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X-RAY COMPUTED TOMOGRAPHY FOR ADVANCED MATERIALS AND PROCESSES

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Due to demanding requirements imposed on current and future high-performance aerospace structures, advanced materials are being developed for and used in a variety of aircraft/aerospace applications. Production costs for advanced materials are generally higher and the payback will be greater for data leading to faster decision making or improvement in the product. The development and qualification of new materials, joining and manufacturing processes for advanced aircraft/aerospace applications is accelerated by the availability of quantifiable data on design characteristics and their variations.

X-ray computed tomography (CT) provides quantitative measurements of material characteristics in terms of the dimensions, density and composition. The sensitivity of CT is dependent upon a number of factors including the test article and the CT system technology employed. The evaluation capability of CT overcomes the limitation of current qualitative inspection techniques to provide an objective measure of material or component condition. The results of studies involving CT testing of various advanced materials, manufacturing processes and joining methods revealed four specific areas in which there is potential for significant economic benefit from CT. These areas are 1) new product development, 2) process control, 3) noninvasive micrography, and 4) material performance prediction.

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SUMMARY

Under a preliminary testing task assignment of the Advanced Development of X-ray Computed Tomography Application program, computed tomography (CT) has been applied to the evaluation of advanced materials and processes. Due to demanding requirements imposed on current and future high-performance aerospace structures, advanced materials are being developed for and used in a variety of aircraft/aerospace applications. The key design characteristics of advanced materials is that they are "tailored" to have the properties required for a given application. Production costs for advanced materials are generally higher and the payback for data leading to faster decision making or improvements in the product will be greater than for traditional materials with well established production methods. The development and qualification of new materials, joining and manufacturing processes for advanced aircraft/aerospace applications would be accelerated by the availability of an evaluation technology that provides quantifiable data on design characteristics and their variations. X-Ray computed tomography (CT) is a quantitative nondestructive evaluation methodology that can provide such data.

CT provides a quantitative measure of dimensions, material density and composition. The sensitivity of CT is dependent upon a number of factors including the test article and the CT system technology employed, but roughly translates to a feature sensitivity of about 1/1000 of the test article size. The evaluation capability of CT overcomes the limitation of current qualitative inspection techniques to provide an objective measure of material or component condition. Additionally, where current techniques do not relate to quantitative damage tolerance criteria, CT has significant potential for use in effect-of-defect evaluations. The results of studies involving CT testing of various advanced materials, manufacturing processes and joining methods revealed four specific areas in which there is potential for significant economic benefit from CT. These areas are 1) new product development, 2) process control, 3) noninvasive micrography, and 4) material performance prediction.

DISCLAIMER

The information contained in this document is neither an endorsement nor criticism for any X-ray imaging instrumentation or equipment used in this study.

1.0 INTRODUCTION

The goal of the Advanced Development of X-Ray Computed Tomography Applications demonstration (CTAD) program is to evaluate inspection applications for which computed tomography (CT) can provide a cost-effective means of inspecting aircraft/aerospace components. The program is task assigned so that specific CT applications or application areas can be addressed in separate task assigned projects. This interim report is the result of a task assignment study. Under the program, candidate hardware is selected for testing that offers potential for return on investment for the nondestructive evaluation system and operation. Three categories of task assignment are employed in the program: 1) preliminary tests where a variety of parts and components in an application area are evaluated for their suitability to CT examinations for their inspection; 2) final tests where one or a few components are selected for detailed testing of CT capability to detect and quantify defects; and 3) demonstrations where the economic viability of CT to the inspection problem are analyzed and the results presented to government and industry. This interim report is the result of a preliminary task assignment study on the use of CT for advanced aerospace materials, processes and joining. Additional task assignment reports that have been issued by the CTAD program are listed in references 1 through 8.

1.1 Computed Tomography

X-ray computed tomography (CT) is a powerful nondestructive evaluation technique that was conceived in the early 1960's and has been developing rapidly ever since. CT uses penetrating radiation from many angles to reconstruct image cross sections of an object. The clear images of an interior plane of an object are achieved without the confusion of superposition of features often found with conventional film radiography. The CT images are maps of the relative linear X-ray attenuation coefficient of small volume elements in the object. The X-ray linear attenuation coefficient measurement is directly related to material density and is a function of the atomic number in the small volume elements. The volume elements are defined by the reconstruction matrix (in combination with the X-ray beam width) and by the effective CT slice height. The CT results can provide quantitative information about the density/constituents and dimensions of the features imaged.

Although CT has been predominantly applied to medical diagnosis, industrial applications have been growing over the past decade. Medical systems are designed for high throughput and low dosages specifically for humans and human sized objects. These systems can be applied to industrial objects that have low atomic number and are less than one-half meter in diameter. Industrial CT systems do not have dosage and size constraints. They are built in a wide range of sizes from the inspection of small jet engine turbine blades using mid-energy (hundreds of keV) X-ray sources to the inspection of large ICBM missiles requiring high (MeV level) X-ray energies. Industrial CT systems generally have much less throughput than medical systems. The CTAD program utilizes a wide range of CT systems, both medical and industrial.

1.2 Scope and Objective

This task assignment, designated "Task 9 - Advanced Materials and Processes," is a preliminary testing task directed at the evaluation of advanced materials, joining techniques, and manufacturing processes for material development in the aerospace/aircraft industry. Due to demanding requirements imposed on current and future high-performance aerospace structures, advanced materials are being developed for and used in a variety of aircraft/aerospace applications. Materials are often called "advanced" if they exhibit properties, such as high temperature strength or high stiffness per unit weight, that are significantly better than those of more conventional structural materials, such as steel or aluminum. Advanced materials include structural ceramics (also ceramic matrix composites (CMCs)), polymer matrix composites (PMCs), metal matrix composites (MMCs), and new high temperature/high strength alloys.

The key to advanced materials is that they are "tailored" to have the properties required for a given application. However, due to the nonhomogeneous nature of advanced materials (which are often a mixture of fibers or particulates and a matrix), problems arise in their manufacture and handling which result in defects unique to these materials, some of which can be hidden or uncharacterized. These defects include: delaminations, porosity, nonuniformities, fiber misalignment, improper layups or fiber volume fractions, honeycomb damage (in sandwich composites), facesheet/webbing disbonds, matrix cracks and damage due to impact. In addition, many advanced material parts are complex, and therefore are difficult to inspect. Advanced materials may include channel shapes with tight radii, multilayered honeycomb structures, injection molded powder metal parts, and diffusion bonded alloys.

Aircraft and aerospace structures are dependent on the joining of materials for their assembly and strength in service. The joining processes of welding, bonding and fastening are used with conventional and advanced materials. The development and qualification of the joining processes for new joining applications would benefit from an inspection technology that has quantifiable data acquisition. For example, with fasteners the geometric shape and alignment of the hole and fastener is critical to the performance of the joining operation. This is particularly true for fastening of composite skins. Measurement techniques for fastener holes and gaps are needed.

Materials fabrication techniques are currently being developed and utilized which offer lower production costs than traditional methods. The materials are often made up of metals, alloys, or plastics. The parts manufactured by these methods can contain defects which are unique to the process and material. This development of new materials and processes is generating a need for improved quantitative nondestructive evaluation measurements. Conventional qualitative methodologies (ultrasonics, radiography and visual) are proving inadequate to fully characterize and understand properties and defects of advanced materials and processes. CT offers considerable potential to reveal three-dimensional quantitative information useful for design and manufacturing inspection and analysis. CT can precisely define the size and location of voids, inclusions, low density areas, and cracks within the inspected component. Depth information is useful in categorizing and evaluating defects. It is sensitive to density variations, and can quantify gradients and materials differences. CT can define the details of internal structure of complex configurations. Because complete spatial information on part configuration and defect location is available from CT, an engineering assessment of the as-built component is possible.

The objective of this task is to determine the technical and economic feasibility of using CT for the inspection and analysis of advanced materials, the development and monitoring of advanced processes, and the evaluation of joining techniques in the aircraft/aerospace industry.

2.0 TEST PLAN

The Task 9 test plan included the acquisition of test samples, CT scanning, and data evaluation. Contacts were established throughout The Boeing Company and the aircraft/aerospace industry to obtain appropriate test samples.

A scan plan was developed for each component in order to effectively evaluate each part and to demonstrate the capability of CT to provide useful information. The potential of CT to serve as an analytical tool for material properties was also investigated. The CT data was evaluated for its technical benefit and an economic analysis was done for the various areas where CT showed payback potential. Finally, this interim technical report was written which describes the effort on this task and summarizes the results.

2.1 Component Selection

Representative advanced materials and components were sought from the Boeing Company and from several aerospace/aircraft manufacturers and material suppliers for use in studying CT capability. Table 2.1-1 lists the parts investigated for this task assignment along with their assigned identification number and evaluation goals.

The majority of materials and components tested in this task were acquired from Boeing and Rohr Industries of Chula Vista, CA, a manufacturer of composites for aerospace applications. Besides Rohr, other industry participants included Greenleaf Corporation, Hi-Tech Ceramics, TRW and Sandia National Laboratory.

2.2 CT Testing

CT testing was performed at appropriate facilities based on the capability of the systems identified in earlier CTAD task assignments , the availability and cost. The quality of the CT imaging is not unique to any particular system utilized but in fact should be obtainable by alternative CT systems that have nearly equivalent resolution and contrast sensitivity for the component size under examination. Approximate values for the level of resolution in line-pairs/mm (lp/mm) and the contrast sensitivity as determined by signal/noise (S/N) ratios are provided where possible.

The example CT image results presented in this report allow the reader to extrapolate the potential of CT on other systems which may provide greater or lesser detail sensitivity. Depending on the features or characteristics that are desired in a material examination with CT, it is possible to make trade-offs of resolution and S/N (choosing higher resolution and lower S/N or vice versa) while still maintaining nearly equivalent feature sensitivity. In some cases though, high resolution may be the determining factor in providing sensitivity to fine feature details while in other cases high S/N may be the requirement for material consolidation measures. In general, high contrast features such as voids and inclusions benefit from high resolution imaging while low contrast material variations such as fiber/resin variations benefit from high S/N.

2.3 Data Evaluation

Data evaluation of the CT results on the advanced material test components primarily consisted of evaluation of the detail sensitivity to features of interest and the usefulness of that information. In some cases comparison with destructive micrographic information was performed. Also where available, correlation to material performance characteristics, such as strength, were made.

The results and data evaluation have been divided into the three main categories: 1) advanced material, 2) manufacturing processes and 3) joining. All the CT systems used on this program displayed their data information on a high-resolution video terminal but hard copy image reproduction techniques varied. Image quality in this report is necessarily reduced (often significantly) from original image displays because of the reproduction process.

Table 2.1-1 Advanced Materials and Processes Samples

PID #	Description	Evaluation Goals
040129	PMR-15 core cowl frame	Delamination
040130	PMR-15 strut, rectangular core	Disbond between insert and skin
040131	PMR-15 strut, oval core	Delamination
040132	PMR-15 curved specimen	Near surface delamination
040133	PMR-15 1 inch cube	Microcracking
040134	PMR-15 square corner radii sample	density distribution
040135	PMR-15 box	Consolidation
040218	Graphite/epoxy w/Nomex core 737 fan cowl	Skin and core separation
040219	PMR-15 Al core panel	Density distribution/material separation
040220	Graphite/epoxy curved core panel	Disbond in the radii
040311	Pultruded CP rods	Density level and distribution
040406	Fiber reinforced polyetherimide test coupons	Fiber distribution; porosity
040407	Injection molded PPS/glass radome	Density distribution; dimensions
050101	Al/Ti/Gr casting with SiC	Consolidation
050102	SiC reinforced Ti MMC plates	Fiber distribution
050103	Drape formed diffusion bonded Ti MMC, large	Fiber distribution
050104	Drape formed diffusion bonded Ti MMC, small	Fiber distribution
040105	SiC reinforced Ti MMC plates	Fiber distribution
050204	ATF graphite epoxy test coupon	Microcracking
050205	Reticulate ceramic filter	Cell size, distribution; clogged material
050306	2D involute block	Density distribution; weave pattern
050307	3D coarse weave ITE block	Density distribution; weave pattern
050308	2D fine weave block	Density distribution; weave pattern
050309	Composite flameholder 106	Delamination
050310	Composite flameholder 108	Delamination
050311	Biaxially stiffened, SiC coated carbon composite	Density distribution; defects in stiffeners
050312	Carbon composite plate	Delamination
050313	CVD 2D woven composite	Porosity distribution
050314	SiC coated composite test sample	coating quality
050315	2D composite involute test pieces	Microcracking
050316	Coated composite w/silicon nitride inserts	Coating thickness
050317	Coated composite w/silicon nitride sleeve	Coating quality; material fit
050318	SiC coated composite "J" section	Coating quality; material fit
050319	Partially coated composite "C" section	Coating quality; consolidation
050509	SiC coated composite plate	Coating quality
050604	Leading edge heat pipe	Internal walling thinning
050705	SPF Ti component	Density especially near bondline
050803	Powder metal injection moldings	Point voids; shrinkage; cracks
050804	Induction brazed MMC panel w/ Ti core	Core-to-facesheet braze quality
050805	Ti honeycomb "T" section	Core quality
050806	Injection molded C-P missile wing	Cracks; porosity; flow pattern
050807	Al oxide cutting tools w/SiC whiskers	Possible voids
050808	Fiber loaded syntactic block	Density gradation
050809	Syntatic/graphite epoxy sandwich defect panel	Delaminations; cracks; material differentiation
050810	Kevlar/epoxy/rubber bottle section	Wall thickness; internal features
050811	Silicon nitride radome	Density distribution; dimensions
050812	Foam radar cone	Density distribution
050813	Al oxide cutting tools w/defects	Internal stringer; cracks; voids
050814	CP lug plate w/fillers	Voids
050815	CP ablative ring	Delamination
060101	Al ducting w/flange weld	Delamination
060110	E-beam welded pressure vessel	Porosity, voids in weld
060307	Fastener hole test block	Cracks
060308	Hi-Lok fastener on graphite epoxy	Collar/nut fit measurement
060309	Fastener	Fit measurement
060310	Sectioned fastener	Fit measurement
060311	Unsectioned fastener test sample	Fit measurement
060312	Unsectioned fastener test sample	Fit measurement
060313	Composi-Lok 2 fastener on PEEK	Fastener/composite fit measurement

3.0 CT FOR ADVANCED MATERIALS

Advanced materials for which CT has been tested in this effort have been subdivided into the major categories of carbon based composites, metal matrix composites and ceramics.

3.1 Carbon Based Advanced Composites

High temperature carbon-based composites have been utilized extensively in a variety of aerospace applications, including ablative nose cones, rocket nozzle throat entries, and exit cones for space vehicles. CT has previously been shown to have application with some carbon composite products, including the exit cones on the Boeing-built IUS rocket [9,10].

As flight technology heads toward higher speeds, there is an increasing interest in oxygen protection of carbon composites used for high temperature aero surfaces on aircraft that operate in earth's atmosphere. Methods for evaluating the coatings and the composite underneath need to be developed. CT has potential to meet this need in some applications.

3.1.1 Carbon Composite Test Specimens

A variety of small carbon composite components were collected for evaluation with CT to determine the technical benefits of CT for this class of important aerospace materials. Figure 3.1-1 is a photograph of three carbon composite blocks approximately 10 cm long. The material each is made from is uniquely manufactured, producing a particular weave pattern and consolidation. Figure 3.1-2 is a CT slice through the three blocks taken on a CT system with medium resolution (nominally 1 lp/mm) and high contrast sensitivity (S/N > 100). The CT image reveals differences in density in the blocks and the weave pattern in the center block.

A 2D carbon composite coupon excised from a larger structure used in high temperature applications is shown in Figure 3.1-3. A photomicrograph of a 7 mm by 4 mm area of the coupon is shown in Figure 3.1-3a and a high resolution (~ 10 lp/mm) CT slice is shown in Figure 3.1-3b. The CT data provides quantitative measures of features such as cracks and voids. The entire volume of a coupon could be CT scanned at a fraction of what it would cost to successively polish and photograph though the complete volume.

3.1.2 2D CVD Weave

Figure 3.1-4 is a photograph of a section of a 2D woven composite manufactured by chemical vapor deposition (CVD). This material was CT scanned for the purpose of determining the void size and distribution. Electron microscopy (EM) revealed that the voids were present, but the actual void trends were obscured by the EM sample preparation. Figure 3.1-5 is a high resolution (~ 10 lp/mm) CT slice of the material. The image shows the weave pattern and the larger voids. However, for this material, even higher resolution (50 lp/mm) with equally thin slicing is needed to image the smaller voids and weave details.

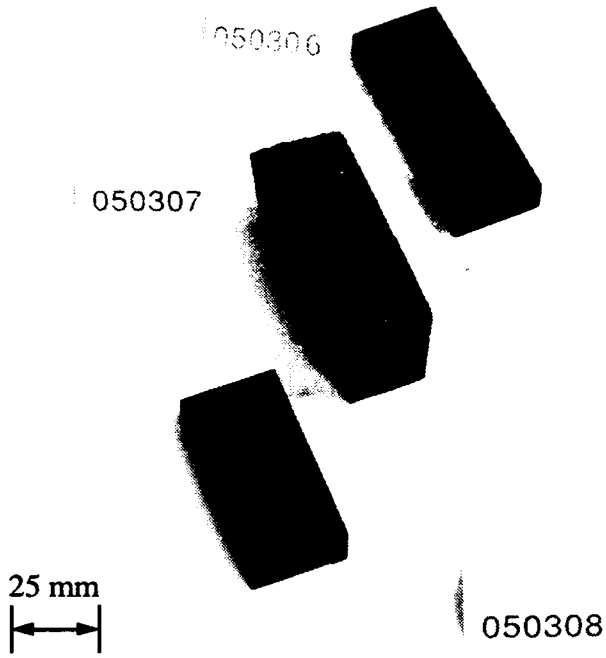


Figure 3.1-1 Photograph of three carbon composite test blocks manufactured by different processes.

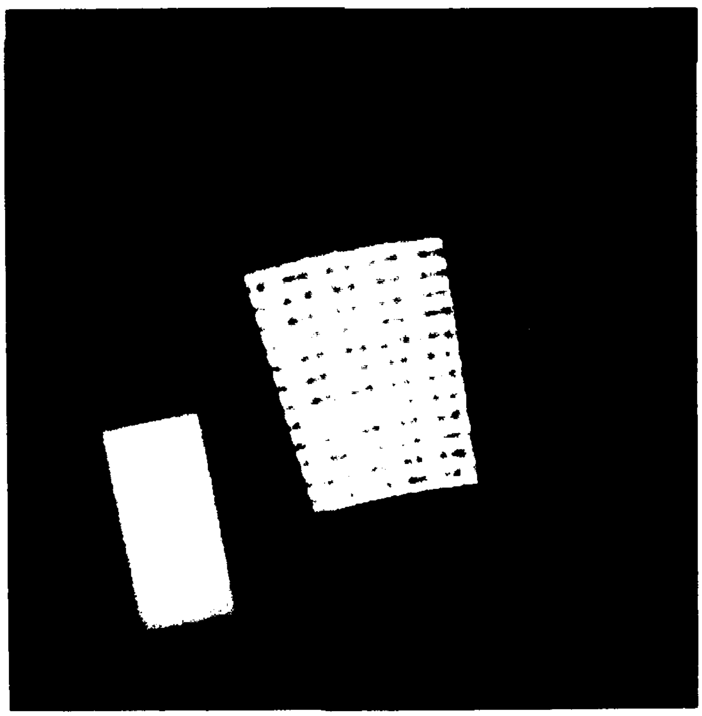
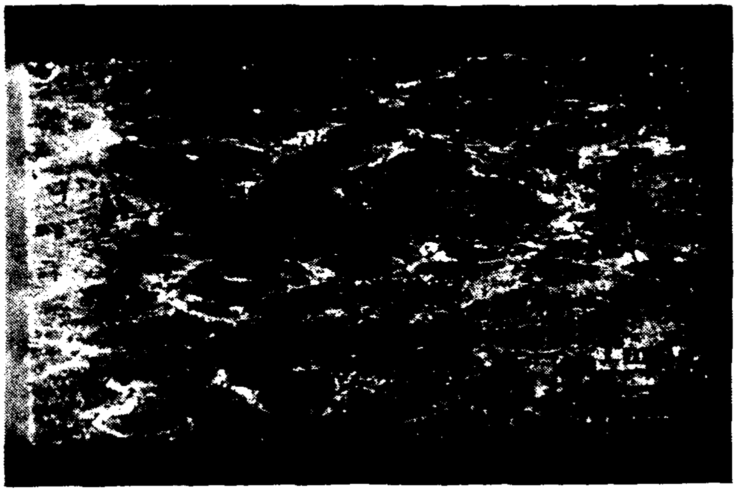
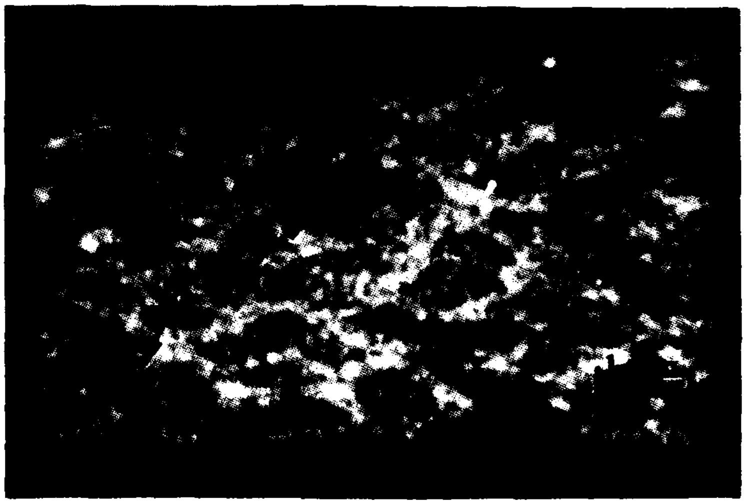


Figure 3.1-2 CT slice of three composite test blocks showing different densities in the blocks and the weave pattern in the center block.



a) Photomicrograph



b) CT image

Figure 3.1-3 Photomicrograph and CT image of a 2D composite coupon.

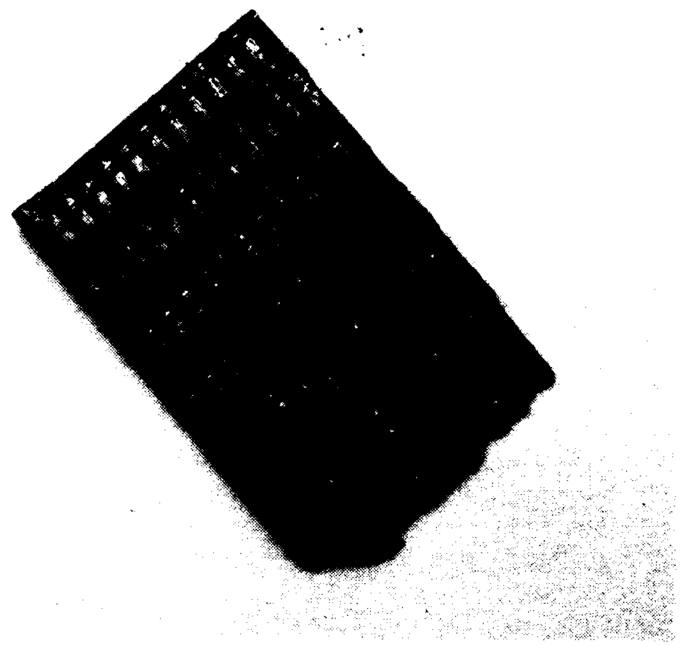


Figure 3.1-4   Photograph of CVD 2D woven composite.

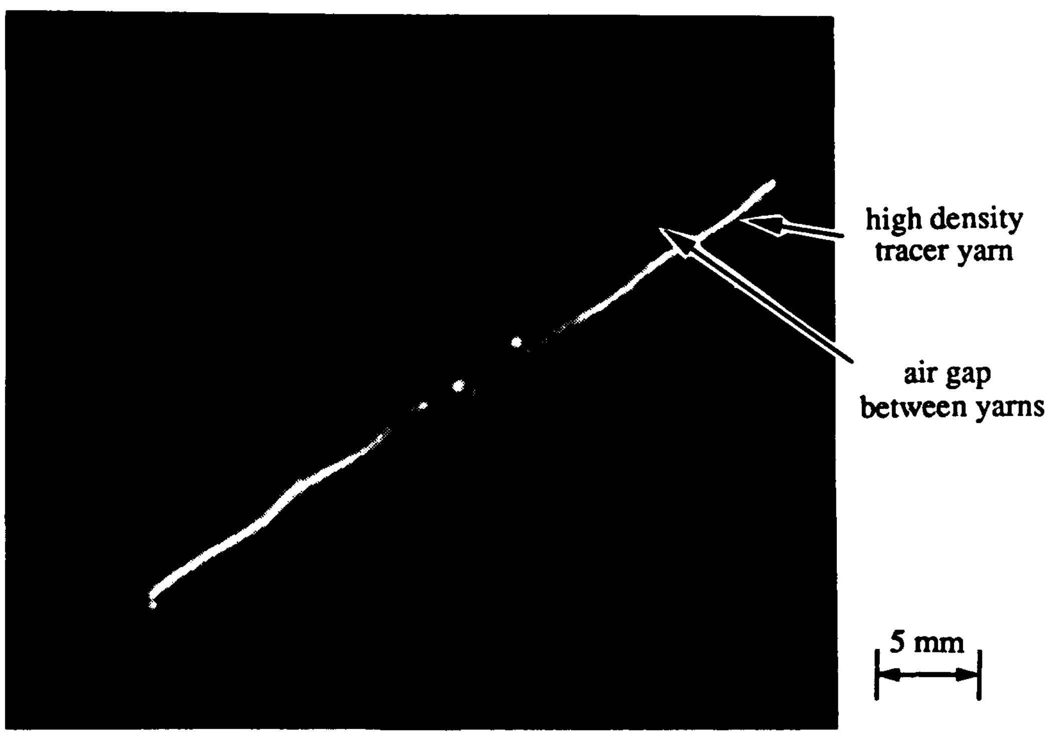


Figure 3.1-5   CT slice of CVD 2D woven composite.

3.1.3 PMR-15 Struts

A photograph of sections from two developmental composite struts made of PMR-15 (a polyimide matrix resin) are shown in Figure 3.1-6. The struts are approximately 125 mm in the long direction. These struts were being developed and analyzed by Rohr Industries for the purpose of replacing metal struts with composite materials to save weight. CT scanning of these struts demonstrated the capabilities of CT for composite development evaluation.

Figure 3.1-7 is a CT slice of the two strut sections taken on a nominal 1 lp/mm CT system with relative high (>100) S/N. Cracks and separations in the material are clearly imaged, and the results correlate with those obtained through destructive sectioning. These defects would be very difficult to evaluate with conventional NDE methods, but are easily imaged with CT. Manufacturing defects such as these ultimately led to a modification in the strut design.

3.1.4 Silicon Carbide (SiC) Coated Composites

Figure 3.1-8 is a photomicrograph of the narrow 10 x 5 mm section of a SiC coated carbon composite test specimen. Figure 3.1-9 is a high resolution (~ 10 lp/mm) CT slice of the section shown at two different grayscale settings. The image on the left (Figure 3.1-9a) reveals various characteristics of the coating, including thickness and density variations. The right image is the same slice, but with the contrast window level set to reveal the consolidation quality of the interior composite material, including density variations and voids.

Figure 3.1-10 is a photograph and 3.1-11 is a high resolution CT slice of a small SiC coated carbon composite test specimen that contains a silicon nitride ring insert. The image reveals porosity in the carbon composite and shows the gap between it and the sleeve. These images are representative of the type of information that can be very helpful to the materials engineer analyzing new design concepts.

Figure 3.1-12 is a photograph of a SiC coated stiffened carbon composite test panel approximately 200 x 200 mm in size (manufactured by Rohr Industries). Before being CT scanned it was tested with ultrasonics and no defects were found. However, CT scanning of the panel on a medium resolution (1 lp/mm) system revealed a defect in the one of the stiffeners as shown in Figure 3.1-13.

3.2 Metal Matrix Composites (MMCs)

Metal matrix composites (MMCs) are being developed for a variety of high temperature, high performance applications in the aerospace industry. Selection of adequate design margins and lifetimes under expected loading conditions requires proper understanding of possible failure mechanisms. The evaluation of material systems for correlation with mechanical properties represents a substantial portion of the material development effort in terms of time and money. High resolution CT should be very effective as a non-destructive method that provides important understanding of MMC microstructural behavior and material forming processes.

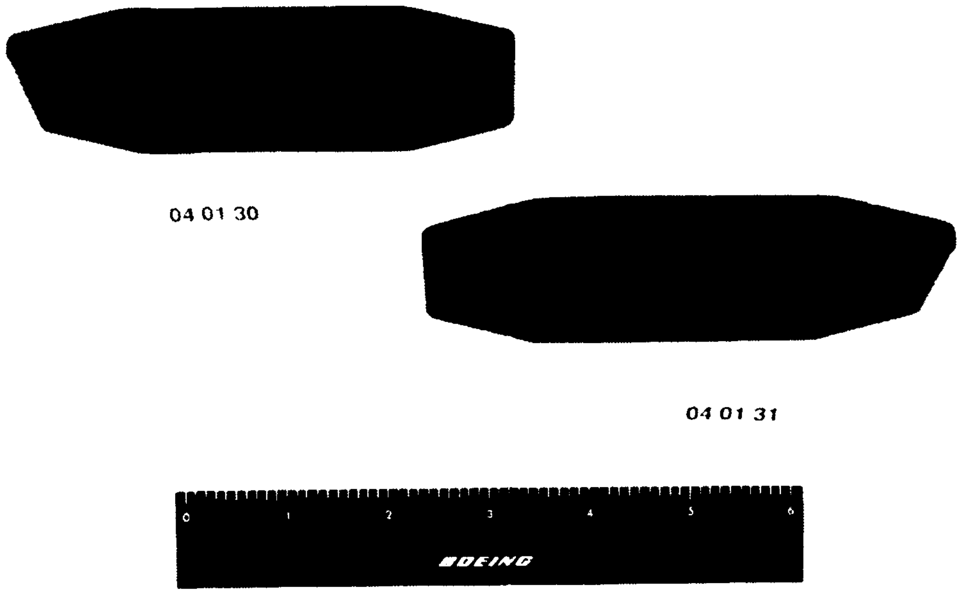


Figure 3.1-6 Photograph of two composite strut sections.

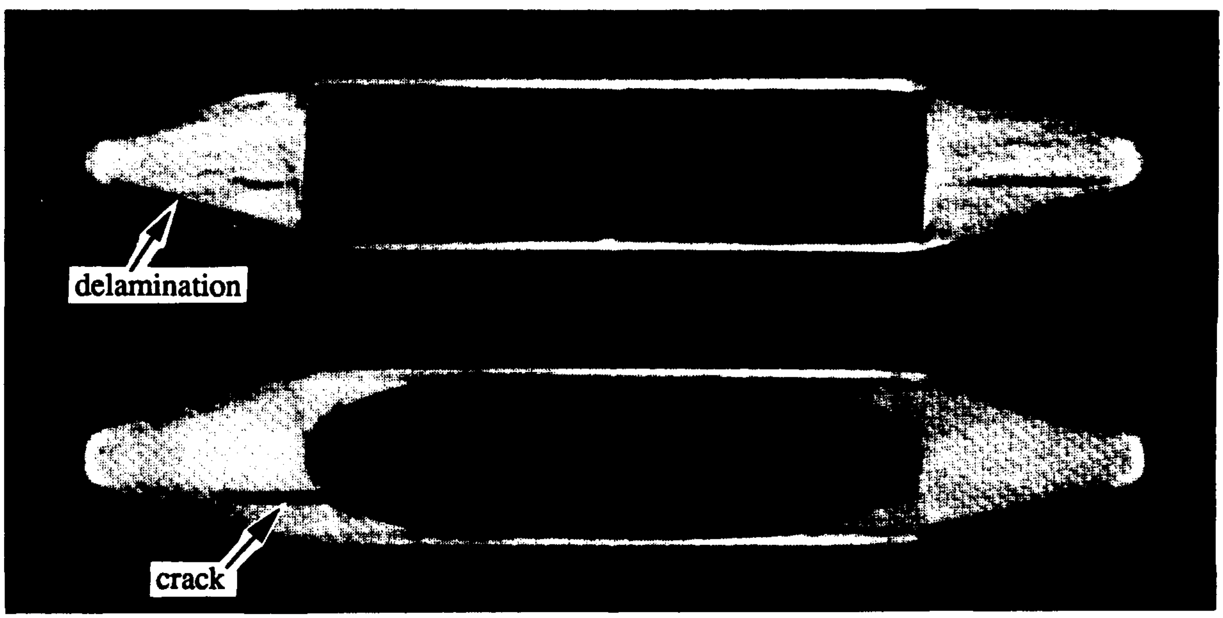


Figure 3.1-7 CT slice of two composite strut sections.

Figure 3.1-8 Photomicrograph of SiC coated test specimen.

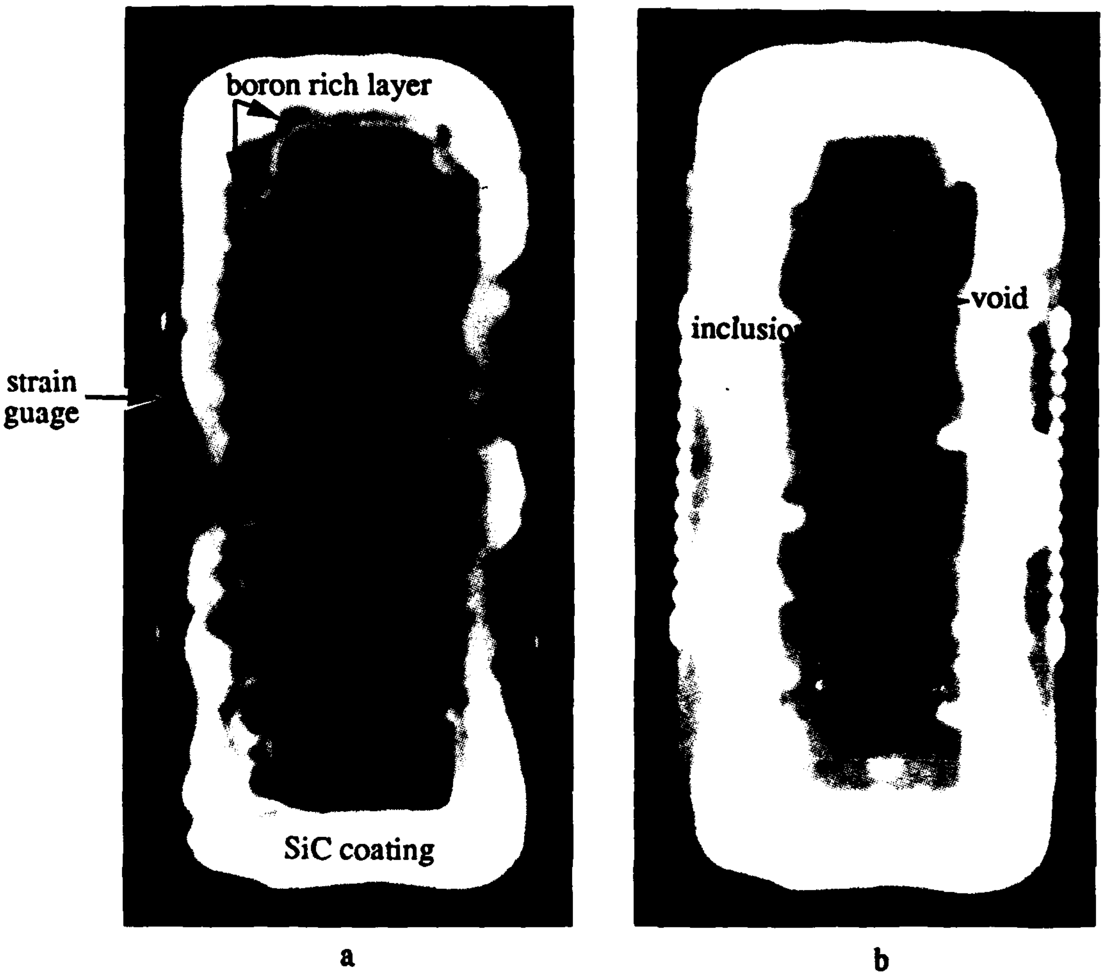


Figure 3.1-9 CT slice of coated test specimen at two contrast settings to show a) coating and b) composite interior.

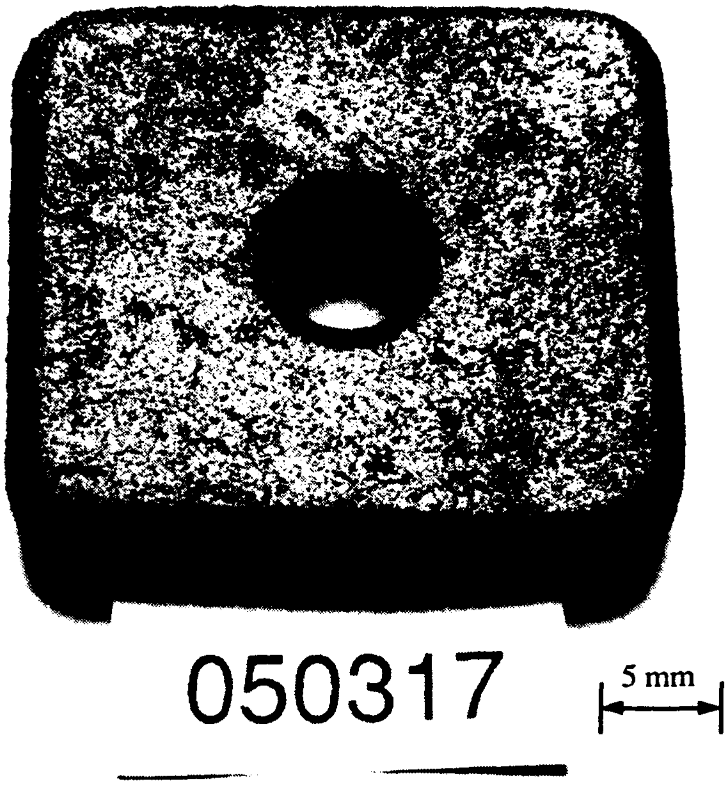


Figure 3.1-10 Photograph of SiC coated specimen with insert.

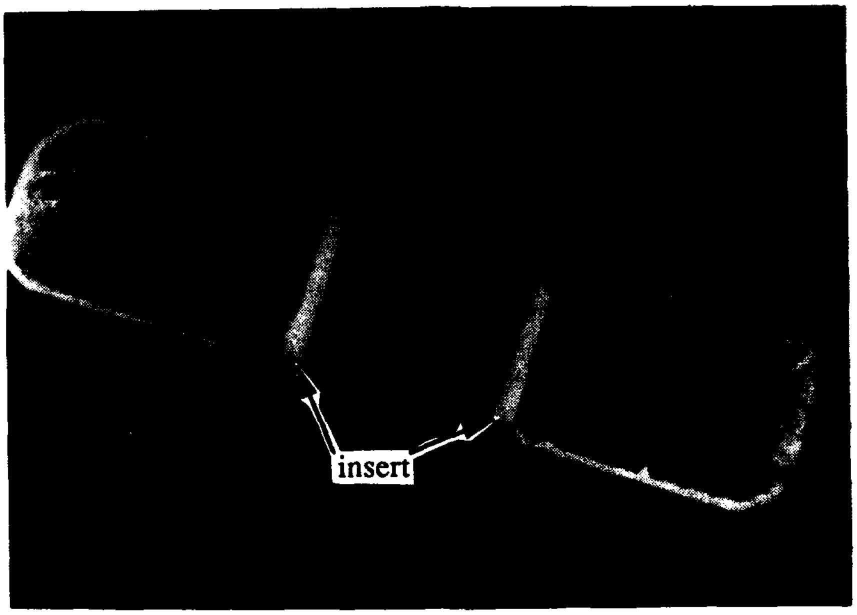


Figure 3.1-11 CT slice of SiC coated specimen with insert.

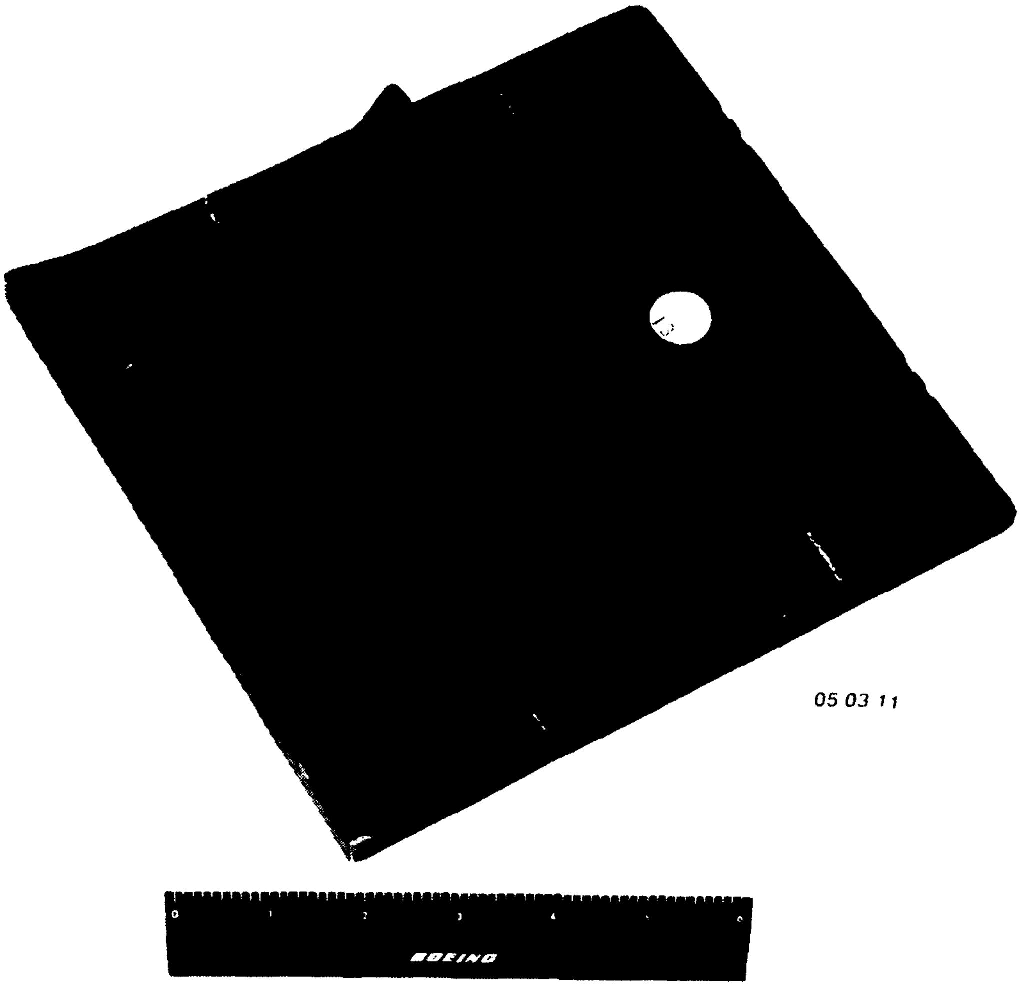
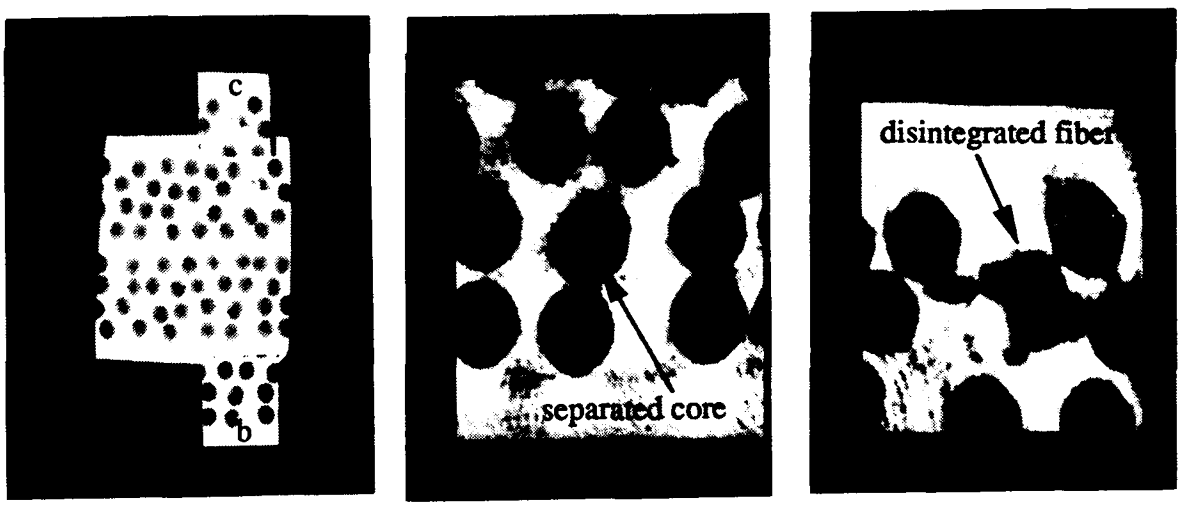


Figure 3.1-12 Photograph of a SiC coated stiffened carbon composite test panel.

Figure 3.1-13 CT slice of the SiC coated test panel revealing a defect in the stiffener which was not discovered by ultrasonic testing.

3.2.1 Continuous Fiber MMCs

The development of MMCs made of continuous fibers has been shown to benefit from the application of high resolution CT. Because of the unidirectional nature of the fibers, these MMC are particularly well suited to CT, which can provide cross-sectional views of the fibers within the matrix. Yancey, et al., [11] have shown that high resolution CT can measure fiber alignment, separation, and distribution in unidirectional silicon carbide fiber reinforced titanium-aluminum (TiAl/SiC) and boron carbide reinforced nickel-aluminum (NiAl/B_4C). The Department of Energy has funded studies conducted by Lawrence Livermore National Laboratory, Sandia National Laboratory, and Georgia Institute of Technology to examine the use of CT for studying continuous-fiber MMC. In one study, different MMCs were scanned using radiation from the Cornell High Energy Synchrotron Source (CHESS) and a CT apparatus with fluorescent screens linked to charge-coupled-device (CCD) detectors [12]. Spatial resolutions on the order of a few microns can be obtained with this microtomography system. Different types of damage were observed, including fiber-matrix debonding in a fatigued sample, fiber fracture, and fiber fragmentation. Figures 3.2-1 a-c (obtained by permission from the authors of ref. 12) are a CT slice of an 8 ply, aligned-fiber TiAl/SiC MMC. These results indicated that using synchrotron radiation as a source for CT can provide resolution on the order of a few microns (0.001 to 0.005 mm), sufficient for materials studies in MMCs. However, there are limitations when using a synchrotron source; limited availability and associated costs.



a b c

Figure 3.2-1 CT slice of an eight-ply, aligned fiber TiAl/SiC MMC a) at low magnification, b) at higher magnification showing SiC fiber with separated core, and c) showing a disintegrated fiber.

The same team that did the above study recently used CT to study crack growth in Al-Li alloy 2090 using a simple load fixture for *in situ* CT scanning of samples under load [13]. Noninvasive *in situ* CT scans of advanced materials will provide invaluable information regarding the evolution of the microstructure which can now only be inferred through post-failure examinations. Material processes such as fatigue crack growth, damage development, environmental degradation, and consolidation during sintering can be studied with *in situ* high resolution CT [14].

The use of microtomography, with resolutions better than 0.005 mm is being pursued by several groups for materials studies. Synchrotrons provide a high intensity, low divergent source with the possibility of energy tuning making them useful for small sample evaluation [12,15,16,17]. In some cases, laboratory X-ray sources can be used [18]. Sample sizes are small (< 1 mm).

3.2.2 Other MMCs

Metal matrix composites may be made by alternatives to continuous fibers, such as chopped fibers or particulate materials. Normally these fibers would be extremely small and would require very high resolutions (a few microns) to image with CT. Examination of these MMCs on CT systems with conventional capability would provide information on global material characteristics of material consolidation and gross defects similar to the results on organic composites discussed in Section 3.1.

3.3 Ceramics and Ceramic Matrix Composites (CMCs)

Ceramic or CMC inspection for texture, structure, or flaws requires high spatial resolution. Internal flaws such as cracks, voids, inclusions, and density variations may exist in a ceramic component, but will often be quite small. Because of the brittle nature of ceramics, catastrophic failure under stress can originate from small defects which are only tens of microns across [19]. External flaws may also exist due to machining or handling. Typical NDE methods for ceramics include low-frequency UT, microfocus X-ray, and ultrasonic microscopy. CT's unique capabilities to map density variations and represent internal structure should mean that CT will find applications in ceramic material evaluation. Allied-Signal's Garrett Auxiliary Power Division is utilizing both CT and ultrasonic microscopy to develop and study high temperature ceramics for the U.S. Department of Energy's Office of Transportation [20]. Investigations into CT of ceramic materials are being conducted in other countries as well [21].

Ceramics undergo various stages of processing before the final product. Unique defects can be introduced at any of these stages, which are often not well understood. By using CT to monitor a ceramic part throughout the manufacturing process, one can better understand the process stages, and how defects are created.

3.3.1 Short Fiber Borosilicate CMC

Figure 3.3-1 is a CT image of a 40-mm diameter disk (with a physically cut edge) of a CMC manufactured by Rohr Industries. The CMC consists of short SiC fibers in a matrix of borosilicate glass, and is produced using the sol/gel process. The CT slice from a medium resolution (1 lp/mm) CT system with high signal to noise (S/N > 100) provides a quantitative measure of the density across the disk. Ideally the density should be uniform and the part free of porosity. The CT image of this sample indicates that the density drops off toward the edge of the sample. The fact that there is no density drop near the flat edge shows that the density changes are in the sample and not due to CT system edge effects. Also a low density feature is detected. This type of information can be used to improve the product by adjusting the process to obtain a more uniform part both internally and near the edge.

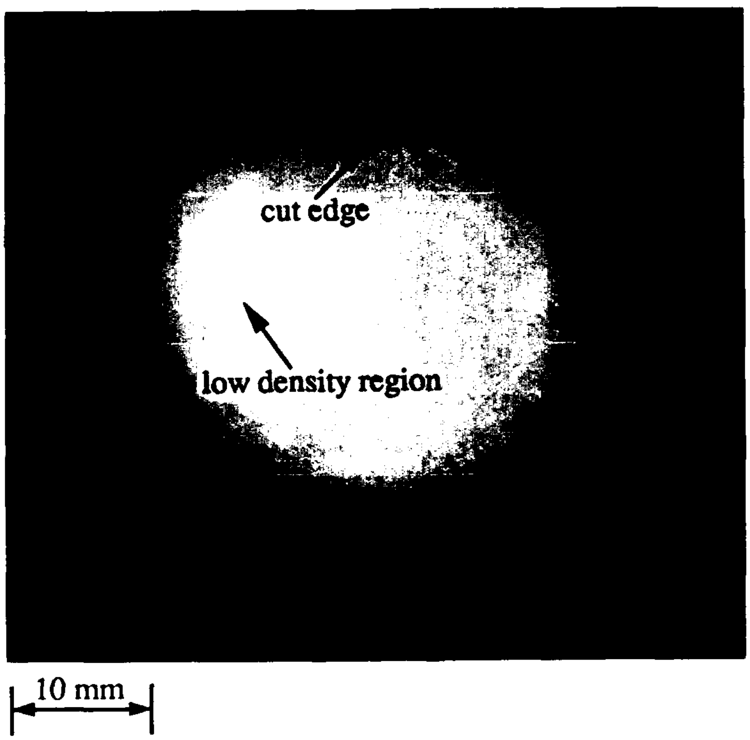


Figure 3.3-1 CT slice of a short fiber borosilicate CMC.

3.3.2 Extruded CMC Bits

An example of a potentially effective use of CT in ceramics manufacture is in the extrusion of ceramic matrix composite (CMC) for composite tooling. Several defective CMC drill bits were provided by the Greenleaf Corporation, Saegertown, PA, for study under this program. A photograph of these bits is shown in Figure 3.3-2. Greenleaf supplies ceramic tooling to a variety of composite manufacturers in the aerospace community. The drill bits shown are made of silicon carbide fibers in an aluminum oxide matrix. The cylindrical shape is produced as the material is extruded through a die in long sections. These extruded rods can have defects such as cracks or extended voids running along the interior which are not discovered until they are later cut into short sections or have the appropriate flukes cut into them to produce the final product. In process inspection using an appropriate NDE method could result in cost savings by identifying defective product before costly machining or by salvaging good sections of a rod from defective areas.

Figure 3.3-3 is a CT slice from a high resolution (~ 10 lp/mm) system of the center bit near its end, revealing an internal crack and some porosity. Scans in the other bits also indicated defects such as cracks, porosity, and extended voids. The unusual blade shape in the image is due to the double helix cut of the flutes. Also, the bottom left edge of the bit extends outside the CT reconstruction field of view. CT is apparently effective in this material system for identifying characteristic defects. Also, like pultrusion, the geometry of this extrusion is well suited for CT. Scanning of this size of part on systems capable of larger components, but lower resolutions (1-2 lp/mm), was not successful in imaging defects like these. But, high resolution systems, 4 lp/mm and above, can provide useful results.

3.3.3 Reticulated Ceramic Filter

A promising application for CT of advanced materials is the rapidly growing ceramic filter industry, where a porous open cell (reticulated) ceramic is used to remove unwanted material from molten aluminum and other alloys. Reticulated ceramics are finding catalyst support, and refractory uses in various industries, but CT may be particularly useful in filtration applications.

Reticulated filters have pore sizes which run from about 8 to 80 pores per linear inch, and are selected for their permeability, strength, and ability to remove impurities. The parameters which determine these properties include porosity, pore size, surface area, window size, coordination number, tortuosity, wall thickness, and wall defects [22]. These parameters are important characteristics which must be carefully controlled and monitored. The current method of cutting up a filter, filling in the air space with a liquid which solidifies, taking micrographs, and then measuring and counting pores is time consuming and costly. CT measurements of the pore size and distribution could be automated, saving on both time and money.

A small section of a reticulated filter was scanned under another task in this program to determine what type of information CT would provide. CT imaging using a high resolution (10 lp/mm) system showed porosity and structural features in the range of 50 μm which can be used for evaluation of the inclusion capture performance of filters. The evaluation results are described in a separate report [23]. Image analyses and statistical processing of the CT data can provide quantitative measurements of key parameters, as has been recently demonstrated by P. Engler, et al., [24].

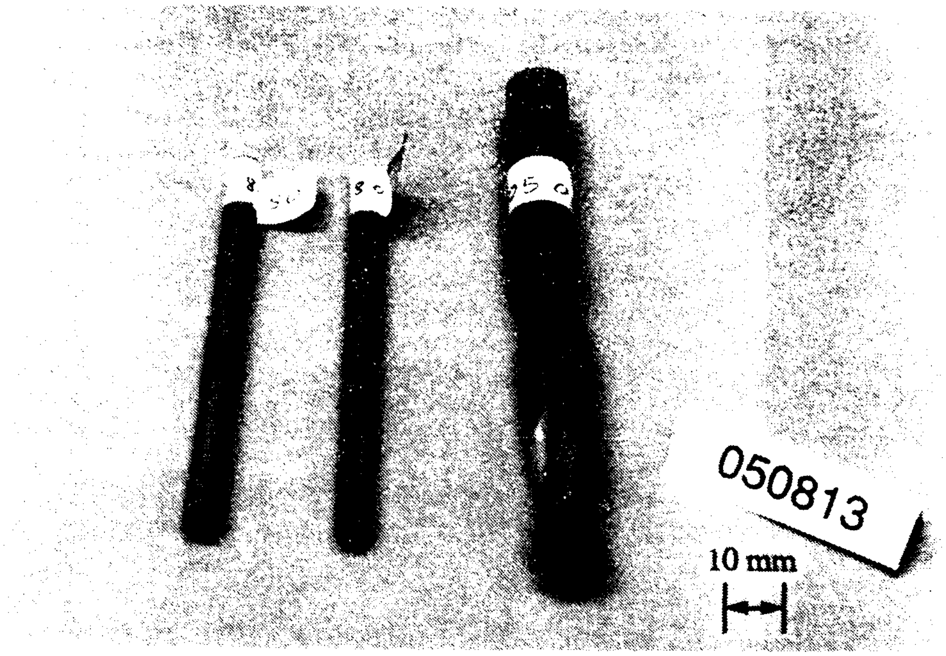


Figure 3.3-2 Photograph of three extruded CMC bits.

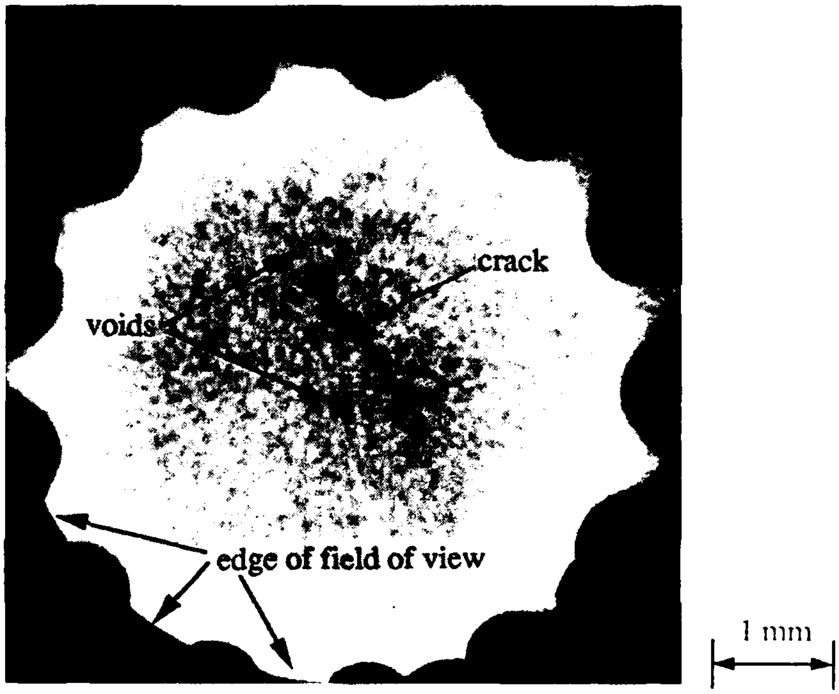


Figure 3.3-3 CT slice of extruded router bit showing defects.

4.0 CT FOR MANUFACTURING PROCESS

Materials fabrication techniques are currently being utilized which offer lower production costs than conventional methods. These materials are often made up of metals, alloys, or plastics. Processing methods include pultrusion, superplastic forming (with and without diffusion bonding) [25], injection molding [26], and powder metallurgy [27]. The parts manufactured by these methods can contain defects which are unique to the process and material.

4.1 In-Line Manufacturing of Composites

In-line manufacturing processes for composites such as pultrusion of PMCs and extrusion of CMCs are well suited to the geometric constraints of CT. CT for pultrusions was the primary subject of an earlier task assignment on the program [4]. Pultrusion is an emerging, economical manufacturing process for composite structures. In a pultrusion system, the composite tapes and fabrics are loaded onto a creel, and the materials are fed into a preform (or shaper), along with any fillers that may be needed. If the fiber is not preimpregnated with resin, it is run through a resin bath or the resin is injected into the die as the material is about to enter. The composite is pulled through the heated die and then cut from the system to produce either a fully or partially cured product. This handleable part is then placed in an autoclave for final cure. A number of variables go into the pultrusion process, including the type of fibers, the epoxy matrix material, pull rate and cure temperature. Destructive testing, such as shear testing of small sections, is the normal method for assessing the quality of the pultrusion manufacturing product. This can be time consuming, costly, and part of the product is destroyed.

The development of pultrusion product involves the establishment of optimum parameters for the process. The goal is to generate a uniformly high strength material. A program to assess the uniformity and strength has been performed for the production of pultruded composite cylindrical rods using nondestructive CT and destructive shear strength measurements. A correlation of the CT measurements to the actual shear strength provides the possibility of nondestructively monitoring shear strength in pultruded product [28].

The pultrusion experiment involved the fabrication of 32 sample rods while varying four different manufacturing parameters: resin, pull rate, pull temperature and cure. Following manufacture, the parts were examined with CT and then shear tested. Four rods with the same resin, temperature, and cure state parameter combinations were scanned at one time at three separate locations. These locations were within the length of rod later used in the shear tests. Figure 4.1-1 is a CT image of one of the scans from a medium resolution CT system. Figure 4.1-2 shows CT value density contours of an enlarged cross section of the top left rod of Figure 4.1-1.

The CT data were analyzed to obtain the mean CT value inside the rod and the standard deviation of the CT values. The values of mean and standard deviation of the relative X-ray linear attenuation coefficient (directly related to material density in composites) were computed for each individual rod at each of the three axial locations respectively. The level of the mean indicates just how dense a particular rod is at the scanned axial station, and the standard deviation is a measure of the uniformity of the density at the same station. The mean and standard deviation for each of the three axial locations were averaged together for each rod. The effects of the resin, pull rate, temperature, cure factors (and their combinations) on the mean CT value and standard deviation were calculated in a spreadsheet program.

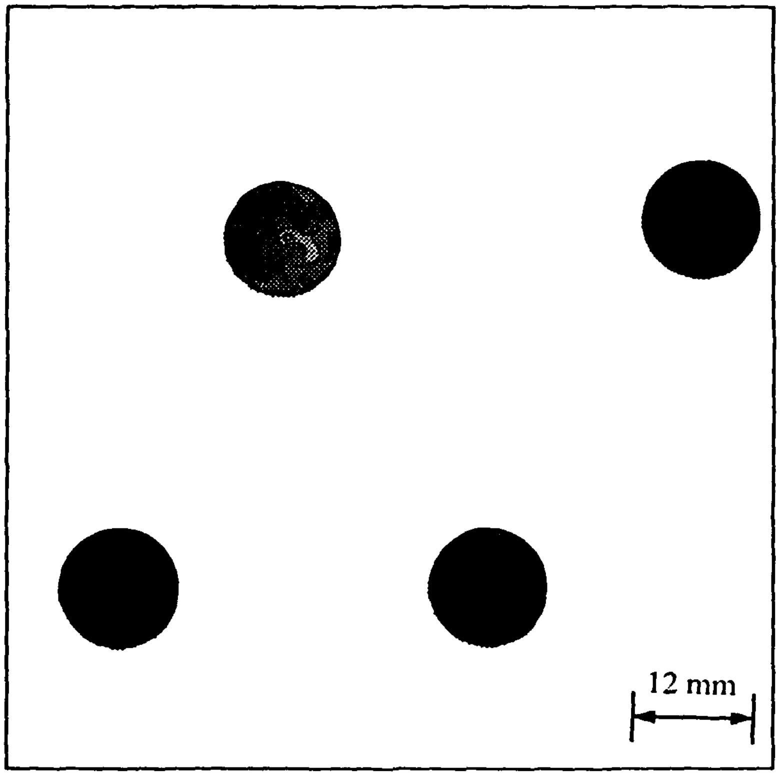


Figure 4.1-1 CT image of graphite epoxy rods.

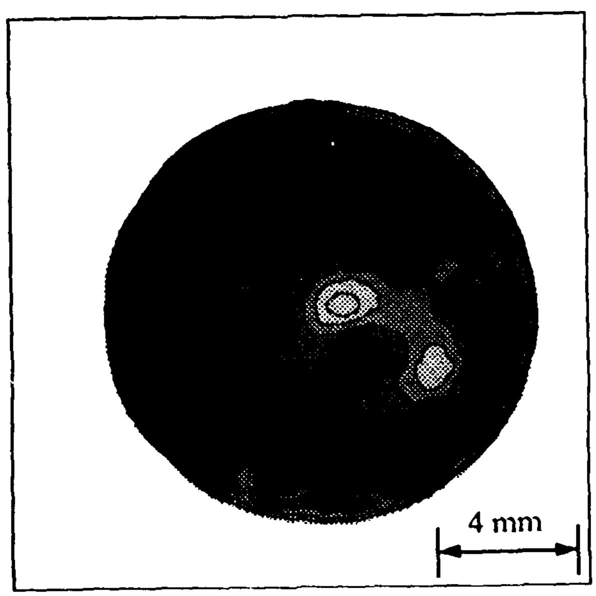


Figure 4.1-2 Enlarged CT image of top left rod in Figure 4.1-1, showing density contours every 0.25 g/cm^3.

The results of the statistical analysis were then compared with the shear strength results: (a) to establish the effect of process variables on the CT and shear strength measurements, and (b) to determine if there is a significant correlation between CT measurements and shear strength which would allow for a nondestructive prediction of material performance.

An analysis of variance test was performed for the CT mean, standard deviation and shear stress. The CT results correlated significantly with the shear strength test data and pull rate for rods produced using a particular resin. Figure 4.1-3 shows the correlation of CT value and pull rate. Figures 4.1-4 and 4.1-5 show the maximum shear strength of all the rods of one resin type as a function of CT mean and standard deviation respectively. Although there is significant scatter in the data, much of this is actually due to the fact that CT is measuring rod differences due to the various factor differences. Figure 4.1-6 shows the maximum shear strength of these rods with the same temperature, and cure factors. There is a strong correlation between maximum shear strength and mean CT value for the rods. (The two samples with the highest shear strength were pulled at the higher rate. As shown in Figure 4.1-3, the CT data correlated very strongly with the pull rate in the material manufactured with a particular resin.) The fact that there is an inverse correlation between standard deviation and maximum shear strength indicates the denser rod is more uniform, as one might expect.

The most significant affect, of the four factors tested, on material density were the type of resin used in the manufacture and the pull rate. One resin consistently provided a more consolidated and uniform rod, regardless of pull rate. Rods produced using the other resin improved in density and uniformity as the pull rate was increased. The processing temperature also had a small, but measurable effect on the mean CT value; the lower processing temperature tended to produce a slightly denser rod than the higher. Finally, post-curing of the rods decreased their density slightly, and reduced the variability in the less uniform rods.

CT data can be used quantitatively for the measurement of consolidation in pultruded composite. Although the data available is limited, the results indicate that CT values correlate to shear strength for a particular resin matrix and pultrusion manufacturing variables. Additional data are needed to generalize this result. The data were insufficient to show any significant correlation in a second resin matrix.

Because CT testing is nondestructive, it can be performed on components that will actually be used, as well as components that will undergo destructive tests. If these results can be confirmed by additional tests, then CT would be demonstrated as technically feasible as an on-line evaluation system for to predict the strength performance of the product during production. This would have a significant impact because the product could be accepted on the basis of engineering criteria of its ability to meet service requirements. With the replacement of qualitative criteria by quantitative measures cost benefits should be achieved by reducing unnecessary scrap and improving product performance.

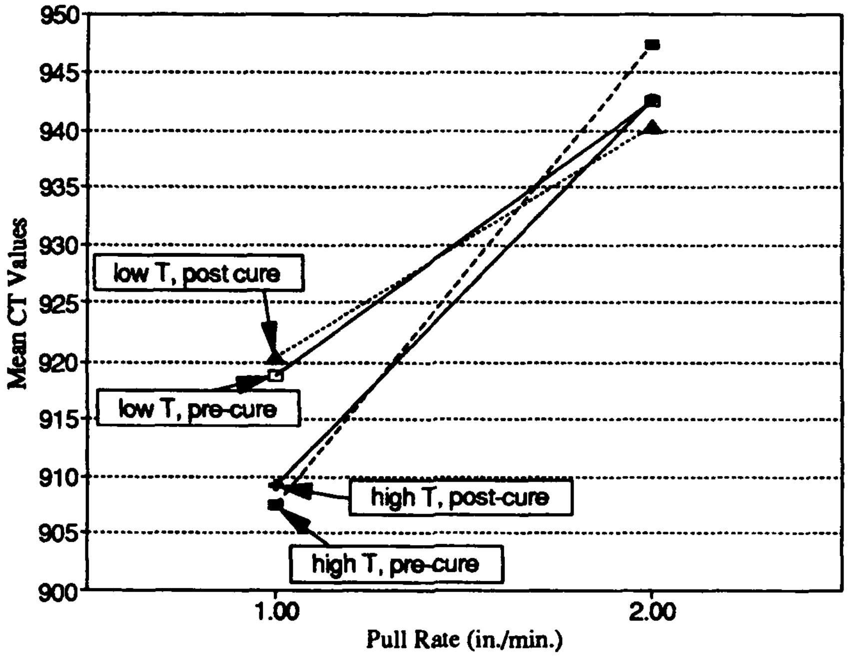


Figure 4.1-3 Effect of pull rate on CT values for pultrusion of composite rod made from one resin type.

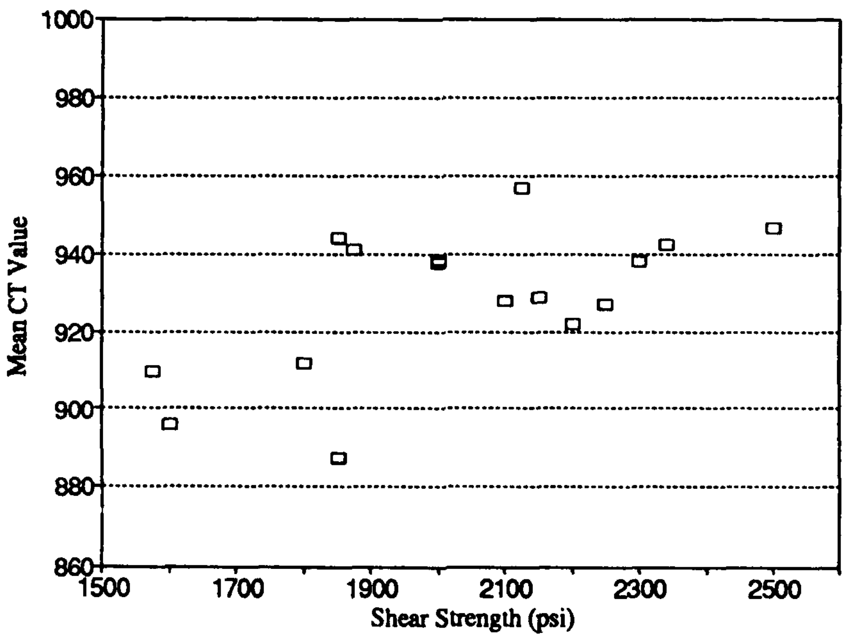


Figure 4.1-4 Shear strength of rods made of one resin type as a function of mean CT values.

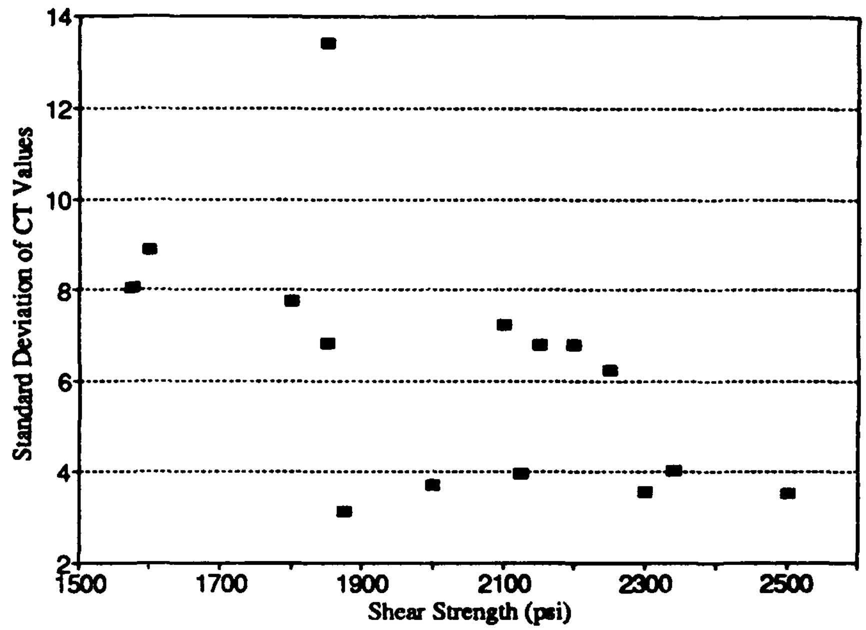


Figure 4.1-5 Shear strength of rods made of one resin type as a function of the standard deviation of CT values.

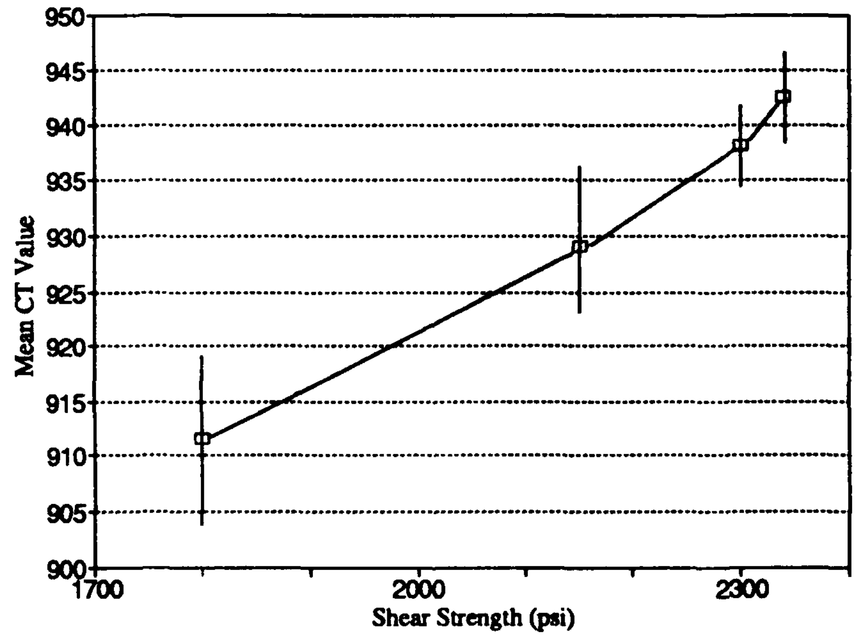


Figure 4.1-6 Shear strength of post-cured rods of one resin type pultruded at 350°C.
(The standard deviation of the CT values for each rod is represented by the bar on each data point.)

4.2 Superplastic Forming

Superplastic forming (SPF), is becoming a significant manufacturing method for the aircraft/aerospace industry. For example, SPF is being used on a variety of components parts produced for the F-15E, a fighter aircraft manufactured by McDonnell Douglas (Figure 4.2-1). Use of SPF over conventional manufacturing methods has translated into savings in the number of parts, the number of required fasteners, weight, and overall production costs [29]. McDonnell Douglas is one of approximately thirty major manufacturers of aircraft/aerospace parts worldwide who currently have in-house capabilities for SPF production, and the number is growing [30].

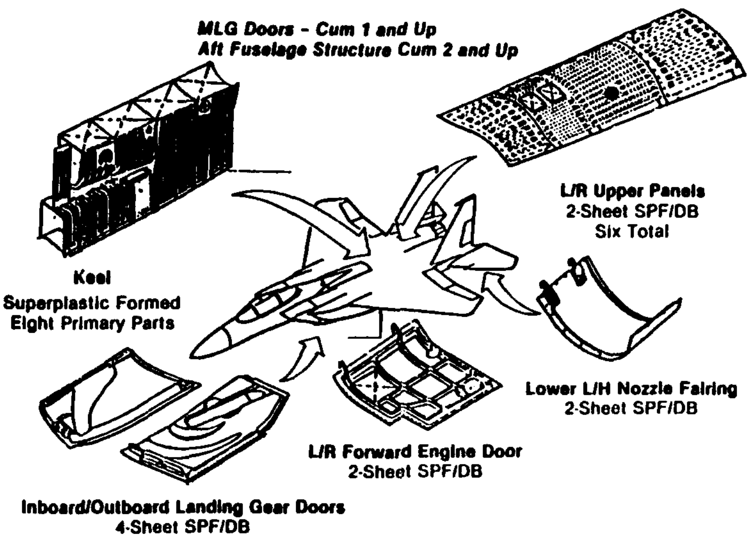


Figure 4.2-1 Superplastic forming applications in F-15E fighter aircraft.

In SPF, a titanium sheet is formed in a die by subjecting it to high pressure inert gas. The sheet and die are held at a high enough temperature to allow the metal to flow easily (Figure 4.2-2). More complex structures, such as wings or door panels, can be formed when more sheets are used. Figure 4.2-3 is an example of a 4-sheet process. Diffusion bonding (DB) of the titanium can occur at high temperatures, thus joining previously separated sheets. Joining of the sheets by laser welding prior to deformation is also used. CT is ideal for inspecting the internal structure of these types of components.

Figure 4.2-4 is a photograph of a superplastically formed, laser welded titanium airfoil section. The internal webbing was formed from a single sheet that was laser welded at selected locations to the two outer sheets prior to the superplastic forming action. Figure 4.2-5 shows a CT image of a cross-section of the part from a medium resolution (1 lp/mm) CT system capable of a field of view to cover the 400 mm long axis of the part. The image reveals the shape and condition of each internal webbing, which should be straight for the best load-bearing characteristics. It also reveals areas in the corners of the airfoil where bonding between the inner and outer titanium layers was not complete. No other current standard NDE method can reveal this type of important information.

Figure 4.2-6 shows a CT image of another SPF airfoil which is under development. The CT scan reveals regions where the webbing has not formed properly, (a web section on the far left of the Figure 4.2-6 image is bubbled outward and is not straight) and the joining, or lack thereof, between the top and bottom surfaces. This information provided the manufacturing engineer with the information necessary to improve the product.

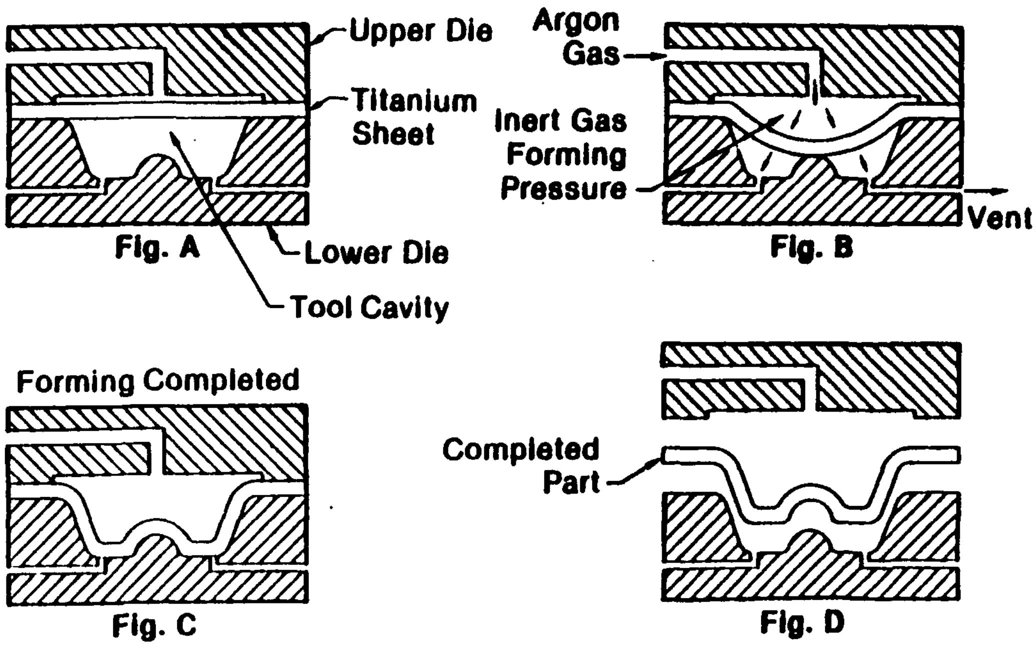


Figure 4.2-2 Superplastic forming (SPF) process.

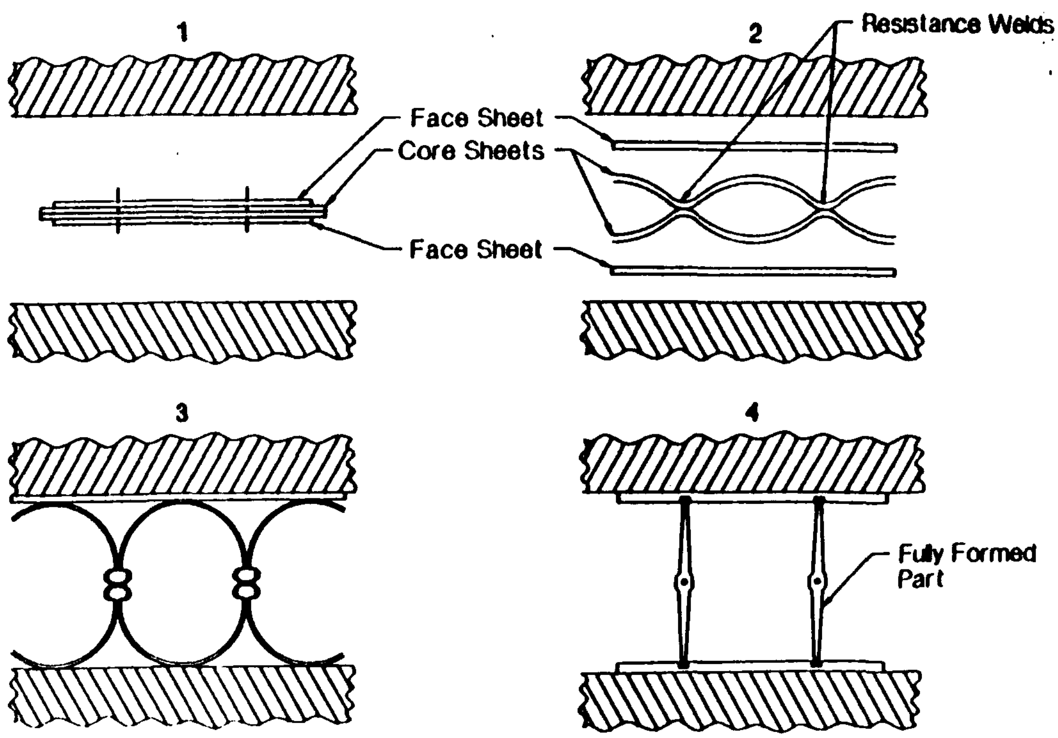


Figure 4.2-3 Superplastic forming with diffusion bonding (SPF/DB); example is a four sheet, rib stiffened concept.

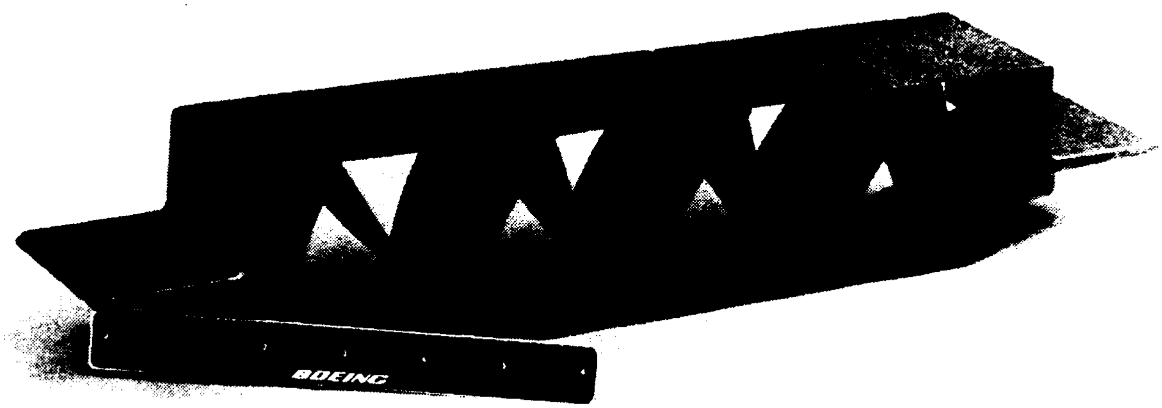


Figure 4.2-4   Photograph of a SPF laser welded titanium alloy airfoil section.

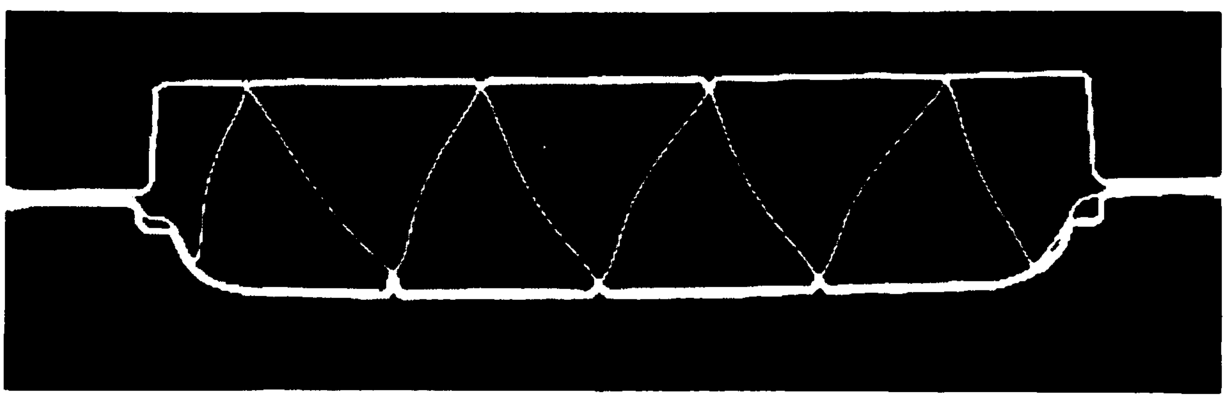


Figure 4.2-5   CT slice of the SPF laser welded titanium alloy airfoil section.

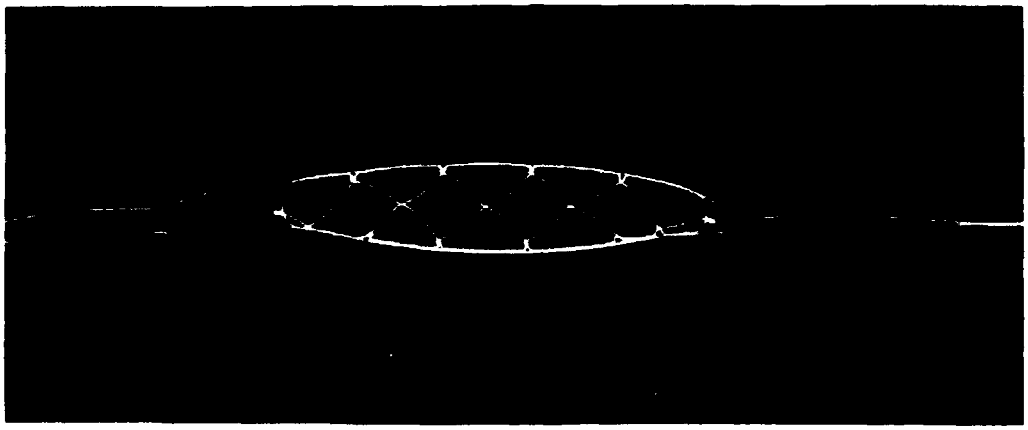


Figure 4.2-6 CT slice of a developmental SPF airfoil showing areas that have not formed properly.

4.3 Injection Molding

Injection molding, not only of plastics, but also of composites, is becoming more common in the aerospace/aircraft industry. Figure 4.3-1 is a simple schematic of the injection molding process. The process cycle involves the high pressure injection of material into a mold. As Figure 4.3-2 indicates, the process has many variables which can affect the final product. Defects such as shrinkage, porosity, flow patterns, and density gradients can occur. These can be identified with CT.

Figure 4.3-3 is a photograph of a carbon phenolic injection molded missile fin. The fin is approximately 360 mm long by 140 mm tall and 130 mm wide maximum on the tapered orientation. A series of CT slices were taken through this fin as means of evaluating its internal consolidation. The lines drawn on the part of Figure 4.3-3 show the locations of the CT slices. Figure 4.3-4 is an example of one of the CT slices along the length of the fin. The structure shape creates a number of streak artifacts in the CT images at this orientation.

Figure 4.3-5 is an enlargement of the previous CT slice. This interior region would be very difficult to inspect by any other NDE method. The CT slice clearly shows voids in the central region.

Figure 4.3-6 shows a CT slice of the central region, taken perpendicular to the Figure 4.3-5 image plane at the location shown. This image indicates the voids and flow pattern in this region. This type of information is useful to engineers for understanding the origin of defects in the injection molding process. From this understanding, they are better able to adjust the process parameters and improve the product.

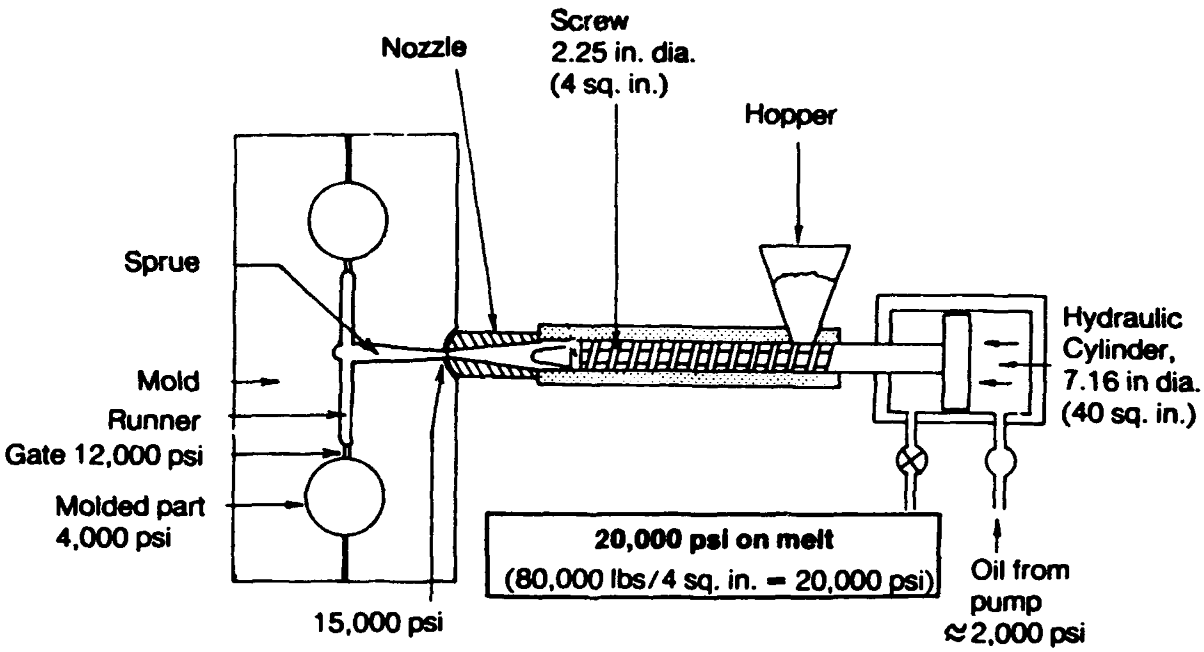


Figure 4.3-1 Schematic of the injection molding process.

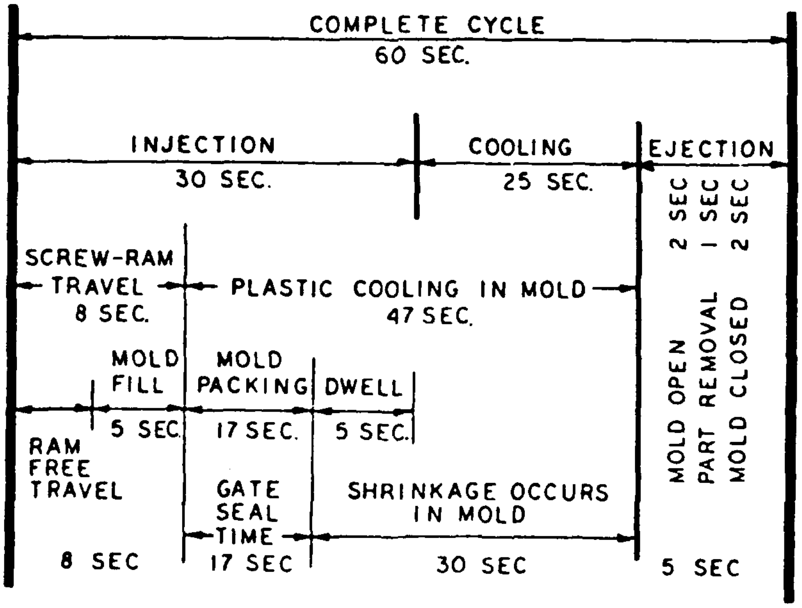


Figure 4.3-2 Schematic of injection molding process cycle.

Figure 4.3-3 Photograph of injection molded missile fin.

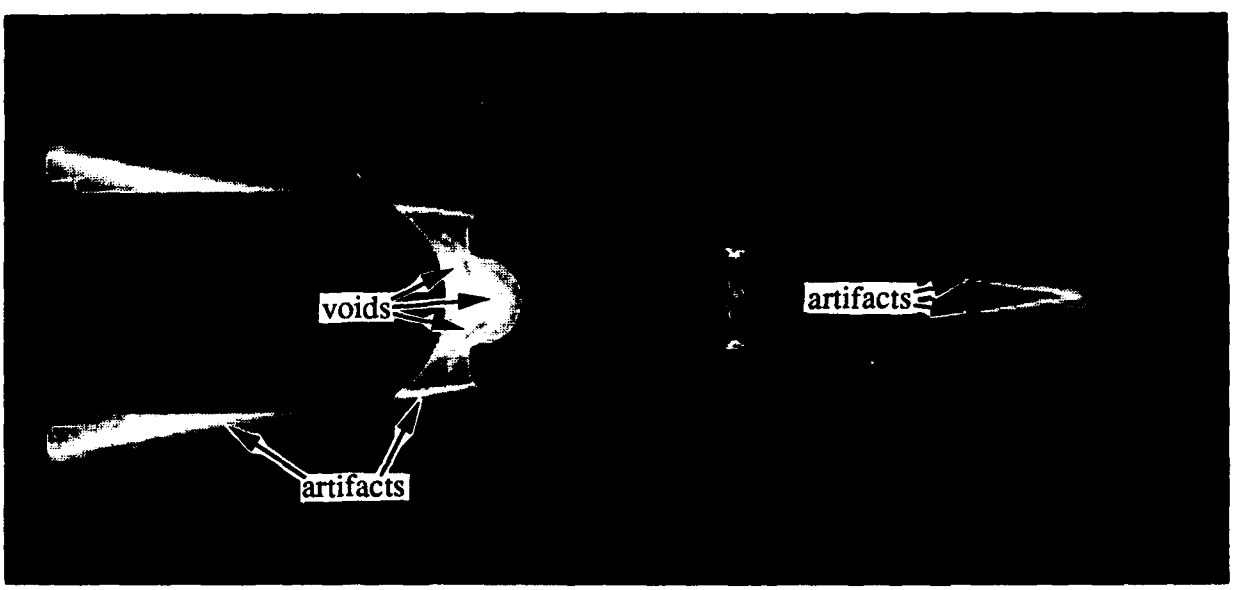


Figure 4.3-4 CT slice taken along the length of the fin.

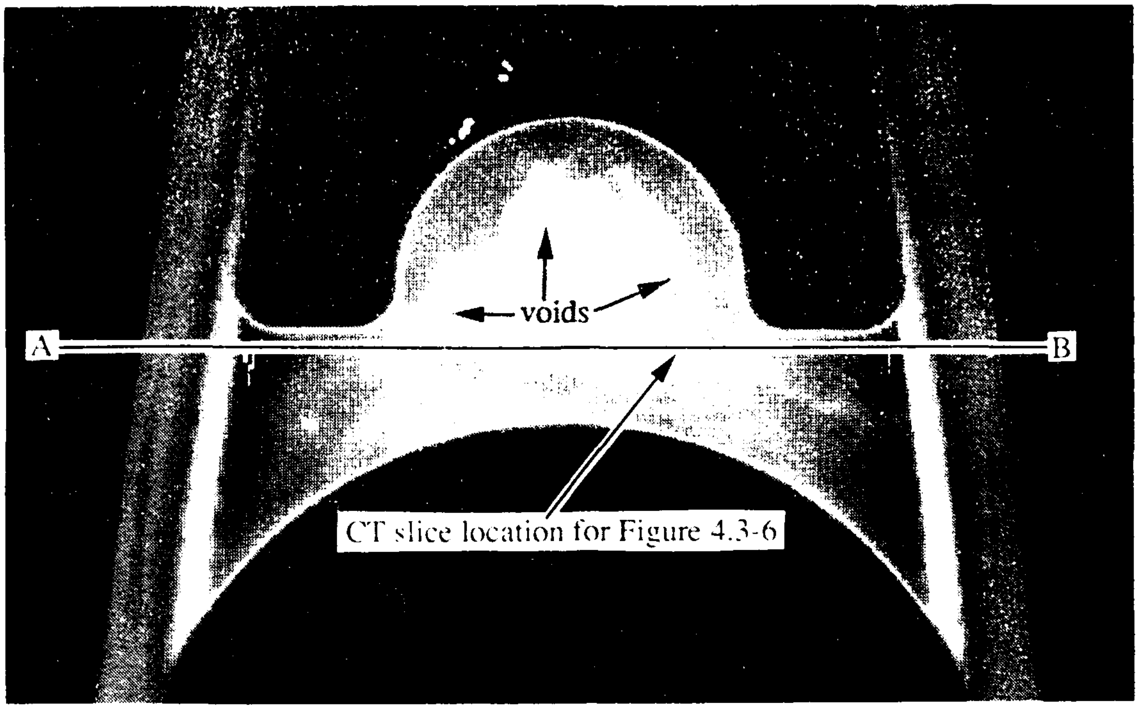


Figure 4.3-5 Enlargement of the interior structure of the fin.

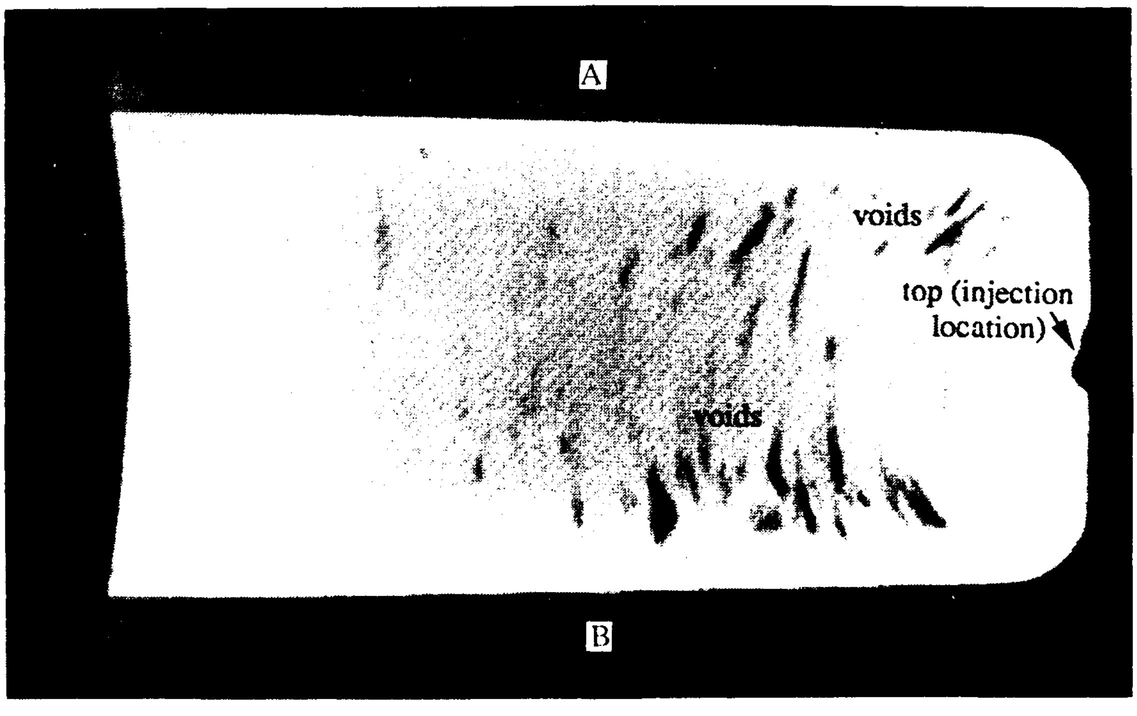


Figure 4.3-6 CT slice of the central region, but perpendicular to the Figure 4.3-5 image plane, showing voids and flow pattern.

4.4 Powder Metals

Powder metallurgy is another manufacturing area that may benefit from CT. Knowledge of the consolidation of material at various stages of the manufacturing process can help one develop and improve their product rapidly and cost-effectively. The benefits would be similar to those found in the manufacture of ceramics (See Section 3.1.3).

4.5 Low Observable Materials

Manufacture of low observable materials for use in stealth aircraft is a growing field. While there is great variety in material type and application, there are generally stringent specifications for dimensions and density variations. CT is ideal for providing a quantitative measure of both dimensions and density, as long as the part is thick enough. For example, Figure 4.5-1 is a photograph of a missile radome of approximately 200 mm diameter manufactured with a special coating. Figures 4.5-2a and 4.5-2b are examples of several CT slices taken through the radome. The density variation and dimensions are easily measured from this data. In Figure 4.5a the composite layer supporting the coating contains numerous low density areas. In Figure 4.5-2b the composite contains a sector of higher density than the majority of the body.

Not only can CT save time and money by reducing costly destructive testing, "good" product does not have to be destroyed. Thus, CT can also be used for quality assurance as well as in the product development cycle.

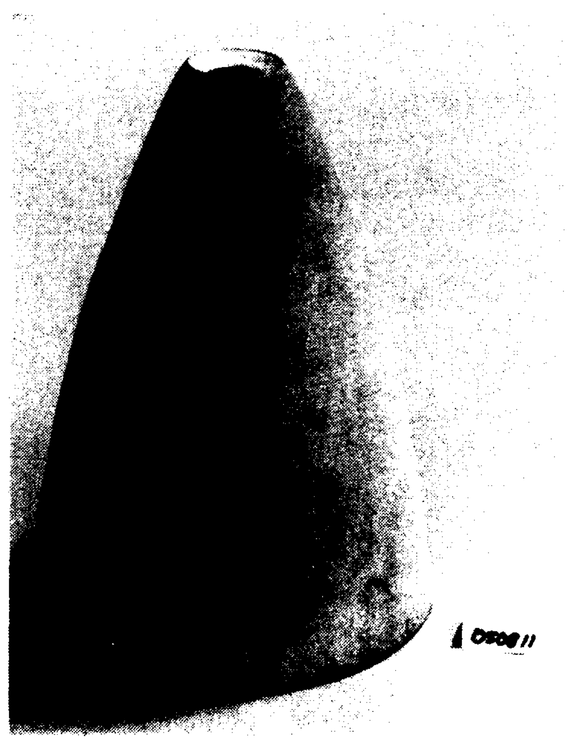
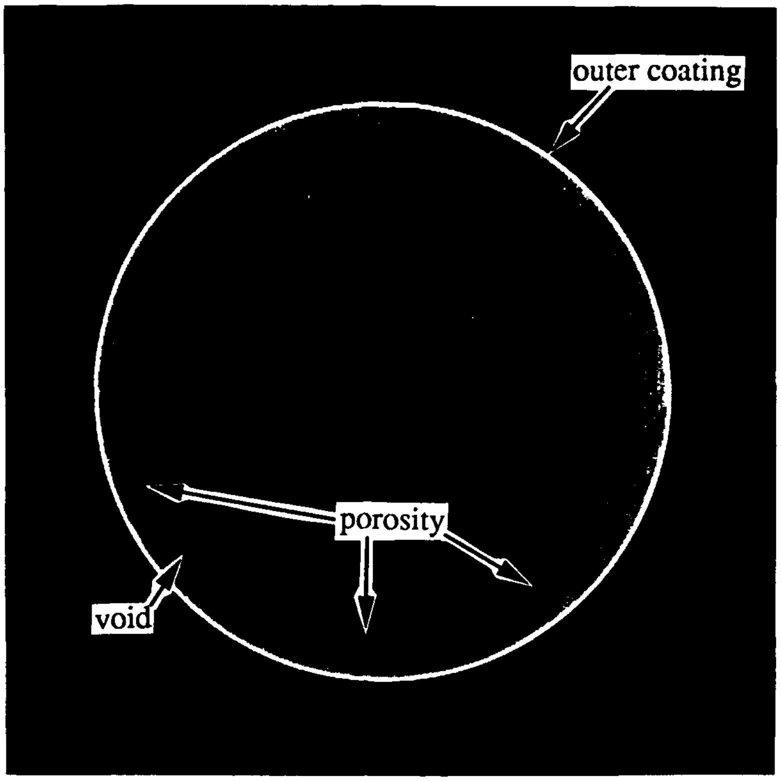


Figure 4.5-1 Photograph of missile radome.

a.



b.

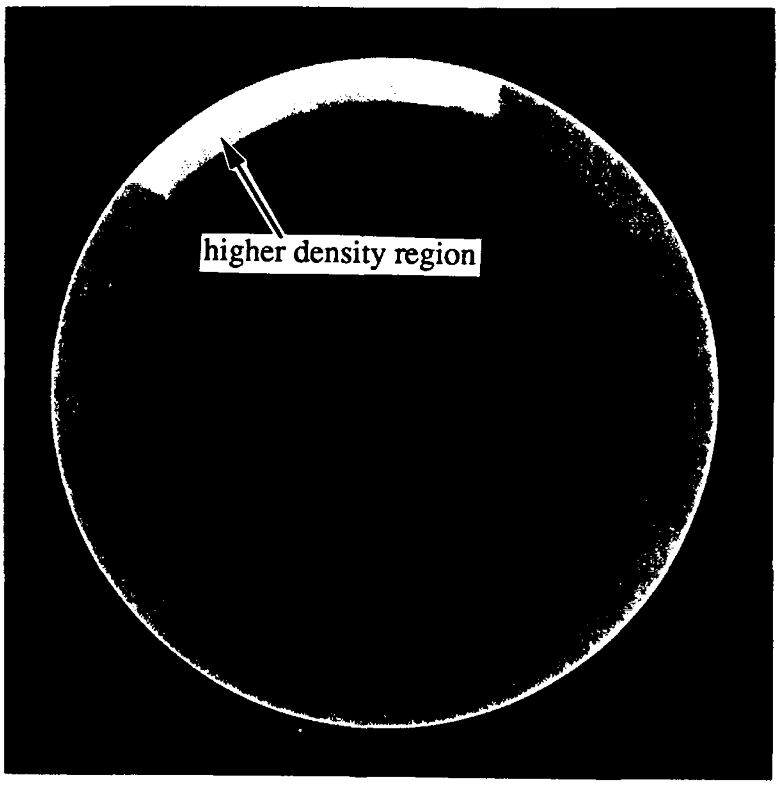


Figure 4.5-2 CT slice of missile radome a) near the center and b) near the base.

5.0 CT FOR JOINING EVALUATION

Aircraft and aerospace structures are dependent on the joining of materials for their assembly and strength in service. The joining processes of welding, bonding and fastening are used with conventional and advanced materials. The development and qualification of the joining processes for new joining applications would benefit from an inspection technology that has quantifiable data acquisition. For example, with fasteners, the geometric shape and alignment of the hole and fastener are critical to the performance of the joining operation. This is particularly true for fastening of composite skins. Measurement techniques for fastener holes and gaps are needed. CT has the potential to assist in the development of various joining techniques.

5.1 Fasteners

Recent advances in fastener design have increased the complexity of both the tooling and the fasteners themselves. This complexity can translate into difficulty in the evaluation of these fasteners. CT can be used to assist in the evaluation of new collars and the tools designed for collar installation.

5.1.1 Segmented Die Lockbolt

Segmented die lockbolts are being developed to replace Hi-lok fasteners on aircraft. Some initial fasteners were CT scanned *in situ* to determine if any gaps existed between collar/nut and the fastening bolt. Previous attempts to answer these questions by cutting open the fastener failed, because this information was lost in the cutting. The part is under stress, and springs apart when it is cut open.

The scans showed that there were no gaps based on the sensitivity of the CT system used. Figure 5.1-1 is an example of one of the scans. The CT scan was performed on a nominal 1 lp/mm CT system. However, tests have shown that gaps as narrow as 0.025 mm will be detected, although not resolved. The CT results, in addition to destructive strength testing, were used to support the recommendation to continue efforts to qualify the bolts for the program.

Locking fastener development can be substantially assisted through CT technology, because other methods of evaluation generally fail to preserve the information sought, i.e. gaps, "goodness of fit", etc. The CT system however must have adequate performance characteristics in order to provide the desired information. For example, in the case of Ti fasteners in a graphite/epoxy panel, the goal was to examine the fit of the fastener in the countersunk hole of the composite. Unfortunately, the higher density titanium produced artifacts which washed out the image of the composite adjacent to the fastener when scanning was performed on a medium resolution CT system. A CT system with a high resolution and sufficient dynamic range to resolve the composite material adjacent to the metallic fastener is needed in this case.

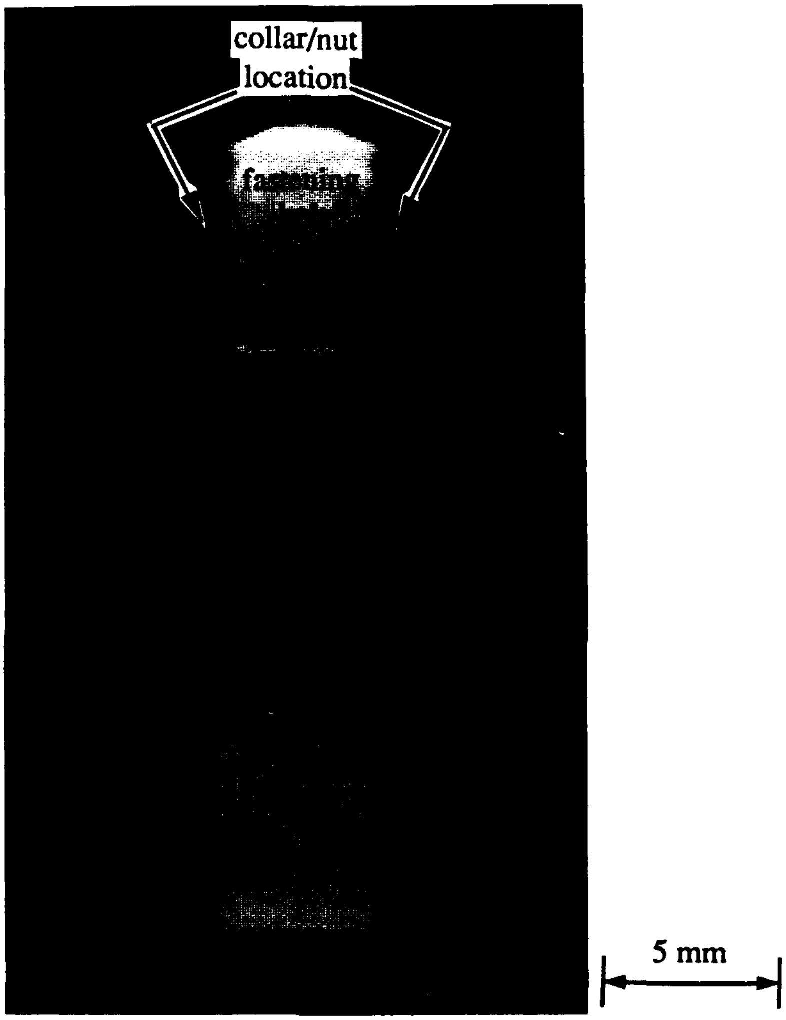


Figure 5.1-1 CT slice of a segmented die lockbolt revealing proper collar/nut fit.

5.2 Diffusion Bonded Components

Diffusion bonded components are often complex and difficult to inspect. While, in general, CT is not going to provide a direct measure of actual diffusion bond quality, the structures which are formed through diffusion bonding can benefit from CT inspection. SPF/DB structures are a perfect example of the usefulness of CT for diffusion bonded components (Section 4.2).

5.3 Weld Evaluation

While film radiography is generally an effective method for inspecting welds for defects such as cracks and porosity, geometry issues can make this method extremely difficult or even impossible. CT may have an advantage over conventional film radiography in many cases, especially when the back side of a weld is inaccessible.

5.3.1 E-beam Weld Sample

Figure 5.3-1 is a photograph of a 304 stainless steel pressure vessel containing an E-beam weld. The vessel is 60 mm diameter at the weld. The weld is approximately 4 mm deep with a 3 mm backup bar behind. Voids are a common problem in E-beam welding. Voids in the backup bar are allowed in this particular sample, but voids in the weld region are cause for rejection. Radiography of the weld cannot tell with sufficient accuracy whether the voids detected are in the weld region or not.

A series of CT scans in axial steps of 0.5 mm were taken of the pressure vessel to image the weld region. A medium resolution CT system was used. Figure 5.3-2 is a CT slice through the center of the weld. Numerous voids are detected and their depths analyzed to determine whether or not they are in the weld or backup bar regions. On each side of the sample in the CT image are steel image quality indicators (IQIs) [see ref. 8, WL-TR-91-4121]. The IQIs consist of thin steel shims containing holes of nominally 1, 0.5 and 0.25 mm diameter. The shim are 0.125 and 0.25 mm thick, mounted between two cylinders of steel so that the holes in the shims represent voids in a quasi-homogeneous steel sample to the CT imaging system. The holes represent voids of 0.2, 0.05 and 0.012 mm^3 in the 0.25 mm thick shim and voids of 0.1, 0.025 and 0.006 mm^3 in the 0.125 mm thick shim. In this scanning sequence the 0.025 mm^3 size void could be readily detected but the 0.012 mm^3 was only marginally detectable. This information provides a measure of the size of voids detectable in the image.

5.3-2 Aluminum Ducting

Figure 5.3-3 is a photograph of an aluminum ducting that is tack welded to a mounting brace. Figure 5.3-4 is a CT slice through the tack welds. The CT image reveals internal defects in the weld. The capability of CT to quantify the defects in these and other types of joints can lead to the establishment of improved procedures for specific joining processes.

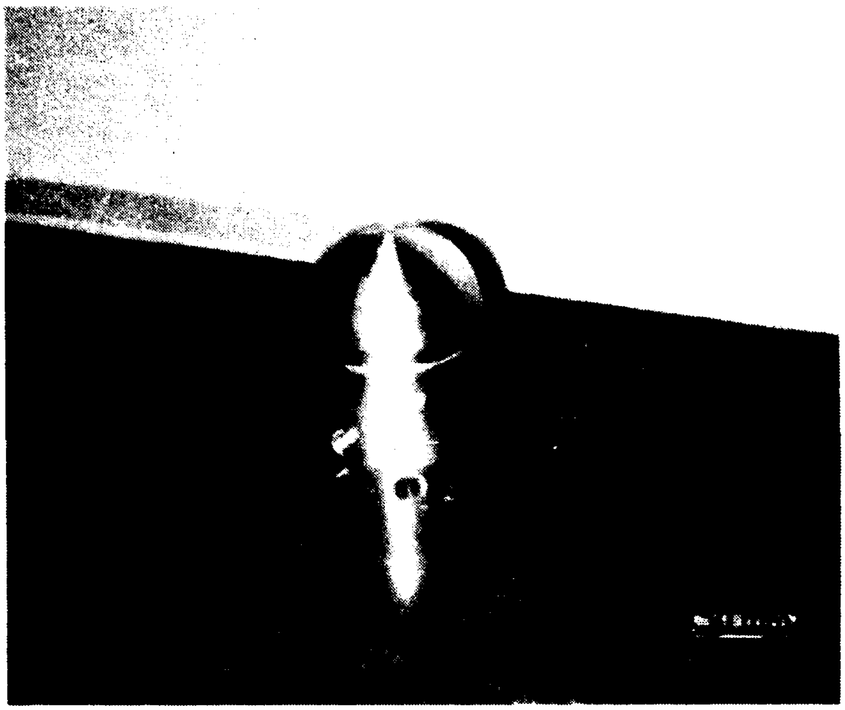


Figure 5.3-1 Photograph of E-beam weld specimen.

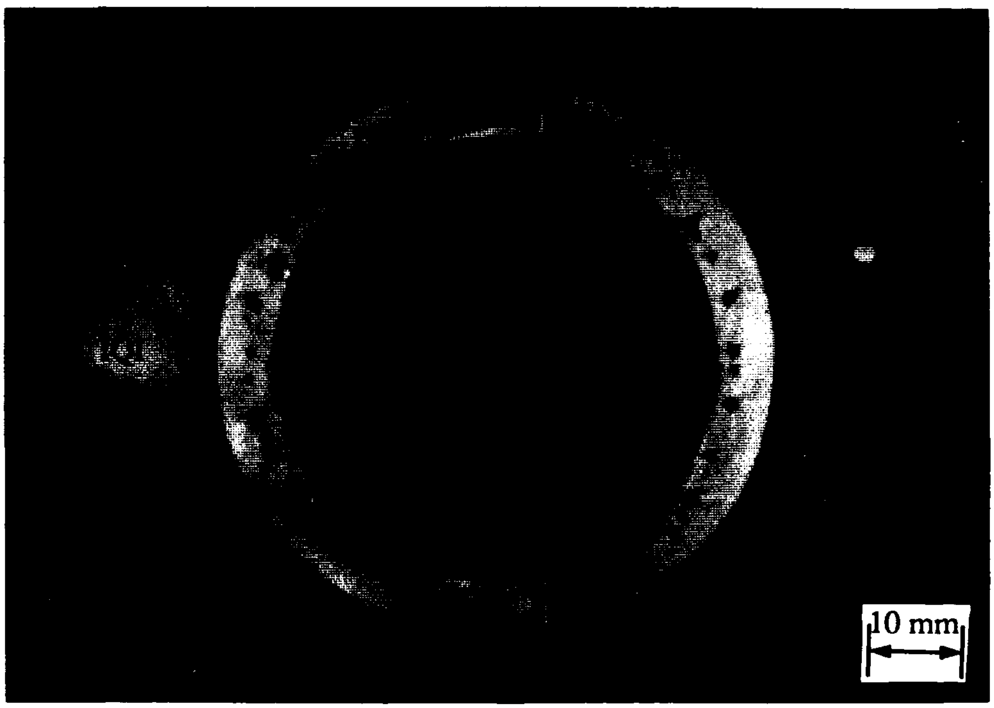


Figure 5.3-2 CT slice taken through the center of the E-beam weld revealing areas of porosity.

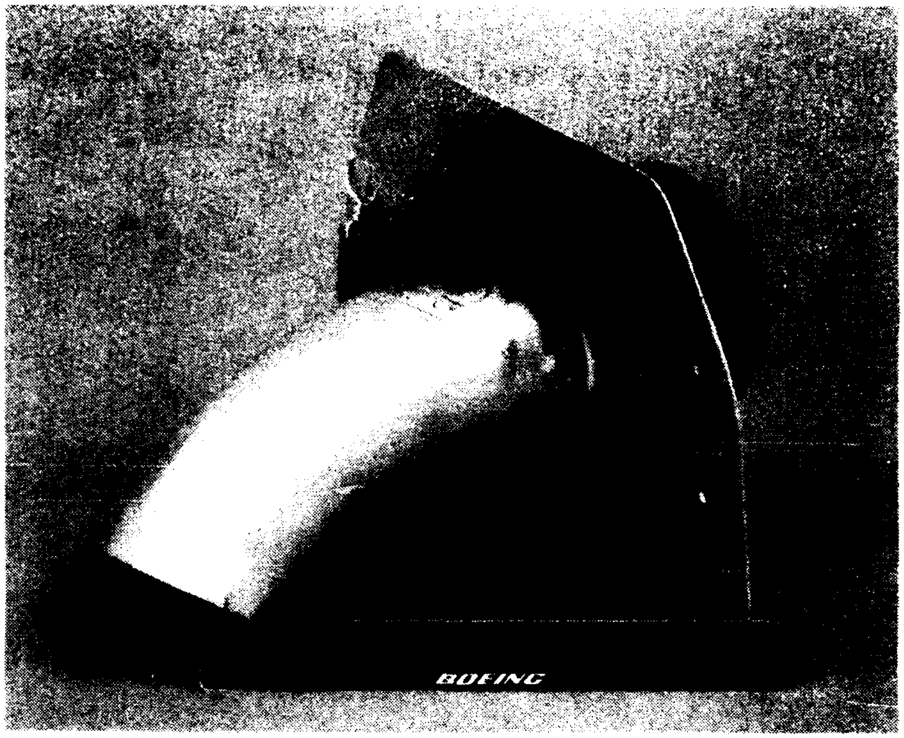


Figure 5.3-3 Photograph of aluminum ducting tack welded to mounting brace.

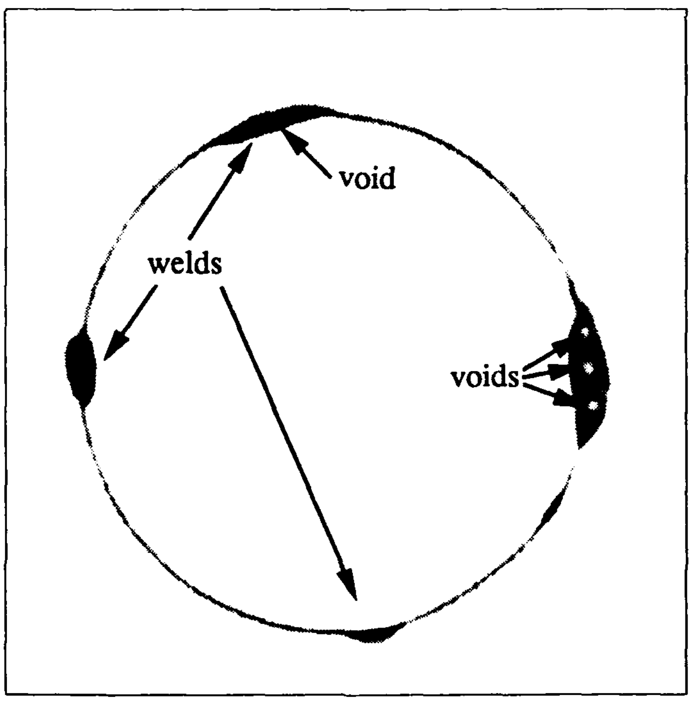


Figure 5.3-4 CT slice of tack welded ducting revealing internal defects.

5.4 Adhesive Bonding

Adhesive bonding is another area of aerospace/aircraft joining that can benefit from CT. CT can provide important information about adhesive bond quality provided there is at least some gap present where materials are unbonded. Ultrasonic testing (UT) is often used to measure bond quality, but there are times when UT may not be practical. For example, if the materials being bonded together are highly attenuative to ultrasonic signals, or the component has a complex shape, UT may not be possible.

Figure 5.3-5 is a photograph of a vibration test beam sample that has an avionics mount adhesively bonded to it. This test beam was CT scanned to determine the bond quality before any avionics vibration testing was done. Figure 5.3-6 is a CT slice across a thick (approximately 1 mm) adhesive bond. The image shows that the bonding is porous on the left hand side and has voids in other regions as well. The amount of "good" area (based upon the presence of adhesive in the image) is considered sufficient to provide adequate bonding for the particular application. In general, CT can provide a quantitative measurement of the percent of adhesive in a region which can be used to assess the quality of the bond.

Figure 5.3-5 Photograph of vibration test beam with avionics mount adhesively bonded to it.

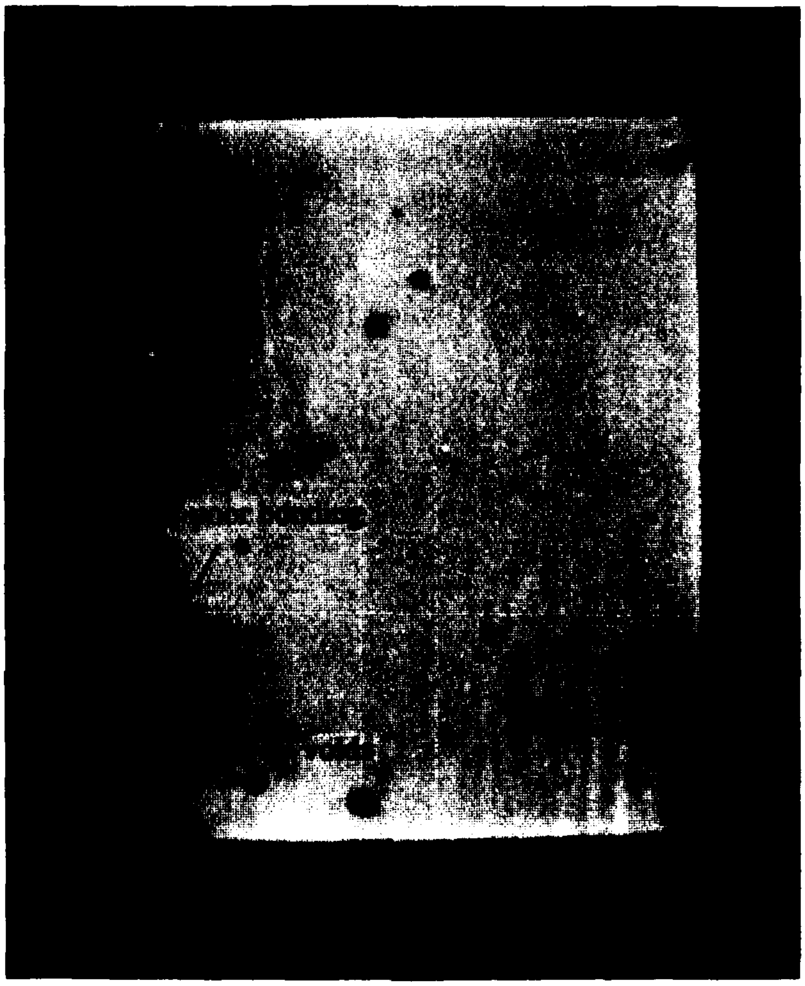


Figure 5.3-6 CT slice taken parallel to the adhesive bond, revealing areas of porosity and large voids in the adhesive.

6.0 PRELIMINARY COST BENEFIT ANALYSIS

The results of CT testing of various advanced materials, joining methods, and manufacturing processes revealed four specific areas in which there is potential for significant economic benefit for CT. These areas are: 1) New Product Development, 2) Process Control, 3) Noninvasive Micrography and 4) Material Performance Prediction.

6.1 New Product Development

In the area of new product development of advanced materials, CT holds significant near-term payback potential for advanced materials. Production costs are generally high for new materials, and the payback for data leading to faster decision making or improvements in the product will be greater than for traditional materials with well established production methods. CT provides different information than most conventional evaluation methods in the form of an X-ray linear attenuation coefficient map with accurate three dimensional spatial locations. Better program decisions can be made when the information available is accurate and quantitative. Also, CT can provide time savings, as an alternative to destructive sectioning. The first articles fabricated must often undergo stringent nondestructive and destructive measurements. Besides being expensive, such tests often result in the loss of one or more components, the cost of which can be substantial if the component is large, complex or a single article. CT can reduce these costs if the defect sensitivity or dimensional measurement accuracy is sufficient to detect critical features. CT is a viable tool to be used in the "concurrent engineering" process which has the goal of bringing products to market faster and at lower overall cost.

Table 6.1-1 lists the steps in a typical new product manufacturing cycle. The relative cost for each step is listed as a percentage of the total cost of developing the component. Actual costs will, of course, vary from product to product. Those steps which can directly benefit from CT are marked with an "x". The steps which can be indirectly influenced by CT are marked with "xx". In this example, 80 percent of the cycle may be benefited or influenced by CT. If CT provided on average 20 percent savings in the cost of these steps, a total of 16 percent savings would be incurred by using CT on the program. Most likely, CT data will provide key information in the analysis steps that will reduce the risk of decision affecting other steps.

Table 6.1-1 CT Benefit to New Product Cycle

New Product Steps	Percent of Total	CT Benefit
design	20	xx
1st manufacture	10	
analysis	15	x
redesign	10	xx
2nd manufacture	10	
analysis	15	x
1st article	10	x
contingency	10	xx

x - step can directly benefit from CT data
xx - step can indirectly benefit from CT data

Figure 6.1-1 shows the savings that might be realized by using CT for new product development. Two curves are drawn, one for CT influencing 80 percent of the product development cycle resulting in a 16 percent overall improvement and CT influencing 40 percent of the cycle for an 8 percent overall improvement. A cost of $8K and $4K is assumed for the CT scanning for the two curves respectively. This value is representative of the costs for CT scanning services for reasonably detailed CT evaluation that a program might plan for several test articles or a number of small samples. This graph shows that a $50K product development program would break even based on the assumptions.

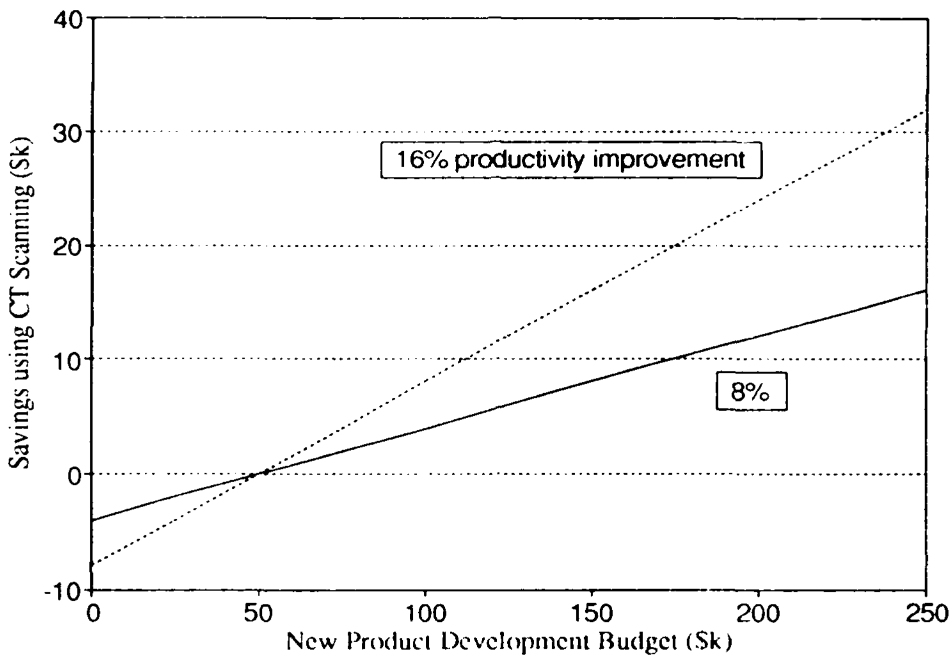


Figure 6.1-1 Cost savings possible by utilizing CT scanning services in the new product development cycle.

6.2 Process Control

CT provides quantitative measurements of features which can be used for defect detection and statistical process control measures in advanced materials fabrication. CT data can save money by improving or maintaining the control on the manufacturing process. Scrap can be reduced both by early identification of defective product, and by reducing the variability in the process itself. An overall gain in productivity is possible, which translates into cost savings. CT is a tool to be used in the "Total Quality Management" concept, which provides feedback on product details to the management system.

The CMC extruded bits discussed in Section 3.3.2 can serve as an example. Currently, a certain percentage of material that is extruded is defective, because it has porosity or long voids in the center. An in-line CT machine would identify the defective regions so that time or money is not wasted preparing bits that will have to be discarded. Defective product is immediately discarded based upon the information provided by CT. Also, the process variables can be modified to bring the product back into control before more defective product is extruded.

Figure 6.2-1 shows how long it would take for a CT system to pay for itself if it were used exclusively for manufacturing process control if production were increased by just 10 percent. In this example, we have assumed $1M, $500K and $200K CT systems operating at 10 percent of the capital investment per year for maintenance costs. Payback on the CT system can roughly be achieved in 3.5, 1.5 and 0.5 years respectively for a $2M/year process.

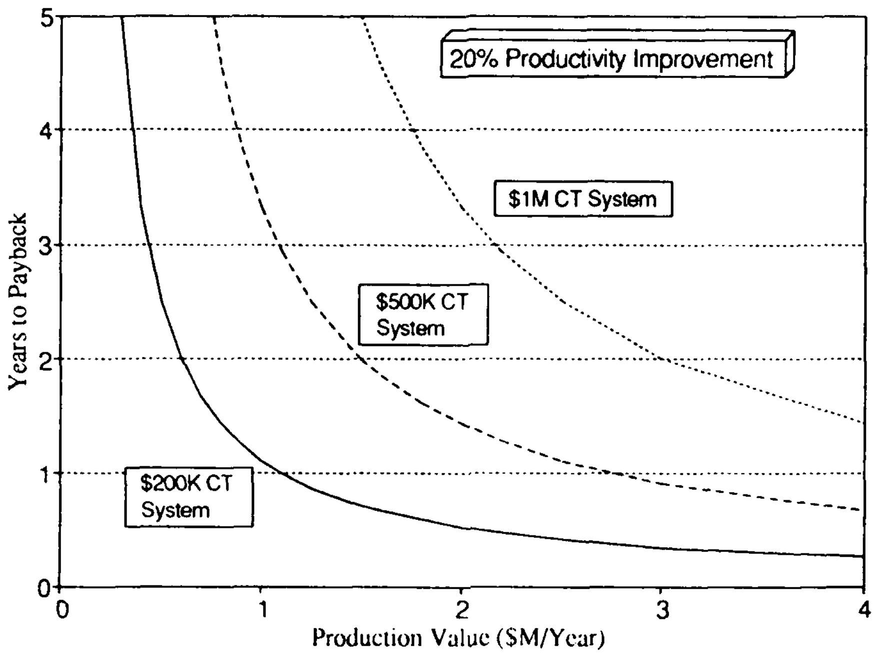


Figure 6.2-1 Estimate time for return on investment in a CT system for manufacturing process control.
A 20 percent productivity improvement has been assumed.

6.3 Noninvasive Micrography

Noninvasive micrography using high resolution CT can be faster and less expensive than traditional micrography for analyzing materials, and it is, of course, nondestructive. Advanced materials are particularly well suited to CT evaluation for noninvasive micrography because they are often composite materials whose constituents possess variations in X-ray linear attenuation coefficient that can be identified by high resolution CT. Of course the CT images and photomicrographs are not identical. Thus the CT image must contain the information of interest desired in the micrographic study of the component.

Because CT is nondestructive, there is the opportunity to gain not only from the less costly slicing than destructive sectioning, but slices can be taken without destroying the component. The additional information available from these evaluations reduces the risk any program faces. Rapid information gain can be used to reduce overall schedules because decisions are made earlier, and with greater confidence. These benefits are difficult to quantify economically but are real. CT scanning can be much faster than conventional micrography and therefore offers some economic advantage. Cost benefit curves for high resolution CT versus conventional micrography are discussed in another CTAD report [23].

6.4 Material Performance Prediction

CT data may correlate directly with part performance, as was shown with the pultruded rod discussed in Section 4.1. Once a correlation has been experimentally established between critical mechanical properties of a component and the CT data, the performance of each component can be "measured" nondestructively.

The cost benefits of nondestructive performance prediction are many. Quality assurance based upon engineering criteria rather than qualitative measures provides for a greater confidence level in the system performance. And, unlike destructive testing of samples, every component can be evaluated for performance. Increased confidence in performance prediction allows a reduction in material cross section for equivalent safety margins, and thus, a reduction in weight. If a 10 percent gain in the strength rating of a material could be realized, then the reduction in weight would translate into a significant cost savings in aircraft production. Figure 6.4-1 shows the curve of cost savings for a 10 percent gain in performance rating as a function of the material production for high performance aircraft, where weight savings are rated at $1100/kg ($500/lb).

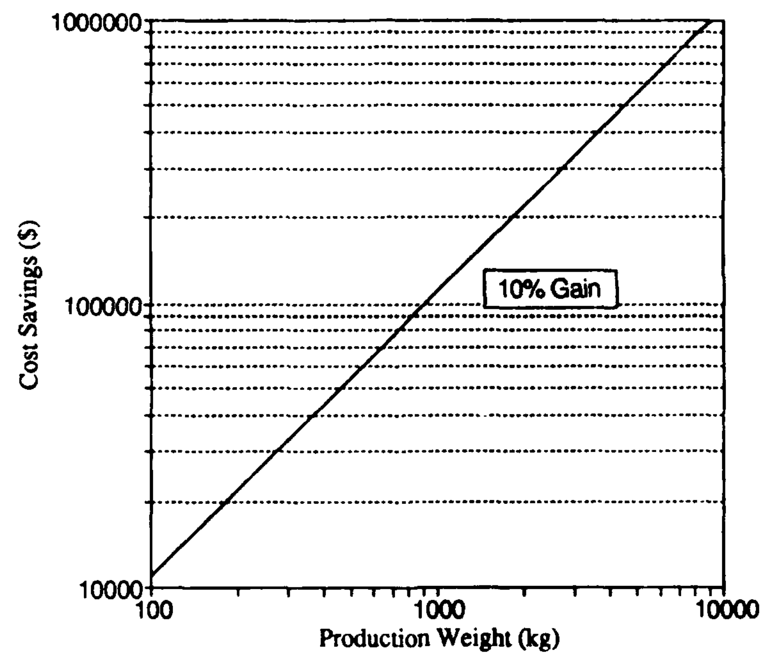


Figure 6.2-1 Cost savings for a 10 percent gain in material performance as a function of production weight for high performance aircraft.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This preliminary task assignment studied the use of CT on a wide variety of advanced materials, processes and joining for the aircraft/aerospace industry, with preliminary conclusions in a number of areas. The CT sensitivity can be tuned to the requirements of the advanced material evaluation. Resolution, contrast sensitivity and component size must be traded-off in the selection of the scanning system or technique. Optimal implementation of CT can provide significant benefits to the development and utilization of advanced materials and processes, and can also be cost effective.

The results of the CT testing revealed four focal areas in which CT currently provides a technical and/or economic benefit. These areas are, 1) new product development, 2) process control, 3) noninvasive micrography, and 4) material performance prediction.

New materials or products usually involve an iterative cycle of manufacture and testing to bring the manufacturing process under control. CT provides important information about the product to the manufacturing engineer which can reduce that cycle time. CT serves as an enabling technology for the development of new materials, products, or manufacturing processes. The information CT provides allows engineers to reduce the cycle time in product prototyping and often "leap frog" product development steps. Reduced development time often results in significant initial cost savings and reduced risk of poor designs being manufactured that can result in enormous savings over the lifetime of a program. CT is a tool to be used in the "Concurrent Engineering" cycle.

CT can be used for developing and controlling a manufacturing process as part of a "Total Quality Management" program. The CT measurements of X-ray linear attenuation coefficient (directly related to density and a function of atomic number) and the accurate dimensional information provided are ideal for making important statistical measurements as well as for defect characterization for many advanced material processes. Under certain conditions, the CT measurements can be correlated to mechanical properties to allow nondestructive performance prediction of advanced materials. When high resolution CT is employed it can be a cost effective replacement for the destructive sectioning and micrography associated with material qualification. This application is referred to as noninvasive micrography.

7.2 Recommendations

Developers of advanced materials should plan for CT scanning services or leasing agreements when costing the development of new materials or components. If the development programs or manufacturing production are sufficiently large, then purchase of a CT system can be cost effective. This is particularly advocated for material production where CT can be used as a process control tool. High resolution CT systems or scanning services should be considered by companies that perform a great deal of sectioning and micrography for advanced material assessment and qualification. The volume of work will determine whether or not the purchase of a CT system is cost effective.

A final testing task should be performed to evaluate further the cost benefits that can be obtained by utilizing CT in the development of advanced materials. CT for material performance prediction is also an area that should be studied to determine its viability as a alternative to destructive sampling and testing. A task assignment to demonstrate to government and industry the benefits of CT in advanced materials should be performed to emphasize the correlation of CT measures to material characteristics.

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