding, module recognition and stacking, cure control, and laminate final inspection. General Dynamics has provided a great deal of support to these programs, and has procured much of the hardware with company funds.

Implementation of automated layup began in earnest in 1980. It has been implemented or is programmed for the following types of F-16 components:

- upper and lower wing skins
- wing inserts
- horizontal and vertical stabilizer skins
- vertical stabilizer inserts
- rudders
- ribs
- spars

Benefits

Based upon a 2206 F-16 production schedule through 1988, and an assumed production rate through 1992 equal to the 1988 level, for a total of 2718 aircraft, labor cost savings were estimated to be approximately \$11,845,000 (in 1982 dollars). This is based upon information developed in a cost analysis performed by General Dynamics for another purpose, which was made available to the study team. This savings figure is strictly from the automation of the tape laying, and did not include savings from the material handling system, or the in-process control and inspection systems, which were developed through other efforts.

However, this savings figure is not appropriate for the purposes here, because the baseline for comparison assumed use of the updated CONRAC and 6-inch Ingersoll machines. Savings based upon a CONRAC-only baseline would certainly be much higher, perhaps twice as high. The dollar savings from moving from a hand layup baseline to the use of all three advanced systems (up-dated CONRAC, 6-inch Ingersoll, and 1-inch/6-inch machine) are probably several times the savings given above. Therefore, professional judgement was used to develop a conservative, benchmark estimate of \$31,485,000 (3 times \$11,845,000, less \$4,050,000 installed cost of equipment).

It should also be mentioned that the laminate obtained with the automated systems is of higher quality and more consistent. Also, the 80 ply vertical stabilizer skin cannot be laid up by hand--the needed pressure cannot be obtained with hand layup. Hand and automated layup have approximately the same material utilization.

General Dynamics Corporation/Forth Worth Division
RELAXED MANUFACTURING DESIGN TOLERANCE CONCEPTS
F33615-74-C-5044
April 1974 - April 1977
\$623,055

Background

It is a common perception among manufacturing engineers that aircraft designers are inherently more concerned with improving aircraft performance--range, payload, maneuverability, etc.--than with minimizing aircraft manufacturing costs. This bias of designers is a natural one, but is aggravated by the fact that they typically have a less than adequate understanding of the relevant design/cost trade-offs for the components they design. Overly stringent dimensional tolerances and surface finish requirements translate into unnecessary manufacturing costs. Given the enormous volume of machining required for aircraft production, even small relaxations in traditional design, tolerance, surface finish, and inspection requirements can translate into enormous manufacturing cost savings.

Project Objective

The objective of this project was to develop quantitative relationships between design features and manufacturing costs in the form of design guidelines for machined parts. The guidelines, to be used by designers, were to yield manufacturing cost savings by relaxing dimensional tolerances and surface finish requirements, and by providing cost/weight tradeoff data for design optimization. Another, although secondary, project objective was to develop numerical control programming guidelines that would reduce manufacturing costs by increasing metal removal rates without unacceptable reduction in product quality.

Project Description

The project was performed in five overlapping and interdependent phases. Phase I was an analysis of F-111 and YF-16 airframe design drawings to identify cost-sensitive geometric features and dimensional tolerances. Phase II evaluated surface finish requirements, identified candidates for change, and assessed the cost effects of such changes. Phase III assessed the effect of dimensional tolerance requirements on cost and weight, and then proposed design relaxations. Phase IV entailed the design, manufacture, and fatigue testing of typical airframe components using the relaxed designs, to demonstrate technical acceptability and cost savings. Phase V developed numerical control programming guidelines for reducing costs, and demonstrated the acceptability of these guidelines by re-programming two F-16 aluminum production parts and machining and testing five of each part.

Project Results

The project was a major technical success, and a large number of guidelines were established for aluminum parts. It was demonstrated that dimensional tolerances for most flanges and stiffeners could be relaxed from the traditional ± 0.010 in to $+ 0.015, - 0.10$ in. This significantly reduces the rejection rate, and the costs of hand finishing and machining. A number of relaxations were found to be feasible on geometric features such as corners of pockets and "lands". Additional undercuts of 0.010 in. (for a total of $- 0.020$ in.) were found acceptable for most corners with small radii. This enables the use of larger finish cutters. For surface finish, it was determined that it is not necessary to eliminate normal milling waves and swirls from aluminum surfaces for the sake of appearance, or to eliminate milled roughness, for the sake of maintaining fatigue strength. A number of NC programming/machining guidelines were also established. Metal removal rates were increased by an average of 100%, without loss in quality, by use of more efficient cutter motion.

Implementation

Implementation of the project findings occurred almost immediately, even before the termination of the contract. The dimensional and design relaxations were adopted across the board for F-16 aluminum machined parts. Just about every one of the several thousand aluminum machined parts in the F-16 were in some way impacted by the guidelines. Almost all the design guidelines were incorporated into the Ft. Worth Division engineering department's Design Handbook for Machined Parts, and all F-16 machined parts drawings have "notes" and other information attached, from one to five in number, which were generated in this project. Relaxation of roughness and hand finishing requirements were implemented through work sessions with personnel from inspection, machine shop, process control, planning, materials engineering, stress analysis, and airframe design organizations. Project personnel taught classes to machine shop, assembly, and inspection personnel, and their supervisors, to instruct them in how to interpret and implement the new guidelines. The guidelines were also incorporated in the General Dynamics/Ft. Worth Division Machined Parts Design Manual, which is corporate-wide in distribution.

Although the NC machining guidelines were technically proven in the project, with production parts produced and flying on aircraft, and although there was general agreement at Fort Worth Division that the NC machining guidelines were practical and usable, they were not implemented. The lack of implementation of the NC guidelines is explained by two factors: they were introduced after the initial programming of F-16 parts; and it was a time of intense pressure to solve F-16 start-up problems and to meet production schedules. The effort to make the required changes could not be marshalled at that time. The guidelines for relaxation of design, dimension, and surface finish requirements were ready for implementation more than a year before the NC machining guidelines and before the award of the F-16 contract. Ft. Worth Division, where the F-16

is produced and where implementation occurred, was between programs, with low staff work loads. It was an opportune time for introducing such basic changes in manufacturing processes. By the time the NC machining guidelines were ready, the situation at Ft. Worth Division had radically reversed.

Benefits

The benefits of the new guidelines are lower rejection rates and reduced manhours required for finish machining and hand finishing.

The Ft. Worth Division Value Engineering Department conducted a rather detailed cost analysis of the new guidelines near the conclusion of the project. Based upon a group of typical F-16 parts produced using the new guidelines, compared with a group of very similar F-111 parts produced using the baseline approach, it was found that the number of manhours required was reduced by 22.3%, and that total part manufacturing costs were reduced on the average by 9%. Elimination of hand finishing accounted for over one-half of the labor hour and cost reductions.

The General Dynamics Value Engineering study determined that dollar savings from use of the guidelines totalled approximately \$7,500-\$15,000 per aircraft (in 1982 dollars). At a production level of 2718 aircraft, total manufacturing savings through 1992 will be \$20.4-\$40.8 million (in 1982 dollars). A point estimate of \$30.6 million was selected for presentation purposes.

All benefits discussed above are from the guidelines on design and hand finish relaxations, since the NC programming/machining guidelines were not implemented. NC programming/machining guidelines represent a major cost reduction opportunity, since over one-half of the machined aluminum parts on the F-16 are candidates for NC re-programming.

General Dynamics Corporation/Convair Division
FEEDBACK CONTROLLED SPOTWELDING
F33615-75-C-5229
June 1975 - April 1976
\$89,500

Background

The use of adhesive bonding in construction of aluminum aircraft structures had been increasing during the previous several years due to some distinct cost and technical advantages over conventional fastening methods. Bonded joints have much lower stress concentration factors associated with the joint, and thus greater utilization can be made of parent material strength in the design of the structures. Also, adhesive bonding has inherent cost advantages, since an entire part can be joined in one operation, instead of using numerous individual fasteners as is often the case in conventional construction approaches.

One drawback to adhesive bonding was that complex, expensive fixtures were required in order to hold the pieces in position while the adhesive cured and to ensure proper spacing of the surfaces to be bonded. The technique of weldbonding offered the potential for eliminating the bonding fixtures needed for assembly of the individual pieces of the structure--the spotwelds perform the function of the bonding fixtures. The potential reduction in tooling requirements is substantial since the tools are occupied only while the spotwelds are being made instead of the entire time the adhesive takes to cure adequately to support the structure.

The key elements in producing high quality weldbonded joints are proper surface treatment, adhesives, and welding operations. Previous work at General Dynamics had surfaced major problems in using resistance welding techniques for the spotwelds. Other previous and ongoing MANTECH programs at Northrop were concentrating on surface treatment and adhesives. What was still needed was to establish the feasibility of utilizing high efficiency feedback-controlled spotwelding equipment for producing high quality spotwelds.

Project Objective

The objective of this project was to establish a production method for weldbonding aluminum by utilizing feedback-controlled spotwelding.

Project Description

General Dynamic's basic approach was to optimize the adhesive bonding process, and then to develop resistance welding equipment to produce quality spotwelds through the adhesive. The program was performed in two tasks. Task 1 was weldbonding process optimization, wherein the

sensitivity of the resistance weld quality to welding parameters, surface treatment, and adhesive type was determined. Structural materials, adhesive systems, and surface preparation methods were subjected to weld-through conditions. The welding parameters were optimized to produce uniform, high quality welds. In Task 2, joint reliability and durability of the weldbonding process selected from Task 1 was demonstrated and verified through metallographic analysis, ultrasonic inspection, and static and fatigue testing. Environmental durability was substantiated by exposing typical weldbonded joints to high static stress and intermittent saltwater immersion for 1000 hours.

Project Results

The project can be considered a technical success. A production method of weldbonding aluminum utilizing feedback controlled spotwelding was established using both paste and film adhesives. The equipment that was used employed four types of modifications to conventional spotwelding equipment. They were: 1) automatic weld-through adhesive control, 2) variable welding pressure, 3) welding expansion feedback control, and 4) welding energy monitoring. This special equipment was capable of automatically melting through paste adhesives or thermoplastic film adhesives and primers, and then automatically installing quality welds.

The automatic weld-through adhesive control provided the capability to automatically weld through high durability film adhesives and corrosion inhibitive metal surface primers. Variable welding pressure was found to be essential for high quality welding through the high resistivity surface treatments and adhesives. Welding expansion feedback control was found to be essential for generating reproducible weld nugget sizes. The weld energy monitor was used to identify welding machine malfunctions and variable extremes that cause welding energy increases and thus oversize welding or expulsion.

Uniform strength, high quality weldbonding was found to be feasible for aluminum alloy 2024-T3 bare, 0.063-inch in thickness, modified FPL surface preparation, and Al396B paste and PL729 film (with PL728 primer) adhesives. Weldbonding with a FPL plus dichromate seal was not successful. Aluminum alloy 7075 could not be successfully weldbonded.

Implementation

Feedback controlled spotwelding for aluminum weldbonding has not been implemented at General Dynamics, due to a lack of aluminum adhesive bonding applications. Weldbonding is being considered for several aluminum applications in re-conditioned Atlas missiles to be used for space missions. This is now only at the paper evaluation stage.

The welding control technology developed in this project has been implemented, but not at General Dynamics. Pertron Controls Corporation now markets a production welding system which has all the capabilities developed in this program and more. Other firms are also thought to be

employ this technology in production welding systems. There appears to be a direct causal relationship between this project and the Pertron Controls Corporation system. In fact, the General Dynamics program manager for this project was one of the founders of Pertron Controls Corporation. Fairchild Republic Corporation used this weldbonding approach for production of a limited number of panel sections on the A-10 aircraft for the purposes of performance field testing and manufacturing cost estimation. This weldbond process is the baseline process for production of vertical stabilizers for Northrop's F-20 aircraft. This application and its benefits will be presented in the Interim Technical Report on Option 3 which includes the Northrop contracts.

Benefits

Since there has been no implementation of this technology at General Dynamics Corporation, no benefits were identified. We do not know the extent of implementation or resulting benefits, if any, for any firms other than General Dynamics and Northrop.

General Dynamics Corporation/Ft. Worth Division
LOW COST MANUFACTURING USING ADVANCED COMPOSITE BROADGOODS
F33615-74-C-5156
May 1974 - August 1975
\$192,223

Background

In the early 1970s, the use of graphite/epoxy (Gr/Ep) composite broadgoods was thought to offer the potential for low cost manufacture of composite aircraft structures. Broadgoods could be either woven (orthogonal) or unidirectional in nature. The desired shapes are cut from the prepreg broadgoods, and then these flat modules are draped over molds to produce structural shapes. The completed lay-up is processed by applying bleeder and vent materials, and the part is cured with temperature and pressure.

Hercules Corporation, with Air Force MANTECH support, had developed a line of pre-plyed broadgoods, which could be ordered with a wide range of orientation configurations. Gr/Ep composites, by any production technique, were not being introduced into aircraft as quickly as had been hoped. However, before the broadgoods draping technique would be ready for production use, it was necessary to determine in precise terms its capabilities and limitations for actual production aircraft structures.

Project Objective

The objective of the project was to establish draping of uncured broadgoods as a technically feasible and economically attractive method for fabricating advanced composite primary aircraft structures. To accomplish this, it was necessary to establish the limits of the process in areas such as fiber orientation, sheet thickness and size, impact of lay-up anomalies such as darts and folds, and material forms.

Project Description

The project was performed in two phases. Phase I established the limitations of the draping variables such as sheet size, thickness, ply orientation, material form, and part geometry. Variables were determined for large shell structures and substructural shapes such as hat-shaped stiffeners. The differences between woven and non-woven fibers were investigated in detail. In Phase II, four fuselage shells with representative substructures simulating a section of YF-16 were fabricated. High cost elements were identified and processes developed to attempt to reduce the costs. Low cost procedures evaluated included machine layup, mechanized cutting, reusable pressure bags, and several abbreviated processing schemes. A final cost analysis compared the costs of draping these structures with the costs of fabricating an equivalent metallic structure.

Project Results

The program answered most of the basic questions regarding how much the shape of the material can be changed while maintaining acceptable properties and how to handle the material and lay it up. A wealth of information on preferred processing techniques for broadgoods was developed. This pertains to such factors as layup over corners, orientation of plies, length of the plies, shear, the best approach for each structural shape and size, etc. Wrinkles were found to be not as major a problem as anticipated. This was important, because it was found to be impossible to remove all wrinkles during lay-up with hand pressure. The cost analyses indicated the manufacturing cost of the composite structure was approximately two-thirds that of a comparable metallic structure.

Implementation

This approach to composites production has not been implemented at General Dynamics. Instead of using broadgoods, the company has made a major commitment to automated tape laying (discussed previously in the Composites Production Integration project). However, many of the techniques developed in this project and the lessons learned have been applied in tape laying operations. Many of these techniques will be used in any future production of shells and substructures from Gr/Ep composites. Implementation of Gr/Ep composites for structural components offers the potential for significant manufacturing cost savings. The use of composites for skins, which has already been implemented, offers attractive weight savings over metallic structures, but only limited manufacturing cost savings. The use of Gr/Ep for primary aircraft structures will occur in new generation aircraft which can be designed from the beginning for use of this material and a particular manufacturing approach. Almost any conceivable manufacturing approach will utilize the techniques and lessons learned in this project.

Benefits

Since implementation has not occurred or is not planned for the near future, no direct benefits were identified. However, the manufacturing techniques and lessons learned in this program have contributed to the implementation of F-16 Gr/Ep vertical and horizontal stabilizer skins, using automated tape laying. More importantly, these techniques will contribute to hastening the time of implementation of Gr/Ep composites for structural applications, which offer much greater manufacturing cost savings.

General Dynamics Corporation/Ft. Worth Division
ACOUSTIC-ELASTIC FASTENER PRELOAD INDICATOR
F33615-76-C-5251
July 1976 - July 1978
\$195,732

Background

Structural mechanical fasteners in aircraft must be installed with a designated tensile preload in order to function in a predictable manner over the anticipated design lifetime. At the time of this project, where preload was important, fasteners were installed with torque control, either by manual wrenching to a specific torque or by the use of torque sensitive shear collars with power wrenches. In either case, the frictional components of the torque typically varied by a considerable amount, on the order of $\pm 20\%$. The traditional solution for this was to use considerably stronger (and heavier) and sometimes more fasteners than would otherwise be required. A capability to measure and control the true clamp-up force on the fastener would yield improved fatigue properties (enhanced durability, longer service life, and failure avoidance) and would enable designers to take full advantage of material strength in specifying fastener size, type, and spacing.

Project Objective

The objective of this project was to develop a working prototype automatic preload measurement and control system with 5% accuracy. Thus, the objective was technical improvement and not manufacturing cost reduction.

Project Description

The system was designed, assembled, calibrated, and tested by General Dynamics staff over the two year contract period. All work was performed in-house at Ft. Worth Division, and the system was constructed from commercially available equipment.

Project Results

The system that was developed utilized the acousto-elastic change in ultrasound travel time through a fastener to directly measure the clamping force. The system's computer control system monitors the travel time of 20 megahertz ultrasound through a fastener in real time as the fastener is being torqued. When the change in travel time reaches a magnitude which corresponds to the desired fastener tension, the computer inactivates the torque wrench, and displays the torque and tension achieved. Before reactivating the torque wrench, the system checks for good acoustic coupling, for faulty fasteners, and for correct fastener length and material.

The system was a partial technical success, since it worked on all flat-headed titanium, aluminum, and steel fasteners which had no safety wire holes or internal flaws. Even with the limitation to flat-headed fasteners, the application base on the F-16 is quite large. Of the 200-300 critical load bearing fasteners used on the F-16, approximately one-half are flat-headed. Also, it is believed that most of the others could be replaced by flat-headed types.

Implementation

The technology has not been implemented in the factory. The F-16 designs were already final and did not call for this process. There is no specific requirement for this system, and its use in production is perceived as an extra, unnecessary expense. The F-16 SPO is not advocating the use of this technology for the F-16.

The system developed in this contract was a working system but was not production ready. Follow-on work would be needed to develop the system for use on the shop floor by production personnel.

There is a reasonable chance that this technology will be used in critical areas on the next generation airplane, but probably not the F-16XL. Also, a General Dynamics field study of unit and intermediate aircraft maintenance organizations revealed that fuel leaks and fastener problems were the two major field maintenance problems. Pressures from USAF maintenance organizations for better fastening techniques may ultimately result in interest in this technology by the F-16 or other SPOs.

Benefits

Due to lack of implementation, no benefits were identified. It is important to recognize that implementation will probably increase manufacturing costs, due to the extra equipment and work involved. Benefits would be improved durability, reduced aircraft downtime, and reduced maintenance and repair costs.

Rockwell International Corporation/NAAO
ADVANCED PRESS DIFFUSION BONDING
F33615-75-C-5016
September 1974 - March 1977
\$793,553

Background

At the time of this project, press diffusion bonding already had a long developmental history. Its technology had been steadily evolving since the 1960s. Through IRAD, Air Force RDT&E support, and two previous MANTECH projects, the technology had been proven out and targeted for use in the production of some of the B-1's numerous titanium components. Press diffusion bonding that was performed before this contract took a very conservative approach. Relatively thick plates were diffusion bonded together to produce a premachined shape. Extensive machining was still required, and the material buy-to-fly ratio was still quite high--in the 10+ range. There still remained a large cost savings potential through improving the technology's capability to produce near-net shape components.

Project Objective

The objective of this project was to establish an improved process diffusion bonding process, with a major emphasis on obtaining significant manufacturing cost reductions.

Project Description

This project was performed in three phases over 32 months. In Phase I, process development work was undertaken for producing near-net diffusion bonded parts. Areas of development were: improving material utilization, controlling and improving the bonding atmosphere, improving press utilization, and extending tool life. It was verified in Phase I that existing ultrasonic testing equipment and procedures were capable of providing reliable inspections of the near-net diffusion-bonded parts that were developed.

In Phase II, the Phase I results were transitioned to manufacturing in order to identify and resolve scale-up problems. Three full-scale B-1 longeron attach fittings were fabricated under production conditions and then destructively and non-destructively tested. One of the full-scale parts was finish machined to drawing dimensions. In Phase III, the technology was demonstrated by producing and testing three full-scale B-1 upper longeron attach fittings. An economic analysis was performed to assess the cost savings from the process.

program in 1975 and updating it to reflect the current B1-B configuration. The estimate was reviewed by Rockwell/NAAO pricing personnel and escalated as required to reflect 1981 constant dollars. Because of the lateness in obtaining this estimate, the 1982 dollar estimate was conservatively taken to be the same as the 1981 dollar estimate provided by Rockwell.

Average weight savings are estimated to be 33% for the numerous B-1B titanium components produced by superplastic forming instead of by the variety of previous production methods.

The cost analysis indicated very large savings for the forward nacelle frame from using superplastic forming as opposed to hot sizing and then assembling individual components. For the aft frame, cost savings were modest for small production quantities, but substantial for large quantities. It was shown that maximum savings are realized by superplastically forming complex one-piece parts as replacements for multiple-piece assemblies. Also, it was learned that the full potential of the technology is achieved by designing to the process capabilities. This can result in a more efficient design, fewer parts, a much lower cost, and reduced weight.

Implementation

Although the specific structures explored in this MANTECH project were not implemented due to design changes, superplastic forming of titanium has been implemented for production of approximately 76 B-1B parts of the following types:

- Aft Nacelle Panel
- Center Beam
- Shear Webs
- Outboard Eyebrow Panel
- Beaded Panel
- Upper Inboard Panel
- Aft Nacelle Inner Skin
- APU Door
- Panel Inner Skin
- Lower ECS Access Door
- Nacelle Skin Panels
- Attach Angles
- Frames
- Center Frame
- Shear Panel

The technology has also been implemented for the windshield frame for the space shuttle.

In addition to its IRAD work preceding this project, Rockwell/NAAO also performed extensive IRAD on superplastic forming of titanium both during and after the project.

Benefits

Although the two specific B-1 components explored in this project were not implemented due to design changes, potential cost savings for them had been estimated to be 55%. For those B-1B parts where superplastic forming of titanium has been implemented for production, Rockwell has provided a cost savings estimate of \$35.9 million (in 1981 dollars). This estimate was developed using a benefits analysis baseline established under the AFML

Project Description

The project was performed in three phases over a 24 month period. Phase I was directed at understanding the range of superplastic properties available in commercial Ti-6Al-4V sheet; the relationship of these properties to the metallurgical condition of the material; the part configurations that are producible; and the resulting characteristics and mechanical properties of superplastically formed parts. Twenty-three parts were formed in six different configurations to assess the forming parameters needed to fabricate components of varying shapes and dimensions.

In Phase II, two full scale B-1 sheet-metal components were produced by the superplastic process. One configuration, the nacelle forward center beam frame, was a completely redesigned part combining several members of the existing assembly. The design of the second configuration, a nacelle aft center beam frame, was not changed. Both parts are Ti-6Al-4V. Eleven forward frame and ten aft frame components were produced. A full range of dimensional, metallurgical, and structural inspection and testing was performed. A cost analysis was conducted which compared the costs of the superplastic process with the costs of individual hot sizing and assembly of the individual parts.

Phase III extended the process to Ti-6Al-2Sn-4Zr-2Mo. The Ti-6-2-4-2 alloy was superplastically formed into the forward frame configuration of Phase II. Structural tests, dimensional analyses, and mechanical property evaluations were performed to determine if the process could be extended to other titanium alloys.

Project Results

The project was a technical success. All 21 full-scale B-1 parts fabricated in Phase II exhibited the capability of being formed to the required configuration. It was demonstrated that, with properly selected forming parameters, Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo sheet up to at least 0.125 inch thick can be superplastically formed into large complex configurations with acceptable properties. Identical process parameters were found applicable for Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo.

Although argon gas was used as the forming medium, and a sealed die was used, there were problems with surface enrichment on the bottom side of the titanium part. This was due to the high process temperature (1,700°F) and from having the bottom side of the sheet in direct contact with the tool. Enrichment occurred on the bottom side only, in depths of .004 to .010 inch. Chemical milling was found to be an effective method for removing the surface enrichment. Also 4140 and H13 steel dies were found to result in part dimensional deviations due to die material shrinkage during forming. Better high temperature die materials were needed for production of parts with close-tolerance requirements.

Rockwell International Corporation/NAAO
SUPERPLASTIC FORMING OF TITANIUM STRUCTURES
F33615-73-C-5005
Feb. 1973 - April 1975
\$191,000

Background

In the early 1970s, the forming of complex configurations in titanium sheet metal presented major manufacturing problems and limitations. Problems such as limited tensile elongation, excessive springback, and compression wrinkling posed major processing challenges. Elevated temperature (1200^oF to 1450^oF) creep sizing was required after room temperature forming. The process was very expensive, involving the use of integrally heated double-action forming dies. Even with these techniques, the difficulties in forming titanium alloys often led to compromises in the design of titanium structures--through the employment of more formable and heavier alloys, the forming of smaller parts which were assembled by joining, or the use of hog-outs from plate or bar. With the use of titanium steadily increasing in aircraft structures, and particularly in large aircraft, a more cost-effective method of forming titanium alloys was greatly needed.

During the 1960s and early 1970s, Rockwell/NAAO had performed extensive IRAD on superplastic forming of titanium alloys. Rockwell obtained many of the basic patents on superplastic forming of titanium during this period. Rockwell's research showed that, at least for small structures, the superplastic properties of titanium could be exploited to permit the forming of many titanium sheet metal configurations that were beyond the capability of existing state-of-the-art methods. Rockwell's forming method showed potential for being a relatively simple, low cost, and yet highly effective production process. It used differential pressure across a titanium alloy sheet, over a single male or female forming tool. What was needed now was to establish superplastic forming of titanium as a qualified production process.

Project Objective

The objective of this project was to establish superplastic forming of Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo as a cost-effective production process. The accomplishment of this required establishing the following: the metallurgical and mechanical property variations permitted by commercially available titanium sheet and their relationship to process parameters; the effects of the process on the material; forming capabilities and limits; process techniques and control requirements; techniques for establishing and predicting parameters for specific part configurations; and the financial attractiveness of the superplastic forming process.

Rockwell International

were based on data collected during this project, and costs for the baseline titanium rib were obtained from Rockwell International. The cost savings were determined to be 43% for the first rib produced and 45% for a total production run of 250 ribs.

Project Results

This project successfully demonstrated significant cost and weight advantages from the use of boron/aluminum metal-matrix composite components in place of titanium diffusion bonded components for major aircraft programs. Handling, layup, and diffusion bonding production techniques were developed for producing good quality large multi-ply boron/aluminum panels in a one-step consolidation process. A boron/aluminum composite B-1 wing rib was successfully fabricated, inspected, and tested during the project.

The composite rib could be directly substituted for a previously designed diffusion bonded titanium rib with substantial weight and cost savings. A composite rib weighs 101 pounds, which is a 33% weight saving when compared with a 150 pound baseline titanium rib. Cost savings for the production of composite ribs instead of baseline titanium ribs were determined to be 43% for the first rib produced and 45% for a total production run of 250 ribs. Cost data showed total B-1 program savings of \$2,263,000 for the production of left-hand ribs only. They would show total saving of \$4,526,000 for the production of both left-hand and right-hand ribs.

Implementation

No information on implementation could be obtained from General Dynamics or Rockwell by the time this report was prepared.

Benefits

No information on benefits could be obtained from General Dynamics or Rockwell by the time this report was prepared.

A preliminary analysis of alternate conceptual designs resulted in the adoption of a project design consisting of an integrally machined 2124-T851 aluminum frame to which a one-piece pseudo-isotropic boron/aluminum shear web panel is attached by titanium lockbolts. Vertical web stiffeners are part of the integrally machined frame structure. The web panel has 40 plies with a pseudo-isotropic boron fiber lamina orientation. This particular laminate configuration was selected to meet project requirements for stiffness, strength, stability, and panel fabrication. The composite wing rib was designed to meet the design parameters and load conditions used for the titanium rib design as provided by Rockwell International. A detailed stress analysis of the boron/aluminum composite rib design indicated that it would satisfy all strength and stiffness requirements.

Handling, layup, and diffusion bonding techniques applicable to production operations were developed for consolidating large multi-ply boron/aluminum panels of consistent and uniformly good quality directly from boron/aluminum green tape in a single pressing. Advanced low-cost production techniques were evaluated for cutting and machining a boron/aluminum panel to the required web contour. Techniques were also evaluated for cutting small fastener holes and large fuel-flow holes in the heavy gauge (0.25 inch) boron/aluminum material.

A full-size boron/aluminum composite B-1 wing rib was fabricated using manufacturing procedures suitable for a large scale production program. The 2124-T851 aluminum frame was N/C machined from a 4.5-inch by 24-inch by 96-inch plate. A 24-inch by 73-inch, 40-ply boron/aluminum panel was laid up and diffusion bonded at Rockwell International. Metallographic, ultrasonic, and radiographic inspection of the panel showed complete consolidation with high quality bonding and uniform density. The straight ends for the boron/aluminum web panel were cut with a diamond circular saw, and the long curved sides of the web panel were rough cut with a diamond band saw. The edges were finish machined by diamond routing on a production tracer mill. All fastener and fuel-flow holes in the web panel were electrodischarge machined. Finally, using the completed web panel as a template, fastener holes were conventionally drilled in the aluminum frame, and then the web and frame were fastened together with titanium lockbolts to complete the boron/aluminum composite wing rib. The completed composite rib weighed 101 pounds. This is a 33% weight saving when compared with the 150 pound baseline titanium rib.

The composite wing rib was static tested to demonstrate its structural integrity and to verify its performance in comparison with the baseline titanium rib. Testing was done for two critical load conditions: Condition 1, which is a 2g flaps down condition, and Condition 2, which is a 2g rear spar failed condition. The composite rib withstood 100% of the design ultimate loads for Condition 1 and 130% of the design ultimate loads for Condition 2 without failure and without any apparent deformation.

A detailed economic analysis compared production costs for boron/aluminum composite B-1 wing ribs with those for the baseline machined and diffusion bonded titanium B-1 wing ribs. Costs for boron/aluminum ribs

General Dynamics Corporation/Convair Division
MANUFACTURING METHODS FOR METAL-MATRIX STRUCTURAL COMPONENTS
F33615-74-C-5151
June 1974 -July 1976
\$519,343

Background

The technology of boron/aluminum metal-matrix composites had advanced rapidly during the few years just before this project was initiated. These advances occurred both in the primary raw material and the secondary structural fabrication areas. Many boron/aluminum metal-matrix composite structures had been built for aircraft and space vehicle applications under numerous government and company sponsored programs. Each new program had expanded the ability to fabricate more complex and cost-effective boron/aluminum components. Boron/aluminum, as an advanced composite, exhibits high specific stiffness and strength, which lead to lower weight components that permit greater range or payload.

The potential use of boron/aluminum composite as a replacement material had previously been assessed for five B-1 components. The assessment was sufficient to identify potential weight and cost savings. Composite material designs were effective in reducing weight for all five components, and they demonstrated significant cost savings with four of the components. A wing rib was selected for detailed evaluation in this project, since it provides an excellent production application in itself, and it is also a generic example for several other B-1 components. It was believed that establishing the technology for this wing rib could pave the way for use of boron/aluminum technology for similar components.

Project Objective

The general objective of this project was to unify the results of many previously completed exploratory development programs and to demonstrate the near-term cost and weight advantages of boron/aluminum components for major aircraft programs such as the B-1. This was to be specifically demonstrated by fabricating a boron/aluminum composite wing rib that could be directly substituted for a previously designed baseline titanium B-1 wing rib.

Project Description

The component chosen for this project was a rib in the B-1 wing located at wing station X_{RS} 188.5. The baseline rib is a 6Al-4V titanium diffusion bonded structure consisting of a web with integral flanges and web stiffeners. It is assembled into the wing structure with bolts. The baseline design parameters and design-load criteria were provided by Rockwell International, Los Angeles Aircraft Division.

Cost studies showed that, for sufficiently large production runs, component manufacturing costs with graphite/polysulfone were slightly lower than aluminum and considerably lower than graphite/epoxy. When compared with aluminum, the much higher costs for initial tooling and materials were more than offset by lower labor costs.

Implementation

This technology was not implemented because of the degradation in mechanical performance of graphite/polysulfone materials caused by solvents. Soon after this project was completed, the Air Force stopped most funding for graphite/polysulfone and related thermoplastic composites due to the solvent problem. Activity has recently increased in this technology area with the introduction of new solvent-resistant thermoplastics that are suitable for composite-matrix use.

Benefits

Due to lack of implementation, no benefits were identified.

Four methods for consolidating A-S graphite/polysulfone laminates were evaluated: press, autoclave, vacuum bag, and hot rolling. Test results showed little difference in ultimate tensile and flexural strengths for laminates fabricated by different methods. Since press consolidated laminates had the highest short beam shear strength and lowest cost, press consolidation at 600 F and 150 psi was chosen for the forming study.

Matched metal tools, matched ceramic tools, and fluid pressure tooling were designed, fabricated, and evaluated for forming capability, tooling cost, and production forming time. Adhesive bonding and ultrasonic spot and seam welding were evaluated as methods for joining graphite/polysulfone composites.

In Phase II, initial studies were made to compare costs for metal and composite fabrication of a DC-10 floor beam and a Convair Model 200 vertical stabilizer. Costs were analyzed for conventional aluminum, graphite/epoxy composite, and graphite/thermoplastic composite. Although tooling costs associated with the use of graphite/thermoplastic material were much higher than those for the other two materials, the man hours required for graphite/thermoplastic fabrication were much lower than for the other two materials. These results, together with pricing trends for aluminum and graphite/thermoplastic materials, showed a potential for significant cost savings through the use of graphite/thermoplastic composites in aircraft structures.

A YF-16 strake was selected as the primary aircraft structural component to be fabricated from graphite/polysulfone material in Phase II of this project because of its complex contour and the relatively high cost of manufacturing the strake from aluminum. The composite material for strake skins was consolidated in an autoclave because a large enough hot press was not readily available. All three of the tooling methods evaluated in Phase I were used to fabricate the different parts of the strake. Matched metal tooling was used for the leading edge, ceramic tooling was used for the contoured skins, and fluid pressure tooling was used for the bulkheads. The leading edge was premolded and then placed in the skin forming mold for final molding and bonding to the formed skin. Three bulkhead components were adhesively bonded in the aft end of the strake to stabilize the skin.

Six full-scale 70-inch long composite strakes were fabricated. A composite strake was interchangeable with an aluminum strake except for fasteners used to attach a strake to the aircraft. The 5.05 pound composite strake weighed 40% less than the 8.46 pound aluminum strake.

Project Results

This project demonstrated that graphite/polysulfone composite material can be consolidated, post-formed, and joined to produce complex shaped aircraft structural components with excellent mechanical properties that are comparable to those for similar graphite/epoxy composites.

General Dynamics Corporation/Convair Division
MANUFACTURING METHODS FOR FABRICATION AND ASSEMBLY
OF ADVANCED COMPOSITE PRIMARY AIRCRAFT STRUCTURE
F33615-74-C-5086
April 1974 - July 1975
\$188,900

Background

One of the major problems in increasing the use of advanced composites to fabricate complex aircraft structural components had been the high cost of both graphite/epoxy materials and autoclave processing required for thermosetting epoxy resin matrices. The use of thermoplastic rather than thermosetting resin matrices in graphite reinforced composites showed a potential for major cost reductions in the fabrication of complex aircraft hardware from composite materials. This is because thermoplastic composite systems lend themselves to rapid consolidation or curing, post-forming, ultrasonic welding, and continuous processing.

Project Objective

The general objective of this project was to demonstrate the potential of thermoplastic resin matrix materials for significantly reducing fabrication and assembly costs in the production of advanced graphite-reinforced aircraft structures. The specific objectives of this project were: 1) to develop reliable and economical manufacturing methods for the fabrication and assembly of aircraft structures using graphite/polysulfone composite material, and 2) to demonstrate and document the cost savings resulting from the use of the graphite/polysulfone composite material to fabricate aircraft components.

Project Description

This project was performed in two consecutive phases. Phase I was concerned with evaluating graphite/polysulfone properties, tooling design, and consolidation, forming, and joining methods. Phase I results were applied in Phase II for the design and fabrication of six YF-16 composite strakes from graphite/polysulfone material.

The specific materials selected for this project were A-S graphite fiber manufactured by Hercules Inc. prepregged with polysulfone polymer (P-1700) manufactured by Union Carbide Corp. Prepregging of the A-S fiber with polysulfone was done by E. I. DuPont. Initial prepregged material had been prepared with N-methyl-pyrrolidone solvent. Testing of laminates fabricated from this material showed low compression properties, poor resin-fiber bonding, and the presence of residual solvent. A laminate sample was then fabricated from material prepared with methylene chloride solvent. Since this test sample had excellent mechanical properties and good resin-fiber bonding, all further material used in this project was prepared with methylene chloride solvent.

Project Description

The project was performed in four phases. In Phase I, tooling materials and tool fabrication concepts and processes were established through materials evaluation and element testing. The mid-fuselage shell section of a composite conceptual design lightweight fighter was selected as the demonstration component. Subscale component tools and component articles were fabricated and evaluated, and cost analyses were made. In Phase II, the tool for the full-scale component was fabricated and tested. The manufacturing plan for fabricating the full-scale components was established, and then the component was fabricated. Phase III consisted of a detailed evaluation of the ability of the tool to yield satisfactory production components. In Phase IV, a production analysis was conducted for a complete fuselage shell structure, including a detailed analysis of manufacturing costs and cost savings.

Project Results

The project is best described as a partial success. Dimensional tolerances and stability were very good. Mold release was good, as was the coefficient of thermal expansion match between the mold and the component to be manufactured. However, the problem of surface crazing could not be solved, and the tool surface must be re-worked after each use.

Implementation

The technology investigated in this program was not targeted to a specific application. This tooling approach has not been implemented at General Dynamics, Fort Worth Division, although Gr/Ep composite aircraft structures are being fabricated there. The relatively flat Gr/Ep structures being fabricated (horizontal and vertical stabilizers, rudders, spars, etc.) do not require the use of this tooling technology. It is likely that the knowledge gained in this project will ultimately be applied at some point in the future when advanced aircraft are designed from the beginning to utilize complex-contoured composite shell structures. Some further development work is still required to bring this technology to production readiness.

Benefits

Due to lack of implementation, no benefits were identified.

General Dynamics Corporation/Ft. Worth Division
LOW COST TOOLING FOR ADVANCED COMPOSITE SHELL TYPE STRUCTURE
F33615-73-C-5119
June 1973 - June 1975
\$563,000

Background

A major requirement for large contoured tools for fabricating graphite/epoxy (Gr/Ep) composite aircraft structures is thermal compatibility between the tool and the shell structure to be made in it. Incompatible thermal characteristics can result in loss of dimensional tolerances or cracking of the composite material. In a previous project for the USAF Materials Laboratory (Advanced Composite Technology Fuselage Program--contract no. F33615-69-C-1494), General Dynamics established a tooling concept that accomplished this. The tool was a self-supporting sandwich structure mold with thin laminated graphite composite skins and vented flexible aluminum honeycomb core.

To make this mold, an intermediate mold had to be fabricated on which the graphite for the final mold could be cured. Since a conventional gypsum master form could not be used in an autoclave, General Dynamics made a solid laminate fiberglass/epoxy tooling mold on which the graphite autoclave-cured component mold could be made. Thus, it was a four step process: master form (gypsum/plaster); tooling form (plaster); tooling mold (fiberglass/epoxy); and graphite sandwich mold. This approach was found to be more expensive than desired, and to result in unacceptable loss of dimensional tolerances due to multiple fabrication steps and different thermal properties of the materials.

After this program, a General Dynamics IRAD program established the general feasibility of using a new, low temperature cure resin system to eliminate intermediate mold making steps. The graphite sandwich mold could be produced directly from the master form. The laminate could be cured on the mold at 120° for 24 hours, and then removed from the tool and cured to completion in an autoclave at 350°. Minimal distortion and shrinkage occurred. Although the IRAD program established the applicability of the resin system and stability of the product after cure, what was needed now was to demonstrate the technical acceptability and economic attractiveness of the process for actual production of full-scale aircraft components.

Project Objective

The objective of the project was to establish the technical feasibility and costs for production of large, highly contoured, complex tools capable of producing Gr/Ep composite shell-type aircraft structures.

Project Results

The project can be considered a technical success. The main problem encountered was the degradation of the tooling surface due to the reaction between titanium and the 22-4-9 steel tooling. Oxidation and leveling treatments developed in this project yielded tool life adequate for production runs. Another problem encountered during the project was localized argon entrapment in laminate bonds. An argon atmosphere was used to prevent near-surface bond line enrichment during the heat-up and soak portion of the bonding cycle. The problem of argon entrapment in laminate bonds was not resolved.

The production of three full-scale B-1 upper longeron attach fittings successfully demonstrated the producibility and repeatability of the near-net shape press diffusion bonding process for non-laminate type joints. The full range of mechanical property tests indicated that the properties of the diffusion-bonded parts were equivalent to those of the parent material. Dimensional repeatability was excellent. Non-destructive testing was also performed, and the parts were found to meet all flight quality requirements. Standard production ultrasonic testing equipment and procedures were found to be applicable to the inspection of these parts.

The economic analysis indicated a potential for average savings of 55% in production costs for the near-net shape diffusion bonding process. The demonstration parts resulted in an improvement in the material buy-to-fly ratio of from 10.2:1 to 2.8:1, when compared to the conventional press diffusion bonding process. In addition to the very substantial material savings, major savings were also realized in machining, inspection, fabrication, and tooling.

Implementation

Near-net shape advanced press diffusion bonding has been implemented in place of premachined shape diffusion bonding for production of the five following components for the B-1B:

- 1 Center Bulkhead Component
- 1 Outboard Bulkhead Component
- 2 Upper Wing Cover Components
- 1 Actuator Fitting

Benefits

For those B1-B airframe components where near-net shape advanced diffusion bonding has been implemented for production in place of premachined shape diffusion bonding, Rockwell has provided a cost savings estimate of \$10.4 million (in 1981 dollars). This estimate reflects the results of recent B1-B producibility studies. The estimate was reviewed by Rockwell/NAO pricing personnel and escalated as required to reflect 1981

constant dollars. Because of the lateness in obtaining this estimate, the 1982 dollar estimate was conservatively taken to be the same as the 1981 dollar estimate provided by Rockwell.

The implementation of advanced press diffusion bonding did not result in any weight savings for finished B-1B components.

Rockwell International Corporation/NAAO
SUPERPLASTIC FORMING/DIFFUSION BONDING PROCESS
F33615-75-C-5058
January 1975 - March 1979
\$1,013,600

Background

Previous IRAD at Rockwell/NAAO, coupled with Air Force MANTECH support, had established the production feasibility of superplastic forming (SPF) of titanium structures. The SPF process exploits the extensive tensile elongation and low deformation stresses of titanium in its superplastic state, enabling the forming of large complex sheet-metal parts. Rockwell IRAD had shown that it was possible to diffusion bond (DB) titanium sheet-metal parts concurrently with superplastic forming. The DB process had already been established and was being used in production of B-1 and Space Shuttle components. The SPF/DB process offered the potential for producing complex, severely formed, variable-thickness titanium parts to replace sheet-metal assemblies and machined parts, with significant cost and weight savings. With the technical capabilities of the process, and its attractive costs, the potential application base for this technology would be enormous.

Project Objective

The objective of this project was to demonstrate the feasibility of SPF/DB processing by producing full-scale B-1 bomber components. Three components were to be produced which represented the three basic forms of SPF/DB structure; i.e. reinforced sheet (one sheet), integrally stiffened structure (two sheet hat shaped), and sandwich structure (three sheet).

Project Description

The project was performed in two phases. Phase I was a process development and refinement effort, and Phase II entailed the production and evaluation of full-scale B-1 parts.

Phase I focussed on establishing methods and tooling to fabricate the Ti-6-4 alloy by SPF/DB and to establish process effects on material properties, and properties of SPF/DB joints. DB parameters were analytically predicted and verified in specimen tests. Bonds of specimens were evaluated by shear strength tests, metallography, and near-surface ultrasonic inspection. After this, the full-scale B-1 one- and two-sheet structures to be produced in Phase II were selected. These were the forward nacelle frame and the APU access door. Subscale parts representing the salient features of the full-scale components were fabricated to develop the best process parameters and to evaluate the quality of the resulting hardware. The subscale parts were evaluated by visual

examination, ultrasonic inspection, and metallographic examination. Tensile, compression, fatigue, lap-shear, and peel tests were performed to evaluate the mechanical properties of the subscale parts.

Phase II was to demonstrate the applicability of the SPF/DB process to full-scale structural hardware in a production environment. This entailed the production and evaluation of three full-scale B-1 structural parts, using the process information and production facilities established in Phase I. The B-1 nacelle lower engine access door, a three sheet sandwich structure, was selected as the third component to be produced, along with the two previously selected components. The three components were designed, tooling was designed and fabricated, and the structures were produced and evaluated. Cost and weight studies on the three full-scale structures were then performed.

Project Results

The SPF/DB process was demonstrated to be a technically feasible and economically attractive production process. DB was shown to achieve parent metal strength bonds. The diverse nature of the three demonstration components, the severity of forming involved, and the intricate DB patterns that were used substantiated the broad applicability of the process. The cost and weight studies on the nacelle frame, APU door, and engine access door showed manufacturing cost savings of 44%, 48% and 34%, and weight savings of 40%, 31%, and 29%, respectively.

Implementation

While SPF and DB processes have experienced rather broad implementation separately, implementation of the combined SPF/DB process appears to have been limited to date. It has been implemented at Rockwell for production of the B-1B hot-air-blast windshield nozzle and manifold. In this application, a two-piece structure of four-sheet titanium sandwich panels replaces a 32 piece structure of welded steel.

Benefits

Although typical cost savings were estimated to be 50% for the implementation of SPF/DB, actual dollar benefits could not be quantified for its implementation at Rockwell. The technical and economic data on alternative manufacturing processes were developed during the B-1A program. When the B-1A program was cancelled, all non-essential information, including that on alternative manufacturing processes, was disposed of. The level of effort that would be required by Rockwell to establish baseline costs precluded the development of a cost savings estimate for this SPF/DB project.

Typical weight savings are estimated to be 30% for the production of

titanium structures by the SPF/DB process instead of by the previously used titanium production methods. They should be even greater for the production of a titanium sandwich-panel structure in place of a welded steel one.

Rockwell International Corporation/NAAO
PLASMA ARC WELDING I
F33615-74-C-5036
Jan. 1974 - Dec. 1975

Background

From Rockwell/NAAO IRAD work, and development work of Aerojet Corporation, it appeared in the late 1960s that plasma arc welding could be effectively and economically employed to butt weld thick sections of titanium and steel alloys. This would allow welding instead of mechanical fastening of thick-section joints, and yield substantial cost savings. Potential near-term applications were primary structural components on the B-1 bomber.

There were four alternative fusion welding processes at this time that were possible choices for replacing mechanical fastening of thick-section members: TIG, gas-metal arc, plasma arc, and electron beam welding. Plasma arc was selected for development because it offered the required penetration capability at the lowest cost. TIG and gas-metal arc welding both require complicated joint preparations and have more limited penetration capability, thus requiring many more passes to perform the weld. These lead to high process costs. Electron beam welding has good penetration capability but requires a vacuum chamber and has other high equipment costs.

Project Objective

The overall project objective was to develop a lower cost process for joining, by welding, thick-section aircraft components and to establish the technology base required to transition this capability to production hardware. Specific objectives were: 1) to establish the equipment and process requirements necessary to perform plasma arc butt welding of Ti-6Al-4V, HP9-4, and HY180, 2) to characterize the mechanical properties of the weld joints, 3) to demonstrate the production application of the process, and 4) to determine the economics of using the process in production.

Project Description

The project was conducted in three phases. Phase I established equipment and process requirements necessary to perform thick-section plasma arc welding. A breadboard welding system was developed and utilized during this phase. It was then improved on the basis of results from the equipment and parameter development tasks. Standard commercial equipment was utilized wherever possible, with modifications as needed. Phase II defined the maximum penetration capabilities of the system resulting from Phase I, characterized the mechanical properties of the weld joints, and

assessed nondestructive inspection procedures. During Phase III, the system was used to fabricate a simulated full-scale production hardware item (a wing carry-through structure upper cover) to demonstrate the technical and economic feasibility of the process. An economic analysis was performed which compared the costs of the plasma arc process with conventional TIG welding.

Project Results

The project can be considered a technical success. All project objectives were met. Evaluation of the mechanical properties of the plasma arc-welded materials showed acceptable static and fatigue properties. One-hundred percent static tensile joint efficiency was obtained with Ti-6Al-4V, and HP9-4 steel. The process was capable of producing welds for 1-inch thick Ti-6Al-4V in two to three passes, and 1/2-inch plate welds in a single pass. Steel plate was acceptably welded in 1/2-inch thick sections.

Implementation

Plasma arc welding was implemented at Rockwell/NAAO in place of gas tungsten arc welding for the production of thick-section titanium-plate upper and lower wing covers for the B-1B aircraft.

Benefits

Rockwell has provided a cost savings estimate of \$5.5 million (in 1981 dollars) for the implementation of plasma arc welding in place of gas tungsten arc welding for the production of thick-section titanium-plate B-1B wing covers. This estimate was developed using a benefits analysis baseline established under the AFML program in 1976 and updating it to reflect the current B-1B configuration. The estimate was reviewed by Rockwell/NAAO pricing personnel and escalated as required to reflect 1981 constant dollars. Because of the lateness in obtaining this estimate, the 1982 dollar estimate was conservatively taken to be the same as the 1981 dollar estimate provided by Rockwell.

The implementation of plasma arc welding did not result in any weight savings for finished B-1B components.

Rockwell International Corporation/NAAO
PLASMA ARC WELDING II
F33615-76-C-5231
Dec. 1977 - Sept. 1978

Background

An earlier USAF MANTECH project at Rockwell/NAAO (F33615-74-C-5036, which was presented above) had proved the feasibility of the plasma arc welding process for butt welding titanium- and steel-plate components. In addition to this kind of welding application, the plasma arc welding process also offered the potential for major manufacturing cost reductions in fabricating multiple-member, integrally stiffened panels and beam-type components. Plasma arc welding would replace mechanical fastening of integrally stiffened panels and, for beam-type structural components, would replace diffusion bonding or machining of forgings, extrusions or diffusion bonded shapes. To apply plasma arc welding technology economically to these kinds of applications, however, required the use of a more complicated, burn-through approach. Although considerable process development work had been undertaken in this area at Rockwell, and there were strong indications that the technique would succeed, the process was not production ready.

Production Objective

The objective of this project was to extend plasma arc welding technology to the fabrication of integrally stiffened structural panels and beam-type elements. Specific objectives were to identify applications with significant potential for cost savings, to characterize the mechanical properties of the arc seam joints, and to demonstrate the application of the process under production conditions for production-type parts. The program applied plasma arc-seam (burn through) welding technology to the joining of Ti-6Al-4V, PH15-7Mo steel, and Inconel 718.

Project Description

The plasma arc-seam welding process employed in this project used a constricted plasma arc in a keyhole mode of operation to join vertical webs to caps. Web tracking was accomplished with an electro-mechanical, servocontrolled system actuated by optical sensors below the cap on each side of the vertical web. The servosensor system automatically (in real time) positioned the torch to maintain equilibrium of sensed energy on each side of the web. The system also incorporated a device that assures constant weld speed along the weld path. The equipment used for the system consisted primarily of standard commercial TIG welding equipment, modified for arc-seam (burn through) welding. The arc-seam tracking and speed control systems were modified versions of the Rockwell-patented "Red Eye" system, which had been developed for TIG welding applications. A 10-inch long torch trailing shield provided atmospheric shielding, with a full-weld-length shielding chamber to protect the weld underbead. Filler

wire was used on some cap/web combinations.

Project Results

The project was technically successful for both integrally stiffened panel and beam-type applications. For both kinds of applications, plasma arc-seam welded structures were found to be functionally equivalent to those fabricated by conventional means, and they met all criteria for flight. A full-scale demonstration article, simulating the fuel barrier bulkhead shear web of an integral fuel tank in the wing carry-through structure of the B-1, was fabricated from Ti-6Al-4V. An economic analysis showed a projected reduction in manufacturing cost of over 50% as compared to the best alternative approach, which involved a combination of diffusion bonding and standard (not burn-through) plasma arc welding. The bulk of the savings was due to reduced labor costs, with some savings from reduced material requirements.

A full-size Ti-6Al-4V structural beam simulating a B-1 longeron attach fitting, with a sine wave configured web, was also fabricated by the plasma arc-seam welding method. An economic analysis indicated a potential manufacturing cost reduction of almost 80% as compared to diffusion bonding, and even more as compared to a forge-plus-machine process. Again, savings result primarily from decreased material and labor requirements. The processing capability for joining sine wave beam-type structural elements was also established for PH15-7Mo steel and Inconel 718, a nickel-base alloy.

Implementation

This technology has not been implemented at Rockwell, nor are there plans to implement it in the near future. Although a small amount of development work may still be required to improve the welding equipment (mainly the torch), the process is essentially ready for use in production. The tooling for the B-1 has already been sunk, and process or equipment changes are particularly difficult to justify after this has occurred. The dollar savings must be very high and be almost certain to be realized, and perhaps most importantly, the changes must not in any way jeopardize the delivery schedule. Other significant near-term future applications besides the B-1 appear unlikely at this time, since there are very few military aircraft with these kinds of titanium, steel, or superalloy applications. Also, aluminum and composite technologies have been advancing rapidly and can now be used for many applications which previously required titanium.

Benefits

No benefits were identified, since this technology has not been implemented.

Rockwell International Corporation/NAAO
LOW COST COMPOSITE WING/FUSELAGE
F33615-77-C-5278
Nov. 1977 - Aug. 1979
\$895,657

Background

At the time of this MANTECH project, Gr/Ep composite technology had mainly been employed in aircraft as a substitute for conventional metals. This was an incremental approach, which did not take advantage of the full savings potential of composites. The Gr/Ep components that were made were generally characterized by numerous material penetrations, large part counts, complex mechanical splices at joints, and complicated fuel sealing procedures. These resulted in structural inefficiencies, and weight and cost penalties. An integral composite structure, designed from the beginning as a composite, could tap the full potential of composite technology. The technology would have a large number of potential applications across a wide range of aircraft types.

Prior to this MANTECH project, Rockwell/NAAO had performed a good deal of IRAD on integral composites and, with support from the Air Force Flight Dynamics Laboratory (Advanced Tactical Systems Study--ATS), had demonstrated the technology at the R&D stage.

Project Objective

The objective of the project was to develop and demonstrate the manufacturing process for a large integral Gr/Ep composite aircraft structure. The wing/fuselage interface structure for Rockwell's advanced tactical fighter aircraft was selected as the application.

Project Description

The project was performed in two phases. Phase I analyzed the manufacturing cost benefits of the integral approach, redesigned the wing/fuselage structure for lowest cost production as an integral composite, and developed a manufacturing plan. Phase II consisted of fabrication and testing of the full-scale structure. A detailed cost analysis was performed, and the manufacturing plan revised to reflect lessons learned. All work was performed under actual production conditions.

A key feature of the manufacturing concept was integral autoclave co-curing of the lower cover and substructure member preforms. The upper cover was cured separately and attached by mechanical fastening. The lower cover/substructure assembly was extensively pre-bled and compacted before curing. The preforms were mated in a complex tool assembly comprising a

lower cover mold form, an adjustable riser set, and a vacuum manifold tube system. The vacuum manifold defined the upper surface of the substructure member, and evacuated a set of thin elastomeric bladder molds which served as pressure membranes in the autoclave cure.

There were some technical problems, particularly with tolerances and the leakage of vacuum seals, but all of them were ultimately resolved.

Project Results

The project verified the technical and economic attractiveness of the integral composite manufacturing approach. Structural tests showed structural integrity equal to or greater than conventionally fabricated structures. The economic analysis showed major cost savings as compared to both aluminum and conventional composite processes--33% and 26% respectively. New ideas surfaced in the cost analysis for reducing costs even further in subsequent production. Respective weight savings were 41% and 18%.

This project substantially advanced the state of the art in manufacturing composite structures. The manufacturing process was essentially proven and, by the end of the project, Rockwell considered that going into limited production would be a low risk undertaking. Material specifications, processing specifications, and inspection instructions were presented in the final report.

Implementation

Rockwell/NAAO has continued development of integral composite technology and has extended the technology pursued in this project. Major differences in the extended approach are automation, non-autoclave curing and lower cost tooling. The extended approach is being supported through an ongoing USAF MANTECH project.

The specific integral composite structure technology pursued in this project will probably be implemented on the next generation fighter currently being considered by USAF and the NAVY. Production implementation is expected in the 1988-1990 timeframe. Advanced integral composite structures technology probably will also find its way into the next generation of bomber aircraft, but over a longer time period.

Benefits

The technology has not yet been implemented, and manufacturing cost savings could not be realistically estimated at this time. It should be noted that, in addition to manufacturing cost savings, other benefits in the form of lighter weight and improved aircraft performance are also expected.

Rockwell International Corporation/NAAO
ADVANCED MULTILAYER DRILLING
F33615-76-C-5158
April 1976 - May 1977
\$123,700

Background

The assembly of the B-1 aircraft requires a large number of large diameter (1/2" to 1") fasteners through multi-material (aluminum, titanium, and steel), thick-layer stacks. At the time of this contract, the necessary fastener holes were drilled with conventional drilling equipment that was operated at a fixed speed and a fixed feed based upon the most difficult material in a stack. This required destacking and deburring of holes, and was a high cost operation.

A previous Air Force MANTECH contract (F33615-74-C-5014) had supported the development of computer-controlled multi-layer drilling equipment at Boeing Commercial Aircraft Company. In this project, Boeing developed two new drill units to improve hole drilling in multilayer stacks. One used a pneumatically operated drill with ultrasonic assist to reduce chip packing and increase penetration rates at given drill speeds. The other was hydraulically operated with computer-controlled variable speed and feed to obtain optimum drilling rates for each material in the stack.

Although there were some burring problems at material interfaces, the technology looked attractive to Rockwell/NAAO for a number of multilayer drilling applications on the B-1.

Project Objective

The objective of this project was to assess the technical suitability and cost-effectiveness of the multi-layer drilling technology, which Boeing had developed, for use in production of B-1 components. The hydraulically operated drilling system was thought to be the most attractive and was selected for assessment in this project.

Project Description

The project was performed in three phases over a 13 month period. In Phase I, a representative B-1 component was selected, shipped to Rockwell's Palmdale California facility, and fixtured for drilling. A B-1 wing outer panel test section, which had already been used at Rockwell for other testing, was used in this project. It was disassembled into two sections and fixtured for both horizontal and inverted drilling.

In Phase II, the drilling equipment was shipped from Boeing, assembled, and checked out. Rockwell staff were trained on the system, and

preliminary holes were drilled. Boeing engineers assisted in this phase.

In Phase III, simulated production drilling of holes was carried out. Holes were evaluated for size, surface finish, and metallurgical quality. Drill point wear was evaluated, and all holes were inspected per Rockwell specifications for drilling holes for straight shank fasteners. An environmental impact study was conducted, and a cost analysis was conducted which compared the costs of the computer-controlled system with conventional drilling.

Project Results

The project can be considered a partial technical success. The holes drilled in the all titanium stacks were generally of good quality, but dimensional control was not totally acceptable. The titanium/aluminum stacks showed rather poor dimensional control, at least for use in production of close tolerance holes. Chip packing in the aluminum laminate was a recurring problem. A cure for this problem was suggested but not tested during the program.

The environmental impact study found no adverse conditions connected with the operation of the computer-controlled drilling equipment. The cost analysis found the computer-controlled system to be more expensive than the conventional process. The high equipment cost of the computer-controlled system was found to be the main reason for its higher cost. The system was extremely heavy (approximately 133 pounds), required a hoist or platform, and required two operators instead of one with the conventional equipment.

Implementation

Rockwell has not implemented this technology and has no plans for doing so in the near future.

Benefits

No benefits were identified, since this technology was not implemented at Rockwell.

Rockwell International Corporation/Rocketdyne Division
INJECTION MOLDED PRECISION ROCKET ENGINE COMPONENTS
F33615-75-C-5270
June 1975 - May 1978
\$243,594

Background

At the time this project was initiated, increasingly high costs were being encountered in fabricating small, complex-shaped, precision metal components that required extensive machining and welding operations. An attractive, potentially low-cost alternative was an adaptation of the conventional plastic injection molding process to manufacture such small components at high production rates. This new manufacturing process would entail the mixing of an appropriate metallic powder with a plastic hydrocarbon binder system and then injecting the mix into a mold with a modified conventional plastic injection molding machine. The molded parts would go through a binder removal process and then be sintered into a dense, useable net shape or near-net shape part.

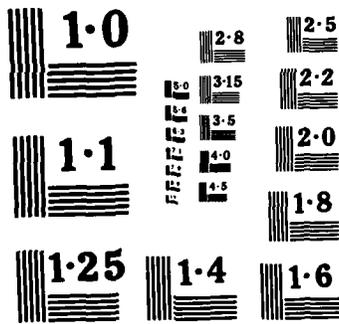
Project Objective

The major objective of this project was to develop an injection molding process for the net-shape production of a low-cost, high integrity columbium alloy thrust chamber and injector for a 100-pound thrust attitude control rocket engine. An additional limited objective was to determine the feasibility of using mild-steel, stainless-steel, and tungsten as alternate materials for injection molding production of small components.

Project Description

This project was conducted in two phases. In Phase I, tensile test specimens for pure and alloyed columbium powders were injection molded, processed, and evaluated to define the necessary processing procedures for later rocket engine component fabrication. Tensile test specimens for mild steel, stainless steel, and tungsten were also injection molded, processed, and evaluated in Phase I to determine processing parameters for potential injection molding applications of these materials. In Phase II, characterization of columbium materials was continued to obtain more accurate process parameters. The main effort in Phase II was the design, injection-molding production, processing, and assembly of net-shape columbium alloy rocket engine components.

Columbium alloys were chosen for this project because of their high temperature properties and their previous use in rocket engines. Since the required columbium alloy powders were not commercially available, alloying constituent powders were mixed with elemental columbium powder before



NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

blending with the hydrocarbon binder. The actual desired alloy was formed during the final sintering cycle. An alloy consisting of 80% columbium, 10% tantalum, and 10% tungsten was selected, since that composition had been used in three different rocket engine thrust chamber programs.

In general, the injection molding process begins with vacuum drying of the powder or powders at room temperature to reduce clumping of powder particles. For an alloy, the constituent powders are combined in the proper ratios and mixed thoroughly at room temperature. A hydrocarbon binder material is then placed in a rotating mixer which is preheated so that the binder will flow. The powder is gradually added to the binder and the mixture is blended to a uniform consistency. The resulting heated plastic-like material is injected into the mold under pressure. After the mold has absorbed enough heat, the part is rigid enough to be removed from the mold. The next step is removal of the binder material from the "green" part through a controlled pyrolytic process. In the final step, the molded part is sintered at high temperature in an appropriate vacuum or gaseous environment to obtain an adequately dense, useable metallic part.

At the beginning of Phase I, several batches of injection molded test bars were produced for both pure columbium and columbium alloy to determine mechanical properties and process repeatability and to establish optimum process parameters. Although optimization of process parameters had not been completed at this point, material properties of the injection molded columbium alloy were found adequate for the design of a 100-pound thrust, radiation cooled attitude control rocket. Further optimization of columbium alloy process parameters was included in the Phase II effort of this project.

During the remainder of the Phase I effort, injection molded test bars were produced for three alternate materials: mild steel, 316L stainless steel, and tungsten. No problems were encountered in mixing these powdered materials with the binder material, injection molding of the mixes, and pyrolytic removal of the binder material from the molded test bars. Because of inadequate sintering furnace temperatures and the need for more careful temperature and environmental control during sintering, the test bars for these materials were not adequately sintered. However, test results indicate the feasibility of producing injection molded parts from these materials if adequate sintering conditions are provided.

In Phase II, an optimization study for the entire columbium-alloy injection molding process was completed to establish parameters for the fabrication of injection-molded thrust chambers and injector assemblies for a 100-pound thrust attitude control rocket. During this phase, a thrust chamber and injector were selected for a rocket engine using nitrogen-tetroxide/monomethylhydrazine propellants, operating at 140-psia chamber pressure, and providing 100-pounds of thrust. The injection molding dies for these components were designed to provide net-shape components after sintering that would require little or no final machining.

Other tasks performed during this phase were a study of available

oxidation resistant coatings for the thrust chamber, an evaluation of various welding and other joining techniques for assembling injector subcomponents, and a study of nondestructive inspection techniques for all components. HiTemco R512E silicide coating was found to be the most suitable for columbium alloy thrust chambers. For this project, electron beam welding proved to be the only satisfactory joining method. Conventional and image-enhanced x-ray techniques were found to be the best for nondestructive inspection of sintered components.

At the end of the Phase II effort, three thrust chambers and six injectors were produced for a planned hot-fire test program to demonstrate the durability of the injection molded columbium alloy rocket components. The hot-fire testing was to be conducted under a program sponsored by the Air Force Rocket Propulsion Laboratory.

Project Results

Injection molding of metals, a new and potentially low-cost process for manufacturing small complex components, was successfully demonstrated in this project. The process was shown to be adequate for the production of columbium-alloy thrust chamber and injector components of a 100-pound thrust attitude control rocket engine. These components were fabricated to near-net shape from elemental powders by the injection molding process. The mechanical properties of injection molded material were equal to or better than those for wrought material.

Although the injection molding procedures are lengthy ones, they are highly versatile and non-labor intensive. It was demonstrated that injection molding of metals has the potential for large cost savings in the production of large quantities of small complex components, such as those that would be required for attitude-control rocket engines on the fourth stage of an MX-type missile.

Implementation

This technology has not been implemented at Rockwell, nor are there any plans to do so in the near future. The reason given for lack of implementation is a perceived high technical risk, and the costs of reducing these risks before production implementation could be approved.

Benefits

Due to lack of implementation at Rockwell, no benefits were identified.

Rockwell International/Rocketdyne Division
MANUFACTURING METHODS FOR TRIAMINOGUANIDINE NITRATE (TAGN)
F33615-76-C-5040
February 1976 - April 1978
\$492,315

Background

At the time this project was initiated, the Air Force had placed priority on the development of advanced cool burning, high impetus, low molecular weight gun propellants. A key ingredient for some advanced cool burning propellants is triaminoguanidine nitrate (TAGN). Prior to this project, Rocketdyne had developed an aqueous phase batch process for the production of TAGN from guanidine nitrate (GN). The Rocketdyne batch procedure combined existing technology to develop an aqueous phase process that eliminated the usual recrystallization step. Batch yields were improved through optimization of the amounts of excess hydrazine and nitric acid during processing. Another feature of the optimized batch process was the rapid removal of byproduct ammonia. Ammonia removal prevents degradation of the TAGN product and shortens the process reaction time. Before Rocketdyne had developed its aqueous batch process, the most accepted process for TAGN production was based on refluxing alcohol solutions of GN with hydrazine.

Project Objective

The major objective of this project was to identify and optimize the most economical continuous process for producing TAGN at production levels from 100,000 lb/year to 10,000,000 lb/year. To attain this objective, key features of the optimized Rocketdyne batch process were to be incorporated into a continuous pilot plant process. A concurrent objective was to develop and demonstrate a practical production method for applying an inhibitor coating to multiple strand TAGN gun-propellant extrusions.

Project Description

This project was conducted in three phases. Phase I included evaluations to select and optimize the most economical method for continuous production of TAGN. It also included the design and assembly of a continuous production pilot plant and cost projections for TAGN production rates of 100,000 lb/year to 10,000,000 lb/year. In Phase II, a series of pilot plant runs were made to optimize product crystallization and filtration techniques and to provide samples for ballistic testing. In Phase III, propellant inhibitor coating materials were evaluated and a method was established for applying the selected inhibitor coating to multiple strand TAGN gun-propellant extrusions.

Initial batch laboratory runs were made to determine if cyanamide

could be used as a process starting material in place of guanidine nitrate and to determine if the filtrate could be directly recycled without cleanup in order to conserve the excess hydrazine and nitric acid that are required. The use of cyanamide instead of guanidine nitrate as a starting material offered both economic and processing advantages. The cost of cyanamide is about one-half that of guanidine nitrate. However, the most important advantage of using cyanamide is ease of handling. It is available in liquid solution which is easier to feed into a reactor than guanidine nitrate powder. Comparisons of batch runs showed that cyanamide resulted in an equivalent TAGN product.

Since the costliest and highest quantity ingredient used in TAGN manufacture is hydrazine, recovery of excess hydrazine was mandatory to minimize TAGN costs. The simplest approach, recovering hydrazine by direct recycling of the filtrate without cleanup, was tested, found suitable, and adopted for the project. Other production factors that were investigated for optimization through laboratory batch runs were ingredient feed temperatures, the sequence for adding ingredients, the mole ratio of nitric acid to hydrogen cyanamide, reaction temperature and reaction time, TAGN product wash solutions and procedures, and product storage.

The continuous pilot plant process that was established for manufacturing TAGN uses aqueous solutions of hydrogen cyanamide, hydrazine hydrate, and nitric acid as starting materials. The starting materials and recycled filtrate containing residual TAGN, hydrazine, nitric acid, and water are fed continuously from storage tanks into a mixer stage cooled to 40°F. The reactants are then transferred to the first of five flow-type reactors that are heated to maintain a reaction temperature of 90°F and evacuated to a pressure of 10 inches in order to draw off ammonia as it is formed during the reaction. The volume of the reactors is adequate for a minimum residence time of two hours.

Next, the hot reaction mixture is fed to a continuous crystallization unit where it is combined with recirculating crystallization slurry cooled to 0°C. Slurry is fed directly to a continuous-belt filter where the filtrate, water wash, and isopropyl alcohol (IPA) rinse are drawn off separately into vacuum pans under the belt. A final IPA rinse is included because TAGN dried after an IPA rinse is much easier to grind than TAGN dried after a water rinse. The TAGN is then air dried and ground to the desired particle size in a fluid-energy mill. Filtrate that is drawn off in the filter stage is distilled to remove excess water. The remaining filtrate, containing hydrazine, nitrates, and residual TAGN is then fed to a storage tank for recycling. The water and IPA mixture drawn off during the IPA wash and the drying stage is also distilled to extract the IPA and return it to a storage tank for recycling.

A total of 43 pilot plant runs were made with durations ranging from 1 to 9.5 hours. Initial runs were made at the end of Phase I to evaluate alternative system components and to optimize process parameters and operating procedures. In later Phase II runs, crystallization was improved, and material was produced for filtration studies and ballistic

testing. Two final runs were made to complete the required production of 1000 pounds of TAGN to be delivered to Elgin AFB for ballistic testing. The last run proceeded smoothly for a duration of 9.5 hours. It could have been extended, but was discontinued since it had fulfilled project requirements.

The initial effort in Phase III was to evaluate isocyanate inhibitor coating materials for continuous application to TAGN gun propellant strands. The use of wetting agent materials to promote easier and more even inhibitor application was also evaluated. Other efforts were concerned with: 1) evaluating the effects of temperature, catalyst level, and humidity on the cure time and quality of coatings; 2) evaluating coating application methods, such as dipping, rolling, and wiping; and 3) evaluating various solvents as carriers for the inhibitor and wetting agent during the application process.

The inhibitor application process that was devised applies a coating by means of a solution well with an orifice wiper at the bottom positioned beneath the TAGN strand extrusion die. Materials selected for the process are isocyanate N-75 for the inhibitor, polyethene glycol 400 for the wetting agent, methylene chloride for the solvent carrier, and dibutyl tin dilaurate for the catalyst. The methylene chloride coating solution has an isocyanate to polyethene glycol ratio of 1.4/1.

Project Results

A continuous process was established for manufacturing triaminoguanidine nitrate (TAGN) using aqueous solutions of hydrogen cyanamide, hydrazine hydrate, and nitric acid as starting materials. Pilot plant process equipment included a mixing reactor followed by a series of flow reactors which had a residence time of 2 to 2-1/2 hours at a reaction temperature between 90°C and 97°C. Crystallization was achieved in a cooled recirculation loop, and the crystallized slurry was filtered and washed in a continuous-belt vacuum filter unit. Filtrate was recycled to recover excess hydrazine used in the reaction step. The TAGN product was ground in a JET-O-MIZER fluid energy mill.

Ballistic testing of propellant made from pilot-plant TAGN confirmed its energy efficiency. The density of the propellant made from continuous-process TAGN was found to be lower than the density for propellant made from batch produced TAGN. There was no satisfactory explanation for this difference.

Based on pilot plant results, continuous-process TAGN manufacturing costs per pound were estimated to be \$8.19, \$3.56, and \$2.83 for production rates of 100,000, 1,000,000, and 10,000,000 lb/year respectively. An equipment list and specifications for equipment and raw materials for a 1,000,000 lb/year production capacity were prepared and included in the final report.

A process was established for applying an inhibitor coating to strands of TAGN gun-propellant material.

Implementation

We were unable to obtain any information from Rocketdyne on implementation by the time this report was prepared.

Benefits

We were unable to obtain any information from Rocketdyne on benefits by the time this report was prepared.

Rockwell International Corporation/Electronics Research Division
MANUFACTURING METHODS FOR ADVANCED BUBBLE DOMAIN MATERIALS
F33615-75-C-5010
September 1974 - September 1975
\$265,000

Background

In 1974, a rapidly developing magnetic bubble domain technology was of considerable interest for both commercial and military data memory applications. Air Force planning was underway for magnetic bubble memories in both airborne and spaceborne systems. The potential advantages of bubble memories for military use at the time were their non-volatility, high data rates, and inherent radiation resistance. At that time, the high data rate and thermal stability required for useable magnetic bubble materials had just been demonstrated, first at Bell Laboratories and then at Rockwell. The emphasis was then on the growth of single crystal epitaxial magnetic garnet films on non-magnetic single crystal gadolinium gallium garnet (GGG) substrates by the liquid phase epitaxy (LPE) method. These films, which support cylindrical magnetic domains called "bubbles", can be used to fabricate memory devices with bit densities on the order of 2.5 M bits/in.².

Work at Rockwell had developed techniques for growing ten films at a time instead of the previous single film growth. This work utilized the largest LPE melts to date and included the development of a rotation reversal technique to attain film-thickness uniformity during film growth. Good reproducible physical and magnetic properties had been obtained for films on 1.25-in. diameter GGG substrates. Methods developed for increasing melt temperatures between runs and for melt replenishment at the end of each day offered a melt with essentially infinite life and the basis for a total manufacturing process to grow garnet films in adequate quantities. The type of film grown in this work was gallium substituted iron garnet which has an inadequate temperature operating range for military applications. More recent work showed that germanium substituted garnet films could be grown. The germanium substituted films provide higher data rates and better temperature stability but require greater film growth control.

For this project, it was proposed to utilize the basic techniques developed for growing gallium substituted garnet films to provide a method for manufacturing calcium-germanium composition garnet films to meet future needs for Air Force data storage devices.

Project Objective

The objective of this project was to establish manufacturing processes for the growth of high quality thin epitaxial garnet magnetic films of advanced bubble domain materials. Process requirements included quantity

production, with excellent reproducibility, of germanium substituted garnet films which have high data rates (0.5 MHz) and operate reliably over a temperature range of -50°C to $+50^{\circ}\text{C}$.

Project Description

All work in this project involved the use of single crystal gadolinium gallium garnet (GGG) substrate wafers. Although earlier work had been done with 1.25-in. diameter substrate wafers, the early work in this project was done with 1.5-in. diameter substrate wafers meeting Rockwell specifications that were purchased from domestic suppliers. Later work in the project was done with purchased 2.0-in. diameter wafers that were becoming more commonly available at that time.

The substrate wafers were polished in-house in a single stage polishing step using a Strasbaugh Polishmaster machine. This single stage process required about 16 hours of machine time per wafer side. The longer polishing time as compared to a multi-stage process was offset by the freedom from handling problems and the reduced operator time for monitoring of the polishing machine. After polishing, the wafers were inspected, de-mounted from the polishing machine, cleaned, etched, and again cleaned to prepare them first for inspection of crystalline defects and mechanical damage and then for LPE film growth.

Melts for the germanium substituted garnet film growth effort in this project utilized the lead oxide-boric oxide flux system with the appropriate oxides of desired ions, including calcium carbonate and germanium dioxide, making up the balance of the melt. New multiple substrate wafer holders were designed and constructed from Pt-5 percent Au alloy wire. The newly designed holders allowed ten 1.5-in. diameter wafers to be inserted and removed without the concern for breakage and contamination from excessive handling experienced with earlier holders for smaller wafers.

Initial studies were made to determine the effects of crucible size, holder design, baffling in the crucible, rotation rates, and holder withdrawal rates on film thickness uniformity. Other studies were made to determine the film growth parameters and resulting film characteristics for the melt compositions and substrate sizes to be used.

The correct elemental composition of the films must be known to develop an effective melt replenishment method to extend melt life over long time periods. Film analysis for this purpose was accomplished using both atomic absorption and electron microprobe methods with good agreement of the results from both methods.

Fifty 1.5-in. diameter films were grown sequentially from the same melt over a period of ten days with no replenishment of the melt. Also, twenty 2.0-in. diameter films were grown from another melt. In each case, the melt volume was approximately 650 ml.

Finally, to prove correlation between film properties and operational characteristics, one of the films grown in this project was used to fabricate an operating storage device. The device was a 16 micron period, 20,480 bit serial register employing a T-bar propagation pattern in the storage region and chevrons in the region where write, erase, and read functions were performed. A conductor first configuration was used. This device operated satisfactorily at the project-goal data rate of 0.5 MHz over a temperature range exceeding the project-goal range of -50°C to $+50^{\circ}\text{C}$.

Project Results

The results of this project demonstrated that good quality germanium substituted garnet films can be grown reproducibly on substrates with large diameters (1.5 and 2.0 in.). These films can be used in advanced Air Force bubble domain storage devices that operate satisfactorily at the required 0.5 MHz data rate and -50°C to $+50^{\circ}\text{C}$ temperature range. Detailed specifications were established for substrate and LPE germanium substituted film materials. Detailed equipment and process specifications were also established for the LPE germanium substituted magnetic film growth.

Implementation

Although this project was technically successful in developing a production process for growing high quality advanced magnetic bubble domain materials, implementation at Rockwell for military use has not occurred. Rockwell implemented this technology in its commercial electronics division briefly in the late 1970s, but later dropped out of the bubble domain memory business. Development efforts were diverted to non-magnetic solid state data storage technologies, which offer much greater cost-effectiveness.

Benefits

Due to lack of implementation at Rockwell, no benefits were identified.

McDonnell Douglas Corporation

McDonnell Douglas Corporation/McDonnell Douglas Electronics Company
IMPROVED MANUFACTURING PROCESSES FOR POLYIMIDE PRINTED CIRCUIT BOARDS
F33615-76-C-5045
April 1976 - December 1977
\$305,302

Background

McDonnell Douglas' interest in polyimide circuit boards as a replacement for epoxy boards is reported to have originated in experience with repeated failures of critical components on boards supplied to McDonnell Douglas Astronautics Company for use in airlock control systems. Repeated failures led to repeated repairs on the boards. During the repair soldering process, a large number of very expensive circuit boards were destroyed. The key differences between epoxy and polyimide resins are their glass transition temperatures (250° F versus 520° F) and stronger foil-to-board interfaces at elevated temperatures for polyimide material. Polyimide boards were known to have a higher repair tolerance and were believed to have a longer lifetime within the operational environments experienced by components of tactical aircraft systems.

McDonnell Douglas Electronics Company undertook IRAD in the area of polyimide boards in the mid-1970s. At that time, there was at least one European (French) source for simple polyimide circuit boards. At about the same time, a USAF survey indicated that, in terms of life-cycle cost, electronic circuit board problems represented a high-cost driver.

Project Objective

The objectives of the project were to establish manufacturing techniques for the fabrication, assembly, and testing of low-cost polyimide printed circuit boards, and to document the results in the form of a processing guidelines handbook. Another goal was to compare the performance and costs of polyimide boards and epoxy boards.

Project Description

The project was performed in four phases. Phase I was a survey of polyimide suppliers to select the material to be used. Phase II characterized production processes for prepreg fabrication, copper-clad laminate fabrication, multilayer board fabrication, and board assembly. A processing guidelines handbook was also prepared in this phase. Test procedures and acceptability criteria were established in Phase III. In Phase IV, full-scale production was demonstrated and life-cycle cost comparisons were made for polyimide-glass and epoxy-glass printed wiring boards.

Project Results

The project was a technical success: all of its objectives were met, and it demonstrated the feasibility of the process. More than 100 boards were fabricated during the project, and they passed evaluations by both McDonnell Douglas and USAF. A "Processing Guidelines Handbook" was prepared, which would make it possible for a company with little or no polyimide experience to begin fabricating boards.

Implementation

As of the end of 1982, McDonnell Douglas had produced over 10,000 polyimide boards for a variety of USAF, other military, and civil sector applications. At least 23 U.S. firms are known to be manufacturers of polyimide circuit boards. A telephone survey to three of these firms confirmed the contention of McDonnell Douglas staff that this MANTECH project contributed in a major way to the transfer of this technology. It also revealed that polyimide circuit board production in the U.S. numbers in the tens or even hundreds of thousands per year. Applications include missile guidance systems, space applications, radars, computers, printers, and a variety of other miscellaneous applications where boards are subjected to high temperatures and/or periodic repairs.

Specific applications of polyimide circuit boards at McDonnell Douglas, and the numbers produced through 1982, are presented below:

<u>Application</u>	<u>No. Produced.</u>
● F-15 Engine Overspeed Protection	2,396
● Cruise Missile (DSMAC, Tomahawk)	2,342
● Aircombat Visual Simulator	2,107
● Laser Communications	100
● Dragon Tracker Test Set	46
● F-15 Head Up Display	60
● Commercial Coal Mining (DIGS)	12
● Commercial Communications (MAVIS) (Production of these is being cancelled)	3,184
	<hr/>
Total	10,247

McDonnell Douglas Corporation/McDonnell Douglas Astronautics Co.-East
MANUFACTURING METHODS FOR RESIN MATRIX PROCESSING
F33615-72-C-1486
January 1973 - July 1976
\$296,700

Background

This project, along with the two that follow, involved the development of manufacturing processes for three-dimensional weaving of carbon composite materials using a circular loom developed by McDonnell Douglas Astronautics Company. McDonnell Douglas had initiated research in this area in the 1960s, foreseeing a need for high-performance heat shields for reentry vehicles. The shape of heat shields is such that a polar pattern of weaving is desirable for shaping the material. Therefore, a circular loom was developed which could weave carbon fibers into the desired shape.

Shortly after the initiation of research into this heat shield production technology, McDonnell Douglas became aware of USAF interest in manufacturing rocket components from the same materials. Development of the technology was thereafter carried out under a combination of IRAD and funding by the Air Force Aeropropulsion Laboratory, now part of AFWAL.

McDonnell Douglas perceived the potential advantages of three-dimensional weaving to include those of increased performance and decreased cost. The use of carbon composite materials in general, and graphite/epoxy (Gr/Ep) materials in particular, to produce airframe components of lighter weight than their metallic alternatives was increasing rapidly. Three-dimensional weaving of composites was seen to offer additional advantages over other methods of fabricating parts from composite materials. Specifically, weaving added three-dimensional integrity over the process of braiding. Braiding is akin to lamination, in that the resulting structure is made up of layers of orthogonal material that are vulnerable to delamination under stress. The use of an automated loom had the potential for lower production costs than the labor intensive process of laying up Gr/Ep tape by hand into a final shape.

Subsequent to the demonstration of the technical validity of the concept of three-dimensional weaving in the R&D phase, McDonnell Douglas undertook to establish the process as a viable manufacturing technology under the sponsorship of the MANTECH program. Three contracts related to the establishment of this process were selected for study in this MANTECH Benefits Analysis Program. The project discussed below and the one that immediately follows were concerned with improving the quality of the material which was produced by three-dimensional weaving. The third project was oriented toward producing a specific system component using the process. All three contracts were in response to a need for a low-cost method of manufacturing components requiring characteristics of light weight and high-temperature resistance. The hope was that such components

Tubing which was drawn according to the new reduction schedule did not yield an acceptable product within the limitations of project resources. An overall yield of only 45% was achieved, as opposed to 90% for conventional processing. This experience was incompatible with realizing the anticipated cost reductions.

Implementation

Neither McDonnell Aircraft nor Wolverine are utilizing this technology, nor do they have any plans for doing so in the near future.

Benefits

Due to lack of implementation, no benefits were realized.

McDonnell Douglas Corporation/McDonnell Aircraft Company
HIGH QUALITY LOW COST TITANIUM TUBING
F33615-75-C-5120
July 1975 - December 1977
\$319,965

Background

Titanium tubing is used extensively in the aerospace sector for hydraulic systems. It is used in F-15, B-1, F-14, F-18, and AV-8B aircraft. Heavier wall titanium tubing is also extensively used in engine applications. Use of titanium tubing was expanding rapidly in the early and mid-1970s, and the cost of titanium tubing was high and on a rather sharp upward trend. Titanium tube production was relatively new, and it was thought that improved fabrication processes offered a good potential for cost reduction. The conventional process for producing titanium tubing was through multi-step reduction by Pilger mills of hollows approximately 1.5-inch O.D. by 0.0250-inch wall. The hollows were extruded from a bored billet, with a typical size of 3-inch O.D. by 1-inch I.D.

Project Objective

The objective of this project was to establish a low cost production process for high quality titanium tubing.

Project Description

The project was performed in two phases. In Phase I, improved methods of tube hollow manufacture were explored, and a comprehensive study was conducted of conventional tube manufacturing processes to identify high cost elements and cost reduction opportunities. A powder metallurgy hollow production process was developed and tested, and a modification to the tube reduction process was tested which lowered the number of reduction steps from tube hollow to final product. In Phase II, the tubing produced in Phase I was evaluated, and 500 feet of 3/8-inch and 5/8-inch diameter tubing manufactured in a Phase II production run was also evaluated.

McDonnell Aircraft served as prime contractor due to its role as a major user of titanium tubing. It was supported by two subcontractors. Wolverine Division of Universal Oil Products Company produced the tubing, and Crucible Materials Research Center supplied the powder metallurgy material.

Project Results

The project was not technically successful. Powder metallurgy produced tube hollows which cracked during the initial reduction pass.

a nineteenth century one which had been developed for the braiding of fire hoses.

Project Results

The program revealed technical difficulties in braiding parts which have other than elliptical or circular cross sections, or in which cross-section dimensions vary abruptly. Structural loading conditions determine the feasibility of utilizing a braided design concept, since braid angle cannot usually be tailored to structural requirements. In the parts produced, the braid angle was not variable enough to produce the fiber orientations which would be necessary for required structural efficiency.

Manufacturing cost savings were found to be realizable only when prepregged tows are used. Their non-availability caused many processing problems in this project. Graphite fiber cannot be braided dry; it must be prepregged and braided under very carefully controlled conditions to avoid fiber breakage and lowering of the quality of the laminate.

It was determined that braiding was best suited for composite components such as ducts and cylinders with fiber orientations at approximately 35 to 65 degrees relative to part centerline. These are often minimum gage designs and are typically less critical than airframe structural components.

Implementation

As a result of the lessons learned in this project, braiding was rejected as a method for automated production of composite aircraft structural components. It has been implemented, although not as a result of this project, for the fabrication of fuel lines for the F-15 and air ducts for the F-15, F-18, and AV-8B. Also, McDonnell Douglas is pursuing braiding as a potential technique for producing combustion chambers for the Advanced Air-launched Strategic Missile (AASM).

Benefits

Due to lack of implementation, no benefits were identified.

McDonnell Douglas Corporation/McDonnell Aircraft Company
LOW COST AUTOMATED FABRICATION OF COMPOSITE STRUCTURES
F33615-75-C-5155

April 1975 - December 1977

\$325,500

Background

In general, non-metallic composite materials can be regarded as lower-weight and, potentially, lower-cost alternatives to traditional metallic airframe components, especially titanium. The baseline method for fabricating composite structures at the time of this project was the building up of layers of fibers, such as graphite or quartz, by hand layup of tape containing the fibers and impregnated with an appropriate resin. Impregnation could be prior to layering (through the use of "prepreg") or subsequent to the layup of each layer. The cutting of the prepreg, laying up, and curing of such components is extremely labor intensive, and thus costly.

Braiding the fibrous elements of composite materials is one potential method for automating the buildup of composite structures. Braiding is a textile process dating from the early 1800s. In the braiding operation, a mandrel is fed through the center of the machine at a uniform rate and fibers from moving carriers on the machine are braided about the mandrel at a controlled angle. The machine operates like a maypole with the carriers working in pairs to accomplish the over/under braiding sequence.

Project Objective

The objective of this project was to establish the feasibility of using an automated braider to manufacture structural aircraft components. Two F-15 components--rudder spars and a primary heat exchanger diffuser duct--were to be produced. Processing parameters, costs, and component quality were to be assessed.

Project Description

The project was performed in four phases. In phase I, a commercially available New England Butt Company 144 carrier braiding machine was evaluated for its capability to produce uniform laminates, and a material specification for prepreg braiding tows was established. In phase II, basic braiding and processing procedures were established and documented in a process specification. In phase III, methods of braider automation were evaluated and a semi-automated control system was installed. An analysis of braiding costs versus hand layup was made for specific parts. Production demonstrations of the selected structural aircraft components were conducted in phase IV. It is interesting that the process design was

processes that environmental rules and prohibitions against cadmium processes are possible.

The cost of IVD processing does appear to have dropped in recent years with the introduction of more automated, higher throughput systems. It may be more economically attractive, from strictly a processing perspective, for a number of coating applications. Estimation of the overall savings from implementation of IVD would be a monumental task. It would require detailed studies at McDonnell Aircraft and a number of other aerospace contractors and job-shop platers in order to establish the processing economics, and a wide range of equipment users and maintainers to establish life cycle costs.

The economics of implementation depend on numerous micro-level variables such as: age and remaining service life of existing plating equipment; the type (i.e. the capability and efficiency) of existing plating equipment; alternative processes available for the specific components that are coated; alternative processes allowable under prevailing and future environmental constraints at each specific processing site (environmental requirements vary greatly from site to site and can drastically affect the economics of IVD); and the equipment utilization rate at the implementing firm, which is likely to vary greatly across firms and within individual firms over time. Due to these factors, the development of defensible estimates of dollar benefits from implementation of aluminum IVD was beyond the resources available to this project. However, it can be said that large, but unquantified, dollar benefits are being or soon will be realized, particularly as IVD systems become more fully automated and as environmental and health constraints make the use of other processes more expensive. McDonnell Aircraft's IVD organization estimates that, for common skin fasteners, its latest generation IVD unit reduces the coating cost from one cent using a paint-type coating (with production by a modern system) to one-half cent with IVD. With several hundreds of thousands of these fasteners per aircraft, savings would be very large indeed, from just this one type of application.

In summary, the IVD process evolved primarily due to the desire for a more environmentally acceptable process to replace cadmium coating processes. Its technical attractiveness has stimulated its use as an across-the-board coating process, and it is now used as a substitute for both cadmium and aluminum anodizing processes. With a high quality, environmentally acceptable process now available, increasing use of the technology can be expected over time, either by choice of the firm or military service or by environmental regulation. Improvements in IVD technology may make it now more economically attractive than some alternative coating processes, especially paint-type coatings. For both environmental and economic reasons, implementation of IVD technology is likely to expand considerably in the future.

6. Airbus

A number of fasteners are known to be IVD coated.

7. Space Shuttle

The spreader beam (a steel part) is IVD coated.

8. Patriot missile

The missile housing (16 in. O.D. by ten ft. length) is IVD coated.

9. Copperhead

Martin Marietta is coating this missile in-house for the Navy.

10. Other Applications

- Wave guides in Raytheon radars
- Wheel weights (American motors)
- A number of "black boxes" for electronic components
- Many bomb rack parts
- Two units have been sold to Japanese companies, three to British firms, and one to a French plating company. Much of the use of these units is for the aircraft and applications described above, but it is likely that they are being used for IVD coating of other components as well.

11. Potential Future Applications

IVD is now fully proven and accepted for use in all Douglas and McDonnell Aircraft Company aircraft. All new aircraft in the foreseeable future will probably use this process, and it will be used as a fix for corrosion or fatigue problems that arise on current aircraft.

Benefits

Very few details could be obtained on the costs of or the cost savings from using the IVD process. However, evidence that IVD coatings do not reduce fatigue life as do anodized coatings was used to justify the use of IVD coatings on F-15 wing skins. Environmental concerns are clearly a key motivating force for implementation of IVD, but it cannot be said that elimination of cadmium processes was mandated and that this process is the least-cost alternative. If this were the case, the costs of the best alternative technology could be compared with IVD to determine savings. However, IVD sometimes costs more than an available alternative, and it is only with the availability of this across-the-board substitute for cadmium

coating applications has been found in the aerospace sector, and applications are increasing in the munitions and automotive industries as well. McDonnell Douglas has identified 38 firms in the U.S. and Europe which are probable near-term users of IVD technology. Specific cases of implementation are discussed in more detail below.

1. F-18 Aircraft

McDonnell Douglas is coating all fatigue-critical aluminum alloy parts, including wing spars, wing ribs, bulkheads, and stringers, and all steel landing gear. The IVD process substitutes for anodizing of aluminium, and vacuum-cadmium coating of steel. Hundreds of components are being IVD coated. Many of the coatings are being performed for McDonnell Aircraft Company by job-shop platers. The F-18 was designed from the beginning to utilize the IVD process, and thus design changes were not required for implementation. Northrop, McDonnell Douglas' major subcontractor for the F-18, has purchased three IVD units and is coating a large number of aluminum components for the aircraft sections that it produces.

2. AV-8B

This aircraft is a modified AV-8A Harrier, which already had its coatings specified coming into the program. However, a number of new coating requirements for the AV-8B have been met with the IVD process. These include new requirements for landing gear and bomb rack components as well as for many small parts such as fasteners.

3. F-15

Fatigue critical wing skins are IVD coated instead of anodized as before. The IVD process is more expensive, but McDonnell Aircraft Company has been able to use slightly thinner skins to get the same properties. No cost information was able to be developed on this. A number of F-15 fasteners and ordnance and missile-launcher components are also IVD coated. Landing gear is not IVD coated, but rather uses a paint-type coating. McDonnell Aircraft will probably use IVD to meet new requirements for heavier versions of F-15 aircraft that are anticipated in the future.

4. DC-10

Douglas Aircraft and most of the airlines are IVD coating engine hangers (for the tail engine). Brake bolts are also being IVD coated.

5. DC-9

Douglas Aircraft is coating a number of small components on the DC-9, including the brake bolts.

within this area, and accelerated toward the part to which it adheres. Coating thickness is a function of part configuration and plating time.

Prior to this MANTECH contract, IVD technologies had been established in the laboratory for coating small parts that could be processed in an eighteen-inch diameter bell jar. The process had been scaled up for the coating of several parts for the Navy. What was needed now was to establish a full-scale IVD system which would have broad utility for applying protective coatings.

Project Objective

The objective of this project was to fabricate and optimize a production-size aluminum IVD system, particularly as a replacement for production cadmium plating. During the project, a full-scale IVD system was to be installed and tested at an Air Force Air Logistics Center.

Project Description

The project was performed in five phases. Phase I established the necessary parameters for equipment specifications. This was accomplished through discussions with personnel at ALCs, engine manufacturers, and aircraft manufacturers to determine the sizes of parts applicable to IVD coatings. At the beginning of Phase II, the coater components were fabricated. The rest of Phase III was devoted to final assembly of the coater and optimizing its capability with respect to cleaning procedures, part loading, and fixturing. The chamber of the system that was fabricated consisted of a right circular cylinder, laid horizontally, with a six-foot diameter and a ten-foot length, exclusive of two circular doors. In Phase IV, aircraft and engine parts were coated and evaluated. In Phase V, operator manuals were prepared and the coater was shipped to Ogden ALC where it was installed, checked out, and operators were trained.

Project Results

The project was a technical success. A production capability for applying aluminum IVD coatings was established. The performance of the coatings was found to meet or exceed all MIL standards and USAF requirements.

Implementation

McDonnell Douglas continued the development of IVD technology with in-house funds and has developed aluminum IVD coating to production status for a wide range of military products. Three rack-type and one barrel-type aluminum IVD coating systems have been placed in production use at McDonnell Douglas. They support production of F-15, F-18, and AV-8B aircraft. McDonnell Douglas produced these systems for sale and, as of early 1983, has sold or leased 32 systems. A British firm has been licensed to produce the equipment. As of early 1983, 57 firms have been identified as utilizing the aluminum IVD coated components. An enormous range of

McDonnell Douglas Corporation/McDonnell Aircraft Company
FABRICATION AND OPTIMIZATION OF AN ALUMINUM ION VAPOR DEPOSITION SYSTEM
F33615-76-C-5209
March 1976 - June 1978
\$370,569

Background

The aluminum ion vapor deposition (IVD) process is an attractive, general-purpose coating process for corrosion protection. It offers an alternative to coatings of vacuum-deposited and electroplated cadmium, diffused nickel-cadmium, anodizing, hot dip, metal spray, and paint. In particular, the aluminum IVD process offers the following advantages over cadmium processes for coating steel parts:

- 1) Tests indicate that aluminum IVD offers better corrosion resistance.
- 2) It can be used at temperatures up to 925°F, versus 450°F for cadmium.
- 3) It does not adversely affect fatigue life of the substrate.
- 4) It does not promote hydrogen embrittlement of high-strength steels, as does cadmium.
- 5) The process does not pose environmental or health problems, as does the cadmium process.

Aluminum coatings can be used in contact with titanium without causing solid-metal embrittlement, and they offer galvanic protection to both aluminum and steel parts. Aluminum IVD coatings are soft and ductile, and therefore they do not have adverse effects on the fatigue life of aluminum components. The IVD process is not confined to line of sight deposition, and parts having complex shapes can be uniformly coated. It is also very attractive due to the fact that it does not present environmental or health dangers. It was thought that, in the longer term, as environmental and health-hazard controls become more stringent, aluminum IVD will become more acceptable and less expensive than alternatives, many of which present major health and environmental problems.

The IVD process conceptually is a simple one. The parts to be coated are suspended over an aluminum evaporator within a vacuum chamber. Aluminum wire is fed into "boats" in the bottom of the vacuum chamber, where it is heated and evaporated. Coating takes place in an inert gas atmosphere under a partial vacuum. The substrate to be coated is suspended on either a rotary holder or a laterally transversing holder. The parts are cathodically impressed at a high voltage, so that a DC glow discharge is established about the workpiece. The evaporated aluminum is ionized

Benefits

McDonnell Douglas conducted an analysis for this project which compared direct labor and material requirements for SPF production with those for the baseline process on a part-by-part, year-by-year basis. This analysis was based on actual production experience. Estimates were also made for 25 parts that have not yet been implemented, but which probably will be by 1985. These estimates were made based upon experience with similar substitutions that have already been implemented. The time period for the analysis, which included only F-15 applications, was 1983 through 1992. The resulting savings figures underestimate the true savings, since SPF was implemented at McDonnell Douglas several years ago.

Savings estimates were based upon F-15 aircraft production estimates in the ten-year corporate strategic business plan. The reductions in direct labor man hours, mostly from avoided machining, amounted to 348,169 hours. These were converted to dollar savings of \$19,149,295 by assuming an average \$55 per hour (burdened MC) labor cost. Material savings, mostly for titanium extrusions, amounted to 115,108 pounds or, at \$24 per pound, \$2,762,592. All dollars are in 1982 dollars. Information on F-18 and AV-8B applications was not sufficiently developed in time to be included in this report.

To summarize, for the F-15, which is the major application, recurring manufacturing cost savings for the 1983-1992 period total to approximately \$21.9 million. Of this, approximately 87% is in labor cost savings, and 13% is in materials savings. Initial capital costs and tooling costs were approximately \$1.6 million. Thus, net overall manufacturing cost savings are approximately \$20.3 million. There may be some minor weight savings in the aircraft, but these would be very small.

addressed both form-before-bond and bond-before-form approaches to SPF/DB, as well as the SPF/DB of external doublers to structural shapes. The project was performed in three phases. Phase I evaluated effects of forming parameters and material variables in SPF of single-sheet, generic-shaped titanium parts. Phase II evaluated methods for SPF/DB of two-sheet titanium structural panels and J-section straight beams. Phase III consisted of project documentation and reporting.

Project Results

The project can be considered a technical success. Process and design manuals, and material and process specifications, were prepared for SPF of single-sheet geometries and for SPF/DB of two-sheet geometries. McDonnell Douglas staff believe that this project was highly successful in eliminating most of the risks normally associated with the introduction of a new manufacturing process. The project successfully defined the process so that potential problems, such as thin-out, could be anticipated and handled in the design of parts and tools and in the selection of the manufacturing approach.

Implementation

As part of its IRAD effort, McDonnell Douglas continued the development of SPF and SPF/DB after this program was completed.

SPF was implemented for production several years ago, even before the final report for this project was submitted. There are currently (1983) 67 parts on the F-15 produced by SPF. New SPF parts are being continuously added, and, by 1992, 103 F-15 and F-15E parts are expected to be produced by SPF. The F-18 and AV-8B also utilize SPF parts, but to a lesser extent.

SPF/DB, while production ready, has not been implemented at McDonnell Douglas. The reason given for lack of implementation was that it would require substantial investment in capital equipment which cannot be economically justified on the basis of anticipated production volumes. McDonnell Douglas is currently engaged in two ongoing SPF/DB development programs. One SPF/DB process is being developed in an IRAD supported program to replace an F-15 nozzle fairing (a weldment), and another one is being developed in an Air Force supported program to replace the trailing edge of the F-4 horizontal stabilizer.

SPF and SPF/DB processes will almost certainly be used on any future McDonnell Douglas aircraft that utilize titanium, such as the advanced tactical fighter and advanced cargo aircraft, but these applications cannot now be identified.

McDonnell Douglas Corporation/McDonnell Aircraft Company
SUPERPLASTIC FORMING/DIFFUSION BONDING (SPF/DB)
LIMITS OF THE MANUFACTURING PROCESS
F33615-77-C-5208
November 1977 - March 1980
\$669,768

Background

SPF/DB of titanium structures was first developed extensively by Rockwell International Corporation. The attractiveness of SPF/DB comes from its capability to produce high-quality parts at near-net shape, in a single production operation, with significant savings in materials and labor as compared to competing processes. The technology proved to be of such general utility that the Air Force sought to transfer it to other U.S. aerospace corporations through the sponsorship of MANTECH programs at other firms which also might apply the technology for aircraft production.

Superplasticity refers to the tendency of certain metals to flow under elevated temperature and pressure, and it is the phenomenon that underlies both the SPF and the DB processes. Superplastic forming is accomplished when a pressurized inert gas pushes a sheet of metal onto a male or female mold within a heated press. Superplastic conditions are obtained, and the metal flows to fit the shape of the mold. Thinning at the radii of curvature is typical and must be controlled to acceptable limits by choices of conditions, tool shapes, and sheet-metal widths. Diffusion bonding is a type of welding where pieces of like metal are bonded under superplastic conditions as the material from the two pieces interflow. Diffusion bonding is performed either in an inert atmosphere or under a vacuum, with the pieces to be joined subjected to physical pressure during the bonding cycle. The SPF and DB cycles often can be performed simultaneously or sequentially in the same tool.

Project Objective

The major purpose of this MANTECH project was to extend McDonnell Douglas' hands-on experience with SPF and SPF/DB processes, and thus to develop a data and experience base to guide the selection and design of parts for SPF or SPF/DB production. The overall objectives were technology transfer and risk reduction, which would hasten the implementation of the technology at McDonnell Douglas.

Project Description

The project was essentially an evaluative one, in which different combinations of techniques and approaches were taken to the SPF and DB of various aircraft parts, and then evaluated and compared. The program

Benefits

The main benefit of this technology to the Air Force is enhanced mission effectiveness. Lower failure rates and easier repair of aircraft electronic components translate into improved readiness and improved mission capabilities. Improved reliability has been confirmed, but not quantified, through discussions with the USAF item manager for the F-15 Head Up Display (HUD) at Robins Air Logistics Center, and with personnel at three other firms that supply polyimide circuit boards to the military. A number of polyimide boards have been installed in the HUD of F-15 aircraft in the 1st Tactical Fighter Wing for evaluation. At the time of preparation of this report, field performance evaluation of the boards had not been completed (or at least not yet documented), but experiential evidence indicates major reliability improvements. If the test data confirm the improvements, which is expected, polyimide circuit boards will be requested for the entire fleet of F-15s.

In terms of dollar benefits, it is clear that the manufacturing costs of polyimide circuit boards are considerably higher--somewhere between 10-20% higher--than for standard ones. There is no doubt, however, that from a "willingness to pay" perspective, the Air Force, as well as other military and commercial users of this technology, are receiving an extremely good value in the purchase of the more expensive circuit boards. There may be life-cycle cost savings from repair avoidance and lower repair costs. However, no information on repair costs appears to be available for the F-15 HUD or other applications. Our information is that USAF repair units do not track the repair cost of these items, and the USAF field test is not tracking repair cost savings.

could ultimately be woven like fabric, using high-speed, automated looms.

Project Objective

The objective of this project was to establish a manufacturing method for the one-step impregnation of three-dimensional carbon or quartz matrices which would not disturb the geometry of the part as established by the three-dimensional weave. The process of centrifugal impregnation had been demonstrated by McDonnell Douglas in the laboratory using small-scale components. This MANTECH project was to scale up the process to accommodate full-sized components. It was to characterize process parameters, including resin properties, preform properties, centrifuge speed, process time and temperature profiles, and preform location in the centrifuge for their effects on product quality and cost. It was anticipated that a successful project would contribute to product improvement by yielding composite components of maximum density. The project would contribute to a lower process cost by reducing impregnation to a single step operation.

Project Description

The project was performed in three phases. Phase I investigated the various centrifuge and raw material process parameters on a subscale basis. Phase II optimized the process parameters to a full-scale process using nine-inch diameter cylinders and a 30-inch arm centrifuge. Phase III certified the process on production-size equipment, and it demonstrated the process by impregnating three-dimensional woven shapes which had been produced in a previous USAF program.

Project Results

The project was a partial technical success. The centrifuge test bed achieved only 120 rpm (vs 180 rpm), resulting in a centrifugal force of 51 g (vs 90 g). Consequently, although a low void content was obtained on some runs, the results were not consistent.

It seemed likely that the problems encountered could have been overcome, but the need for further progress was superseded by the discovery that the desired results could be achieved at a lower cost through simple pressure impregnation and cure.

Implementation

Neither the component process of centrifugal cure nor the overall process of three-dimensional weaving of composites has been implemented at McDonnell Douglas for production hardware.

Subsequent to this project, McDonnell Douglas was able to prove the

technical feasibility of three-dimensional weaving of composite structures. The lack of implementation is apparently attributable to the fact that McDonnell Douglas has not undertaken hardware programs which can utilize the technology, rather than to inherent shortcomings of the technology itself. A more efficient three-dimensional weaving machine would probably have to be built before the process would be cost effective. The knowledge gained from this project and the other related ones provides a good foundation from which to build such equipment should the need arise in the future. Therefore, three-dimensional weaving of composites appears to be a longer-term MANTECH-supported technology which is now in the aerospace toolkit and has a good potential for future payoff, but whose time has not yet come.

Benefits

Due to lack of implementation, no benefits were identified.

McDonnell Douglas Corporation/McDonnell Douglas Astronautics Co.-East
DENSIFICATION OF COMPLEX SHAPED WOVEN COMPOSITE PREFORMS
F33615-72-C-1665
July 1972 - July 1975
\$538,997

Background

Prior to this project, packing, i.e., densification, of woven carbon fibers was performed manually on a large circular loom developed by McDonnell Douglas for three-dimensional weaving of composite preforms. The process was labor intensive and costly, and densities were not always uniform. What was needed was a faster automated process which would result in uniform, repeatable densities. Such a development program could build upon the expertise McDonnell Douglas had obtained in building a working loom and automating all other weaving functions.

Project Objective

The objective of the project was to automate the densification process in the weaving of composite preforms through the scale-up and application of a switchblade autopacker design.

Project Description

The program was conducted solely in-house at McDonnell Douglas Astronautics-East, in two phases. Phase I established the process for densification of continuous Circular Woven Preform Structures. Phase II established the processing for densification of complex-shaped woven preforms.

Project Results

The project was a technical success; all objectives were met. The autopacker was successfully scaled up to provide continuous high-speed packing coordinated with loom operations. The preforms that were produced were of higher quality in density of weave and uniformity, and the labor hours required for preform production were substantially reduced. However, the production volume required to economically justify the cost of the equipment was found to be quite high.

Implementation

The autopacker was used in subsequent development projects, but the three-dimensional weaving system has not been implemented for production. As discussed under the previous project, the technology is essentially production ready but there is no need for it at the present time;

lower-cost alternatives (two-dimensional braiding, tape layup, etc.) are acceptable. Several other firms are thought to be now using weaving in development work on new-generation rocket nozzles. The MX rocket nozzle is one near-term application where three-dimensional weaving may be utilized (FMI and AVCO are the leading candidates for the production contract at this time).

Benefits

Due to lack of implementation, no benefits were identified.

McDonnell Douglas Corporation/McDonnell Douglas Astronautics Co.-East
INTEGRAL ROCKET-RAMJET CARBON-CARBON SCALE-UP
F33615-77-C-5070
May 1977 - October 1979
\$449,585

Background

At the time of this project, a new-generation advanced strategic air launched missile (ASALM), which was to utilize rocket-ramjet propulsion, was under development at McDonnell Douglas. This was to be a replacement for the SRAM. Carbon-carbon combustors are lighter weight and more durable than ablatively-lined metal combustors. Therefore, they offer a potential for extending the range of such missiles. In addition, a lower-cost component might be achieved if integral component weaving could be utilized. With AFWAL support, McDonnell Douglas had performed a number of R&D programs which had led to the production (by weaving) and successful testing of several subscale combustors. What was needed now was to establish the production capability of the weaving process for this type of component by scaling up the process to produce a full-scale carbon/carbon rocket-ramjet combustor.

Project Objective

The objective of this project was to establish manufacturing methods and to prepare manufacturing specifications for full-scale rocket-ramjet combustors made from carbon-carbon composites. The ultimate objective was enhanced mission capability of this strategic missile system. It was hoped that costs could be minimized, or perhaps reduced, but costs were of much less concern. The Air Force Aeropropulsion Laboratory sponsored performance testing and evaluation of the full-scale motor cases under a separate contract.

Project Description

This twenty-nine month project was structured to fabricate three full-scale carbon/carbon combustors. Fabrication involves preform weaving, processing, and machining. McDonnell Douglas Astronautics Company (MDAC)-East performed the weaving; Pfizer performed heat cleaning, chemical vapor deposition, and pyrolytic graphite coating; MDAC performed resin impregnation and pyrolyzation; and Weaver Industries performed the machining.

A three-dimensional weave pattern was employed. Nondestructive evaluation procedures and quality control procedures were developed, along with material and processing specifications during the manufacture of the three combustors.

Project Results

This project resulted in the successful fabrication of two full-scale (56 inches long by 18.75 inches in diameter) combustors, the largest parts ever woven from carbon composite materials. They showed excellent material properties and performed well in performance tests. The third combustor was damaged during manufacture when a cooling line ruptured during a pyrolytic graphite coating step, introducing steam into the coating chamber and oxidizing the combustor.

The project successfully demonstrated that three-dimensional woven carbon-carbon is a viable material for an integral rocket-ramjet combustor. However, producibility problems remained. The combustors as manufactured were slightly deformed, and individual cooling steps did not always yield uniform results. Progress was made toward solving these producibility problems, but further work was needed to achieve confidence for actual production use.

Implementation

Three-dimensional weaving has not been implemented for the ramjet combustors or for any other applications at McDonnell Douglas. The 85-inch length of the combustor in the final ASALM design was beyond the capability of the McDonnell Douglas loom. The carbon-carbon processing part of the technology was used later in an Air Force program to process braided carbon-carbon integral rocket-ramjet combustors for the ASALM. However, the ASALM program was ultimately cancelled. McDonnell Douglas may participate in the Advanced Air-launched Strategic Missile (AASM) program, but will probably use braiding to produce the combustors. MDAC is currently conducting an IRAD program in which it is producing, by braiding, three prototype carbon-carbon combustors applicable to AASM.

Benefits

Due to lack of implementation, no benefits were identified.

McDonnell Douglas Corporation/McDonnell Douglas Astronautics Company
MANUFACTURING METHODS FOR REENTRY VEHICLE ADVANCED COMPOSITE SUBSTRUCTURE

F33615-76-C-5013

October 1975 - May 1978

\$875,424

Background

Reentry-vehicle design practice at the time of this project involved the use of an external ablative heat shield and a structural metal shell. A reentry vehicle was fabricated in sections that were joined after their internal components were installed. The substructure shell is the primary load-bearing element of a reentry vehicle. It must carry reentry loads as well as loads presented by a nuclear encounter. It also supports internal components of the reentry vehicle. Aluminum-alloy construction was being widely used for reentry vehicle substructures, usually in the form of a monocoque or rib-stiffened shell structure.

The addition of maneuvering capabilities for reentry vehicles imposes requirements for structures with increased stiffness and strength and with more complex surface geometries that can accommodate control devices. A higher longitudinal stiffness is required to minimize aeroelastic body bending that results from the high lateral loads produced during a maneuver.

In an effort to provide the required stiffness and strength in a low-cost, light-weight structure, composite materials capable of withstanding temperatures greater than 350^oF were investigated. Formulations of graphite/epoxy and graphite/polyimide showed the greatest potential for providing the required mechanical properties at elevated temperatures.

Project Objective

The objective of this project was to establish low-cost fabrication and processing procedures for manufacturing an advanced composite substructure for a maneuvering reentry vehicle.

Project Description

The composite substructure selected for demonstration in this project was based on the Air Force Small Evader Program (SEV) design configuration and on the Advanced Maneuvering Reentry Vehicle (AMaRV) forward control section. These substructure components represented a level of complexity and detail, for both internal and external components and their assembly, that are found in optimized reentry vehicle designs. This allowed the project to establish realistic manufacturing methods for producing reentry

vehicle composite substructures.

This project was performed in five phases. Phase I was a manufacturing configuration assessment. Fabrication procedures were optimized in Phase II, and processing procedures were optimized in Phase III. Phase IV was a full-scale manufacturability demonstration. In Phase V, reports and specifications were prepared. There were two tasks within each phase: one task covered work on graphite/epoxy materials, and the other task covered work on graphite/polyimide materials.

The overall effort was planned to produce conical sections of the payload and control components with cocured stiffening rings. The vehicle configuration was similar to that for the Air Force Small Evader.

Project Results

After modifications to the vehicle design configuration were completed, fabrication procedures were optimized for the materials being used. Because of the match in coefficients of thermal expansion, bulk graphite was selected as the material for fabricating the female tools used in curing the composite skins. Female tools were chosen for two reasons: to eliminate any tendency for hoop fibers to buckle or wrinkle during final cure, and to permit internal frames to be cocured with the skin to eliminate secondary bonding operations. The cocuring would avoid tolerance problems associated with post-cure bonding of internal structural parts inside a cured skin.

Difficulties in controlling the position of the conical preform during cocuring required the skin and internal frames to be cured separately and then bonded together with a paste adhesive. This approach worked fairly well and produced structures with good visual appearance and good aerodynamic surfaces. Numerous problems were encountered with voids and wrinkles in the finished parts. These problems resulted from the conical shapes of the parts and their expansion during curing at elevated temperatures.

The completed structure was static tested by applying external pressure in an autoclave. This test resulted in catastrophic failure of the structure at approximately 80% of the design load. The failure occurred under a pressure of 147 psi at 75°F (room temperature), while the design ultimate load was 184 psi at 350°F. A review of the failed structure revealed the following possible causes for its premature failure: premature failure of test-setup shrouds; an unbalanced radial load on the aft cover; excessive loads on the stiffening rings; frame leg transverse instability; and insufficient frame stiffness. It was concluded that the level of effort required to conduct a detailed stress analysis of the failed structure was not justified and that the cost to determine the exact cause of failure exceeded the value of this knowledge for the SEV design.

Implementation

McDonnell Douglas has not implemented this technology and has no plans for doing so in the near future. Although bulk graphite is being used throughout the industry in the curing of graphite composite materials at high temperatures, its use is not associated with the performance of this project.

Benefits

No benefits were identified, since this technology was not implemented at McDonnell Douglas.

McDonnell Douglas Corporation/McDonnell Douglas Astronautics Company
MANUFACTURING METHODS FOR PROCESSING FINWEAVE CARBON PREFORMS
F33615-75-C-5156
April 1976 - February 1978
\$169,850

Background

High-quality nose tips for reentry vehicles is a paramount requirement for ballistic missiles because of the need to maintain uniform aerodynamic profiles during reentry. Uniformity of material and density are of the utmost importance in maintaining a uniform ablation of material as a reentry vehicle enters the atmosphere. The process for densification of fineweave carbon preforms developed at the Union Carbide Y-12 facility at Oak Ridge, Tennessee was particularly suited for the densification of carbon materials to be used in nose tips.

Project Objective

The objective of this project was to establish an industrial source for the standard densification processing of large (4 X 4 X 11 inches) 2-2-3 carbon-carbon composite preform billets.

Project Description

This project was initially set up to densify and evaluate seven government furnished material (GFM) carbon-carbon preforms over a 15-month period. Due to project modifications, a total of ten GFM preforms were densified and evaluated over a 24-month period.

This project was performed in four phases. Phase I was concerned with preform qualification. Preform processing in Phase II was separated into three tasks: Task 1 concerned producibility using the equivalent industrial standard process (EISP); Task 2 concerned manufacturability using the EISP; and Task 3 concerned producibility using the improved industrial standard process (IISP). The properties and performance characteristics of the densified billets were assessed in Phase III. Project reports and material and process specifications were prepared in Phase IV.

Process modifications were made after the successful densification of preforms in Task 2 of Phase II, and several preforms were densified for the Minuteman program under a separate contract. The development of an improved industrial standard process (IISP) was made possible by the experience gained in this project and other simultaneous projects.

Project Results

Use of the Union Carbide process resulted in densified carbon preforms with properties and performance characteristics that were at least equal to those for preforms densified through the use of the EISP at other facilities. McDonnell Douglas demonstrated the capability to densify large, three-dimensional graphite fiber preforms using both the EISP and IISP schedules. Two of the billets densified during this project were machined into nose tips; one of these was successfully flown on an advanced reentry system.

Process modifications indicated that billet density could be improved by using treated pitch for impregnation and by eliminating the chemical vapor deposition step used in rigidizing the preform. The process was demonstrated to be very forgiving, since substandard weight or microstructure conditions resulting from processing anomalies could usually be corrected through additional processing cycles.

The processing specifications developed during this project should be usable by other industrial sources with similar processing equipment for densifying fineweave carbon-carbon preforms with 15V coal tar pitch.

Implementation

McDonnell Douglas has performed no carbon-carbon densification in more than three years now and has no plans for doing so in the near future. McDonnell Douglas remains qualified as a processor of carbon-carbon materials.

Benefits

No monetary benefits were identified, since this technology was not implemented at McDonnell Douglas. The one benefit that can be attributed to the performance of this project is an increase in potential processors of carbon-carbon materials.

Northrop Corporation

Northrop Corporation/Electronics Division
MANUFACTURING METHODS FOR A MINIATURE RADIATION HARDENED PLATED WIRE MEMORY
F33615-73-C-5088
July 1973 - July 1976
\$616,360

Background

At the time this contract was initiated, several "smart" weapon systems were being developed by the Air Force to have greater accuracy and survivability in combat environments than existing weapon systems. Nearly all of these systems, and maneuvering reentry vehicles in particular, required electronic memories that were reliable in high-radiation conditions. The state of the art at the time was plated-wire memories, which rely upon magnetic fields set up around crossed sets of specially plated, small-diameter (0.002 inch) wires connected to appropriate timing, control, and sensing electronics.

Several systems had been built before this project that were functionally adequate to perform the memory functions in flight computers for weapon systems. The sizes and weights of these memories, however, prevented their use in reentry vehicles.

Project Objective

The purpose of this project was to demonstrate the applicability of new manufacturing methods and techniques for the production of plated-wire memory subsystems. The primary objectives were to achieve significant reductions in both size and power requirements from those for previous radiation-hardened plated-wire memory designs. Since the intended application was in reentry vehicles, the resulting equipment was required to withstand the thermal, mechanical, and nuclear-radiation environments specified for reentry vehicles.

Project Description

This project was performed in three phases: Phase I was concerned with systems analysis and design of the plated-wire memory package, Phase II was concerned with its fabrication and mechanical and electrical testing, and Phase III was concerned with the evaluation and testing of its nuclear radiation hardness.

In Phase I, The basic ground rules listed below were followed in order to develop a design for an easily producible memory package that would meet the project objectives.

1. The baseline memory configuration was to utilize the prominent features of the reentry-computer tradeoff and technology (RC-TOT)

study together with developments from SAMSO sponsored hardened-memory systems (HMS), with the exclusion of any medium-scale integrated circuit development activity.

2. No new special semiconductor components were to be developed.

3. The approach to nuclear radiation hardness was to use available hardened components and then determine by analysis the level of circuit radiation hardness.

Project Results

This project resulted in the development of a miniaturized plated-wire memory system that met all of the mechanical, electrical, and radiation-hardness requirements for the reentry environment. Development of the Beam Lead Interconnect Package (BLIP), with its radiation hardness and space saving characteristics, was a crucial factor in the success of the project. One problem with the memory hardware fabricated during the project was its serviceability. This problem was alleviated in subsequent hardware by relaxing the size reduction requirement.

During the project it was realized that the then current sense amplifier design also needed to be miniaturized, and the conceptual design for an appropriate sense amplifier IC was developed. This IC was further developed and put into production through follow-on MANTECH and SPO support.

Implementation

The miniaturized plated-wire memory that was developed during the project and the miniaturized sense-amplifier IC that was identified and conceptually designed during the project were both implemented in the memory systems currently being produced for the MX missile system, although the Beam Lead Interconnect Package (BLIP) technology has been superseded by LSI and VLSI packages. The implementation has occurred at Rockwell, which won the USAF production contract for these systems..

In the sense amplifier IC design that originated in this project, a single IC replaces the six discrete components and four IC's that were required in the previous design.

Benefits

Cost estimates from Rockwell showed that the manufacturing cost for each sense amplifier using the previous design would have been approximately \$650 (1982 \$). Since the present cost for manufacturing a sense amplifier with the new IC design is \$116 (1982 \$), there is a saving of \$534 (1982 \$) per sense amplifier. With 33 sense amplifiers in the

Northrop Corporation/Aircraft Division
LOW FLOW, LOW PRESSURE PREPREGS
F33615-76-C-5169
August 1976 - December 1979
\$329,593

Background

In order to reduce costs associated with the fabrication of composite structures, a great deal of effort had been expended by the Air Force and airframe manufacturers to develop methods which would not need high pressures or autoclaves for curing various resin systems. The development of resin systems that could be properly cured at low pressures would also make possible the easy development of field repair procedures.

A significant factor in the development of new resin systems is the need for placing bleeder materials in a layup to remove excess resin in the amount necessary to achieve the desired tack and handling characteristics of the prepreg material. Eliminating the labor hours needed to tailor and apply bleeder materials and eliminating the time required to prebleed material before its final cure would combine to yield substantial decreases in end-item costs.

A new resin system, Hystel modified epoxy (HME), which had been developed under Air Force contract, had exhibited the desirable characteristics of low-flow, low-pressure cure and substantial resistance to structural property degradation when exposed to moisture. These characteristics made it feasible to explore the possibility of using the HME resin system in the fabrication of a composite airframe structure.

Project Objective

The objective of this program was to demonstrate the suitability of a zero-bleed, vacuum-bag cureable graphite/HME material for producing durable, high-quality, low-cost composite structures. This would entail the development of commercial hot-melt prepregging procedures for the HME resin system, the development of preliminary design data for the graphite/HME material, and the fabrication of demonstration structural subelements.

Project Description

Originally, this project was to be performed in three phases. As intended during Phase I, Hercules developed HME resin systems that are compatible with hot-melt prepregging procedures and provided material to Northrop for the development of initial design data.

processes were cocuring, zero resin bleed, reusable rubber vacuum bags, vacuum pressure curing, and ion graphing. Other evaluated processes were the use of elastomeric tooling and thermoplastic resin systems. These other processes were rejected because they were found to be not sufficiently developed for use in this project.

The manufacturing processes developed in the Phase I project were tested to show their suitability for structures other than honeycomb core panels. A hat-shaped stiffened skin section was fabricated without resin bleed and was found to have excellent structural properties and an aerodynamic surface after being cured under a vacuum pressure of 15 psi in an oven at 300^oF.

In Task 2, the repeatability and cost competitiveness of the project approach were demonstrated by fabricating several components for the cockpit section and testing them for static strength and fatigue strength. After the design and manufacturing approach for component fabrication was proven, an entire cockpit section, containing 27 graphite and graphite-fiberglass/epoxy hybrid subassemblies, was produced and tested. This cockpit section was shown to be structurally sound by testing it with an internal pressure of 10 psi, which was its maximum load condition.

The Task 3 cost analysis indicated that the design and manufacturing approach in this project, if fully exploited, had the potential for reducing production labor hours by approximately 60%. Average labor-hour savings of 42% were obtained for fabricating the 27 components.

Dimensional control, configuration stability, and the quality of aerodynamic surfaces on the cockpit section were shown to be excellent. Manufacturing fit-up tolerances for final assembly operations were well within those allowable, even with a mixture of components fabricated from different composite materials.

Implementation

Northrop has not implemented this technology. However it is a candidate for future use in production of the Advanced Tactical Fighter in the 1988-1990 timeframe.

Benefits

No benefits were identified, since this technology was not implemented at Northrop.

Northrop Corporation/Aircraft Division
LOW COST MANUFACTURING CONCEPTS OF ADVANCED PRIMARY AIRCRAFT STRUCTURES
PHASE II
F33615-76-C-5051
January 1976 - May 1977
\$403,588

Background

This project was a follow-on effort to the Phase I project (contract no. F33615-74-C-5153) described previously.

Project Objective

The objective of this project was the further development and establishment of production manufacturing methods for the fabrication and assembly of advanced composite primary aircraft structures that would be cost competitive with or lower in cost than comparable advanced aluminum primary aircraft structures.

Project Description

In this Phase II project, the results from the completed Phase I effort were incorporated with other developments in the industry into the design and manufacture of a five-foot section of a forward-fuselage cockpit component.

The project was divided into three tasks. In task 1, related manufacturing process developments throughout the industry were evaluated and processes suitable for the structure to be manufactured were selected. Representative subcomponent structures were fabricated to validate the use of manufacturing methods developed in the Phase I project.

In Task 2, structural components were fabricated and tested to verify the structural adequacy of components representative of those to be used in the construction of a five-foot forward-fuselage cockpit section.

In Task 3, a cost analysis was performed to evaluate the cost effectiveness of the design and manufacturing methods that were used in the production of the five-foot forward-fuselage test section in Task 2.

Project Results

The Task 1 survey and evaluation of related industry developments included the processes developed at Northrop in the Phase I project as well as several processes developed by other companies. The Northrop Phase I

structure must be investigated further to determine if these techniques can be used in future designs.

One development which proved to have a substantial cost advantage without any degradation in structural properties was the use of reusable rubber vacuum bags during consolidation and cure cycles. This was accomplished through the development of special tooling which clamped a rubber vacuum bag to the base tool to form an air-tight seal. Both butyl and silicone bag materials were evaluated. Butyl material was able to withstand repeated cycling at 350^oF and 1000 psi, and silicone material was able to withstand repeated cycling at 450^o-500^oF and 1000 psi.

Considerable effort was expended on evaluating the ability of composites to withstand the impact of large caliber projectiles fired through tanks fabricated by various methods from different composite materials and sealant systems. The results indicated that most of the projectile damage to a fuel tank is produced by a hydro-ram effect produced by a projectile as it moves through the tank. This effect can be greatly minimized by including a crushable core or some other energy absorbing material in the tank structure.

Implementation

Northrop did not implement any of these technologies. A follow-on contract (F33615-76-C-5051) was performed to extend the more promising technological approaches for use with integral composites. This follow-on work is presented in the next individual project report.

Benefits

No benefits were identified, since this technology was not implemented at Northrop.

benefits of the different manufacturing methods with a simplified design approach in order to establish the potential cost savings and production feasibilities for the methods under consideration.

Various honeycomb sandwich panels were fabricated and tested to determine the mechanical and dimensional effects of the six manufacturing methods. Test results were analyzed during manufacturing-design tradeoff studies for both individual and combined effects of the various manufacturing methods. Cost-analysis studies were performed continually to identify potential cost savings and high cost centers for production of the forward-fuselage structure.

After the test panel results were analyzed, a series of structural elements representative of those contained in the forward-fuselage structure were fabricated using the more promising manufacturing methods identified during the first task. The structural elements were tested under both static and dynamic loadings to prove their structural integrity. The test data were analyzed to establish tolerance limits for property degradation as a function of the various manufacturing methods. The results were used in manufacturing-design trade-off studies to identify viable design changes that would be required to reduce costs for components in the final design of the forward-fuselage structure.

Finally, the manufacturing methods that had been successfully developed were used to manufacture a section of the forward-fuselage structure in order to demonstrate the tolerance stability, cost competitiveness and manufacturing producibility of those methods developed during this project.

Project Results

Rapid curing through internal resistance heating was investigated only briefly and was not pursued in the later part of this project, although it is believed to have a potential for cost savings if implemented in future designs.

Ion graphing was shown to have a definite correlation to the degree of resin cure in a given resin system. Each resin system seems to have a unique bulk-resistivity curve that is a function of cure progress. The value of this technique as a potential process control parameter or quality assurance indicator should be investigated further.

The ability to produce structurally adequate composite parts without resin bleeding or pressure (autoclave) curing was investigated in detail. The use of atmospheric pressure (vacuum bag only) curing rather than autoclave curing, resulted in structures with higher resin content and higher void content. A higher resin content leads to higher weight structures. Test results showed that atmospheric pressure cured parts with unidirectional fiber orientation had only slightly poorer structural properties. The impact that this material degradation has on a completed

Northrop Corporation/Aircraft Division
LOW COST MANUFACTURING CONCEPTS OF ADVANCED PRIMARY AIRCRAFT STRUCTURES
F33615-74-C-5153
May 1974 - July 1975
\$514,065

Background

Before this project, most work on composites had pushed composite materials to their limits by utilizing them at their highest allowable working stress and strain levels. This emphasis placed many limitations on design and manufacturing methods. For example, parts of a structure have to be joined in such a way as to minimize the impact of non-continuous fibers through the joint. This requires the fabrication of large parts without joints, designing structures so that joints are placed only in low stress areas, or using heavier joints to handle stress concentrations resulting from fiber discontinuities and the use of fasteners.

The emphasis in this project was the development of design guidelines and fabrication procedures that would allow cost effective uses of composites. With the proper application of these guidelines, a designer would be able to produce a design which takes advantage of the properties of composite materials without pushing these materials to their usable limits, which drives up costs. The idea that weight was to be saved, regardless of cost, was an important, but secondary consideration in this project on the use of composite materials.

Project Objective

The objective of this project was the development of manufacturing methods for the fabrication and assembly of advanced-composite primary aircraft structures that would be cost competitive with comparable advanced-aluminum primary aircraft structures. The intent was to provide for designs which have equal or lower costs than aluminum structures, and which may have the substantial weight savings that can be achieved by the use of composites.

Project Description

Project activities were designed to utilize the synergistic benefits of integrating low-cost manufacturing methods with simplified design guidelines for composite materials. A two-task program was performed to establish the design and manufacturing parameters necessary to ensure the production of a successful cost-competitive advanced forward fuselage structure. The six manufacturing methods, all of which showed promise for lowering manufacturing costs, that were investigated are: co-curing, rapid curing, reusable rubber vacuum bags, vacuum-bag pressure curing, zero resin bleed, and ion graphing. These investigations were designed to utilize the

Implementation

Aluminum weldbonding has been implemented on a flight-test basis by the Fairchild Republic Corporation. Mid-fuselage panels for the USAF/Fairchild A-10 were constructed using the weldbond process and installed on the A-10 for flight-test comparisons with current adhesively bonded panels.

Aluminum weldbonding has been selected for production of the Northrop F-20 vertical stabilizer. A vertical stabilizer design with aluminum skins weldbonded to a cast aluminum frame was selected over an alternate design with composite skins and a built-up substructure. In comparison to the alternate design, there is a 60% recurring cost reduction, due mostly to labor savings, and a 25% weight saving in favor of the weldbond design.

Among other F-20 components being considered as candidates for weldbonding are a 3-foot by 4-foot engine removal door in the fuselage section and leading-edge extensions for the wings. These components, also designed with aluminum skins weldbonded to a cast frame, are estimated to have weight savings of 37% over alternate designs. Another possible candidate for future aluminum weldbond implementation is Northrop's advanced tactical fighter (ATF) which is now in the conceptual design stage.

Benefits

The estimated cost saving for each weldbonded vertical stabilizer is \$50,000. Northrop has estimated a production volume of 1200 F-20 aircraft through 1992. However, since actual production of the F-20 has not yet begun, and given the uncertainties in the ultimate market for this aircraft, we have conservatively used half of the Northrop estimate in developing a cost benefit figure for the implementation of weldbonding methods. For a production level of 600 aircraft, the total cost savings amount to an estimated \$30,000,000.

Weight savings for each F-20 vertical stabilizer were estimated to be 30 pounds, which is 25% of the estimated alternate design weight.

No benefits can be assigned to other F-20 components, since the final decisions to implement weldbonding have not been made for these.

The third type is a surface scratch test in which a prepared surface is exposed to a salt fog for 2000 hours. These tests were performed on four different material combinations to determine if there were any material dependent effects. The material combinations tested were: 2024-T3 alclad bonded to 7075-T6 bare, 2024-T3 bare bonded to 7075-T6 bare, 2024-T3 bare bonded to 2024-T3 bare, and 7075-T6 bare bonded to 7075-T6 bare.

Project Results

Tests on the subscale panels indicated that weldbonded panels had static strengths equal to or higher than those for adhesively bonded panels. Fatigue and pressure tests also showed that weldbonded and adhesively bonded panels had comparable strengths. Weldbonded A-10 fuselage panels were shown to be structurally equivalent to those made by the adhesive bonding process.

Project studies indicated that for optimum fatigue properties in lightly loaded members the necessity of producing Class A weld nuggets is not critical. In contrast to standard spotwelding criteria, optimum fatigue performance was achieved with subsized, defect-free, and round spotweld nuggets. In addition, the surface treatment process developed for weldbonding was found to provide a more stable surface than spotweld etching, and it may be attractive for use as a cleaning procedure in standard spotwelding operations.

The use of in-process monitors and welding controls based on the principle of nugget expansion was found to be a powerful manufacturing tool for ensuring high quality spot welds. Further development work in this area and in shortening weld cycle times were recommended to make the weldbonding process even more economically attractive.

Cost analyses indicated that assembly cost savings on the order of 47% could be attained by direct substitution of the weldbonding process for adhesive bonding.

According to results from the addendum to this contract (TR 78-4081), the two adhesive bonding systems and the weldbonding system rank in terms of decreasing environmental durability as follows: PABST, FPL, and weldbonding. Wedge tests did not realistically evaluate the durability of weldbonding, since test specimens were not prepared with spotwelds. Coupons prepared with spotwelds prevented crack propagation past spotwelds for a period of six months. The wedge tests in a 95% to 100% relative humidity environment at 120°F and the constant load salt water immersion tests were both found to be completely ineffective for comparing the environmental durability of the three joining systems.

Base metal alloy and temper were found to affect the durability of a joint. Material combinations rank in terms of decreasing durability as follows: 2024-T3 bare and 2024-T3 bare, 2024-T3 bare and 7075-T6 bare, 7075-T6 and 7075-T6 bare, and 2024-T3 alclad and 7075-T6 bare.

candidate for the production of panels and related aircraft components. Damage tolerance, nondestructive inspection, and cost information were also to be evaluated during the project.

The objective of an addendum to this contract was to rank the three most widely accepted joining systems (FPL, PABST, and weldbonding) with respect to environmental durability when they are used to join aluminum alloys.

Project Description

After the promising results from previous development work, the next step was to scale-up the weldbonding process and to incorporate its use in a production aircraft. Mid-fuselage beaded panels for the USAF/Fairchild A-10, which were being produced as adhesively bonded components, were selected as the demonstration articles for this project. Northrop performed this project in association with the Fairchild Republic Corporation, the prime contractor for the A-10, and with additional support from the Convair Division of the General Dynamics Corporation.

Test panels representative of the A-10 fuselage panels were first constructed using the weldbonding process. These test panels were compared by Fairchild on a direct one-to-one basis with the adhesively bonded panels being used in the A-10 aircraft. In order to scale-up the process to produce full-size fuselage panels, Northrop conducted preliminary optimization studies to extend the developed process to include the 2024-T3 clad and 7076-T6 bare materials combination used by Fairchild. In addition, damage tolerance, environmental durability, and reliability were evaluated for the developed system. Available feedback-control and weld-monitoring systems were also evaluated with the purpose of improving the reliability of weldbonded joints. Cost studies were undertaken to develop baseline cost data for implementing the weldbonding process on a production line.

One of the primary concerns in the use of adhesively-bonded and weldbonded structures is premature failure due to a time-dependent crack growth in a bond joint under the combined influence of applied stress and a corrosive environment. This type of failure is commonly termed "environmental stress cracking", and resistance to environmental stress cracking is referred to as environmental durability. The addendum to this contract was targeted to rank weldbonding, FPL, and PABST joining technologies with respect to environmental durability.

In order to compare environmental durability of the weldbonding system with that of the other two adhesive bonding systems (FPL and PABST), three different types of tests were used. One type is a wedge test, where two parts joined by an adhesive are separated by a wedge at the join line; the load on the wedge and the separation distance are measures of bond durability. Another type is a constant load salt water immersion test where a constant load lap shear test is conducted in a salt water bath.

Northrop Corporation/Aircraft Division
ENVIRONMENTAL DURABILITY OF THE WELDBOND, FPL AND PABST JOINING SYSTEMS
F33615-76-C-5412
December 1977 - May 1979
\$698,669

Background

The use of adhesive bonding in the fabrication of aluminum aircraft structures had been increasing for several years, since it had some distinct technical and cost advantages over conventional fastening methods. Bonded joints have much lower stress concentration factors than conventionally fastened ones, and thus parent metal strength can be utilized to a much greater degree in structural designs. Cost advantages are possible, because an entire structure can be joined in one operation instead of by the many individual fastening operations required for conventional joining techniques. However, bonding fixtures have been required to keep components in position and to ensure their proper spacing while the adhesive is cured. The technique of weldbonding for aluminum aircraft structures has the advantage of eliminating the need for bonding fixtures during adhesive curing. Spotwelds serve in place of the bonding fixtures. Potential savings in tooling are substantial, since tools are occupied only while spotwelds are being made, instead of during the entire time that an adhesive takes to cure adequately so that it can support the structure.

Aluminum weldbonding was initially developed abroad and later introduced into the United States where the process was evaluated by the Lockheed Company in Georgia under Air Force sponsorship. When tested under high-load transfer conditions, weldbond joints had shown four times the static strength and ten times the fatigue life of spot-welded joints. One barrier to the acceptance of weldbonding as a production process for aircraft structures had been the complex problems associated with the surface preparation that is necessary for the production of high-quality spot welds with adequate environmental durability (corrosion resistance).

Through its performance of corporate IRAD and MANTECH contracts F33615-74-C-5027 and F33615-75-C-5083, Northrop had developed a surface treatment and weldbonding process which had proven to be ready for manufacturing scale-up. This process utilizes a low voltage phosphoric-acid/sodium-dichromate anodize (P/SD) surface treatment, together with B. F. Goodrich A-1444B adhesive and a precise welding procedure.

Project Objective

The main objective of this project was to establish the fabrication and assembly parameters required for the weldbonding of aluminum alloy structural panels in order to make the weldbonding process a viable

both static and dynamic loading conditions either in air or in salt solution, good flow properties, good corrosion resistance, and good handling properties for its use in the production of full-size components.

The best film adhesive, Hysol EA9628, had a bond strength comparable to that of the selected paste adhesive, but its weldability was poor because of an inability to melt through the film before spotwelding. Various methods for melting through film adhesive before spotwelding are being developed, and they may improve the quality of welds made through film adhesives.

Welding schedules were developed for welding through anodized surfaces and paste adhesives to produce welds with spot strengths and nugget structures that meet MIL-W-6858C standards except for porosity. Weld-quality monitoring systems were developed in which monitoring factors correlated reasonably well with weld strength. These factors included weld current, nugget expansion, and electrode indentation measurements. The correlation between welding energy and weld strength was fair. Further investigation of acoustic emission techniques for weld-quality monitoring was recommended.

Implementation

Information and experience gained during this project were used in a weldbond durability follow-on project at Northrop (contract F33615-76-C-5412), which is the next one discussed in this option report. Weldbond process implementation for fabricating aircraft structures is described in the next individual project report.

Benefits

Cost and weight savings associated with aluminum weldbonding of aircraft structures are described in the project report which follows.

Task 1 concerned the selection of materials and processes for the fabrication of a weldbonded aluminum aircraft structure. It included the selection of state-of-the-art aluminum alloys, adhesive systems, and surface treatments processes. Both unsupported-film and paste adhesives were considered. Several surface treatment processes with the potential for providing adequate environmental durability and weldability were also investigated.

Task 2 was concerned with establishing process controls by determining allowable latitudes in surface treatment parameters that allow for production of Class A welds with a high degree of environmental durability, establishing adhesive system process controls, and determining optimum welding parameters for the selected surface treatment and adhesive systems. Interaction of the adhesive system with the welding process was characterized during Task 2. Also, in-process monitoring methods and NDI inspection methods were investigated, and NDI standards were established.

Task 3 was concerned with evaluating the mechanical properties and environmental durability of the weldbonded joints produced according to the specifications established in the first two tasks.

Project Results

Aluminum alloy materials were selected from the ones most commonly used in aircraft structures. Alloys 7075-T6 and 2024-T3 were selected for this project as the materials to be weldbonded. Material thicknesses used during the project ranged from .040 inch to .090 inch; the most common thickness used was .063 inch. Adhesive selection criteria were: Class A weld-through capability, adequate strength after curing, multiple cure capability, and a capability for filling bondline voids easily without draining from vertical joints. Based on these criteria, two paste adhesives and one film adhesive were selected for further project evaluation.

Weldbond surface treatment selection was based on results from a previous MANTECH project at Northrop (contract F33615-74-C-5027) entitled "Development of Corrosion Resistant Surface Treatments for Aluminum Alloys for Spot Welding Bonding." Two methods developed during that previous project met the requirements for the present project. One of these methods was designated as FPL+60, and the other one was designated as low-voltage phosphoric-acid/sodium-dichromate anodize (P/SD). The P/SD surface treatment was finally selected because of its slightly superior environmental durability, superior surface oxide layer uniformity, and lower cost.

Mechanical property and environmental durability testing included wedge tests and dead-weight loaded lap shear tests in a 3.5% salt-water solution. Results from these tests were used to select one of the three adhesives that had been identified at the beginning of the project. The selected paste adhesive, B. F. Goodrich 0500PE130, had high strength under

Northrop Corporation/Aircraft Division
ADVANCED ALUMINUM WELDBOND MANUFACTURING METHODS
F33615-75-C-5083
June 1975 - March 1976
\$195,000

Background

The use of adhesive bonding in the assembly of aircraft structures had been increasing for several years due to some distinct cost and technical advantages over conventional fastening methods. Since bonded joints have much lower stress concentration factors, parent metal strength can be utilized to a much greater degree in structure design. Cost advantages are possible because an entire part can be assembled in one operation instead of the conventional assembly using many individual fasteners. Bonding fixtures are required, however, in order to hold the components to be joined in position while the adhesive cures and to ensure the proper spacing of surfaces to be bonded.

The technique of aluminum weldbonding for aircraft structures can eliminate the bonding fixtures required for adhesive-bonding assembly of structures--spotwelds serve as the bonding fixture. Potential savings in tooling and cure time are substantial. Weldbond tools are occupied only when spotwelds are being made, while bonding fixtures must hold and support the structure during the entire time that it takes for an adhesive bond to cure adequately.

The key elements in producing high quality joints are proper surface treatment, adhesive application procedures, and welding operations. All three must be evaluated as variables in a single system, because of their interactive effects on the final adhesive bonds. Surface preparation techniques used for weldbonding in the past had resulted in poor corrosion resistance in finished joints. Weldbonded structures exposed to aggressive environments had failed prematurely. Methods for improving the corrosion resistance of weldbonded joints were needed before the weldbonding process could be used in military and commercial aircraft production.

Project Objective

The objective of this project was to establish a production method for weldbond process control in which surface preparation, adhesive application procedures, and spot-welding variables are optimized in order to ensure both environmental durability and consistent spot-weld quality.

Project Description

In order to evaluate the effects of all parameters that have an influence on weldbond quality, this project was divided into three tasks.

memory unit for each of the 250 MX systems to be built, the total cost savings for manufacturing this particular component amount to approximately \$4,400,000 in 1982 dollars.

Information from Northrop indicated that the memory system in the MX system is approximately fifteen pounds lighter than it would have been with the previous design. This lighter weight translates into major cost savings, since estimates from the MX SPO show that, on a design/build basis, a one pound weight reduction in the MX system results in overall program (250 MX systems) cost savings of approximately \$3,000,000 (1982 \$). For a fifteen pound weight reduction, the savings amount to \$45,000,000 in 1982 dollars.

Thus, total savings from this technology are estimated to be \$49,400,000 (\$4.4 mil plus \$45 mil) in 1982 dollars.

In Phase II, Hercules was to scale up prepregging to a commercial level and furnish prepregged material for industrial evaluation. Also, Northrop was to expand the design data base through elevated-temperature tests and tests of moisture-conditioned specimens. In Phase III, fuselage subelements were to be fabricated and tested by Northrop to demonstrate the compatibility of the HME system with low-cost manufacturing procedures. Cost data were to be accumulated during Phases II and III in order to demonstrate the cost advantages of using the low flow, low pressure HME resin system.

Design data obtained during the latter part of Phase I showed that transverse properties of the HME prepregged material were not adequate for structural applications. The project was therefore redirected by substituting T300/288 prepregged material for the industrial evaluation and subelement fabrication phases. In previous Northrop MANTECH programs, this alternate material was shown to have the capability for low-flow, low-pressure curing, but it was subject to substantial degradation upon exposure to moisture.

Project Results

The project was not technically successful. In Phase I, it was found that the transverse properties of HME prepregged materials were not adequate for structural applications. Because of this, a previously developed T300/288 prepregged material was substituted for the industrial evaluation and subelement fabrication and testing phases of this project.

Components fabricated from the alternate T300/288 prepreg material were cured at temperatures ranging from 212°F to 320°F under a pressure of 15 psi (vacuum only). Structural-properties testing of these components showed greatly inferior structural performance for this alternate material when it is compared to more conventional composite materials.

Implementation

Northrop has not implemented this technology and has no plans for doing so in the near future.

Benefits

No benefits were identified, since this technology was not implemented at Northrop.

The Boeing Company

The Boeing Company/Boeing Commercial Airplane Company
MANUFACTURING METHODS FOR BRAZED TITANIUM HYBRID STRUCTURES
F33615-74-C-5047
February 1974 - February 1976
\$423,785

Background

Titanium is used extensively in primary structural applications in military aircraft. This is due primarily to its attractive strength-to-weight ratio and stiffness, which are particularly important when an aircraft must operate at high speed and high temperatures. Conventional design and manufacturing procedures call for the production of critical, highly stressed titanium components by machining them either from rough forgings or plate material. This results in large amounts of unutilized material and high "buy-to-fly" ratios. A typical structure produced in this manner has large load bearing areas at primary attach points, a thin shear web to minimize weight, and multidirectional web stiffening flanges.

In alternative production methods that had been used, stiffeners and chords are attached to shear webs with mechanical fasteners. However, assembly costs are high and stress concentrations around fasteners degrade the fatigue life of such designs. What was needed was a new, lower-cost method for joining combinations of wrought components, such as forgings, extrusions, sheet, and plate, into large, precision titanium hybrid structures.

Project Objectives

The objective of this project was to demonstrate the technical feasibility and economic attractiveness of producing aluminum brazed titanium (ABTi) hybrid structural components for large, critically stressed airframe applications.

Project Description

The structural component selected for evaluation in this program was a highly stressed engine support beam for the USAF YC-14 prototype STOL transport which was being developed by Boeing at the time this project. During Phase I of the project, the support beam was redesigned from a machined forging to a hybrid structure utilizing a web stiffening approach (dual shear webs brazed to a honeycomb core). This redesign eliminated the deep pocket machining required by the original design, and was expected to yield large cost savings. Phase II followed with the manufacture and testing of subscale test components to verify the structural integrity of the system and to evaluate the cost impacts of the processing options. Full-scale structural components were fabricated in Phase III. There was

an emphasis on cost tracking during Phase III to obtain data for a credible comparison with fabrication costs for conventional structures. Phase IV was an analysis of the cost-effectiveness of the ABTi fabrication procedure that was developed. Structural testing of the full-scale components was deleted from the project due to lack of funds caused by higher than anticipated machining costs.

Project Results

Aluminum Brazed Titanium (ABTi) structures were shown to be structurally adequate for the selected application. Cost and weight savings were both estimated to be on the order of 40% for large components such as the one selected for this project. Several modifications were necessary to the original braze cycle specifications due to the formation of an unacceptable by-product (Titanium Aluminide) which prevented adequate bonding. An improved cycle was developed to achieve an adequate braze joint and accomplish the project objective.

Implementation

The only case of ABTi implementation to date at Boeing is for the 757 APU plenum floor. This part is flat, approximately 2-feet by 3-feet, and approximately 3/8-inch thick. It is a structural part and functions as a fire wall.

ABTi has been evaluated for a number of components on 727, 767, 757, and 737-300 aircraft but has not been selected due to the availability of lower cost alternatives. SPF/DB, another MANTECH-supported technology, has been shown to be generally more cost-effective, and may seriously limit the future potential of ABTi technology. Also, the high cost of honeycomb has limited its feasibility. The rather limited use of titanium in commercial transports also tends to restrict the application of ABTi technology at Boeing.

ABTi technology has been transferred to Boeing Military Airplane Company (BMAC) in Wichita, Kansas. BMAC was given responsibility for acoustic technology, to which it was thought this technology could contribute.

Benefits

For the 757 APU plenum floor, ABTi was selected over built-up stainless steel or titanium on the basis of weight savings. The ABTi structure is seven pounds lighter than a built-up titanium part, and fourteen pounds lighter than a stainless steel part. Boeing staff stated that there are also probably substantial manufacturing cost savings, but that information on cost savings is not readily available. ABTi manufacturing costs, although thought to be less than, or certainly no

greater than the baseline process, were not used to justify the implementation.

Boeing has determined that, at a \$1.00 per gallon fuel price, a one pound weight saving on the Boeing 757 aircraft saves the typical commercial user approximately \$21 per year per aircraft in fuel costs. If it is assumed that the fleet of 757s will number 500 in 1992, with the number increasing in a straight line manner from 20 in 1982 to 500 in 1992, and counting aircraft beginning in the year after implementation (to be consistent with the study methodology), this yields a total of 2,360 aircraft years between 1982 and 1992. Thus, total savings for 1982-1992 would equal \$346,920 ($\$21/\text{lb.}/\text{acft}/\text{yr.} * 7 \text{ lbs. saved}/\text{acft} * 2,360 \text{ acft. yrs}$). Rounding to the nearest ten thousand dollars for presentation purposes yields \$350,000 in savings.

Of course, the above benefits estimate understates the longer term savings. The savings from the use of this technology over the entire service lives of all 757s, and not merely in the introduction period analyzed above, will probably be at least several times the amount computed above. Also, the fleet of 757s is likely to number much more than 500. Finally, at least some additional applications of ABTi technology in existing and new generation aircraft are likely in the future.

The Boeing Company/Boeing Commercial Airplane Company
MULTI-LAYER FASTENING SYSTEMS
F33615-74-C-5014
April 1974 - February 1976
\$614,438

Background

At the time of this project, the design of large, high performance aircraft (B-1) included the frequent use of large-diameter fasteners at many critical joints. These joints were typically in thick, multimaterial stacks containing layers of steel, titanium, and aluminum. Existing machinery and controls required constant drill speeds and feed rates that were set for the most difficult material in a stack. Since drilling speeds and feed rates could not be varied, the costs of producing the required fastener holes were very high. The lack of a good understanding of the effects of burrs on fatigue performance of the joints resulted in a conservative approach to the setting of destack and deburr requirements. Also, because of this lack of understanding, there was no assurance that desired structural performance could be achieved.

Project Objective

One objective of this project was to develop two new-technology drill units. One of these units was to be an ultrasonic assisted power feed for a conventional drill, and the other was to be a hydraulically driven drill unit with microprocessor controlled drill speed, feed rate, and torque sensing for detecting chip packing and drill dullness. Another objective was to characterize burr formation and its impact on structural fatigue performance.

Project Description

As originally planned, this project was to be performed in four phases. In Phase I, the two new-technology drill units were developed. One was a conventional pneumatically driven screw-feed drill with an axially driven ultrasonic power feed assist, and the other was a hydraulically driven drill with microprocessor controlled drill speed, feed rate, and torque sensing. The Phase II efforts were directed toward defining the degree of burr formation at the interfaces of different structural materials under different drilling conditions and toward defining the effects of burrs and burr removal methods upon projected structural fatigue strength. In Phase III, the new drill units were evaluated to assess their capabilities for improving hole generation rates within the constraints defined in Phase II while maintaining equivalent fatigue strengths. Originally, one drill unit was to be selected and evaluated under actual production conditions in Phase IV, but this phase of the project was dropped.

Project Results

The hydraulically driven drill unit was developed first because of the availability of off-the-shelf variable speed drives and the ability to hydraulically vary the feed rate while drilling and hydraulically move the spindle toward and away from the work for chip clearing. The hydraulic drill unit proved to be a viable method for hole production, and its microcomputer linkage provided valuable feedback to the operator through screen displays and printed output. In comparison with conventional drilling methods, the hydraulic unit reduced hole production time by approximately 75%.

The ultrasonically assisted drill unit was developed under subcontract by the Grumman Aerospace Corporation and the Branson Corporation. Among the problems encountered during the development of this unit were: operating difficulties while drilling large-diameter holes because of the required high-thrust loads; difficulties in calibrating the strain gauge torque sensing equipment; and difficulties in achieving adequate acoustical coupling for the ultrasonic unit on the tool. The last problem was, by far, the most significant one, and it remained unresolved at the end of the development phase. Preliminary tests showed that ultrasonic assist produced a reduction in drilling thrust with little or no reduction in torque. It appeared to be useful only for drilling titanium.

Characterization of the mechanism of burr performance and its impact on fastener system performance proved to be of great importance. Several tests indicated that the presence of burrs in multi-material stacks had little or no effect on fatigue performance. In many instances, destack and deburr operations actually reduced fatigue performance. Recommendations were made to minimize or eliminate destack and deburr operations in many multi-material fastening applications.

Implementation

The drilling units to be developed in this project were intended for production of an aircraft similar to the B-1. The hydraulic unit was evaluated at the B-1 facility by Rockwell International Corporation under another MANTECH contract (No. F33615-76-C-5158), where it was found not to be cost effective in production. The primary reason for this was that a large array of existing conventional drilling machines would have to be replaced with the more expensive new machines. Weight was another important factor, since two operators were needed to position the new drill unit.

The only use at Boeing of technology similar to that developed in this project is associated with its automatic spar assembly tool (ASAT), which is being used for assembling Boeing-767 wing spars. All spar materials to be joined are aluminum, and none of the drilled holes are deburred before

fasteners are installed by the ASAT. Eliminating this deburr requirement is the only application that could be associated with project results.

Benefits

The only identified benefits from this project at Boeing are the costs avoided by not deburring the Boeing-767 spar assemblies. Information on cost savings was not available at the time this report was prepared.

The Boeing Company/Boeing Commercial Airplane Company
HIGH INTEGRITY FORGINGS OF ALUMINUM AND TITANIUM ALLOYS
F33615-71-C-1693
1971 - May 1977
\$590,000

Background

The use of high integrity precision forgings in airframe structures has a potential for producing significant cost savings without sacrificing structural integrity or taking weight penalties. Savings result from minimizing the amount of machining required to produce a finished part or, in some cases, eliminating the machining requirements altogether. For aluminum forgings with plan view areas up to about 150 sq. in., this goal had been met in many cases by using precision forgings which often required no machining except for the drilling of attachment fastener holes. It is commonly held to be true that when as-forged surfaces are left intact, fatigue properties and resistance to stress corrosion cracking and other metallurgical properties are better than when surfaces are machined.

At the time of this project, parts with plan areas greater than 200 sq. in. were commonly produced by machining all surfaces of blocker type die forgings. Additional barriers to the use of precision aluminum forgings in the larger plan area parts was the difficulty in maintaining the thin web and rib sections typically required on airframe structures to minimize weight.

Project Objective

The objective of this project was to establish economical processing procedures for manufacturing complex, precision aluminum and titanium forgings with plan areas greater than 200 sq. in. The static and fatigue performance of precision forgings were to be compared with that of machined conventional forgings. These comparisons were to be made with full-scale parts in order to establish any performance differences.

Project Description

In order to achieve the program objectives, a medium-sized hinge rib component of the Boeing 747 was selected as a demonstration component. This rib is located on the leading edge of the wing and is one of the hinges supporting a variable camber foreflap. The complexity of this part is typical of advanced technology airframe components. Web thicknesses are 0.060 in. and rib thicknesses are 0.100 in. In the baseline process, the part is machined from a 265 sq. in. forging weighing 37 pounds, resulting in a 212 sq. in. part weighing only 5.5 pounds. Precision die forging of this part required a significant extension of current forging technology for aluminum and an even greater extension for titanium.

Precision die forged parts and similar conventionally forged parts were both produced during the project, and the costs of both types of parts were compared.

Project Results

Precision forging of aluminum alloys to produce finished parts with plan areas greater than 200 sq. in. was shown to be very difficult at best. During the forging operations, there were considerable difficulties associated with die deflections under press forces on the order of 6000 tons, and the project web thickness requirement of 0.060 in. was not obtained. Other considerable problems were die breakage, and tearing of the forging as material moved during the forging operation. Development and production of blocker preforms helped to minimize tearing of the forging material and allowed a minimum web thickness of 0.130 in. to be achieved. Material properties of forged parts were shown to be comparable to those for parts produced with conventional methods.

The machining time required for a precision forged part was shown to be on the order of one hour, which is far less than the ten hours required for a conventionally forged part. However, the nine hour savings was partially offset by an additional \$100 cost for precision forging.

Precision forging of titanium alloys was discovered to be not feasible due to the extremely high press forces required and the inability to achieve the required rib and web thicknesses. The minimum obtainable web thickness was calculated to be 0.185 in., while the required web thickness was 0.060 in. Titanium fabrication by casting was pursued in lieu of forging due to these problems. Titanium castings were made to the desired dimensions and were tested both under static and dynamic loading conditions. The tests demonstrated a static strength comparable to that of forged and machined parts. However, the cast parts failed at less than 10% of the characteristic life of the die forged parts.

Implementation

The precision forging processes demonstrated in this project for producing parts with plan areas of greater than 200 sq. in. have not been implemented at Boeing. Over the past several years there has been extensive utilization of precision forging techniques for manufacturing parts with plan areas of less than 150 sq. in. Many of these parts are similar to the part demonstrated in this project, and their production by precision forging may have been encouraged to some extent by the results of this project.

Benefits

Due to lack of implementation, no direct benefits were identified for this project. The only benefit which can be attributed to this project is the advancement of precision forging technology to the point where it is acceptable by designers for smaller, easier to produce parts.

The Boeing Company/Boeing Commercial Airplane Company
MULTI-AXIS LASER CUTTING
F33615-75-C-5091
February 1974 - August 1975
\$112,386

Background

Because of the difficulty of cutting titanium and high-strength steels, there was a need to pursue the development of a technology that would allow high speed cutting of these materials with little or no tool wear. Laser cutting appeared to be the best choice at the time of this project. The use of laser cutting during the fabrication of formed sheet metal aerospace components was seen to have a large potential for manufacturing cost savings. Up to 50% of the labor cost in fabricating many sheet metal parts could be attributed to edge trimming operations. This was due to difficulties in cutting many high-temperature, high-strength materials and the high costs associated with available cutting techniques.

Project Objective

The objective of this project was to provide the aerospace industry with laser cutting techniques that would be effective with components formed from difficult-to-cut sheet metal alloys. A secondary objective was to further extend the existing technology for laser cutting of flat components.

Project Description

The use of multi-axis laser cutting technology with formed components involves five basic axes of motion to position a cutting head so that it is perpendicular to a component's surface at all times. The first task in this project was a concept configuration analysis in which several different means of providing five-axis manipulation were evaluated with respect to fabrication cost, probability of success, laser-beam transmission efficiency and accuracy, suitability for a shop environment, portability, safety and general versatility.

The following tasks were concept selection and hardware design and construction. A portable prototype unit containing a 250-watt CO₂ laser was tested by using it on several different production parts. Trim templates developed for the laser cutter were patterned on production tooling. Cutting was demonstrated for titanium alloys and high-strength steel with thicknesses ranging from 0.025 inch to 0.125 inch. Production parts used for laser cutting demonstrations included a Boeing-737 wing-to-nacelle fairing formed from 0.045-inch thick Ti-6-4 and a Boeing-727 auxiliary power unit shroud formed from 0.050-inch thick

stainless steel.

Project Results

The required motions were manually directed in a manner similar to an existing process where a router is moved over an overlay template. Focus quality problems were traced to a distorted mirror which was replaced before laser test cuts were made. There were also minor problems due to excessive drag when the cutting head was moved over a template. These problems were minimized by hardening the cutting head's guide piece and by coating the template with an anti-spatter fluid to keep metal blown out of the cut from sticking to its surface.

Test panel cuts made with the prototype laser cutting unit showed a high probability that the laser cutting process could be used for tasks being done with the use of bandsaws or nibblers. Test results showed that titanium and 4130 steel can be cut much faster with a multi-axis laser than with a bandsaw or nibbler. Because of its higher reflectivity and thermal conductivity, stainless steel can be cut faster by mechanical means than by laser methods.

Except for fume vanadium, which was slightly above the maximum exposure limit, the levels of particulates in the air during laser cutting were below the maximum exposure limits. A nitrogen shield was used to reduce the amount of nitrogen dioxide produced during cutting. In general, it was determined that no health hazards existed during cutting operations on steel, stainless steel, or titanium.

The project was technically successful. It resulted in a feasible method for using a portable laser unit for multi-axis metal cutting.

Implementation

Boeing has not implemented this technology and has no plans to do so in the near future. Although the technology is essentially production ready, it was determined that its application would not be extensive or general enough to justify the expense of implementing it.

Benefits

Due to lack of implementation at Boeing, no benefits were identified or this project.

The Boeing Company/Boeing Commercial Airplane Company
FEASIBILITY OF CUTTING ALUMINUM ALLOYS WITH A 6-KILOWATT LASER
F33615-76-C-5275
March 1976 - March 1977
\$25,000

Background

Based on results from previous Air Force sponsored work on laser cutting of high-strength steels, the Aerospace Industries Association (AIA) began to pursue laser technology as a possible means for high-speed production of aluminum alloy parts with numerically controlled machinery. Since aluminum is the major constituent of all civil and military aircraft, the economic advantages of laser cutting processes were of primary concern to the AIA.

In order to establish the technical limitations of laser cutting, the AIA initiated a program to determine the feasibility of cutting aluminum alloys with a 1-kw laser. The results of that program showed that a 1-kw laser could cut 0.020-inch thick 2024-T3 and 7075-T6 alloys and produce edges which have static strengths, corrosion resistances, and fatigue performances equal to those for blanked edges that had not been enhanced by such procedures as sanding or routing. When 0.040-inch thick specimens of the same alloys were laser cut, their edge properties were severely degraded. This degradation was apparently due to large heat-affected zones adjacent to the cuts.

More recently, multi-kilowatt lasers had been developed, and preliminary tests with thicker materials had shown significant improvement in the quality of cut edges. On the basis of these developments, this project was initiated under joint funding by the AIA and AFWAL/MLT.

Project Objective

The objective of this project was to establish an effective manufacturing method for the laser cutting of aluminum alloys and to demonstrate its potential for aerospace structural fabrication applications.

Project Description

This project was performed in three Phases. Phase I was concerned with selection of an optimum jet nozzle configuration and selection of a gas for the cutting environment. Testing during Phase I was done at the United Technologies Research Center. A 6-kw coaxial electric discharge CO₂ laser with an unstable resonator mirror configuration was used for all tests. Various nozzle types, gas types and pressures, and laser power levels were evaluated with respect to their effects on cut quality.

Hughes Aircraft Company

test procedures and acceptability criteria that were established and, subsequently, the industry as a whole has been slow to accept them. At the present time, there is a follow-on contract for disseminating the technology to several suppliers of military high voltage power supplies.

Benefits

Due to lack of implementation at Boeing, no benefits have been notified.

Project Description

This project was performed in two phases. In Phase I, government and industrial power supply users were surveyed to determine the causes of high voltage failures. Also in Phase I, data on the physical and electrical characteristics of numerous encapsulating materials were obtained from suppliers. These characteristics were evaluated for operation in a typical airborne high voltage environment, and candidate materials were selected and tested. Those materials that met all of the required program parameters were further tested for processing and manufacturing suitability. Manufacturing processes and material controls were then developed for the two materials, Silastic E and Stycast 2651, that were selected. Finally, The high voltage power supply for a B-52 EVS display was selected as the demonstration article to be produced and evaluated in Phase II.

In Phase II, two of the EVS display high voltage power supplies were fabricated and encapsulated. These power supplies were subjected to various analyses and tests, including: 1) a design and packaging analysis; 2) packaging encapsulants validation tests; 3) a repairability optimization evaluation; 4) breadboard verification tests; 5) power supply assembly potting tests; and 6) electrical, environmental, and life tests.

Project Results

The survey data indicated that most high voltage failures are due to process deficiencies rather than materials or design parameters. Project test results were combined with a review of accepted industry practices to establish guidelines for the design and fabrication of high voltage sections for airborne power supplies. These guidelines, published as Volume II of the project report, were used to modify an existing power supply design for the EVS display. Modified power supplies were fabricated and tested under adverse conditions to establish lifetime and failure-rate data. Some early failure problems were encountered due to marginal sizing of driver transistors. These problems were eliminated later in the project through the use of higher power rated transistors. Of the commercially available elastomers that were evaluated for their suitability as encapsulants for high voltage electronic circuits, Dow Corning Silastic E was found to be highly suitable in all aspects considered during this project.

Implementation

The technology addressed in this project has not been implemented at Boeing. Since there are known technical advantages in using the guidelines established by the project, it is highly likely that they will be implemented in the future. No Mil specifications have been prepared for

The Boeing Company/Boeing Aerospace Company
MANUFACTURING TECHNOLOGY FOR AIRBORNE HIGH VOLTAGE POWER SUPPLIES
F33615-77-C-5015
April 1977 - December 1978
\$330,389

Background

At the time of this project, the Air Force had a growing need for airborne high-voltage power supplies for use in radar systems, electro-optical viewing system (EVS) displays, and communication equipment. This need has continued to grow, with most of the applications requiring voltages in the range of 4 Kv to 60 Kv and power levels up to 2000 watts.

Design considerations for airborne power supplies include the usual concerns with size and weight. An important additional consideration is the ability to operate at high altitudes. The low air density at high altitudes creates problems by greatly reducing heat transfer rates and lowering the breakdown voltages of air gaps between components. In order to avoid these high altitude problems, many airborne power supplies are sealed under pressure in a special gaseous environment. Others are sealed in a liquid environment with suitable properties or encapsulated within a solid material which protects components from mechanical vibration and maintains a high corona onset voltage for arc protection. Solid encapsulation is the method addressed in this project.

Solid encapsulation (potting) of components has some major advantages over other methods, particularly when durability of containers and leakage of liquid materials onto other systems are considered. The electrical resistivity of a potting material is of prime concern for high voltage power supplies. Since there are no potting materials with ideal electrical, thermal, and mechanical properties, any choice of potting material is a compromise that provides the best available properties for a given application. Materials which have desirable qualities in one area, such as high thermal conductivity, will often have marginal properties in other areas of interest, such as insulation, adhesion, and ease of processing.

The processing of potting materials is also a very important factor in providing adequate electrical insulation. The presence of voids or air bubbles in potting material greatly reduces its corona onset voltage.

Project Objective

The primary objective of this project was to optimize the manufacturing processes for encapsulating airborne high voltage power supplies. Potting materials and processing techniques and controls were to be surveyed in order to select for development and testing those that had the potential for yield improvement, reliability, and cost reduction.

Project Results

The Phase I effort resulted in a large amount of information concerning the usage of various sheet metal forming processes in the aerospace industry. The rather vague results from Phases II and III led to the conclusion that not enough is known about the interaction of variables involved in the production of sheet metal parts. Attempts to correlate theoretical formability concepts with brakeforming and hydroforming processes failed because of an inability either to determine incipient part failure or to match part configuration to available formability limit curves.

Boeing's assessment of the formability data available at the time of this project was that, while these data may have been credible and useful in their existing manufacturing environment, they were too narrow in scope and versatility to support ICAM program objectives. Most of the data were empirically generated for specific materials and specific processes. Also, many of the various test procedures used were specific to a particular aerospace company. These data were typically limited only to very basic variables, such as heat-treat condition and material thickness, although formability is also substantially affected by other variables, such as thickness tolerance, alloy composition, metallurgical structure, anisotropic properties due to rolling direction, surface condition, work hardenability, and strain rate. The interaction of each of these variables with the others must also be taken into account in the design of any new machines for the automated manufacture of sheet metal parts.

Implementation

This project was Task III of a larger ICAM sheet metal program. Its purpose was to establish the formability data and analytical techniques needed to support the development of computerized sheet metal machinery and designing an advanced sheet metal fabrication shop. After the project was completed, the emphasis of the entire ICAM sheet metal program was changed from the development of computerized "hands off" machines to the integration of existing state-of-the-art machines and materials handling equipment. This change took place in the September to October 1981 timeframe. The overall ICAM sheet metal program is continuing at the present time, and its implementation is anticipated in the near future.

Benefits

Although the results of this project were utilized in the redefinition of the ICAM sheet metal program objectives, no benefits can be identified, since there has been no implementation.

The Boeing Company/ Boeing Military Airplane Development Division
COMPUTER AIDED MANUFACTURING (CAM) ARCHITECTURE - TASK III
SHEET METAL FABRICATION TECHNOLOGY
F33615-77-C-5013
January 1977 - September 1977
\$69,412

Background

Large quantities of batch manufactured sheet metal parts are used in the fabrication of aerospace systems. Producing these parts requires many labor-intensive processing steps as well as a substantial amount of support labor. Technological advances in this field have been slow to emerge, as evidenced by the fact that manually operated equipment is still the norm in most sheet metal fabrication shops. Advances in this technology could result in high potential payoffs through reduced costs of military and commercial aerospace systems.

Basic information regarding the formability of sheet metal materials was needed in order to make decisions about which areas to pursue in the automation of sheet metal processing. At the time this project was begun, the emphasis of ICAM sheet metal efforts had been on the development of new machines and processes to replace manual operations.

Project Objective

The objectives of this project were to identify the processes currently used to produce aerospace sheet metal parts, determine the relative uses of these processes for various part configurations, assess available sheet metal formability parameter data, and develop recommendations for further work in this ICAM area.

Project Description

This project was performed in five phases. In phase I, a data base study produced a tabulation of the frequency of usage of various sheet metal forming processes for production of sheet metal parts by Boeing Commercial Airplane Company (BCAC). This BCAC sheet metal parts data base contained information on approximately 284,000 different parts produced by BCAC shops in the Seattle area. In Phase II, a literature search of formability limit data and theory and an industry survey were undertaken in order to determine the methods currently in use for establishing sheet metal fabrication processes. In Phase III, the information gathered in Phase II was evaluated to assess its credibility and usefulness for meeting the objectives of this ICAM sheet metal project. In Phases IV and V, data formats and recommended future data gathering approaches were developed to obtain the information required for further ICAM development.

final destructive testing. Destructive failure occurred at a total load of 38,600 pounds, which is 29% above the design ultimate load of 30,000 pounds.

Implementation

Boeing has not implemented the EMC process, and it has no plans to do so in the near future. Although efforts to improve the process have continued at Boeing and elsewhere, there are currently no production applications for this technology.

Benefits

Due to lack of implementation at Boeing, no benefits have been identified for this technology.

cost breakdown that was required for the Air Force Fabrication Guide.

Other work, funded by Boeing, that was related to this project included development of the tooling used for component manufacturing and repair of the radial sine wave web structure in the thirteen-foot demonstration article.

Project Results

The EMC process uses elastomeric mandrels that are allowed to expand against autoclave pressure in one direction to control cure pressure. Their expansion in the other two directions is restricted to maintain control of part dimensions. Parts were produced with adequate dimensional control and composite densities. Porosity in the mold tool required a modification of the envelope-bagging tool. As a result, difficulties were encountered in fabricating the five-foot Phase I article when a vacuum bag broke during the cure cycle, which caused a larger than usual number of voids and delaminations. These problems were overcome before proceeding to Phase II fabrication.

The final design of the thirteen-foot Phase II article was based on a finite element analysis of a preliminary component design. Modifications to the Phase II debulk cycle specifications were based on the results of Phase I observations. During the fabrication of this article, its honeycomb core was partially crushed. Apparently, this was due to the autoclave pressure of 45 to 50 psi that was used. The substandard flexural strength exhibited by the composite material was also due to the cure pressure of 45 to 50 psi that was used, which is considerably lower than the usual 85 psi used for laminate structures. Nondestructive testing revealed a large number of problem areas in the thirteen-foot component. The problems included cracking of the chord, a partially crushed core, and cracking of plug areas in the sine wave web to chord cap transition.

A photoelastic coating was applied to the test box that was fabricated by cutting the thirteen-foot test article in half and joining the halves together with ribs and skin sections. Both photoelastic and strain-gauge measurement techniques were used to verify analytically determined load paths and strain levels. These measurements revealed additional problem areas. Acoustic emission sensors were then applied to the test box to warn of impending part failure.

Full load testing of the box structure was terminated at approximately 46% of the design ultimate load because of high acoustic emission counts in critical areas. X-ray inspection did not indicate any cracks or anomalies other than the ones detected in the original inspections. The critical stress areas were apparently created through oversights in stress analysis and part design rather than through any defects in materials or the fabrication process.

The sine wave web was repaired to strengthen critical areas before

The Boeing Company/Boeing Commercial Airplane Company
LOW COST COMPOSITE WING/FUSELAGE MANUFACTURING
F33615-77-C-5138
November 1977 - October 1979
\$563,960

Background

During the previous several years, there had been a steady increase in the use of composites for aircraft manufacturing. The attractive strength to weight ratio and stiffness of composite systems were expected to lead to their continued increasing use. Conventional manufacturing methods for integral composite structures called for the individual hand layup and partial cure of detail components which are then assembled into major airframe components, such as wing boxes, ribs, or spars. Assembly and joining methods do not allow full utilization of the potential of composite materials, since fibers do not carry through from one detail to another, and they must be spliced at a join line. This results in a great deal of extra weight and higher manufacturing expenses. Also, the relatively short shelf lives of existing resin systems limit the time available for layup of large structures. Because of differences in thermal expansion for conventional tooling and composite materials, it is difficult to control dimensional variations of a part as it is being cured.

Project Objective

The objective of this project was to develop and demonstrate a production ready manufacturing method for low-cost production of advanced composite wing/fuselage structures suitable for advanced Mach-2 class fighter aircraft. The process selected for this project was elastomeric molding cocuring (EMC).

Project Description

This project was performed in two Phases. Phase I was concerned with the design and manufacture of a five-foot long component which incorporated all the major manufacturing considerations that were anticipated for the project. Sections cut from the five-foot Phase I demonstration article were tested to prove the structural integrity of the article.

Phase II was concerned with the detailed design and manufacture of a thirteen-foot long component of a hypothetical blended wing body frame for an air-to-surface class aircraft. The EMC process was used in the manufacture of this component. A test box frame was fabricated by cutting the thirteen-foot component in half and joining the halves together with ribs and skin sections that were also manufactured in Phase II.

Detailed cost tracking was performed during both phases to provide the

Implementation

This project was aimed at achieving better utilization of tapered fastener potential in the C-5B aircraft wing. Another MANTECH project to pursue dimensional evaluation of tapered fastener holes was performed by Lockheed at about the same time as this Boeing project. A capacitance probe was developed during the Lockheed project.

The mechanical probe developed in this Boeing project was not implemented for several reasons. The number of tapered fasteners used in the C-5B wing was reduced in a redesign to approximately 10% of original number used. The redesign took place in the same timeframe as this project. The need at Boeing for dimensional evaluation of tapered fasteners has been minimized, since Boeing has moved away from using tapered fasteners. This is primarily due to the difficulties in assuring their proper application and installation. Another factor that influenced Boeing's decision not to pursue this technology was the successful development of a capacitance probe by Lockheed. This probe is being used by Lockheed for C-5B production. It is also being marketed by Lockheed for commercial use.

Benefits

Due to lack of implementation at Boeing, no benefits have been identified for this project. However, Lockheed is using its capacitance probe in C-5B aircraft production. Thus, in the broader sense, implementation and benefits have resulted from the overall MANTECH effort to establish the technology for dimensional evaluation of tapered fasteners.

would have a measurement inaccuracy of no more than 20% of the hole tolerance requirements and would be capable of hole measurement and evaluation, including set-up time, in less than two minutes.

Hole sizes to be evaluated ranged from 3/16-inch diameter by 1/4-inch deep to 1-inch diameter by 5-inch deep. Since taper measurements on a 1/4-inch deep hole would mean very little, it was decided that a 3/16-inch diameter by 1-1/2-inch deep hole would be used as the small test-hole size, and the 1-inch diameter by 5-inch deep hole would be used as the large test-hole size.

Two different measurement system approaches were developed and evaluated for their feasibility: one system used a mechanical contact probe, and the other was an optical measurement system. Both systems used the same manipulator mechanism, data handling equipment, and software. Data reduction algorithms were developed to compensate for misalignment of the measurement-system and hole centerlines to avoid misleading out-of-round or skew indications. Each measurement approach was evaluated by measuring a sample of holes that were produced in the shop to known tolerances and comparing the output of the measurement system with the known hole dimensions.

Project Results

Design of the equipment to be evaluated began with the mechanical contact probe system. It was based on commercially available linear variable differential transformer (LVDT) sensors attached to a mechanical lever arm to measure the displacement of the end of the lever from a known location. This approach was shown to be accurate to within 0.0001 inch, which is well within the tolerance range of the holes and therefore met the sensor development objective. The mechanical probe was capable of measuring the surfaces of all holes to be evaluated in this project.

During the early part of the optical measurement system design effort, it became apparent that the sizes of optical components needed for sensing changes in optical paths caused by variations in hole profiles would obviate their use in 3/16-inch diameter holes, and a 3/8-inch instrument diameter was selected for the optical probe. Later evaluation of prototype hardware showed that, due to state-of-the-art limitations in optical sensors at that time, the optical approach was impractical even for large hole sizes. Therefore, the optical approach was abandoned.

Software developed for this project was written in FORTRAN IV and run on a Data General Corporation NOVA 840 minicomputer. Tables of dimensional data and tolerances for each type of fastener to be used were stored in the computer memory. As hole measurements were being made, they were compared with the stored fastener data, and go/no-go decisions were made on the basis of recommended limits from the manufacturers. A printed summary table of hole dimensions included rejection messages describing the out-of-tolerance characteristics responsible for the rejections.

The Boeing Company/Boeing Commercial Airplane Company
DIMENSIONAL EVALUATION OF TAPERED FASTENER SYSTEMS
F33615-76-C-5283
August 1976 - August 1977
\$199,819

Background

The proper use of Taper-Lok and other compressive stress-inducing fastener systems in aircraft structures has been proven to greatly inhibit the initiation of fatigue cracks at fastener locations. When these fasteners have been properly utilized, the enhanced fatigue-crack resistance and its resulting increase in service life have significantly decreased the life-cycle cost of aircraft structures. Since generation of uniform compressive stress at the fastener-hole interface is of great importance, the fit of a fastener in its hole must be very good. Dimensional variations of fasteners are generally much smaller than those of holes, because fasteners are manufactured on high precision grinding machines, and holes are typically produced in the field by drilling and reaming. Consequently, the most important factor in the proper utilization of tapered fastener systems is the dimensional tolerances of tapered holes. With the equipment that was available at the time this contract was begun, hole quality was extremely difficult to determine and control. Typical methods included blue pin bearing check, air gaging, and measuring head protrusion. None of these methods produced a quantitative measure of hole quality. They were of questionable value for indicating hole quality and were also quite labor intensive and expensive. Because of the expanding use of tapered fastener systems and the limitations of existing inspection methods, there was a great need for a more reliable and faster method of establishing the acceptability of production tapered fastener holes.

Project Objective

The objective of this project was to evaluate inspection techniques capable of producing credible information for determining the acceptability of tapered fastener holes. Two methods were to be selected, and hardware for them was to be developed in order to establish a capability for evaluating the acceptability of the holes.

Project Description

The project began with an evaluation of the specifications developed by fastener system manufacturers for such parameters as size, taper, straightness, perpendicularity, and roundness. Although most parameters had been established, the manufacturers had not defined such terms and qualities as straightness and taper. Tolerances were taken to be 25% of the interference range for each type of fastener to be evaluated in this project. A self-imposed objective was to build a measuring system that

was a prime candidate for a no-force cutting device that would be positioned by commercially available numerically controlled (NC) machine tools. When it was realized that a NC platform could be used to control a router instead of a router board, the need for new aluminum cutting methods was obviated.

Benefits

Since this technology was not implemented, no benefits were identified.

In Phase II, the effect of power level and cutting speed on cut quality were investigated. Coupon tests were used to evaluate cut edge quality and the heat-affected zone. Complex fixtures and several innovative test methods, such as a spiral traverse cut, were devised to vary cutting speed during this phase.

In Phase III, test specimens were evaluated metallurgically for stress concentration, size of heat-affected zone, and grain growth. Specimens were also tested mechanically to determine the effects of laser cutting on the mechanical properties of the test material.

Project Results

Four different jet nozzle configurations were evaluated. These included a needle jet nozzle at a 10-degree angle with the laser beam; an off-axis jet nozzle at a 30-degree angle; a concentric jet nozzle at a 30-degree angle; and concentric jet nozzle that was coaxial with the laser beam. The coaxial jet nozzle was selected through visual observations of edge structures. The gas types evaluated were carbon dioxide, oxygen, helium, and air. Carbon dioxide and air were both found to be suitable for use in the cutting process, and air was selected for economic reasons.

Fatigue and tensile strength tests were conducted by Boeing, Lockheed, and McDonnell Douglas. These tests indicated that laser cut specimens had fatigue strengths roughly equal to those observed for blanked specimens, although there seemed to be a tendency for blanked specimens to have slightly better properties. They also indicated that a laser cut edge had a stress concentration less than that for a drilled open hole and greater than that for a hole filled with a fastener.

The results from this project showed that it is feasible to use laser-cut aluminum without edge enhancement in component fabrication where sheared or blanked edges are acceptable. They also showed that edges cut with the laser equipment employed in this project could not be used where machined edges are required or where hole filling fasteners are required.

Implementation

Boeing has not implemented this technology and has no plans to do so in the near future. Boeing staff were unaware of any use of laser cutting for aluminum parts in the industry today.

Laser cutting of aluminum was being pursued as an alternative to blanking and routing. Routing produces a machined edge that allows higher stresses in component design, but it requires complex fixtures, called router boards, in which material to be routed is clamped to hold it firmly against the cutting forces. This time consuming fixturing procedure could be eliminated if a no-force cutting method could be used. Laser cutting

Hughes Aircraft Company
MANUFACTURING METHODS PROGRAM FOR IMPATT DIODES
F33615-72-C-1837
July 1972 - June 1974
\$275,431

Background

At the time this project was undertaken, the use of millimeter wave semiconductor devices was limited primarily to laboratory experimental projects. Most of the higher frequency (above 60 GHz.) power drivers were tube devices with very limited reliability, and they were generally unsuited for field applications. Solid state X-band and millimeter wave devices were needed for a large variety of military and commercial electronic devices being developed at the time. Much of the new military communications and detection equipment required these devices as power drivers. The development of the ability to produce high reliability solid state devices was necessary for the implementation of these technologies.

Project Objective

The project's objective was to transition IMPATT diodes from the laboratory to the production environment. A lowest cost manufacturing process was to be developed for reliable production of high quality IMPATT diodes.

Project Description

The project was divided into five phases. During Phase 1, the processes involved in manufacturing IMPATT diodes were investigated and the results used to develop a design better suited to large scale production techniques. The production design was based on a 35 GHz. (ka-band) diode with a rated power output of 100 mW.

Phase 2 efforts concentrated on verification of the production design developed in Phase 1. A major development during this phase was the utilization of arsenic doped substrates in place of the antimony doped substrates previously used. This change significantly improved the device characteristics as well as the process yields.

The major effort during Phase 3 was the establishment and documentation of the manufacturing methods and quality control procedures required for IMPATT diode production. The bulk of the material in the published specifications was produced during this phase.

Initiation of pilot line processes followed as Phase 4 and involved the production and testing of 10 diodes according to the specifications developed in Phase 3. Testing conducted during this phase included life tests and environmental qualification testing. Two diodes were delivered to the Air Force for testing. Acceptance test procedures and requirements

for in-process control documentation were also established.

The final phase of the project consisted of the verification of the ability to apply the process specifications to the production of IMPATT diodes for other frequencies and the production of a number of devices in a limited pilot production mode. This was accomplished by the production and delivery of 100 ka-band diodes, 5 V-band diodes, and 5 X-band diodes using the production methods and controls established during the project.

Project Results

This project resulted in several improvements in process yields and device characteristics. The wafer yield (indicating factors such as substrate quality, substrate resistivity, and control of epitaxial growth and diffusion) increased from less than 25% before the project to 90% at the completion of Phase 5. Chip yield (indicating such factors as wafer thinning, large area bonding, photolithography, etching and punchout processing) increased from less than 50% to 68%. The packaging yield was increased from less than 30% to 73%. Estimates of process yield improvements are based on the pilot production run of 100 Ka-band diodes produced during Phase 5 of the project.

Device performance improvements were due largely to the use of arsenic doped high purity substrates. The performance increases achieved are listed below:

- 1) Improved RF efficiency: 5% as compared to 3%.
- 2) Stable forward voltage (and hence RF output power) under temperature and current stress. Less than 5% change as compared to 30% to 50% before the project.
- 3) Greater reliability: Higher mean burn out temperature: 375°C to 400°C compared to 300°C to 325°C.

Implementation

The development of these solid state devices has allowed the industry as a whole to develop an entire new line of communications equipment which utilizes the higher frequency bands above 75 Ghz. At Hughes this product line includes many of the communications satellites as well as military communications and test equipment now being developed for the millimeter wave bands.

IMPATT diode production at Hughes utilizes the advances in production methods developed in this project. Other manufacturers utilize similar procedures in the production of devices having similar applications (gunn diodes, FET transistors, etc.).

Benefits

The major benefit from the development of highly reliable solid state IMPATT diodes was as an enabling factor in the development of state-of-the-art satellite communications equipment. Hughes Aircraft's millimeter wave product line today is currently running at a level of approximately \$20 million per year. MANTECH involvement in this project probably accelerated the development of the processes which would have been developed by industry over a longer period of time.

Most manufacturing cost savings accrue from improved overall process yield. There were also some economies made in labor and material inputs. Overall, the manufacturing cost per diode was reduced to about one-tenth of its former amount. Savings per diode amounted to approximately \$65.00 in 1974, and thus approximately \$109 in 1982 dollars. With a total production volume of approximately 2500 annually, this translates into savings of \$272,500 per year, and at least \$2,725,000 through 1992.

The improved life characteristics and improved stability over time and temperature changes also result in large dollar savings and large mission benefits. Although known to be substantial, these benefits could not be quantified with an acceptable degree of certainty.

Hughes Aircraft Company
MANUFACTURING METHODS PROGRAM FOR X BAND TR LIMITERS
F33615-74-C-5102
March 1974 - November 1976
\$412,783

Background

In order to minimize weight in airborne radar systems, a single antenna is used for both transmit and receive functions. Since all antenna systems are imperfect to some degree, they will all "reflect" power back into the receiver section. The maximum reflected power is generally on the order of 10% to 20% of the transmitter output. However, when there is an antenna arc, due to antenna damage or the presence of foreign material in the antenna structure, as much as 80% of the transmitter output power can be reflected to the receiver. Assuming operation with a 50kw peak output transmitter, this requires protection of the receiver amplifier sections from RF power on the order of 40kw. The existing radar design for F-15 aircraft was only capable of handling approximately 600w of reflected RF power.

In advanced, high power, high duty cycle radar systems there is the additional requirement of being able to transition at high speed from the conducting state to the non-conducting state.

Project Objective

The objective of this project was to establish manufacturing methods for producing advanced microwave limiters with improved power handling capability. The thrust of the program was technical, not cost.

Project Description

The project was divided into the six phases listed below:

Phase I	Modification of the design.
Phase II	Electrical tolerance limits.
Phase III	Mechanical tolerance limits.
Phase IV	Aging and test procedures.
Phase V	Layout of unbalanced pilot line.
Phase VI	Pilot production run.

Phase I of the program was a design study to modify the existing design in order to meet the project objective of higher power handling capability.

Phase II involved the manufacture of prototype hardware according to the design developed in Phase I, and testing of the hardware to determine practical electrical tolerance requirements for the design.

An effort similar to Phase II was conducted as Phase III for the mechanical aspects of the prototype hardware, with special attention to each subassembly component. Manufacturing and testing procedures were assessed in this phase.

In Phase IV, aging or burn-in requirements were determined, and development of test criteria, procedures, and equipment needs for acceptance testing of complete limiters were completed.

Layout of the manufacturing processes suitable for large quantity production of the limiters and life testing of five limiters were undertaken in Phase V.

Phase VI was undertaken to produce ten complete limiters in a pilot production line with a continuous flow of parts. Formal specifications for the limiters were developed during this phase.

Project Results

The major design modification requiring a new manufacturing process and specialized tooling was the scaleup of the comb line filter from a four element to a nine element device while maintaining extremely tight tolerances. The comb line filter is a tightly toleranced mechanical device inserted in the waveguide in which the multipacting effect takes place. Theoretical analysis of the design indicated that tolerances as small as plus or minus 0.00004 inch would be required for the comb line filter elements in order to maintain a satisfactory impedance match. It was determined in the program, however, that tolerances as large as 0.0002 inch could be allowed in the individual gaps if all gaps were tuned as a composite circuit. This was essentially the enabling factor for increasing the power handling capability of the multipactor.

Major components and assembly steps for the comb line which required development of manufacturing methods or tooling were the tuning screw holder assembly, body assembly, final braze assembly, bakeout assembly and final assembly.

The comb line is machined out of copper to the tolerances stated above and joined to the body and tuning screw assembly by a braze technique. Introduction of braze material as a preform, which was relied upon to maintain tolerances between the components being joined, caused problems early in the program because of variations in the thickness of the braze joint as the material melted. Redesign of the components so that the braze material was not responsible for maintaining tolerances was successful in minimizing the change in voltage standing wave ratio (VSWR) during the braze process. This change greatly simplified the final tuning of the device, and it reduced the number of labor hours required for manufacture.

During final assembly, conditioning of the secondary emitting material is required for proper operation of the multipactor. Tests performed during the contract showed that a staged, two-step process produced a

multipactor with improved low level power handling capability. It also reduced flat leakage power without degrading peak power handling capability.

Test equipment and procedures developed as part of this contract to measure such parameters as insertion loss, VSWR, and recovery time allowed the testing of production limiters at a rate of 12 per month with a high level of quality assurance. Standard test procedures and equipment lists were developed and published as part of the contract final report.

Implementation

The lessons learned in this program have been applied to all multipactor production at Hughes. Retrofits have been made or ordered for most F-14 and F-15 radars with pre-MANTECH multipactors, and all new ones incorporate the technology. F-18 radars incorporated the improvements from the beginning. The F-16 uses a different kind of radar, not made by Hughes. All new Hughes multipactors incorporate this technology.

Benefits

Manufacturing costs of the pre-MANTECH limiter and the present design are essentially the same. Cost savings benefits have been realized as a result of this program both in the areas of lower failure rates of the limiters themselves and lower failure rates of the receiver front ends on the F-15, F-14, and F-18 aircraft radar systems. The benefits analysis presented below is based upon information furnished by personnel at Hughes Aircraft and Warner Robins Air Logistics Center, coupled with Applied Concepts' estimates of the application base through 1992.

As of 1 April 1983, a total of 639 F-15 radar sets of this type had been fielded by the Air Force. 464 had the pre-MANTECH limiters (603H) and 175 had the high power limiters (1735H). During the 2.2 year period from 1 January 1981 to 15 March 1983, a total of 278 multipactor limiters were repaired. Of this total, 229 repairs were on the pre-MANTECH limiters and 49 were on the high power limiter which resulted from the MANTECH project. The high power limiter was introduced on all new radar sets produced after December 1978, beginning with radar set number 464.

For the purpose of this analysis, it is assumed that failure of the limiter in operation results in failure of the receiver parametric amplifiers or FET amplifiers. This is a reasonable assumption considering the extremely low power input to the receiver compared to the power output of the transmitter, 50 milliwatts compared to 50kw. The cost associated with repair or replacement of the receiver front ends must therefore be included with the cost of repair of the limiters. These costs are on the order of \$4800 for repair of a receiver amplifier and \$1600 for repair of a limiter, for a total of \$6400. Hughes serves as the repair depot for the Air Force for this item. These costs do not include the considerable cost of removal, shipment to Hughes and replacement into the aircraft, or the mission impact of radar downtime. Based on discussions with both Hughes

Aircraft and Warner Robins ALC staff regarding the difficulty in diagnosing the failure of a limiter in the field (they are just now deploying field test units for the multipactor units), the number of receiver failures caused by the low power handling ability of the original limiter is probably much larger than the number of limiters diagnosed as faulty. With the documented failures as stated above, a lower bound dollar benefit can be established as follows:

$$\begin{aligned} \text{Pre-MANTECH units} &= \frac{229 \text{ repairs}/464 \text{ units}}{2.2 \text{ years}} = .224 \text{ repairs/unit/year} \\ \text{repairs/unit/yr} & & & \\ \\ \text{Post-MANTECH units} &= \frac{49 \text{ repairs}/175 \text{ units}}{2.2 \text{ years}} = .127 \text{ repairs/unit/year} \\ \text{repairs/unit/yr} & & & \end{aligned}$$

The resulting difference is .097 repairs/unit/year. Since a repair costs approximately \$6400 (direct costs only), this translates into a savings of \$621 per unit per year. The benefits can be extrapolated through 1992 for the fleet of F-15, F-14, and F-18 aircraft by multiplying \$627 per unit per year times the number of operational aircraft years of these types expected during that time (each aircraft has one limiter). The assumptions regarding fielded aircraft volumes and the results of the extrapolation are presented below.

Estimated Total U.S. Operational Aircraft Years with High Power Limiter
from Yr. of Implementation +1, thru 1992

<u>Aircraft</u>	<u>Total # Aircraft Years</u>
F-15	11,025
F-14	7,017
F-18	<u>5,139</u>
TOT = 23,181	

The estimate of overall savings from use of the new limiter through 1992 is (23,181)(\$621) = \$14.4 million (in 1982 dollars). The actual figure could be much higher than this, as new aircraft and new derivatives of the above aircraft which use the high power limiter are introduced. Again, the \$14.4 million figure does not include avoided equipment removal, shipment, and reinstallation costs, or the mission impacts of non-functional radar or aircraft downtime.

Hughes Aircraft Company
MANUFACTURING METHODS FOR DETECTOR GRADE INTRINSIC SILICON
F33615-75-C-5283
February 1976 - June 1978
\$553,037 (USAF); \$362,000 (ARMY)

Background

The manufacture of high quality, high sensitivity detectors for IR laser guidance systems requires ultra high purity silicon as a starting product. Resistivity of the silicon used in these processes needs to be in the range of 9,000 to 30,000 ohm-cm. in order to produce consistently high quality products. Boron is the contaminant of most concern in processing of high purity silicon and is the most difficult to eliminate from the manufacturing processes.

Refining of high purity polysilicon rods is accomplished by the use of a vacuum float zoning process where high purity polysilicon material is melted as it passes through an RF induction coil and impurities are evaporated or "floated" to an unused area of the crystal as it is grown. Multiple zoning passes are required to produce the high resistivity material required by this project. Vacuum float zoning is widely used in industry for purifying and increasing the resistivity of silicon materials. However, at the time of this project there were no facilities in the U.S. that could manufacture silicon with a resistivity in the range required for high quality detectors.

Before this project, the only source for high purity (high resistivity) silicon for production of the laser detectors for the Laser Maverick, Hellfire, and PAVEWAY guidance systems was Wacker, a German company. They were manufacturing large quantities of low to medium resistivity silicon and supplying the high purity silicon as a byproduct of their manufacturing process. The price of the material was rather high--fluctuating across the \$20-\$40 per gram range in the years immediately preceding this project.

Given the criticality of this material, it was thought that a U.S. source should be established. It was also hoped a U.S. source would result in lower prices.

Project Objectives

The primary objective of this project was to establish a domestic source for high quality intrinsic silicon for manufacture of 1.06 um. laser detectors. The secondary objective was to reduce costs. The project was a joint Army/USAF effort, with USAF the lead service and program manager.

Project Description

Basic manufacturing processes for detector grade intrinsic silicon crystals and polished wafers were established during the first 18 months of the project. This included establishing specifications and measurement techniques for the raw material with Dow Corning Corporation, a subcontractor and material supplier for this project. Improvements in the zoning processes and crystal growth processes included scaling up the size of the zoners and control of the materials handling procedures.

Boron is the contaminant of most concern in the manufacture of silicon in this resistivity range. Most other contaminants can be removed from silicon by several zoning passes in vacuum by volatilization or by segregation ("floating" to another area of the crystal) and freeze out in the zone at the end. Atomic boron does not evaporate from silicon significantly and its distribution coefficient is too near unity to be removed by segregation. Since boron is present in nearly all materials in amounts which are significant with respect to the purity of the silicon involved with this project, nearly any source of contamination is a possible source of boron contamination.

Automation studies were primarily data gathering tasks for future automation of zoners for the growth of dislocation-free crystals. This requires very precise simultaneous control of several parameters affecting crystal growth. Manual (two hands) operation implies a limit on the ability to control more than two parameters in real time without going to step-wise adjustment, which causes discontinuities. The variables of most concern were the upper rod axial speed, lower rod axial speed, RF power, growing crystal diameter, and melt zone dimensions.

Wafers produced in the project were shipped to RCA and Hughes to fabricate samples of the Laser Maverick and Hellfire detectors, which were evaluated for performance, uniformity, and process yield.

Project Results

Technically, the project was extremely successful. Material and process specifications were developed which produced material of unprecedented purity, with high resistivity. Tests conducted on detectors fabricated from this material by RCA and Hughes indicated significantly lower dark currents than detectors processed from other available material. Uniformity from quadrant to quadrant as well as from device to device was much better with the material produced under this project. This project resulted in the establishment of a domestic source of very high quality silicon capable of supplying material to the specifications of detector manufacturers in production quantities.

Production estimates for 15 Kg of this silicon per month indicated that automation of the process would decrease the labor cost by a factor of 3, material cost by a factor of 2.8, and the number of zone refiners needed from 9 manually operated to 4 automated machines.

Implementation

The processes and material specifications developed in this project are being used at Hughes for the manufacture of high purity silicon but in very limited quantities. Production machines have been developed through two subsequent MANTECH projects and company IRAD funding. Automation of the process has not been implemented primarily because of a lack of demand for large quantities of the material. The Air Force continues to obtain its supplies of this material from Wacker, due to Wacker's lower price.

Hughes estimates indicate that the long range market for this material is unsure at best, and it probably will not increase in the foreseeable future. Newer weapons systems appear to be moving to other guidance-system technologies.

Benefits

The one known benefit resulting from this project is the availability of high purity silicon from a domestic source. Hughes staff stated that the price of the foreign-produced material dropped from approximately \$38.00 per gram to \$5.00 per gram shortly after the material became available from Hughes. Project resources were insufficient to verify that this price drop resulted from domestic availability. Therefore, no definite monetary benefits could be attributed to this project.

Hughes Aircraft Company
FULL WAFER LARGE SCALE INTEGRATION (LSI) MODULE APPLICATION
F33615-75-C-5242
October 1975 - September 1976
\$324,750

Background

LSI circuits offered the potential for significant cost, size, performance, and reliability advantages in the manufacture of digital logic systems. Complex medium scale integrated (MSI) circuits and large scale integrated (LSI) circuits had been developed that functionally replaced from 20 to 200 small scale integrated (SSI) circuit packages. Many different LSI design and fabrication approaches had been taken, but none had been considered optimum across the wide range of requirements for various general logic systems, such as data and signal processors and digital controllers. During the two to three year period before this project, impressive developments were made with LSI approaches that respond to those requirements. In general, the approaches had been based on computer-aided design (CAD) of arrays and on the use of cells, chips, and packages that can be used for a wide range of applications. They included CAD programs for layout, routing, and testing; complete user design guidelines; characterized standard circuit families; and fabrication, interconnect, packaging, and testing procedures for LSI arrays.

The Hughes full wafer technology was an important standard-cell LSI design approach using an optimized library of well-characterized SSI/MSI circuit types. CAD programs were used to select, locate, interconnect, and generate tests for these circuits to produce a complex full wafer logic function design. A value engineering study conducted by Hughes for the F-15 SPO showed that full wafer LSI might be implemented in the F-15 radar signal processor (RSP) to increase its reliability and reduce its production and life-cycle costs.

Project Objective

The general objective of this project was to establish the manufacturing techniques required to incorporate an established LSI technology into an on-line facility for manufacturing F-15 RSP modules. Specific objectives included selecting a candidate RSP module, redesigning it to incorporate full-wafer LSI components, and then demonstrating its producibility with a pilot production run. The incorporation of LSI technology in RSP modules was expected to result in increased reliability and reduced acquisition and life-cycle costs for the F-15 radar.

Project Description

This project was to be performed in two phases. In Phase I,

manufacturing techniques and processes were to be developed for producing LSI modules. In Phase II, the producibility, reliability, and cost effectiveness of LSI modules were to be demonstrated through a pilot production run. Phase II was cancelled, however, because of design changes in the F-15 radar at that time which incorporated other cost effective technology.

Phase I was initially concerned with the selection and LSI design conversion of one of 29 candidate modules in the F-15 RSP. The clutter canceller module was selected and converted to a partial full wafer LSI design. Manufacturing techniques were developed and process control and quality control procedures were established for the repetitive production of full wafer LSI modules. Fabrication, assembly, and test procedures were examined at both the wafer and module levels. Fixtures for LSI wafer tests and module tests were designed and assembled. The LSI wafers were tested before and after packaging. A clutter canceller module was assembled and tested for the adequacy of its thermal design. It was then successfully tested for its functional interchangeability with a reference module of the existing design. The module was then installed in an F-15 radar signal processor which was connected to an F-15 radar test station. After a minor solder-bridge problem was corrected, all test requirement document (TRD) tests were run successfully, and thus LSI module interchangeability was fully demonstrated.

Project Results

This project was technically successful in that it demonstrated the possibility of applying full wafer LSI technology in a retrofit while maintaining form, fit, and function interchangeability. The technical problems encountered were all of the human error start-up variety and were easily corrected. Yield, thermal performance, and electrical performance exceeded original expectations. Although Phase II of this project was dropped, and the technology was not implemented, some project accomplishments have other potential applications. The project demonstrated the full wafer LSI capability for incorporating changes of the kind typically encountered in initial system design, which illustrates the advantage of having spare circuits available--a feature unique to full wafer LSI. It also demonstrated the capability for the "mix or match" of predesigned circuits in a precision step-and-repeat operation with outstanding yields for the first articles produced. A combination of this capability with the superior multilayer process developed in the project permits a new approach to moderately complex, fast turn around, low cost LSI design. Techniques were also developed for removing, repairing, and replacing large multi-lead ceramic packages without damaging the remaining assembly.

Implementation

Phase II of this project was cancelled because of design changes in F-15 radar at that time which incorporated other cost effective technology, and Hughes therefore has not implemented this technology and no plans to do so in the near future.

Benefits

Since the technology was not implemented, no benefits were identified.

Hughes Aircraft Company
ALUMINUM FLUXLESS BRAZED ANTENNA MANUFACTURING METHODS PROGRAM
F33615-75-C-5266
June 1975 - June 1977
\$592,359

Background

Phased array antennas for use in aircraft radar systems need to be light weight and rigid, and they must conform to tight mechanical and electrical tolerances. The baseline manufacturing practice was, and still is, to fabricate the antenna by machining sections out of relatively thick plates and then electron beam (EB) welding the sections together. Material utilization is low, and each antenna requires over 2600 inches of EB welds. A method of fabricating antennas in one piece, which met the design requirements, would have a potential for large cost savings. Minor weight penalties were thought to be acceptable to get the costs down.

Project Objectives

The objective of this project was the development of a fluxless brazing technique to reduce the manufacturing costs of thin walled planar array antennas for airborne radar systems.

Project Description

Cost and weight studies were performed on the baseline magnesium design and a design based on an aluminum part joined by fluxless brazing (a process developed by AVCO for fabricating heat exchangers). The studies indicated that fluxless brazing offered a large potential for cost savings, approximately \$5000 per antenna, with an acceptable weight increase of 15%, or 1 pound. With AVCO as a subcontractor, three one-piece aluminum antenna arrays were fabricated with a fluxless brazing process and evaluated by Hughes Aircraft for possible replacement of the current magnesium antenna on the F-15 radar system. Process specifications were prepared to facilitate the implementation of the fluxless brazing process for production hardware.

Project Results

The project demonstrated a capability to fabricate planar array antennas which met the electrical performance requirements of the F-15 radar system using the fluxless aluminum brazing technique. Although there were some minor discrepancies in the dimensional specifications of the three finished arrays produced, electrical performance appeared to be within specification for all parameters measured. The weight of the complete 36 inch diameter array panel was found to be only 0.5 pound over the weight of the baseline magnesium panel, well within the 1.0 pound target. After fabrication of the third array, nearly all of the process parameters were understood and documented well enough to be implemented in the production environment. These specifications were fairly complicated

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BENEFITS ANALYSIS OF PAST PROJECTS VOLUME 2 INDIVIDUAL
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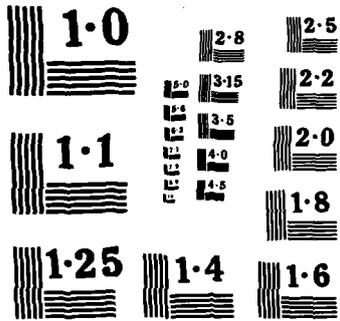
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NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

and had to be followed closely in order to produce consistently good parts. There was some difficulty in getting production personnel to follow the specifications closely enough to produce consistent results.

Probably the most significant problem that was not resolved, and which remains unresolved today, is the non-homogeneous composition of the aluminum sheet stock used to construct the components. This probably caused the variations in material movement which were observed during the braze cycles, and is likely to be a significant problem to be overcome if this process is to be further developed in the future.

At the completion of the program, the cost estimate of the aluminum fluxless brazed antenna array increased from the projected \$6150 to \$7300 per panel based on production quotes from AVCO. These prices still reflect an estimated savings of \$3850 over the cost of the magnesium panel before the project. (All \$ are 1982\$).

Implementation

Fluxless brazing of large, thin walled aluminum structures has not been implemented to date by Hughes or anyone else to our knowledge. According to Hughes staff, the process is not being pursued by AVCO and rights to pursue the technology have been transferred to General Tool Co. of Cincinnati, Ohio.

Benefits

Benefits from this project are primarily in the area of increased understanding of the fixturing of large, complex, thin walled structures, and a better understanding of how to design the components to allow the fixturing to be provided by the components themselves. These design concepts have been implemented in the design of the F-18 radar antenna and, with a reduction in the overall diameter of the antenna from 36" to approximately 24", allow the antenna to be fabricated in one piece instead of in quadrants as was the case with the F-15 antenna. However, the joining technique and materials (electron beam welding of magnesium) used in construction of the F-18 antenna is the same as that used on the F-15 antenna before this project was undertaken. No dollar savings have been established.

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