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MACHINE CASTING OF HIGH TEMPERATURE ALLOYS
FOR TURBINE ENGINE COMPONENTS

FEBRUARY 1977

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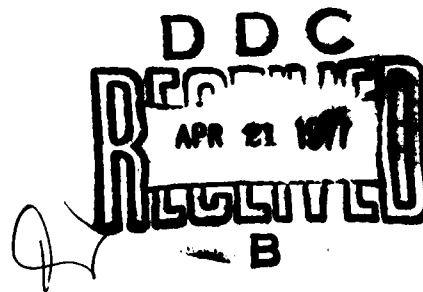Interim Report   Contract Number DAAG46-76-C-0029

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A program has been initiated to evaluate the capability of machine casting for fabricating components for gas turbine engines such as compressor airfoils. The goal is to evaluate the capability of the process to produce an end product of high quality on an economic basis.

During this reporting period, machine casting activity consisted of continuing equipment modifications to an already existing unit which improved die filling and decreased transfer time. Concurrently, partial assessment of process parameter effects using Rheocast Haynes Alloy 31 (X-40

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cobalt-base alloy as a vehicle was performed. Machine casting preforms containing varying volume fractions of solid were injected at different die temperatures. Evaluation of the resultant product indicated that internal porosity was much lower in those parts made from initially high volume fraction solid preforms and that surface condition was improved with increasing die temperature.

In addition to the above work, a heat treatment response study was performed and some limited mechanical property evaluation was conducted. Heat treatment studies indicated that long term annealing followed by aging treatments yielded microstructures similar to those of the conventionally cast and heat treated Haynes 31 alloy, indicating the ability to largely eliminate those chemical hetergenities peculiar to the thixotropic state of the input material. Tensile testing at room temperature and $1000°F$ indicated that yield strengths were higher than the nominal yield strengths for conventionally investment cast X-40 at both temperatures, while both ductility and ultimate strengths were somewhat lower. Fractography indicated the presence of pre-existing voids as the probable cause of the lower ductility.

A mechanized transfer system has been designed and is presently being constructed. This system will significantly reduce transfer time even further, and will enhance uniformity of machine casting unit operation so as to better assure product reproducibility and reliability.

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SUMMARY

For the past several years, the Defense Advanced Research Projects Agency (DARPA) has been sponsoring a program directed towards the "Machine Casting of Ferrous Alloys". Pratt & Whitney Aircraft recently joined the DARPA effort to conduct an evaluation of the applicability of machine casting for the economic fabrication of high quality components for gas turbine engines such as compressor airfoils.

During the reporting period, a series of modifications were made to an existing machine casting unit to reduce the transfer time and attempt to more consistently attain 100% die fill. These modifications resulted in reducing the transfer time from over six seconds to approximately four seconds and significantly enhanced the die fill. Concurrent with this activity, a partial assessment of process parameter changes using Rheocast Haynes Alloy 31 (X-40), a cobalt-base superalloy, was performed. Parameter variations studied included volume fraction solid levels in the casting preform of 0.5 and less than 0.2, and two die temperatures, 600 and 1000°F. Evaluation of the resultant casting indicated that parts made from initially high volume fraction solid preforms were more sound and that surface condition was improved in the parts cast into the higher temperature die.

In addition to the above work, a heat treatment response study was performed. This study indicated that annealing at 2250°F for 8 hours followed by ageing at 1650°F for 24 hours resulted in microstructures similar to those of conventionally cast and heat treated Haynes 31 alloy. This behavior indicates that the heterogenous nature peculiar to the thixotropic state of the input material can be largely eliminated through heat treatment.

Limited tensile testing at both room temperature and 1000°F indicated that yield strengths of thixocast material exceeded the nominal yield strengths for conventionally investment cast Haynes 31 at both temperatures, whereas tensile strengths of thixocast material was lower than nominal values for conventionally cast Haynes 31. Ductility of the thixocast material were lower than those for conventionally cast material at both test temperatures. Fractography indicated the presence of voids, caused by shrinkage and/or foreign particle inclusions, as being the probable cause of the lower ductility.

A mechanical transfer system has been designed and is presently being constructed. The system will mechanically transfer the casting preform from the preheater directly into the loading assembly of the machine casting system and will automatically trigger the injection cycle. This system will both significantly reduce transfer time and enhance uniformity of machine casting unit operation so as to further improve product reproducibility and reliability.

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I. INTRODUCTION

A. BACKGROUND

The objective of this experimental program is to determine the potential of machine casting for economically producing high quality, ferrous and superalloy gas turbine engine components such as airfoils. The current manufacturing techniques for the fabrication of airfoils include investment casting and precision forging. However, machine casting offers the potential for significant cast savings when compared to these fabrication techniques.

The feasibility of conventionally die casting ferrous alloys in airfoil shapes as shown in Figure 1 has recently been explored. It has been shown that compressor airfoils (currently precision forged and machined) could be die cast in ferrous alloys such as AM 355 (AMS 5610) and AISI 410 steels with the requisite dimensional accuracy. However, examination of resultant parts indicated that the overall nondestructive quality was lower than that found in current forged hardware. This was attributed to the presence of internal shrinkage and gas porosity which is a characteristic of current commercial ferrous die casting technology.
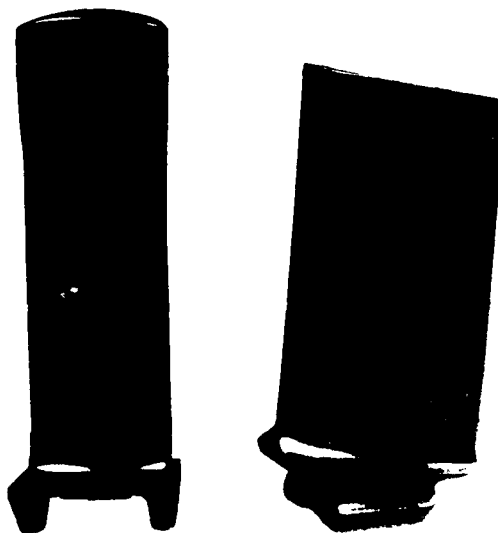
Figure 1   *Die Cast Ferrous Alloy Compressor Vane (left) and Compressor Blade (right) Approximately 1.5X)*

High cycle fatigue testing of the die cast ferrous airfoils indicated that the presence of internal voids adversely affected the fatigue strength of the material. Fatigue strengths for the die cast AM 355 blades were about 60% of the fatigue strength levels normally achieved in forged AM 355 blades. Reduction of porosity through hot isotatic pressing (HIP) improved attainable stress levels to 80% of normal fatigue strength indicating the potential for the die casting of critical components for gas turbine engines provided that internal casting soundness could be achieved.

More recently the Defense Advanced Research Projects Agency (DARPA) has initiated programs directed toward the "Machine Casting of Ferrous Alloys".[1-6] One of the innovative approaches being pursued involves forming high temperature alloys in the thixotropic state in order to obtain improved product quality.[7-10] The anticipated quality improvement results from the fact that a thixotropic alloy is injected in the machine casting system in the slurry (partially solid) state, thereby improving die fill characteristics. In addition, since the metal is partially solid at the time of injection, less shrinkage porosity results and the castings spend a shorter time in the die before they are completely solid. The lower temperatures associated with the thixotropic input material as contrasted to current die casting practice should provide for improved die life by reducing the thermal shock experienced at the die face.

Pratt & Whitney Aircraft Group has recently joined the DARPA Machine Casting Activity. The program described in the following section is the P&WA part of the overall DARPA effort and involves applying the machine casting process to the fabrication of gas turbine components in order to see if this approach has the potential to significantly improve casting quality.

B. PROGRAM DESCRIPTION

During the course of the program thixotropic processing of ferrous and superalloy materials into gas turbine components will be evaluated. A general outline of the program is presented in Figure 2.

A continuing effort to improve the machine casting system will be conducted throughout the program. This will include both equipment modifications and mechanization of various steps in the process. Concurrent with this effort will be a series of planned experiments designed to determine the influence of critical process parameters, such as rheocast preform temperature, gate velocity conditions, die temperature and gating configurations on casting quality.

A comprehensive metallurgical characterization will be performed, including microstructural analysis and a determination of alloy heat treatment response. Mechanical property evaluation, including high temperature tensile and creep rupture testing as well as high frequency fatigue testing, will be conducted as well. This information will be used to determine the feasibility of applying machine casting concepts to the fabrication of critical gas turbine components. An assessment of overall part quality, using standard nondestructive testing methods, will also be incorporated into this feasibility analysis.

In addition to the metallurgical characterization of machine cast components a preliminary economic analysis of the process comparing it with existing fabrication techniques will also be performed.

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                    │     MACHINE CASTING     │
                    │           OF            │
                    │ HIGH TEMPERATURE ALLOYS │
                    └─────────────────────────┘
                                 │
                    ┌─────────────────────────┐
                    │      PRELIMINARY        │
                    │       CAST PART         │
                    │      EVALUATION         │
                    └─────────────────────────┘
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STATISTICAL TEST PLAN	AUTOMATIC
— PREFORM TEMPERATURE	TRANSFER SYSTEM
— GATE-VELOCITY	DESIGN & EVALUATION
— DIE TEMPERATURE	
— IN GATING DESIGN	

PART EVALUATION
 — NON DESTRUCTIVE TEST
 — MICROSTRUCTURE
 — PROPERTIES

PROCESS
EVALUATION

NON DESTRUCTIVE EVALUATION	MICROSTRUCTURAL ANALYSIS & HEAT TREATMENT RESPONSE	PROPERTY EVALUATION
— VISUAL		— TENSILE
— ZYGLO		— CREEP RUPTURE
— X-RAY		— HIGH CYCLE FATIGUE

OVERALL
ASSESSMENT &
ECONOMIC ANALYSIS
OF MACHINE CASTING
PROCESS

Figure 2   *General Outline for DARPA - P&WAG Machine Casting Program*

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II. EQUIPMENT DESIGN AND MACHINE CASTING EXPERIMENTATION

The following is a description of the equipment utilized in the machine casting process as well as review of the casting progress made during the reporting period.

A. EQUIPMENT DESIGN

Pratt & Whitney Aircraft has under independent funding modified an injection molding press for use in their machine casting projects. This equipment (Figure 3 and 4) will be utilized throughout this machine casting contract as a method of producing high temperature alloy gas turbine shapes. The press is a converted transfer press originally used for the forming of thermosetting plastic parts and consists of a press frame, die assembly, hydraulic die clamping system and hydraulic injection system. These details are depicted in Figures 5 and 6. Clamping force on the die assembly is maintained at approximately 25 tons, and injection force is limited to 6000 pounds to prevent die separation. Injection speed is currently restricted to a maximum of 4 in/sec. The addition of an accumulator system (presently) being installed (Figure 6) will allow the attainment of ram velocities up to 20 - 30 in/sec. In addition, the use of a servo-valve system, a part of the accumulator package, will allow a high degree of latitude and control of pressure and velocity and permit the establishment of pressure-velocity profiles through the use of limit switch control on the servo-valve system. An instrumentation recording system, shown in Figure 7, automatically records process parameter data such as ram velocity, pressure, and ram position. The die assembly, shown in Figure 8, and the preform loading cradle and liner, previously shown in Figure 5, are H-11 tool steel. The die assembly is heated by means of cartridge-type resistance heaters placed in ports machined into the die halves which are thermally insulated from the rest of the press frame. Die temperatures as high as $1100°F$ can be maintained. A simulated airfoil shape was designed for use in the trials to be discussed below in order to facilitate the experimental procedures.

Figure 3   Machine Casting Unit

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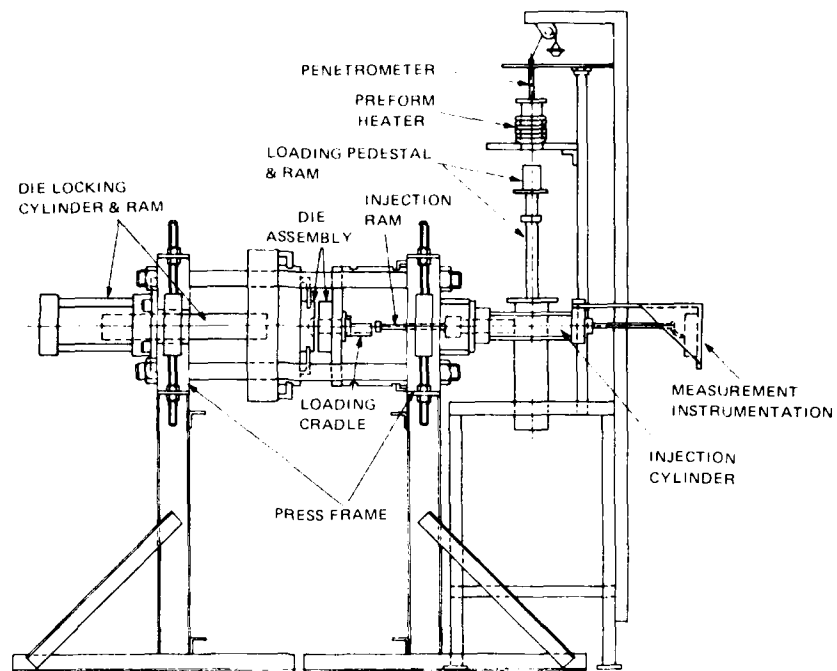
Figure 4   Schematic of Machine Casting Unit

Figure 5   Machine Casting Unit Showing A) Injection Ram, B) Preform Loading Cradle with Preform and Container in Place and C) Die Assembly

8
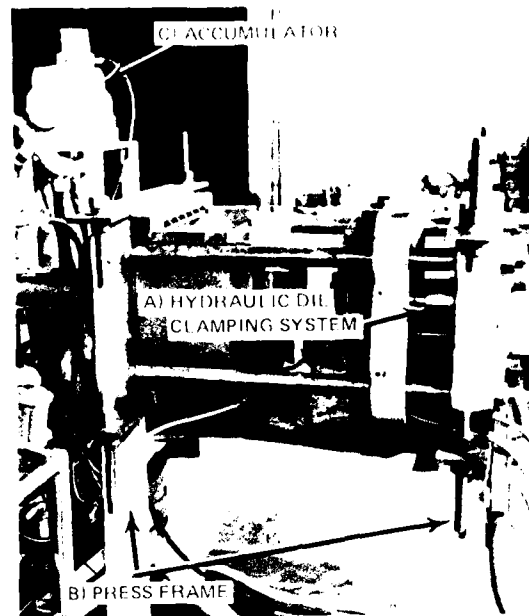
Figure 6   *Machine Casting Unit Showing A) Hydraulic Die Clamping System, B) Press Frame and C) Accumulator*
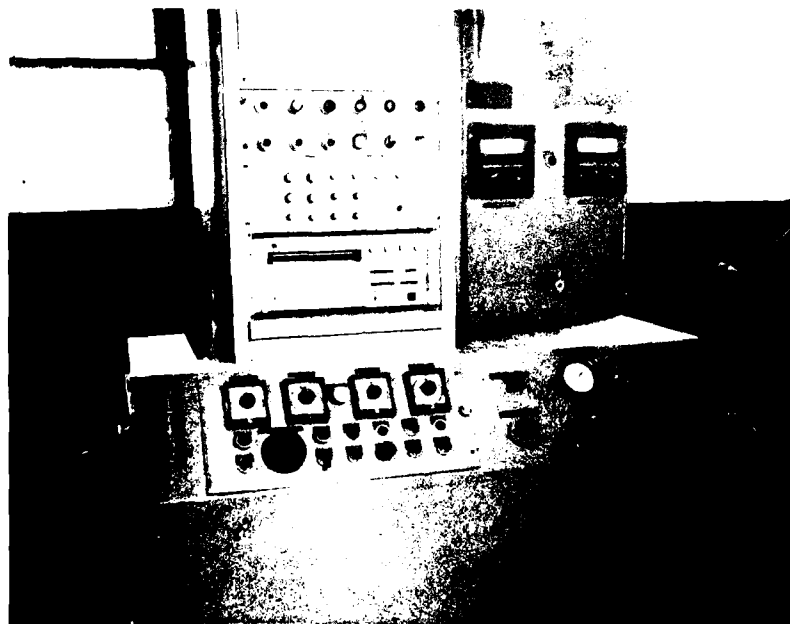
Figure 7   *Instrumentation Monitor Console for Measuring and Recording Machine Casting Unit Process Parameters*
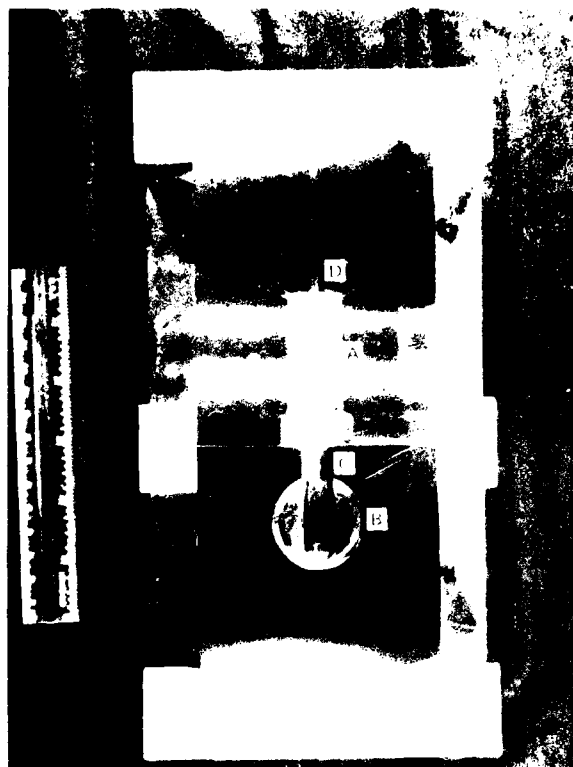
Figure 8   Machine Casting Unit Die Assembly Showing A) Die Cavity, B) Entry Port, C) Gate and D) Vent

The thixotropic alloy preform, usually of cylindrical shape, is preheated to the desired processing temperature in a directly coupled, inductively heated furnace as shown in Figure 9. The induction coil is powered by a high frequency Pilar power supply. The preform is placed in a ceramic container which is in turn positioned on a pedestal attached to a hydraulically activated cylinder. The preform is then raised into the furnace. The proper volume fraction solid in the heated preform is achieved through the use of a variable load penetrometer. After the penetrometer stylus penetrates the preform indicating that a given volume fraction solid has been achieved, it is removed from the furnace by means of lowering the platform and is then manually transferred to the machine casting unit and placed in the preform loading cradle and is injected into the die.

B.   SERIES I - INJECTION TRIALS

An initial series of injection trials (approximately 25) were conducted to determine the capabilities of the machine casting system. Haynes 31 (alloy X-40), a cobalt base superalloy used as an investment cast turbine alloy, was employed for this experimentation. Melt stock was supplied to MIT for conversion into rheocast form in their continuous rheocasting apparatus [4]. A typical quenched rheocast microstructure of the alloy is shown in Figure 10.

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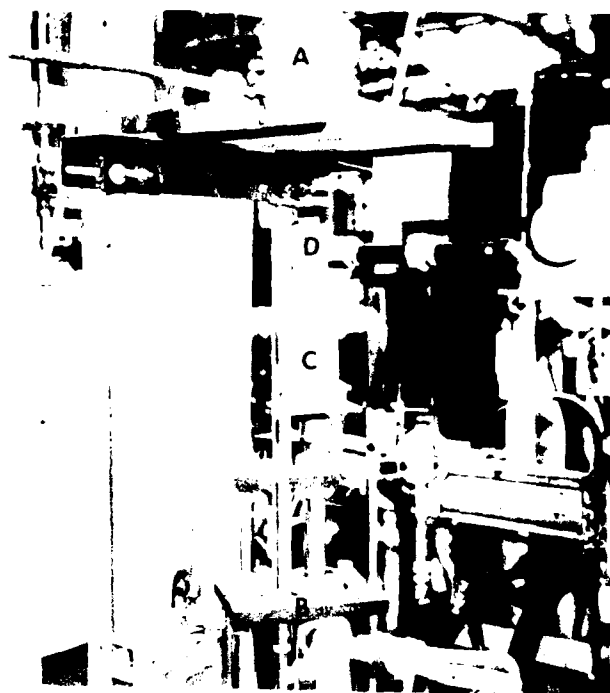
Figure 9   Preform Heater Showing A) Induction Furnace, B) Loading Cylinder, C) Pedestal and D) Preform and Container
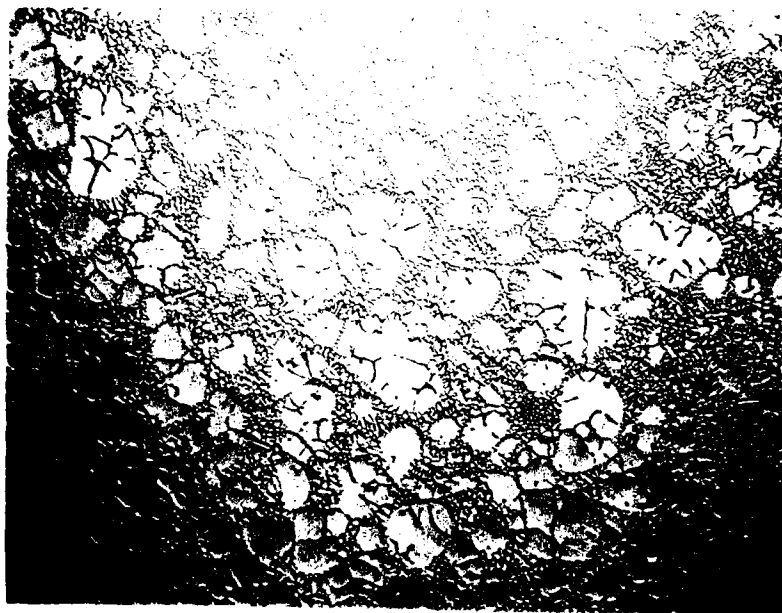
Figure 10   Haynes 31 Quenched Specimen Taken From Continuous Rheocast Run Preformed at MIT (50X)

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In this initial series of injection trials die temperature and rheocast preform volume fraction solid were varied by varying the penetrometer load. It was found that with the then-existing system the transfer time for the preform (5-6 seconds) into the injection unit was too long to provide adequate die fill. This was further complicated by the fact that the ingate length was excessively long. Modifications were made to the system to alleviate these conditions. Sufficient quantities of test material were obtained to machine tensile specimens for a preliminary property investigation. The results of this testing are reported in Section II-E.

One other complicating factor which was observed in the initial injection series was that the Fiberfrax container system used to hold the rheocast preform tended to adhere to the preform surface and fragments of Fiberfrax ended up as inclusions in the injected casting. In addition, transfer of the preform from the heater to the machine casting unit was impeded by the lack of strength of the Fiberfrax container at the preheat temperature. This resulted in the periodic loss of the entire test specimen through leakage of the alloy from the container. To alleviate this problem both mullite and shell molded Al_2O_3-SiO_2 tubes with Fiberfrax bottoms were evaluated. The three types of containers are shown in Figure 11. The preform containers are cut to about two inch lengths and Fiberfrax discs, soaked in colloidal SiO_2, are then positioned in one end of the tubes and the assembly is baked to bond the Fiberfrax in place. The preforms are loaded in the containers, heated in the furnace (vertical position) and manually transferred to the loading cradle (horizontal position). The injection ram then punches out the Fiberfrax bottom while injecting the preform material into the die. Because of the smaller size of the ram relative to the preform container inner diameter, neither the Fiberfrax nor the container fragment to the point where additional inclusions are injected into the part forming portion of the die. The injection sequence is shown schematically in Figure 12. As a result of the ease of handling provided by the tube regidity, the use of this type of container design reduced transfer time to about 3.5-4.5 seconds. Furthermore, it was found that the Al_2O_3-SiO_2 shell material provided additional shock resistance as contrasted to the high density mullite and it therefore has been selected for further evaluation.
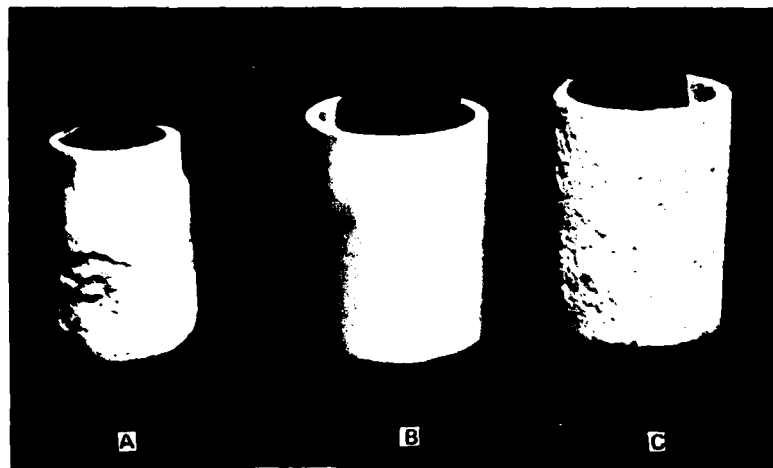
Figure 11   Preform Container   A) Formed Fiberfrax Container, B) Mullite Tube With Fiberfrax Bottom and C) Al_2O_3 - SiO_2 Shell Container With Fiberfrax Bottom

12
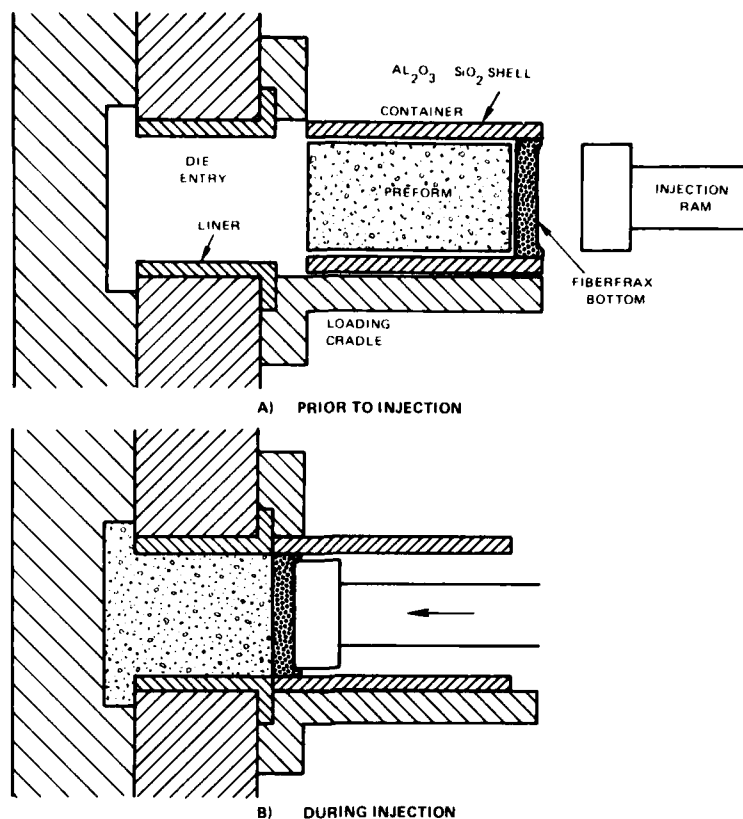
Figure 12   Schematic Representative of Injection Process using $Al_2O_3 \cdot SiO_2$ Shell Containers With Fiber-frax Bottom

One other significant modification which was made to the machine casting unit at this time was to change the preform heater from a susceptor coupled induction system to a directly coupled induction system using a specially designed induction coil which helped to minimize axial temperature variations. Direct coupling resulted in reducing preform heat up time from about 20 to 2-3 minutes.

C.   SERIES II – INJECTION TRIALS

After the aforementioned modifications were made to the machine casting system a second series of castings (approximately 35 trials) was made. The first trials in this series clearly indicated that the die full characteristics of the system were significantly improved. Examples of simulated airfoil castings so produced are shown in Figure 13 and a comparison with a compressor vane is shown in Figure 14. In order to gain a further assessment of the influence of injection parameters on blade quality both preform volume fraction solid and die temperatures were varied as before in the Series I trials. Since preform volume fraction solid is measured by means of a penetrometer the solid content of the specimen could be adjusted by varying the penetrometer weight. The penetrometer stylus used was 0.150 in. in diameter and the two weights employed were 50 and 25 gms. The heavier weight yielded more reproducible results when judged on the basis of metallographically determining the volume fraction solid present at the preheat temperature.

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A – CONVEX SURFACE

B – BACK OR FLAT SURFACE

*Figure 13 Machine Cast Fluxocast Nodulized Airfoil Cast Into Modified Die Assembly Showing A)
Convex Surface and B Back or Flat Surface*

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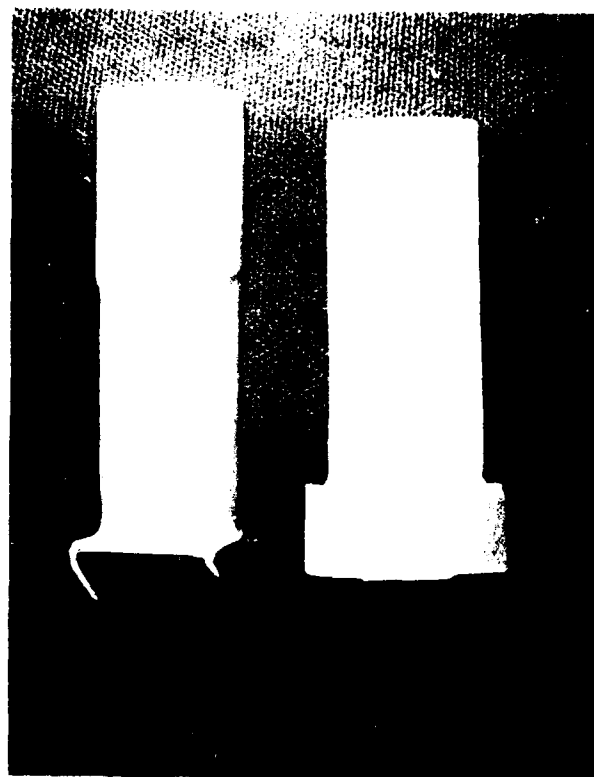
A) COMPRESSOR VANE
CONVENTIONALLY FORGED

B) SIMULATED AIRFOIL
MACHINE CAST

Figure 14   Comparison of A) Conventional Forged Compressor Vane With B) Machine Cast Simulated Airfoil

Die temperature was varied between 600 and 1000 F to gain an initial assessment as to its influence on part quality. It was possible to control the die temperatures to within about ±20° F of the desired set point temperature.

In addition, basic machine settings controlling injection speed (4 in sec) was held constant for all castings made in this test series. In the interest of promoting plane front filling with the viscous alloy slurry, a relatively large (0.06 ² in.²) gate was employed. Under these conditions the die cavity fill time was calculated to about 0.032 sec.

D.   SERIES II   CASTING TRIAL EVALUATION

The castings made with the above mentioned variations in preform and die temperatures and reduced length of die ingate were examined both metallographically and nondestructively (radiography and visual examinations). The metallographic evaluation indicated that at the low penetrometer load (25⁰) the resultant castings were generally near or all liquid as shown in Figure 15. The higher penetrometer load (50g) resulted in a higher volume fraction solid (≈ 1 2) more typical of the values commonly used in the earlier MIT work (see Figure 15B).
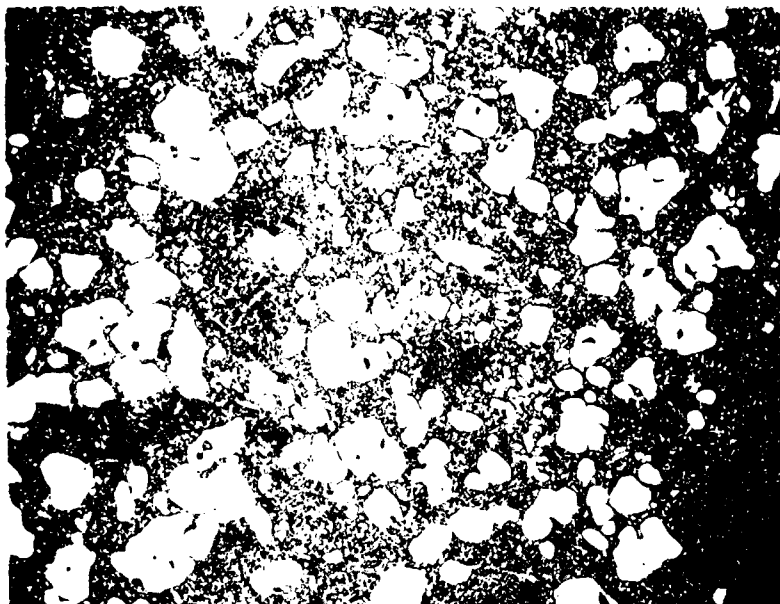
A) LOW V/O SOLID

B) HIGH V/O SOLID

Figure 15   Machine Cast Simulated Airfoil Showing Resultant Microstructure From A) Part Using 25g
Penetrometer Load (Low V/O Solid) Load and B) Part using 50g Penetrometer Load (High
V/O solid) (50X)

The microstructure that existed at the remelting temperature was found to be preserved by the rapid cooling of the slurry in the die. During such solidification, the surfaces of the primary solid particles provided heterogeneous sites for nucleation of dendrites, Figure 16. Furthermore, as observed in Figure 16, the growth of these dendrites was more rapid at particular locations on the surface of the primary solid particles. The apparent orthogonality of these preferred growth regions suggests <100> - type orientation for these regions. Since the primary solid particles are oriented randomly in the slurry, this results in a corresponding random mix of dendrites at the prior liquid regions. The implication of this observation on mechanical properties will be discussed later, in this Section.
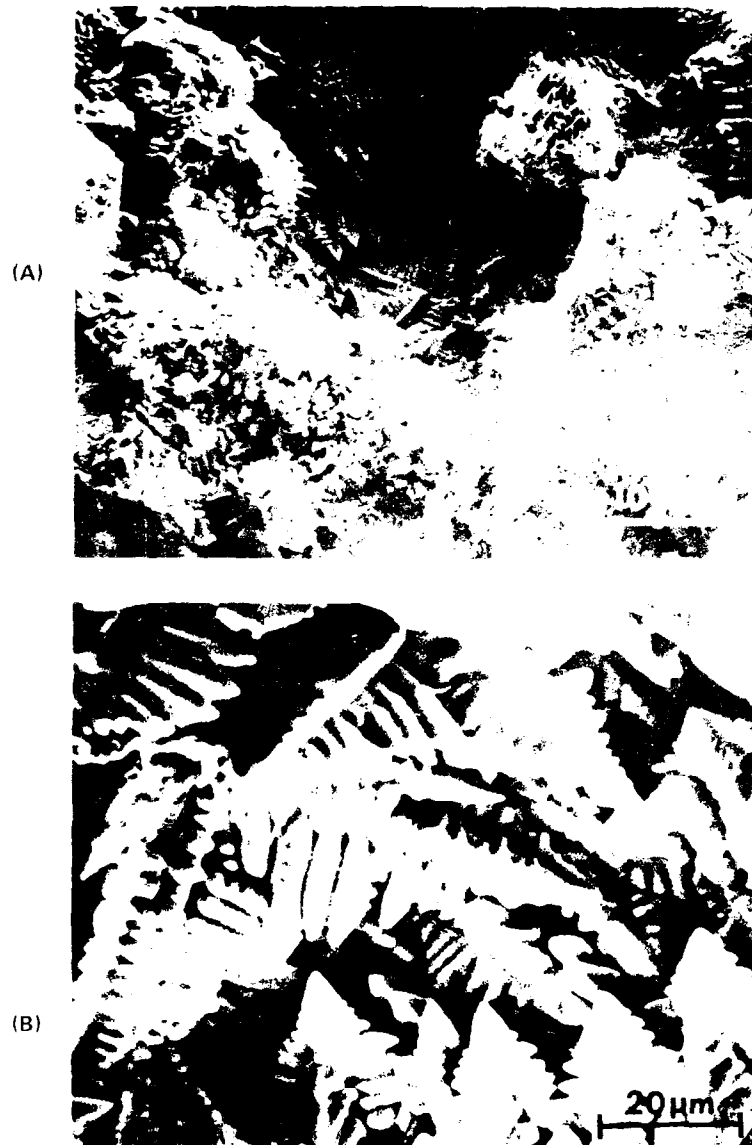
Figure 16   Scanning Electron Micrograph of Haynes 31 Showing A. Heterogeneous Nucleation of Dendrites on Surface of Primary Solid Particles During Machine Thixocasting and B. The Random Dendrite Structure in the Prior Liquid Region

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Another microstructural feature of a typical machine thixocast simulated airfoil section, shown in Figure 17, is the presence of a previously 100% liquid layer at the surface. At present it is not known whether the liquid layer is caused by a possible temperature gradient on the reheated slug or whether it is a rheological phenomenon associated with the flow of a particulate stream.

(A)

400µm

LONGITUDINAL DIRECTION

◄ PRIOR LIQUID
LAYER

◄ MIXED SOLID/PRIOR
LIQUID STRUCTURE

(B)

1mm

◄ PRIOR LIQUID
LAYER
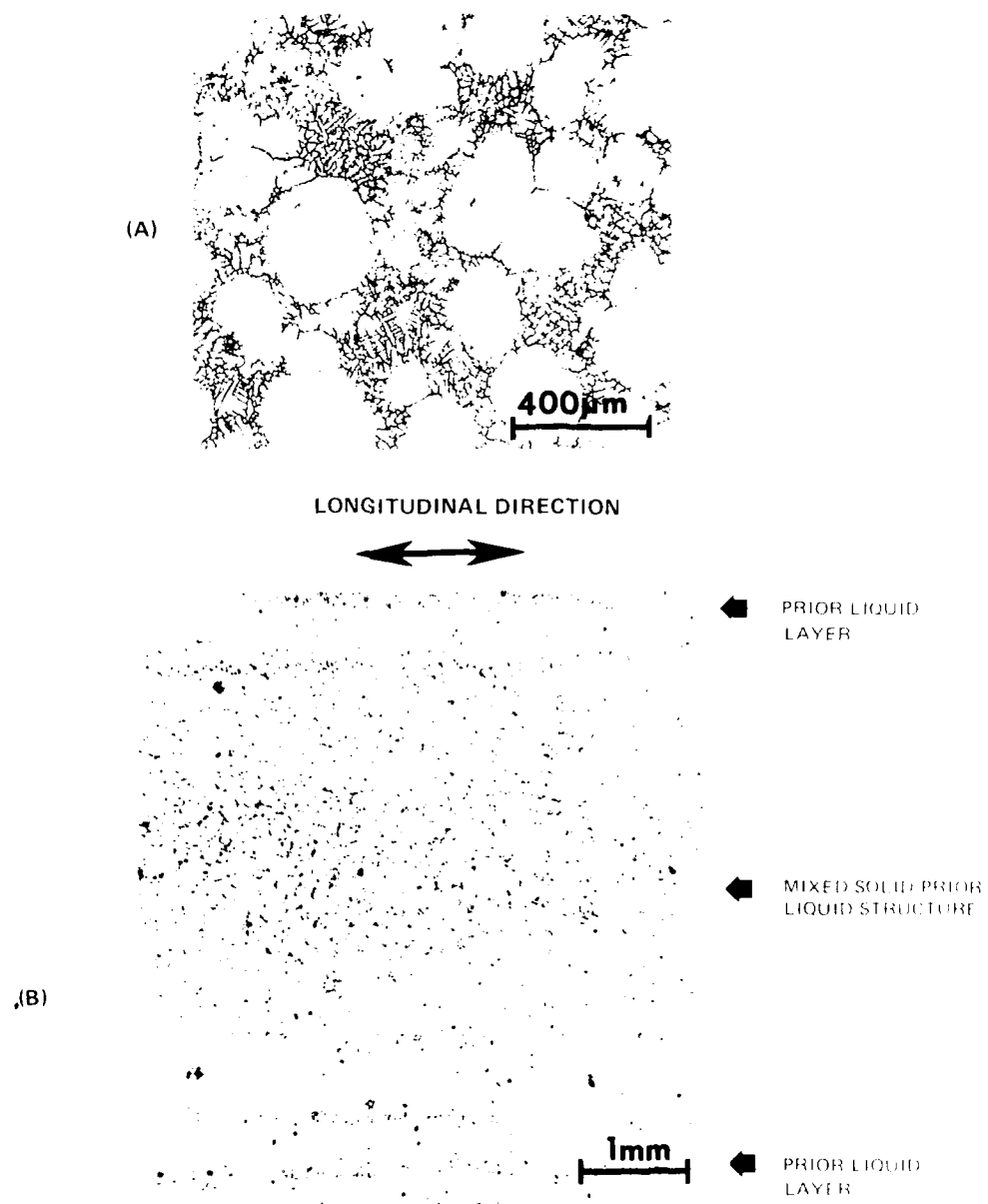
Figure 17   Microstructure of Machine Thixocast Haynes 31 Simulated Airfoil Section From Preliminary
Runs. A) General View and B) Detailed Microstructure Near Center of the Airfoil Section
Showing the Quenched Rheocast Microstructure Showing the Solid/Prior-Liquid Mixture at
The Center of the Airfoil and The Prior Liquid Layer at the Surface.

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Radiographic analysis indicated a significant difference in quality between castings initially containing low volume fraction solid and those containing high volume fraction solid. Examination of radiographs, shown in Figure 18 revealed that the degree of shrinkage type defects was higher in the low volume fraction solid containing materials than in the high volume fraction solid materials. These data are consistent with the propensity for shrinkage type defects associated with the present commercial die casting of liquid alloys.

A) LOW V/O SOLID   B) HIGH V/O SOLID
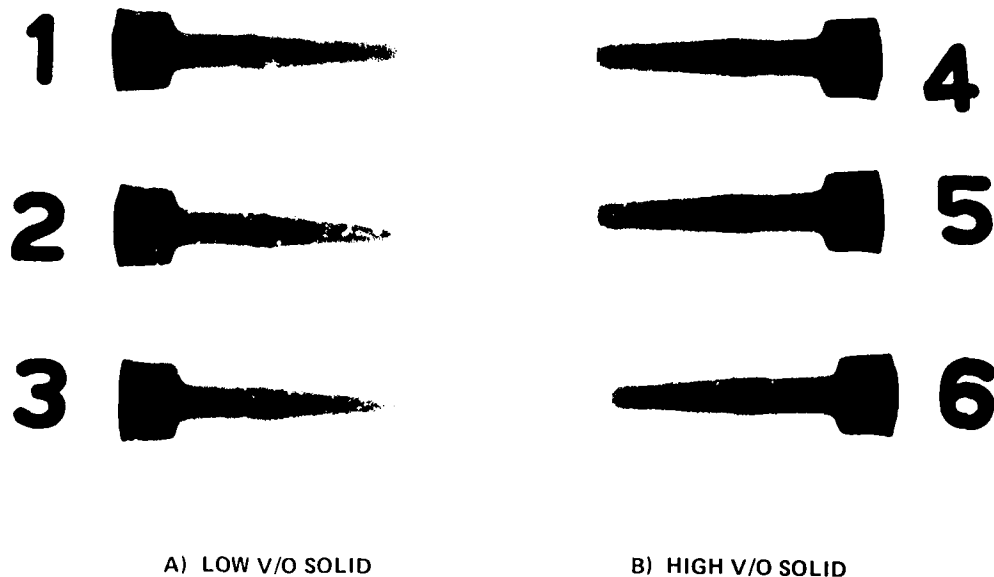
Figure 18   Radiograph of Machine Cast Blades Showing A) High Levels of Porosity Associated With High Preheat Temperature (Low V/O Solid < 20 V/O) and B) Low Levels of Porosity Associated With Lower Preheat Temperature (High V/O Solid ~ 50 V/O)

Visual examination of cast parts showed a difference in surface texture between those parts cast using a die temperature of 600°F and a die temperature of 1000°F. A much smoother surface existed at the higher die temperature as shown in Figure 19. This effect will be more thoroughly studied and documented as a future task of this program. There appeared to be no surface smoothness differences resulting from variations in preform temperature.

E. MECHANICAL PROPERTY EVALUATION

As discussed in Section II-B sufficient quantities of test material were produced in the first series of injection trials to gain a very preliminary assessment of alloy tensile behavior. It should be noted, however, that this material was processed at low volume fractions of solid and therefore contained shrinkage pores. Additional material processed at high volume fractions of solid contain less porosity and are currently being machined into test specimens.

A) 1000°F
DIE TEMP
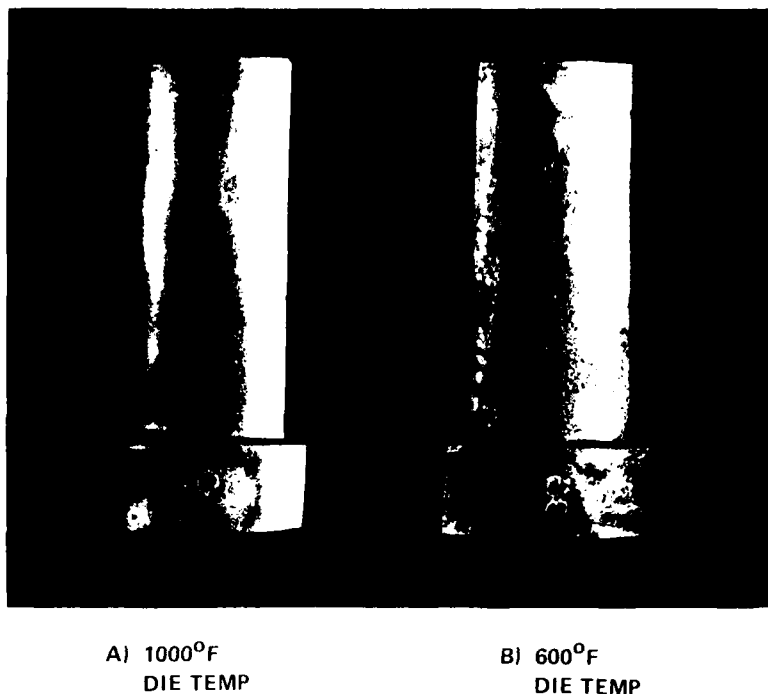
B) 600°F
DIE TEMP

Figure 19   *Comparison of Machine Cast Simulated Airfoil From Trials Employing A) 1000°F Die Temperature and B) 600°F Die Temperature*

The tensile properties of thixocast Haynes 31 from the Series I injection trials are presented in Table I. For comparison, typical tensile data for conventionally cast Haynes 31 material are also included. It can be seen that the yield strengths of the thixocast materials are higher than those of the conventionally cast material at both room temperature and 1000°F, while the tensile ductility of the machine thixocast sections is lower than that found in the conventionally cast material. The reason for this lower ductility is apparent from examination of fracture surfaces. The fracture in this specimen prematurely initiated at relatively large shrinkage pores and resulted in the lower values for the ultimate tensile strength and ductility. Figure 20 shows a scanning electron fractograph from specimen MX01-05 which was tested at room temperature. The general appearance of the fracture resembles that of powder metallurgy alloys. In this case, the granular appearance resulted from fracture along the interface between the primary solid particle and the prior liquid regions, although transparticulate fracture has also been noted. It is interesting to note that dimples typical of ductile-type fracture surface, indicating that the machine thixocast material possesses intrinsic ductility. Detailed fractography shows that all other tensile failures in the machine thixocast material can be attributed to similar types of fracture origin, namely pores caused by the presence of alloy shrinkage or foreign material believed to be "Fiberfrax". The appearance of all the fracture surfaces is qualitatively the same as that shown in Figure 20. A more transparticulate type of fracture was found to be associated with the elevated temperature test results (Figure 21) in which more dimple areas were also observed in the machine thixocast material at both room temperature and 1000 F (Figure 22).

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To determine the intrinsic ductility of the quenched rheocast microstructure, wafers of 0.050 inches thick were cut from cast sections, which did not contain observable defects. Two wafers were bent over a cylinder of 0.20 inch radius at room temperature. No crack was observed in either piece after the bending. The tensile strain at the outer surface of the bent wafers is approximately 10%, and clearly demonstrates the intrinsic ductility of the quenched rheocast microstructure.

This limited testing suggests that the intrinsic tensile strength properties of machine cast X-40 are at least equivalent to those of the investment cast alloy.

TABLE I

TENSILE PROPERTIES OF MACHINE THIXOCAST HAYNES 31
FROM PRELIMINARY RUNS

S/N	Microstructure	Test Temperature (°F)	0.2% YS (ksi)	UTS (ksi)	% El	% RA
MX01-01	Thixocast	R.T.	52	52	1.0	-- --
MX01-05	Thixocast	R.T.	71	82	2.9	4.0
AMS 5382	Conventionally Cast	R.T.	50	83	4.0	7.0
MX01-02	Thixocast	1000	43	59	6.1	10.9
MX01-06	Thixocast	1000	43	47	3.0	7.8
AMS 5382	Conventionally Cast	1000	26	65	10.0	8.0

(A) 50X

400 μm

200μm

(B) 100X

Figure 20   Appearance of the Room Temperature Tensile Fracture of a Machine Thixocast Simulated Airfoil Section. A) Topographic Feature on Fracture Surface, and B) Longitudinal Section Which Includes Fracture Surface

200μm

(A) 100X

20μm
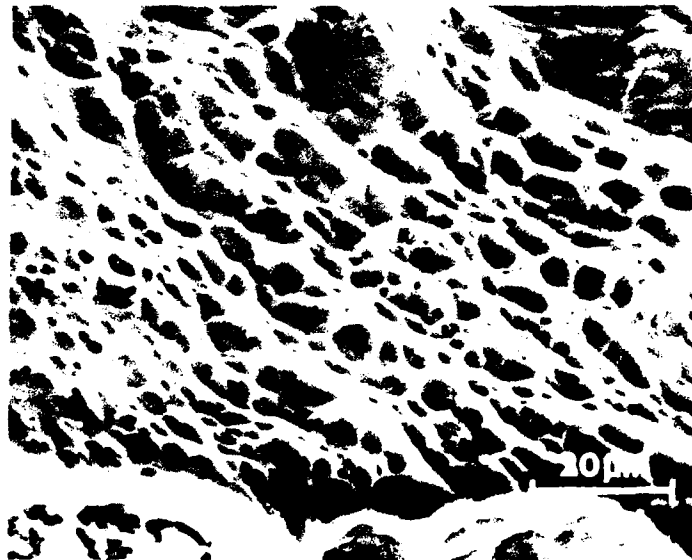
(B) 1000X

Figure 21   Appearance of the 1000 F Tensile Fracture of a Machine Thixocast Simulated Airfoil Section
A) Longitudinal Section of the Fracture Surface and B) Ductile Fracture Surface

23
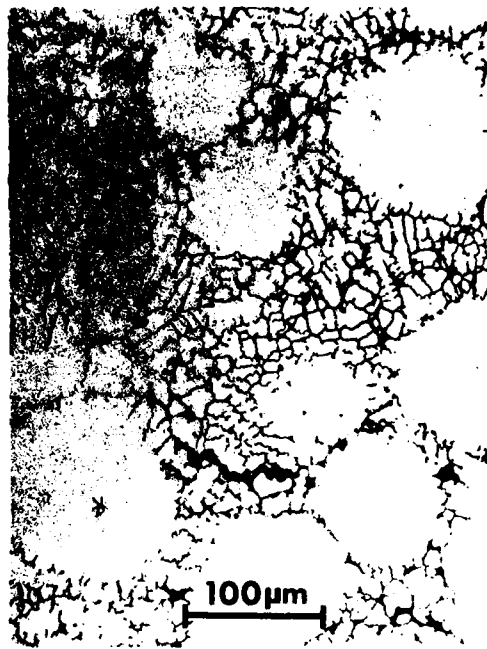
Figure 22 Longitudinal Section of a Tensile Specimen Showing Interdendritic Mode of Cracking in the Prior Liquid Regions (200X)

F. HEAT TREATMENT STUDIES

A study of the heat treatment response of rheocast Haynes 31 alloy has also been performed. The microstructures of the rheocast Haynes 31 after solutioning at 2250°F and aging at various temperatures are shown in Figure 23. The solution treatment results in partial dissolution of the primary carbide (M_7C_3) and coarsening by coalescence of the initially pearlite-appearing primary carbide (Figure 23a) which is not the case in the as-received rheocast structure structure (Figure 24). Preferential precipitation of $M_{23}C_6$ type of carbide at sub-grain boundaries and grain boundary regions is barely observable after aging at 1350°F for 24 hours. Much heavier precipitation of $M_{23}C_6$ carbide is observed when the aging was conducted at 1500°F. Discrete carbide particles are distributed rather uniformly, those in the grain matrix tend to align along crystallographic directions (Figure 23c). Similar observations can be made of the aging at 1650°F except that the distribution of the carbide particles is less uniform, and they tend to cluster at grain boundary regions (Figure 23d). The observed relative quantities and distributions of the $M_{23}C_6$ carbides precipitated during aging at various temperatures are those expected from the C-shape temperature-time-transformation (TTT) precipitation kinetics of $M_{23}C_6$ carbides. In this respect, the aging response of rheocast Haynes 31 may be considered as typical of those conventionally solidified.

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40μm (B)

(D)

Figure 23   Microstructure of Rheocast Haynes 31 After A) Solution Treatment of 2250°F/8-Hr/Rapid-Air-Cool, B) Solution + 1350°F/24-Hr Age, C) Solution + 1500°F/24-Hr Age, and D) Solution + 1650°F/24-Hr Age
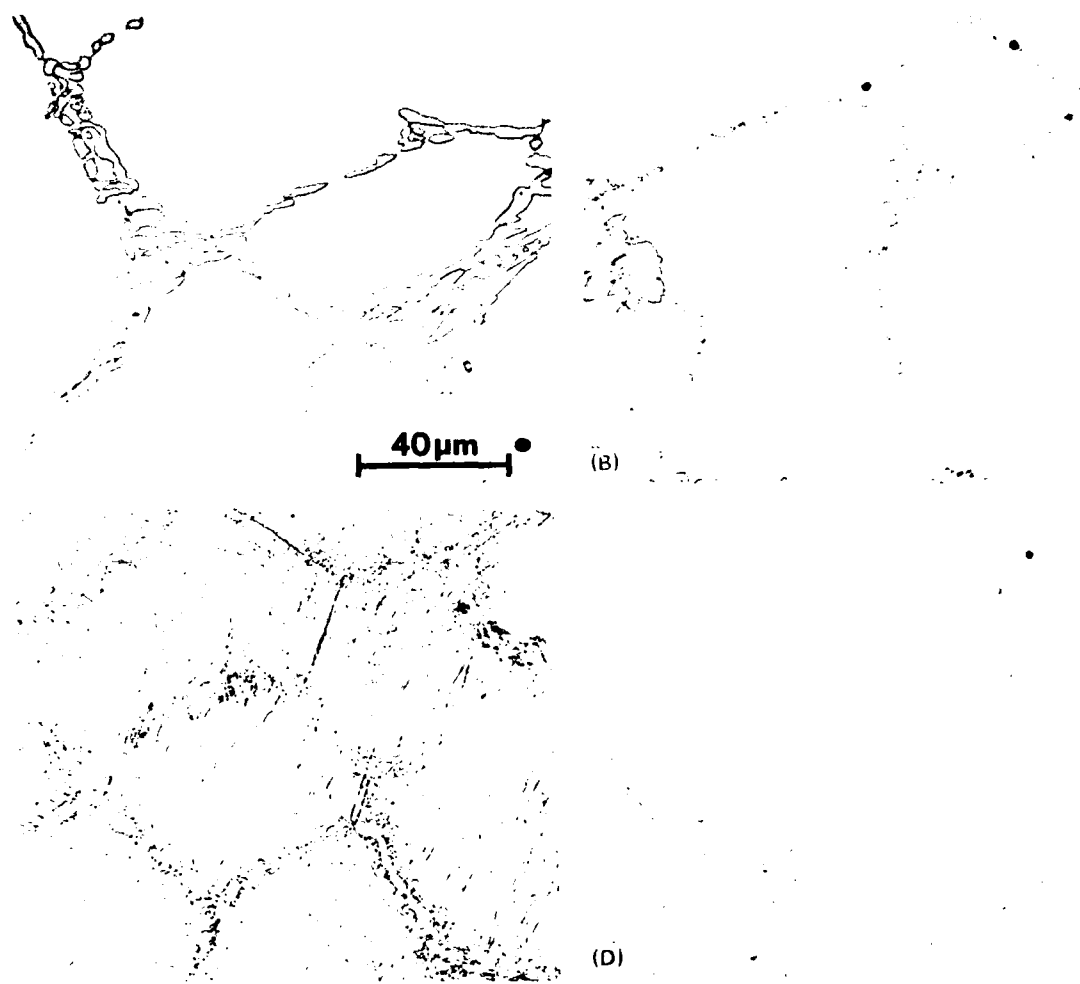
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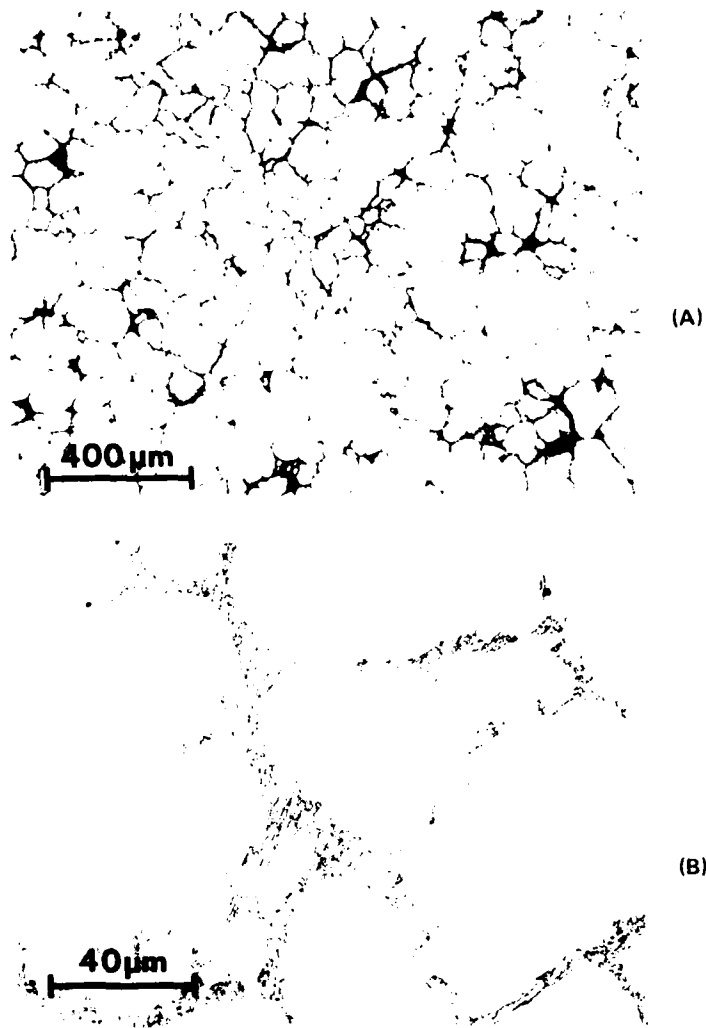
Figure 24   *Microstructure of As-Received Haynes 31: A) General View and B) Carbide Structure at the Boundaries*

The room-temperature Rockwell hardness corresponding to the microstructures shown in Figure 23 is illustrated graphically in Figure 25. The hardness after the solution treatment at 2250°F is the same as the as-received rheocast material, RC 27, indicating that very little additional carbon went into solution during the heat treatment (for comparison, the hardness of a vacuum cast Haynes 31 is RC 26). The hardness increases with aging temperature, and reaches a maximum at about 1500°F which corresponds to precipitation of rather homogeneously distributed $M_{23}C_6$ carbide particles (Figure 23c). Aging at temperatures above 1500°F resulted in heterogeneous precipitation and coarsening of $M_{23}C_6$ carbide particles, thus the observed decrease in hardness.

These heat treatment response studies have shown that the rheocast microstructure can be solutionized and aged in a manner similar to that experienced with conventionally cast material. This type of response may be critical to certain classes of age hardenable superalloys in order to achieve the desired mechanical property levels. In the case of Haynes 31, the alloy is normally used in the as-cast condition for airfoil applications. Therefore, mechanical property testing of the machine cast product will be performed in the thixocast condition. If necessary, a suitable solutionizing and aging treatment will be given to the machine cast product to further improve mechanical property response.
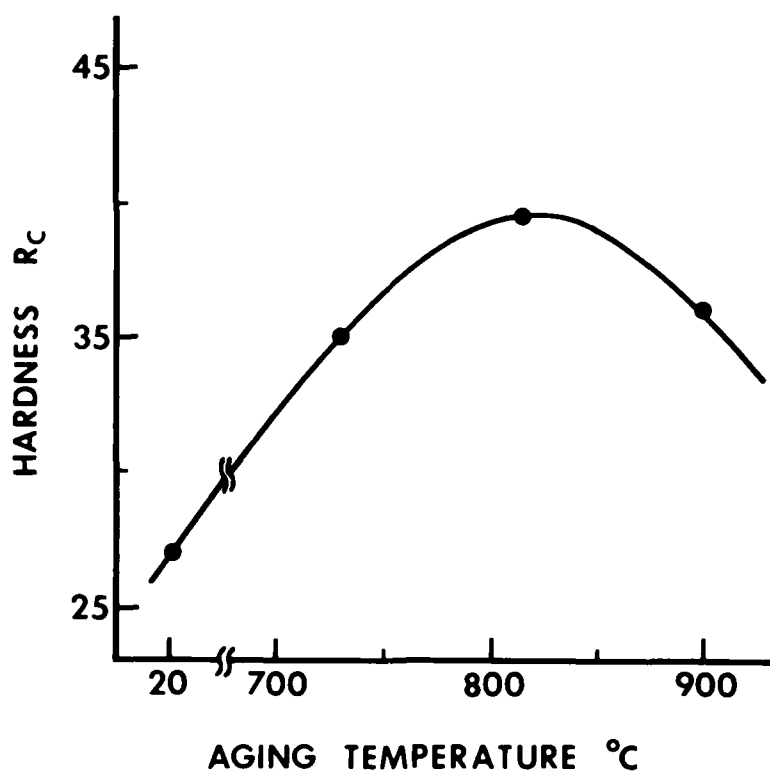
Figure 25   Hardness of Rheocast Haynes 31 vs. Aging Temperature. The Heat Treatment Conditions and Their Resulting Microstructures are Those Given in Figure 24.

G. SUMMARY OF WORK

The results achieved to date on this program have shown the potential of thixocasting for the fabrication of airfoil-type components using rheocast superalloys such as Haynes 31, a cobalt-base alloy. A machine casting facility has been improved to the point where reproducibility of operation has been achieved. The unit has been used to thixocast a number of simulated airfoils which under the proper processing conditions have yielded material with the desired microstructure and has demonstrated a potential for improvements in nondestructive quality. In addition, tensile properties measured from specimens machined from thixocast Haynes 31 alloy showed promising property levels compared to those for conventionally cast Haynes 31 (AMS 5382), especially when considering the very nature of the data and the quality of the thixotropic material involved.

Concurrently with this activity, a heat treatment response study was also performed which has shown that the rheocast material, when solutionized and aged, behaves in a manner similar to the conventionally cast product.

In summary, thixotropic processing to date appears to have a significant potential use for the fabrication of high quality gas turbine components. This aspect will be more fully investigated between now and the conclusion of the present P&WA effort with DARPA.

III. FUTURE PLANS

During the course of the next investigation period, a statistical test plan, described in Appendix A, will be employed to further evaluate the influence of process variables on the machine cast part quality. By taking this statistical approach it will be possible to maximize the information gained in the program utilizing the minimum number of test conditions. In addition, a more comprehensive mechanical property evaluation will be performed on selected machine cast components. One other aspect of the program is to design and construct an automatic transfer device for taking the rheocast specimens from the preheat chamber to the loading cradle. The details of these planned activities are discussed below.

A. PARAMETRIC BEHAVIOR

The overall quality of machine cast components is significantly affected by several process variables. These include preform temperature (or more correctly, volume fract·on solidified), gate velocity, die temperature, transfer time and gating configuration. In order to assess these parametric effects, a statistical test has been prepared and is described in detail in Appendix A. The test matrix from this plan is shown in Figure 26. This type of matrix can be repeated for a variety of gating configurations. Transfer time currently involves a manual preform transfer arrangement which will be recorded for each individual run. The parametric variables for each gating configuration (including transfer time) will be evaluated for their effects, either individual or combined, on the overall quality of blades as measured nondestructively and microstructurally. The results of this statistical analysis will then be used to optimize processing parametrices.

TEXT MATRIX

	T1		T2	T3		DIE TEMPERATURE
	V1	V3	V2	V1	V3	GATE VELOCITY
S1	X	X		X	X	
S2			X			
S3	X	X		X	X	

% SOLID

X = TEST POINT

Figure 26   Statistical Test Matrix for Evaluation of Machine Casting Parameters

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B. MECHANICAL PROPERTIES

Selected specimens from the statistical survey described above will be evaluated for mechanical properties. Testing will consist of evaluating creep rupture, and high cycle fatigue properties and room and high temperature tensile strength. These specimens will be selected based on microstructural considerations as well as overall nondestructive quality. In particular, the radiographic quality will be evaluated for mechanical property specimens to assess soundness of the specimens, thereby insuring that the testing represents the inherent strength behavior of thixocast material. These data will then be compared to baseline data generated on as-cast Haynes 31 (AMS 5382) materials to determine the applicability of the process for the fabrication of critical components. If necessary the alloy will be heat treated to provide additional mechanical property improvement.

C. PROCESS AUTOMATION/MECHANIZATION

Machine casting processes are dependent on a variety of factors including starting material costs, die life, ability to cast multiple parts, etc. However, a major factor in achieving high part quality is process reproducibility. Parametric studies will point toward the proper processing conditions to achieve high quality parts, however, part reproducibility is primarily a function of the consistency of the machine casting equipment operation. In order to achieve operational reproducibility, it is necessary to automate/mechanize wherever possible to insure minimal variations in the optimized processing procedures.

At present, the machine casting facility is operated manually in the following fashion. The preform and container are loaded on the hydraulic loading ram which then locates the preform in the furnace. Power is applied to the induction coil which directly couples with the preform. When the proper temperature (volume fraction solid) is reached, the penetrometer stylus pierces the specimen. At this point the loading ram is withdrawn from the furnace by manual valve operation. The operator transfers the preform to the loading cradle on the machine casting unit with a pair of tongs and then actuates the injection ram with a foot pedal.

Each of these operations is keyed to the skill of the operator and will normally occupy a combined interval of from 3.5 to 4.5 seconds under ideal conditions. Also, this length and variability of transfer time can adversely affect the quality of the machine cast part because of variable and excessive preform heat losses. These can readily be compensated for through the use of automated control of the process.

As assessment of automated transfer of the rheocast specimen machine casting unit will be made a part of this program. A simple means of process control is shown in Figure 27 and basically consists of limit switch control in the heating, transfer, and injection steps of the process. The preform heater will be located directly above the loading area of the machine casting unit. The preform and container will be placed on a hollow pedestal attached to a loading ram and located in the heater. When the part reaches the proper volume fraction solid, the penetrometer will pierce the preform. The downward movement of the penetrometer will trigger a limit switch which will activate the loading ram. The platform which holds

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the pedestal is both parted and hinged and has a cam follower wheel attached. As the platform is lowered, the wheel will follow the cam surface shown in Figure 27. The cam surface will translate the preform and container from its initial vertical position to a horizontal position directly into the preform cradle. When the preform reaches its final position, another limit switch is tripped which in turn activates the injection ram. The ram travels through the platform "port" and the hollow pedestal, and then through the preform container injecting the preform into the die. This transfer and injection can occur as quickly as two seconds with variations of as little as ±0.1 second. Cylinder dampers, alignment rods, cover shields, etc. will also be added to assure consistent alignment and operation.

Refinement of process parameters will be greatly enhanced by consistent processing conditions and will also allow a more meaningful evaluation of those parameters which will have the most significant affect on overall machine cast part quality.
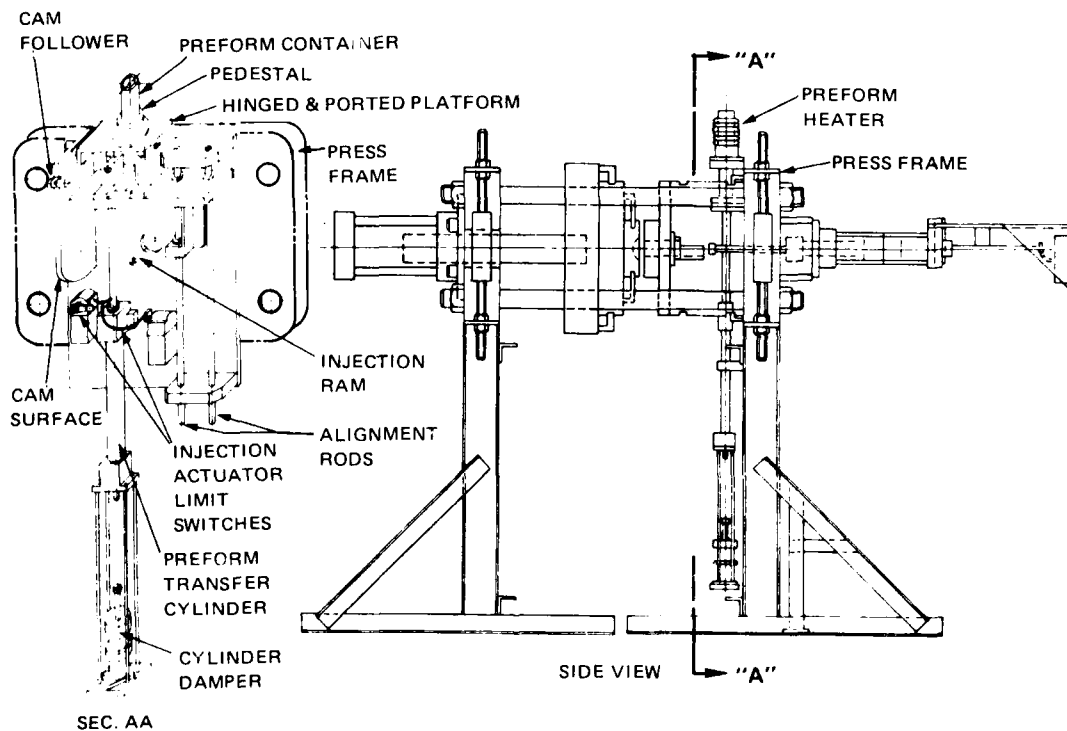

Figure 27   Schematic of Automatic Transfer System for Use With The Machine Casting Unit

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APPENDIX "A"

STATISTICAL TEST PLAN
FOR
MACHINE CASTING

Statistical methods are used to plan, analyze, and process results of experiments containing factors corresponding to those associated with complex development problems. By varying these factors in a planned manner, it is possible to isolate and study the effect produced by any one factor, or combination of factors upon the problem.

The use of statistical techniques widens the scope of the program by providing the maximum use of test information. By implementing these methods in the test program, cost savings are achieved through the reduction of the number of tests required and the time to obtain productive information is minimized.

For these reasons, statistical techniques will be used throughout the machine casting program where it is considered the most cost effective means of providing the desired information.

PROGRAM PLAN

Initially, the factors of gate velocity, die temperature, volume percent solid, and gate placement will be investigated for their effect upon blade quality. A statistically designed test program of the Box-Wilson type will be employed in this stage of the program. Shown both schematically and in matrix form below, testing will be conducted for each of the gate sizes to be examined.

The test plan illustrated not only quantitatively measures the impact of the four variables on blade quality, but it assesses the blade quality. Furthermore, the statistical plan permits a quantitative evaluation of the relationship between the variables and the response parameter; this is a capability which is not generally possible with the typical engineering approach.

The tests will be fully replicated for each gate geometry. The rational for repeat tests is threefold:

(1) The possibility of extraneous random effects introducing bias into the test results can be detected if such should occur.

(2) A measure of the inherent variation in the machine casting process can be obtained and used as a reference point when assessing the reproducibility of the process.

(3) It provided a means of analytically assessing the significance of the process variable effects.

DATA ANALYSIS DECISION TECHNIQUE

The Analysis of Variance (ANOVA) and regression analysis will provide the means of identifying the significant effects of the variables and evaluating their trend.

The ANOVA will be applied to the data contained in the factorial design illustrated. This analysis rests on a separation of the variance of all the observations into parts, each of which quantitatively measures the variability attributable to some specific factor or combination of factors. This method of analysis, therefore, has two important advantages over nonstatistical methods:

1. The analysis results in consistent assessments of the factor's effect on the response. If two or more independent analyses of the data are performed, they will arrive at the same measurement of the relationship between the factors and the response.

2. The analysis provides a method of interpreting the degree of certainty of the relationship between the factors and the response, i.e., whether the measured effect of the factor associated with the response is real of if it is due to random variation.

The table which follows illustrates the mechanics of the ANOVA and how the significant factors are identified.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Main Effects				
Die Temp (T)	SS_T	DF_T	$(SS/DF)^T$	MS_T/MS_E
Vel (V)	SS_V	DF_V	$(SS/DF)_V$	MS_V/MS_E
Vol. % Solid (S)	·	·	·	·
Gate Geometry (G)	·	·	·	·
Interactions				
TXV				
TXV				
·				
·				
·				
SXG				
TXVXS				
TXVXG				
·				
·				
·				
VXSXG				
TXVXSXG				
Error	SS_E	DF_E	$(SS/DS)_E$	
Total	SS_{Total}	$N_{Total}-1$		

The use of the F-test in the ANOVA is as follows:

1. A table of the probability that the ratio of mean squares will be equal to or exceed a given value (F - table) may be found in most statistical textbooks. The value to be used in this table is determined by: (a) stating a probability (confidence level) that one wants to associate to the statement of whether the factor caused a significant change in the response, and (b) knowing the number of degrees-of-freedom associated with the numerator (the factor mean square) and the denominator (the error mean square) of the ratio. The confidence level to be used will be 90%.

2. If the test index of any first or higher order factor is greater than or equal to the F - table value, the factor will be considered to have a significant effect on the response.

3. If the test index is less than the F - table value, it will be concluded that there is insufficient evidence to believe that the factor had a significant effect on the response.

Multiple regression analysis will be used to develop a response surface incorporating the variable main and interaction effects identified as significant process variables in the ANOVA. The mathematical model of the machine casting process will thus be based on meaningful parameters and will be considered a useful description of the physical quantities that go into making up the process. The relationship will be of the form

$$Y = a + b_1 x_1 + b_2 x_2 + \ldots \ldots$$

Where Y = quality characteristic measurement
x_i = variable *main or interaction effect*
a = intercept
b_i = the average change in the response associated with the change in the variable

The values of a and the b_1's are determined from the standard least squares solution whereby $\Sigma (Y_i - Y)^2$ is minimized. Y_i is the actual response obtained from the test program and Y is the response calculated from the regression equation.

MACHINE CASTING SCHEMATIC

GATE VELOCITY

TEST POINTS

DIE TEMPERATURE

VOLUME PERCENT SOLID
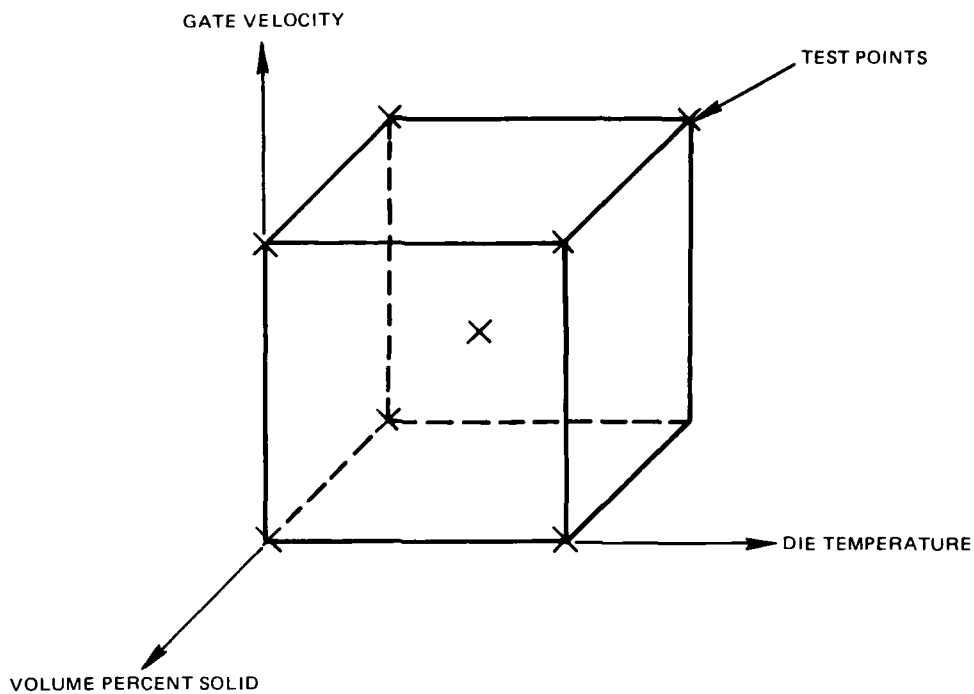
MACHINE CASTING MATRIX

	T1		T2	T3		DIE TEMPERATURE
	V1	V3	V2	V1	V3	GATE VELOCITY
S1	X	X		X	X	
S2			X			
S3	X	X		X	X	

VOL. % SOLID

X = TEST POINT

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Watertown, Massachusetts 02172
Machine Casting of High Temperature
Alloys for Turbine Engine Components
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Corporation, Pratt & Whitney Aircraft Group.
East Hartford, Conn. 06108
Technical Report AMMRC CTR 77-6 - Contract
DAAG 46-76-C-0029 D/A Project ARPA
Order No. 2267, AMCMS Code 6410 Interim
Report, 1 March 1976 to August 1976

Key Words

Die casting
Solidification
Heat persistant alloys
Iron alloys
Compressor parts
Turbine parts
Quality assurance

The objective of this program is to evaluate the capability to machine cast parts for gas turbine engines. Machine casting in the thixatropic state is being evaluated. Partial assessment of process parameter effects, using Rheocast Haynes Alloy 31, was performed. Machine casting preforms of various volume fractions of solid were injected at different die temperatures. Results indicated internal porosity and surface condition were improved with increasing die temperature and volume fraction solid. A heat treatment response study and some limited mechanical property evaluations were also conducted. Heat treatment studies indicated long term annealing followed by aging yielded microstructure similar to conventionally cast heat treated Haynes 31 alloy.