WL-TR-93-4048

X-RAY COMPUTED TOMOGRAPHY FOR CASTING DEMONSTRATION

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May 1993

Interim Report for Period September 1991 to May 1993

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1, 1993	Interim Sept. 1991 - May 1993

4. TITLE AND SUBTITLE

X-Ray Computed Tomography for Casting Demostration

5. FUNDING NUMBERS

F33615-88-C-5404
PE: 63112F
PR: 3153
TA: 00
WU: 06

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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10. SPONSORING/MONITORING AGENCY REPORT NUMBER

WL-TR-93-4048

16. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; Distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Computed tomography (CT) has been applied to cast products demonstrating benefits to product development, dimensional measurements and critical region evaluation. The CTAD program has produced data in a number of reports demonstrating the quantitative measurement capability of CT and its advantages for castings.

CT is a measurement tool which can enable greater use of casting by assuring quality in complex structural applications. CT allows an engineering evaluation of castings for a number of criteria such as internal defects, porosity content, three-dimensional location of features and, internal and external dimensions. As casting complexity and part value increases, the application of CT increases in cost effectiveness relative to other technologies. For critical regions of a casting, CT can be superior to radiography for detail sensitivity and relatively inexpensive.

Educational material is needed to aid engineers in understanding the applicability and benefits of CT to their problems. Example stories have been used by the CTAD program to demonstrate the areas of CT application and cost benefits. Readers of the case study stories are able to extrapolate from the examples to their problems and evaluate the benefits that CT may provide them.

14. SUBJECT TERMS

Computed Tomography (CT), Aluminum, Titanium, Casting, Reinforcement, Economics, Nondestructive Evaluation, Flaw Characterization

15. NUMBER OF PAGES 42

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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ACKNOWLEDGEMENT

The authors acknowledge the input from a number of individuals for information on castings and other past examples. Thanks are due to T. Reinhart, H. Herbert and T. Drinkard of Boeing Materials Technology and Liaison Engineering and also to Alcoa and Howmet for examples presented in this report.

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.

SUMMARY

Computed tomography (CT) has been applied to the nondestructive evaluation of cast products, demonstrating cost-effective benefits to product development, dimensional measurements and critical region evaluation. One of the problems with conventional film X-ray or ultrasonic evaluation of castings is that as casting geometry increases in complexity, it becomes more and more difficult to locate and size internal flaws due to ambiguities in the data. Computed tomography is an X-ray based evaluation method which unambiguously maps the location and size of internal flaws relatively independent of casting geometry complexity. Further the data is in digital form for processing. The quantitative measurement capability of X-ray CT allows an engineering evaluation of castings for a number of criteria such as internal defects, porosity content, three dimensional location of features and, internal and external dimensions.

CT provides flaw characterization capability in critical regions of castings with superior sensitivity compared to conventional radiography. This capability allows the evaluation of regions which tend to have defects in the developmental stages of a casting process, and can assure material quality in the same region during production. CT evaluation provides internal dimensional measurements in castings that are as good or better than destructive sectioning. Dimensional measurements to better than 0.050 mm (0.002 inch) are fairly easy to achieve with the CT system configurations tested. The benefits of eliminating destructive sectioning as a means of inspection have been demonstrated. The three-dimensional location capability of CT allows CT data to be converted to CAD/E workstation files. CT can be effectively used to acquire casting geometry in drawing formats (reverse engineering) and reconstruct components for visualization as part of the engineering analysis. As casting complexity and part value increases, CT increases in cost effectiveness relative to other technologies.

Although CT can be used cost effectively for engineering evaluation of specific casting problems, wide acceptance of CT will require specifications and design "call out" for CT on drawings. There is also a need for lower cost CT systems that can be employed in the foundry on the size and types of product cast for aircraft that can be competitive with other casting inspection technologies. Advances in high throughput CT with adequate sensitivity are required. The combination of digital or real-time radiography with CT also offers a compromise for 100 percent casting inspection that is beneficial to casting evaluation methodologies and can be cost effective.

Educational material is needed to aid engineers and designers in understanding the applicability and benefits of CT to their problems. Example stories have been used by the CTAD program to demonstrate the areas of CT application and cost benefits. Readers of the case study stories are able to extrapolate from the examples to their problems and evaluate the benefits of CT. The CTAD program has produced data in a number of reports demonstrating the quantitative measurement capability of CT and its advantages for casting that are available from Wright Laboratory.

1.0 INTRODUCTION

The goal of the Advanced Development of X-Ray Computed Tomography Applications Demonstration (CTAD) program is to identify applications for which computed tomography (CT) be used cost effectively for the evaluation of aircraft/aerospace components. The program is task assigned so that specific CT applications or application areas can be addressed in separate task assigned projects. 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; and 3) demonstrations where the viability of CT to the inspection problems are analyzed and the results presented to government and industry. This interim report is the result of a demonstration task assignment study on the use of CT for castings. Additional task assignment reports that have been issued by the CTAD program are listed in References 1 through 15.

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 has utilized a wide range of CT systems, both medical and industrial.

1.2 Scope and Objective

This task assignment, designated "Casting Demonstration," is a demonstration effort on the benefits of CT to aircraft structural castings. The scope and objective of the effort involved the development and presentation of materials showing the useful application of CT to aircraft castings. A formal presentation of the CTAD program results included this material at the Air Force Computed Tomography Applications Workshop held May 5-7, 1992, in Salt Lake City, Utah. In addition to the Air Force workshop demonstration, the educational materials on the application and benefits of CT are available from WRIGHT LABORATORY in the "Interactive Multimedia Presentation for Applied Computed Tomography, (IMPACT)" software that operates on Macintosh workstations.

This task assignment also reports on additional example stories of CT benefits to castings not reported in earlier task assignment reports. These examples include detection of defects and engineering evaluation of suspect or rejected parts for recovery of investment.

2.0 BENEFITS

2.1 Aerospace Castings

Castings used in the aircraft and aerospace industry include aluminum, magnesium, titanium, steel and nickel alloys. Compared to forgings and billet machined parts, castings are far less expensive to manufacture. Castings can be produced in complicated shapes that are impossible to produce with machining techniques. However, castings are rarely used as primary structure in aircraft because of the perceived poor control over design allowables for the material strength and ductility. They are used as secondary structure, but often include significant safety factors. Aircraft casting design requirements may also dictate the use of a casting factor to be added for material allowable concerns, which can range from 1.0 to 1.5. However, the conservatism of many designers eventually results in actual safety factors of between 3 and 6 in many cases. The safety factors increase the overall weight of the castings, which defeats the cost and weight savings that castings would otherwise offer. Also, the criteria for accepting castings has very little to do with their ability to provide operational service. That is, the present inspection criteria are not requirements on casting performance, but rather are comparisons to qualitative standards. The significant rejection level of aerospace castings can result, in some cases, in sufficient increased costs that offset the other benefits of using castings.

The benefit of casting to aircraft applications involves more than a simple cost savings. Table 2.1-1 lists some of the pertinent issues. Casting cost savings for aircraft applications will vary depending on the part design and the potential alternatives. Examples and evaluations performed by the casting industry and airframers have shown castings, in many cases, to provide between 30 and 50 percent cost savings. Weight savings also are very often found with castings because the design of a complex structure can be more efficiently achieved. The weight savings is, however, strongly dependent on casting factor and safety factor issues noted in the paragraph above. The casting replaces a number of built up components and when fasteners are eliminated, the part count and inventory savings are significant. The drawing of the casting will be more complicated than any one individual drawing for the multipart assembled unit; however, the single drawing will in general be a significant savings (estimated on the order of 40 percent of the effort) over the set of drawings for a built up product. Drawings are also easier to maintain with a single part replacing a number of piece drawings. Finally, schedules are improved because only one part is needed and no time is required to assemble the unit.

Table 2.1-1 Benefits of Castings for Aircraft Structure

Benefit	Estimated Average Effect
Cost Savings	30 - 50 percent
Weight Savings	10 percent
Reduced Part Count	10's to 100's
Reduced Inventory	10's to 100's
Reduced Drawings	60 percent less drawing effort
	Easier to maintain
Schedule Savings	Months

2.2 CT for Castings

For all these benefits, castings are not being fully utilized in airframe structure. Concerns exist about consistency of the casting process in terms of material allowables, dimensional tolerances and potential internal defects. Computed tomography offers an enabling technology for the casting manufacturer to bring the casting process into control and assure a consistent high quality product. Table 2.2-1 lists some of the benefits of CT to the casting process. Essentially, CT provides quantitative feature measurements that can be used by casting engineers as part of the control and evaluation. Table 2.2-2 lists CTAD report sections that discuss in detail some of these benefits using casting examples.

Table 2.2-1 Benefits of CT to Aircraft Structural Casting Process

Problem	CT Advantage
Internal dimensional measurements	Casting need not be cut Data can be input to CAD/E workstation Final dimensions can be compared to casting modelling
First article inspection	CT can nondestructively evaluate a complete first article
Defect location	3D location of flaws Castings can be repaired Information on defect location allows process refinement
Process and material consistency	CT can verify the effects of processes such as HIPping CT can be used to supplement testing programs
Critical flaw size/location	Flaw size criteria can be varied throughout casting for optimizing performance/cost critical regions can have highest quality evaluation
Salvage	CT quantifies features for MRB evaluation
Selective reinforcement	CT can be used to evaluate the selectively reinforced region of a casting

Table 2.2-2 Casting Benefits Described in Previous CTAD Casting Reports

Benefit	Report No.	Section
Internal Dimensional Measurements	WRDC-TR-89-4138	Section 3.3 Dimensional Measurement
	WL-TR-91-4121	Section 4.0 Dimensional Measurement
	WL-TR-92-4032	Section 3.1 Discharge Fitting Section 4.2 CT for Design Geometry
Acquisition		
Defect Detection/Location	WRDC-TR-89-4138	Section 3.1 CT Correlation to RT Section 3.2 Full Scale Parts
3D Flaw Measurement	WRDC-TR-89-4138	Section 4.4 CT for Critical Region Inspection
	WL-TR-91-4121	Section 3.0 Engineering Analysis
Flaw Analysis with Finite Element Modeling	WL-TR-91-4121	Section 3.0 Engineering Analysis
Process and Material Consistency	WL-TR-92-4032	Section 3.2 Hydraulic Manifold (HIP Eval.) Section 4.1 CT for Material Testing
Critical Flaw Size/Location	WL-TR-91-4049	Section 4.4 CT for Critical Region Inspection
	WL-TR-92-4032	Section 3.3 Flap Control Unit
CT Sensitivity	WL-TR-91-4049	Section 3.0 Casting Feature Sensitivity

Dimensional tolerances are very important in most castings. Measurement of dimensions on complex castings is often a critical, time-consuming process. Destructive sectioning of the part can destroy "good" castings in order to obtain the required information during both the development and production phases. Nondestructive internal and external dimensional measurements are a significant benefit from CT scanning. The CT data are cross sections, just like drawing sections. The CT image can, therefore, be transferred to an engineering workstation for comparison of the as-built with the design. This capability of CT can be competitive with other "software gauging" technologies, such as coordinate measuring machines, for complex external shaped castings that fit within CT system handling capabilities. For internal measurements, CT is the only alternative to destructive sectioning and measurement. The accuracy and precision of CT dimensional measurements can be very high (better than 0.050 mm), depending on the casting size and complexity. Measurements on first articles can also be made nondestructively.

When a new casting is being developed, a very common problem is a high incidence of manufacturing flaws in a particular region, requiring iterative cycles of manufacturing and testing. The cycle involves identifying and evaluating flaws, so that the process can be altered or refined to eliminate them in succeeding castings. CT usage can reduce the number of cycles required because of the superior definition and location of the defects. CT is also beneficial to monitoring the results of processes that affect the casting quality. CT measurements before and after hot isostatic processing (HIP) have been shown to nondestructively measure the performance of HIPping on a particular casting.

Regions of a casting that are expected to "see" critical stresses often require more thorough inspection than the rest of the casting. Critical regions can be monitored with CT to ensure quality. When anomalies are identified in castings, the CT data are useful for materials review board (MRB) decisions. The advantage of CT for casting product development is that CT can characterize anomalies that may be overlooked in complex castings, or be merely qualitatively indicated by radiography.

As castings become more complex and reinforcement is added, CT will provide critical information to assure the correct reinforcement placement and necessary quality. In selectively reinforced castings, metal matrix composite inserts are placed in the casting to provide high performance characteristics at specific locations. The positioning of the inserts and the presence of any defects within or around the inserts will need to be evaluated when those structures are implemented.

2.3 CT Economics

While CT certainly has technical benefits, it must also be economical in order for it to be applied by casting engineers, foundries and manufacturers. Earlier task assignments reported on economic considerations for CT of castings [7,13]. The economic considerations depend heavily on the value of the casting and assumptions on how well CT aids in the development and decision making used in casting applications. In general, the economic conclusion of the CTAD program is that present technology CT is only economically applicable to complex, high value castings. Figure 2.3-1 shows graphically this interpretation, that CT applies to more complex, costly castings. Table 2.3-1 summaries the economic findings of the program in terms of areas where legitimate cost savings were recognized.

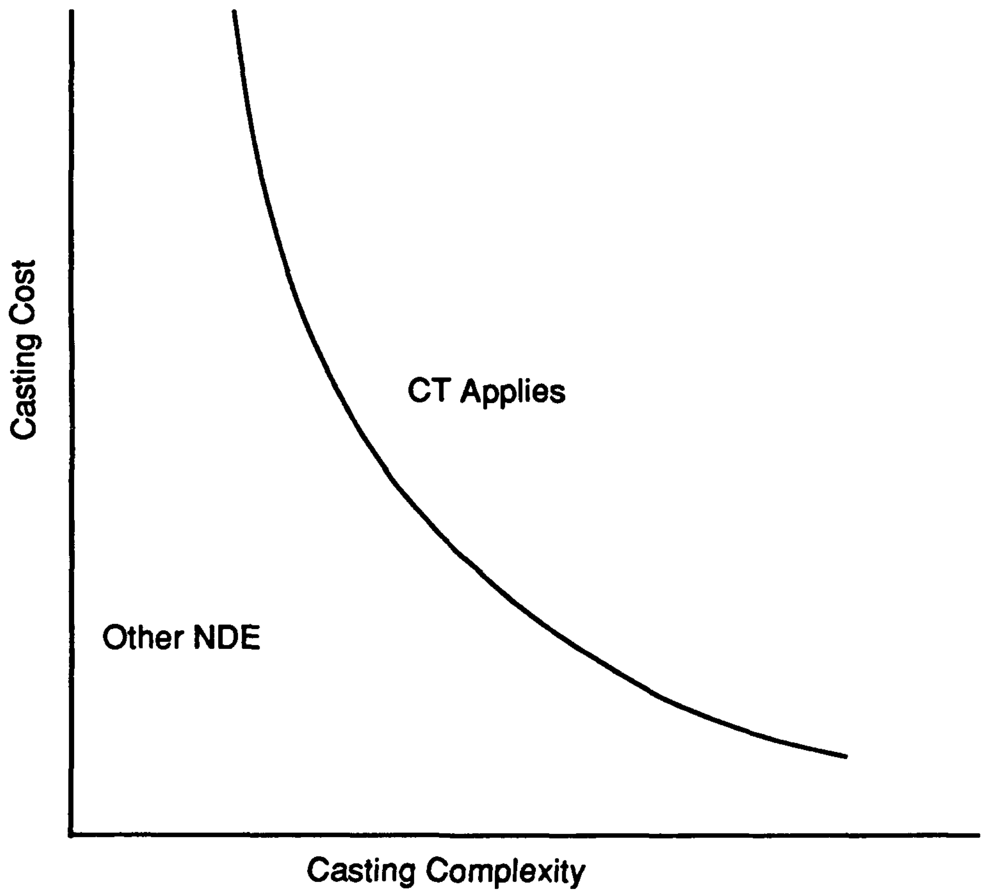


Figure 2.3-1 Graphic depicting the type of castings that can be cost effectively aided by CT.

Table 2.3-1 Economic Benefits of CT Casting

Example	Present CT Technology Economic Benefit
MRB Decisions	CT information enabled decisions to allow acceptance of a cast structure for an aircraft that was grounded, awaiting the replacement part. Significant savings resulted CT allowed evaluation of defect criticality for repair of cast parts when latent defects were found after subsequent manufacturing steps. Savings of 10 to 100 times the original casting value were realized
Dimensional Measurement	CT data provided greater flexibility and information on internal condition for correcting the casting process. Direct cost savings were difficult to quantify because CT data are superior information that may ultimately reduce the number of interactions in a development but may cost slightly more to acquire than simple sectioning.
Geometry Acquisition	The transfer of CT data to CAD/E workstations was very cost effective for a complicated geometry castings that fit the inspection envelope of a CT system. Savings were estimated at about 50% of alternative costs.
Critical Region Evaluation/Process Development Measurements	CT examination was superior to radiography in thick section regions of castings that are normally difficult for film radiographic methods. The 3D location of features and the dimensional measurements provided important information to correct processes. Savings were not quantifiable because CT examination is not required by specification. However, the use of CT did improve the overall product. For widespread application of CT, costs must fall within the margins that companies will pay for ensuring that their products are high quality.
Process Control	CT data on the result of casting processes provided useful measurements for understanding the process. Savings were difficult to estimate because the value of improved knowledge could not be quantified.

While there are specific examples of cost savings using presently available CT technology on castings, many of the cost saving scenarios are "soft." That is, the CT data provide greater information for better decision making. However, it is unclear what value to put into this savings. In the Task 6, "Full Scale Casting" report [7], the cost benefit of CT was estimated to provide a 10 to 20 percent improvement in the development cycle. This estimate, based on experience working with casters, resulted in a curve showing the size of foundry that would find current CT technology beneficial. Figure 2.3-2 repeats this figure from that report.

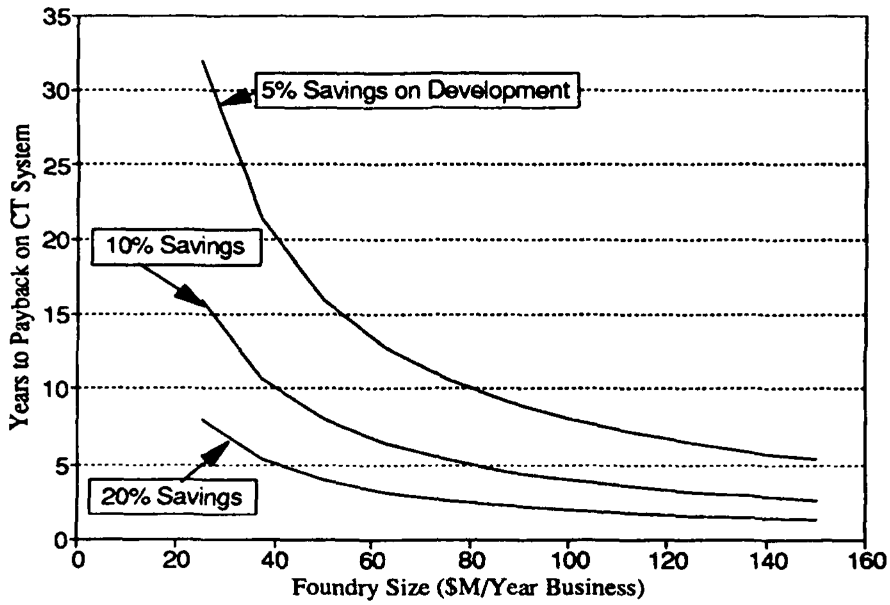


Figure 2.3-2 Estimated time for return on investment on $2M CT system used for new product development in foundries of various size. Values given for 5, 10 and 20 percent savings on development.

In addition to the economic consideration of Figure 2.3-2 for the use of CT in foundries, the CTAD program addressed the application of CT to casting activities at various steps in the casting process. In the Task 12 "Casting Development" report [13], the analysis of the cost benefits showed how CT could be used to support the casting process. The task 12 results are repeated in Appendix. These results rely on the CT scanning costs being a fraction (10 to 20 percent) of the casting value. Because present CT scanning costs can range from $10 to over $100 per CT slice depending on the part size, this requirement fits the previously summarized general conclusion that CT applies to more complex, high value castings. Without a dedicated CT system internally available, a foundry might very well spend $300 to $1000 per casting for evaluations. If CT were applied to every casting, then the castings would need to have significant (greater than several thousands of dollars) value. Of course, if only a few castings are to be evaluated out of a significant run, then the costs can be considered as a fraction of the total casting contract value.

Likewise, it should be emphasized that if a CT system is available, a single CT slice for a critical region evaluation can be relatively fast and inexpensive to obtain. The value of information obtained can be quite high.

2.4 CT Technology Improvements

For CT evaluation to achieve broad base, routine inspection application in the casting industry, improvements to current technology are needed. Table 2.4-1 lists improvement factors that are needed for CT to gain cost effectiveness in the casting industry. The primary areas of improvement are lower capital cost, higher throughput and greater detail sensitivity for the low cost, high throughput CT technology.

Table 2.4-1 Improvements to CT for Aircraft Structural Castings

Improvement	Goal
Lower Capital and Operating Cost	Combined CT amortized capital and operating costs need to be within a factor of 2 and preferably below a factor of 1.5 over existing NDE for CT to be considered as a viable alternative for current routine foundry inspection applications.
High Throughput	CT system throughput must meet the throughput of present film radiography for cast products. This wiil require very high speed scanners or "cone beam" approaches. CT data storage and review has advantages over film that would be readily adopted if costs were very close to existing film recording methods.
Greater Detail Sensitivity	While CT has sufficient detail sensitivity to casting features that is equivalent or exceeds radiography for some regions of a casting, it does not have adequate sensitivity in all regions of a casting. For example, thin walled castings are better evaluated with film radiography than current CT technology.

Computed tomography system costs will need to be reduced for general foundry application. Because there are no aircraft structural castings that require CT examination by specification, the only incentive to change from present approaches is through cost savings. Overall cost savings can be achieved using CT even if its direct expense is higher than radiography because it offers other benefits (e.g. nondestructive dimensional measurements, 3D location of defects for repair, etc.) However, the margin above present radiographic capital and operating costs must be low for foundries to make that additional investment.

Throughput of CT systems must be increased for routine casting inspection. Conventional single slice industrial CT examination is not practical for typical castings. Very high throughput scanners or "cone beam" approaches will be needed with large data storage. The problem with this approach to date has been limitations in data acquisition and handling to provide adequate 3D detail sensitivity throughout the part. Improvements in data handling, storage and image manipulation will make the throughput issue of CT less of a problem in the future.

Finally, there remain instances where CT does not offer as high a sensitivity as radiography. This occurs primarily in thin walls and some regions of large structures. While CT has fundamental sensitivity and measurement advantages over film, these are realized mostly in thick sections or complex geometries. CT systems can be designed for very sensitive digital radiography to provide the radiographic equivalent examination in thin regions and CT in thick sections. Such a capability will need greater versatility than generally available with many industrial CT systems in order to position the casting for proper radiographic views. Nevertheless, there are technical approaches for CT systems that can provide both radiographic and CT imaging with detail sensitivity meeting present casting criteria. The expense of this technology must now be reduced to be competitive with the existing casting NDI methodology.

3.0 EXAMPLES

The CTAD program has shown that CT can be cost effectively applied to casting product development and engineering evaluations. The mechanism for introducing individuals involved in casting technology to the benefits of CT has been the use of example stories. This section includes example stories on casting defect and process evaluation not previously reported in early interim reports.

3.1 Defect Evaluation

3.1.1 Manifold Engineering Review

A very useful application of CT is to evaluate defects that are detected by other methods to establish their criticality, and decide the final disposition of the component. An example of such an application is an hydraulic reservoir which failed a pressure test after final assembly. The reservoir is used in the hydraulic control system that actuates flight control surfaces of an aircraft, and therefore is a flight critical item. The failure was in a manifold casting which is welded onto the reservoir. The manifold was weld repaired and then film radiographed, at which time some porosity in one of the manifold ports was detected. Because the radiographic method was not capable of assessing the extent of the porosity, the reservoir with the attached manifold was examined with CT. The main concern was whether or not the porosity was too close to some threads in the port, thus constituting a potential failure possibility.

Figure 3.1.1-1 shows the reservoir mounted on a medium resolution CT system, ready for scanning. A series of CT slices were made in the vicinity of the observed porosity, and one is shown in Figure 3.1.1-2. From this image, it is easy to see that the porosity is in the threads, and thus the manifold had to be disqualified. This positive location of the porosity in the threads was confirmed when the port was later removed and sectioned. One photomicrograph taken at 25X through the entire thickness of one wall of the port is shown in Figure 3.1.1-3, confirming the results of the CT slice image in Figure 3.1.1-2 and the correctness of the decision to disqualify the threads.

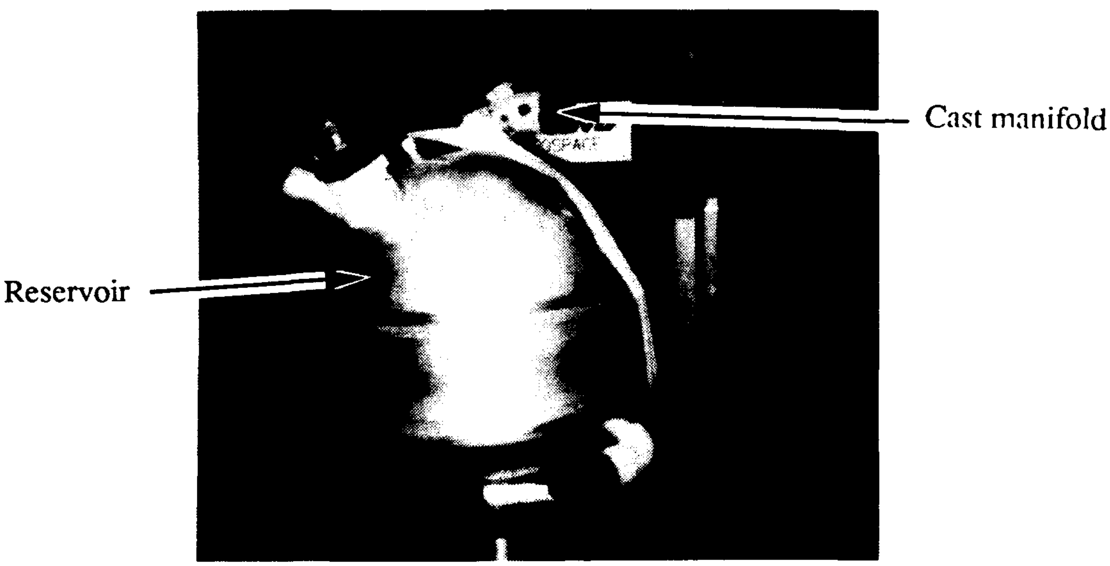


Figure 3.1.1-1 Hydraulic reservoir mounted on a medium resolution CT system for evaluation.

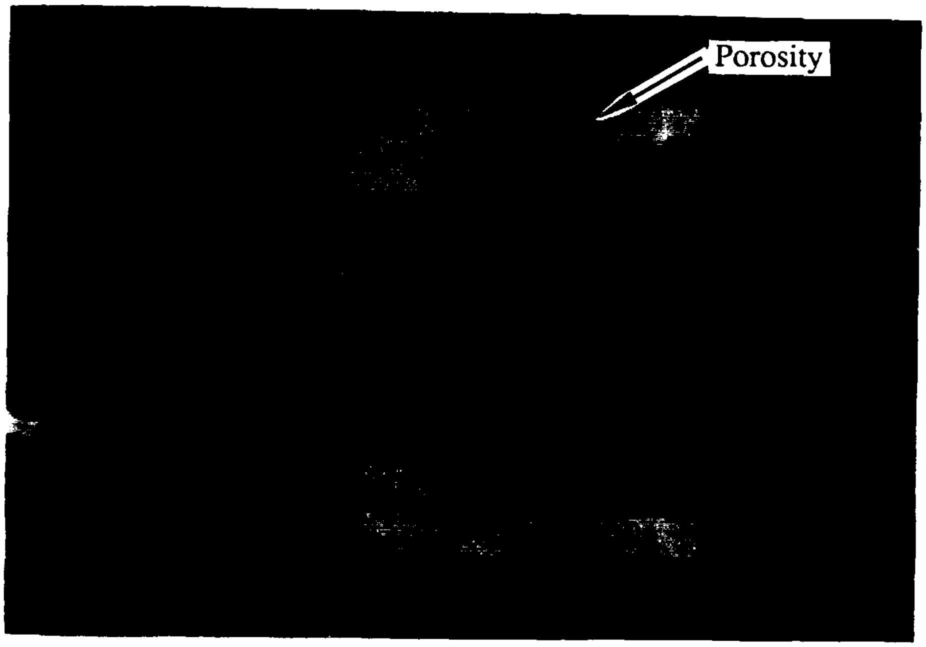


Figure 3.1.1-2 CT image of the reservoir showing porosity near threads.

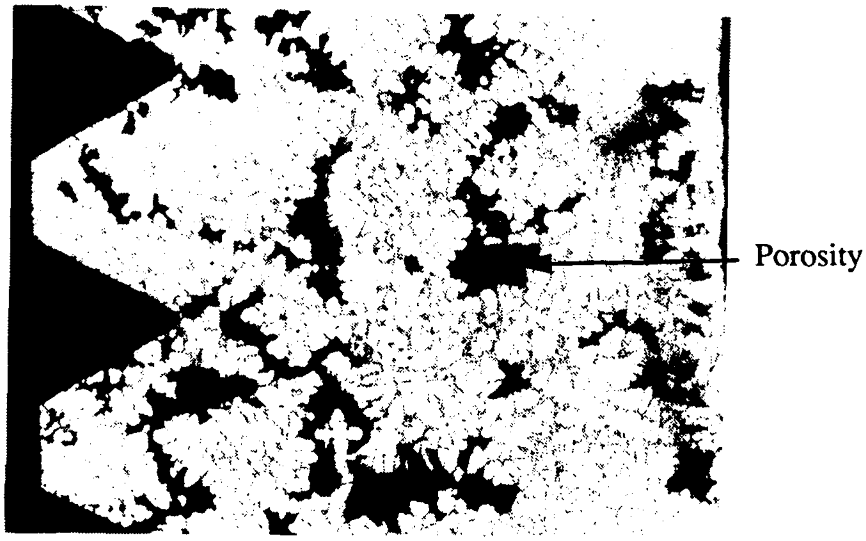


Figure 3.1.1-3 Photomicrograph of porosity in threads, 25X.

Normally, at this stage in the assembly process, such a flaw would require the entire reservoir to be discarded, which constitutes a loss of $30,000. Once the final closeout weld is made, the reservoir cannot be further heat treated, because quench of the interior would not be possible. In this case, however, the precise knowledge of the flaw location, available by CT, made it possible to cut out the flawed port and weld another port in its place locally on the manifold without compromising the integrity of the reservoir/manifold assembly. This was done, and the reservoir was retested, qualified for flight and installed on an airplane.

This is a very good example of the value of CT in engineering evaluations. The $30,000 reservoir was saved by cutting out a $100 port and welding another in its place, at a total cost of about $500. No other method could have given the necessary information to allow the reservoir to be saved, and without CT, the loss would have been the full $30,000. Although it is highly unusual for a manifold to slip through with such a flaw and actually be welded onto the reservoir, once such an event occurs, if the manufacturing facility has ready access to a CT system it is possible to recover. The savings in this case was about $29,000.

3.1.2 B-17 Tail Wheel Defect Evaluation

In support of the Smithsonian Institution, The Boeing Company was involved in the refurbishment of a 307 Stratoliner. Figure 3.1.2-1 is a photograph of the number 903 stratoliner delivered to Pan Am in 1940. This aircraft underwent a number of owner/operator changes in its lifetime until it was acquired by the Smithsonian in 1972. The refurbishment of the aircraft required a replacement tail wheel. An aluminum tail wheel was found (one of only four known to still exist) from a B-17 (which used the exact same wheel), and purchased. The wheel is shown in Figure 3.1.2-2.

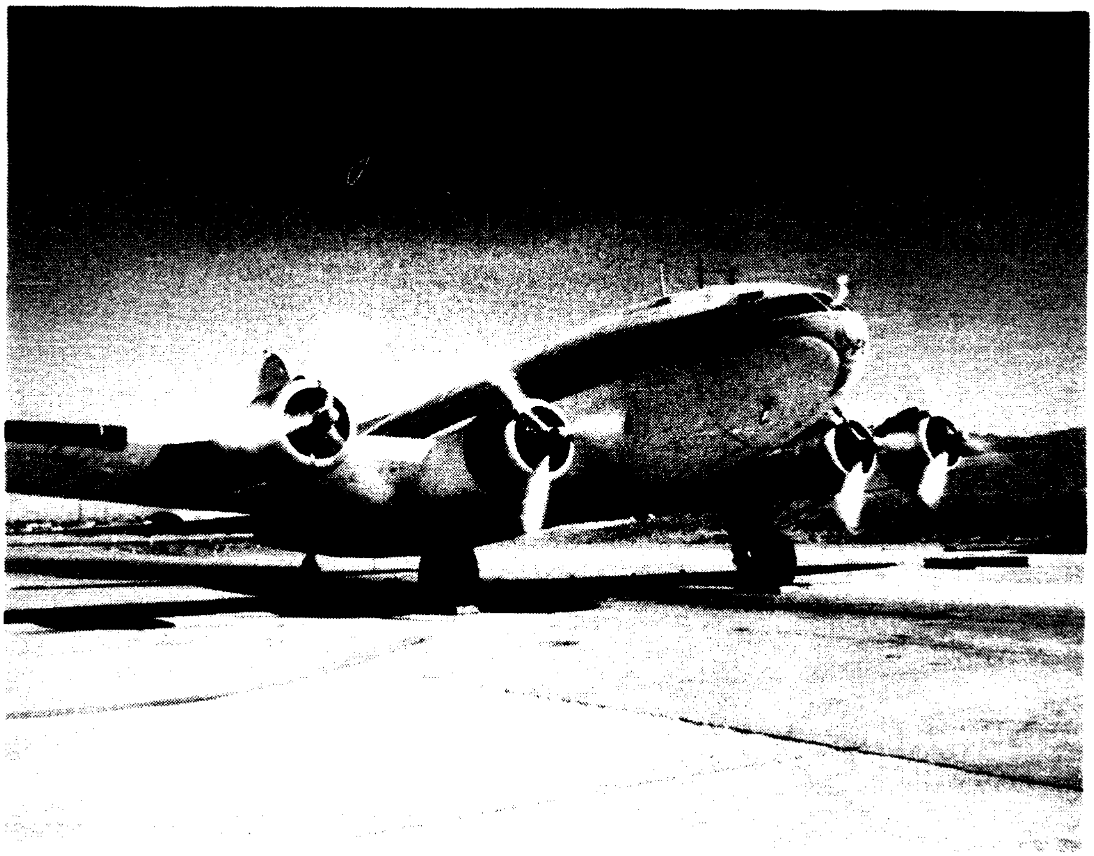


Figure 3.1.2-1 Photograph of the 307 Stratoliner.

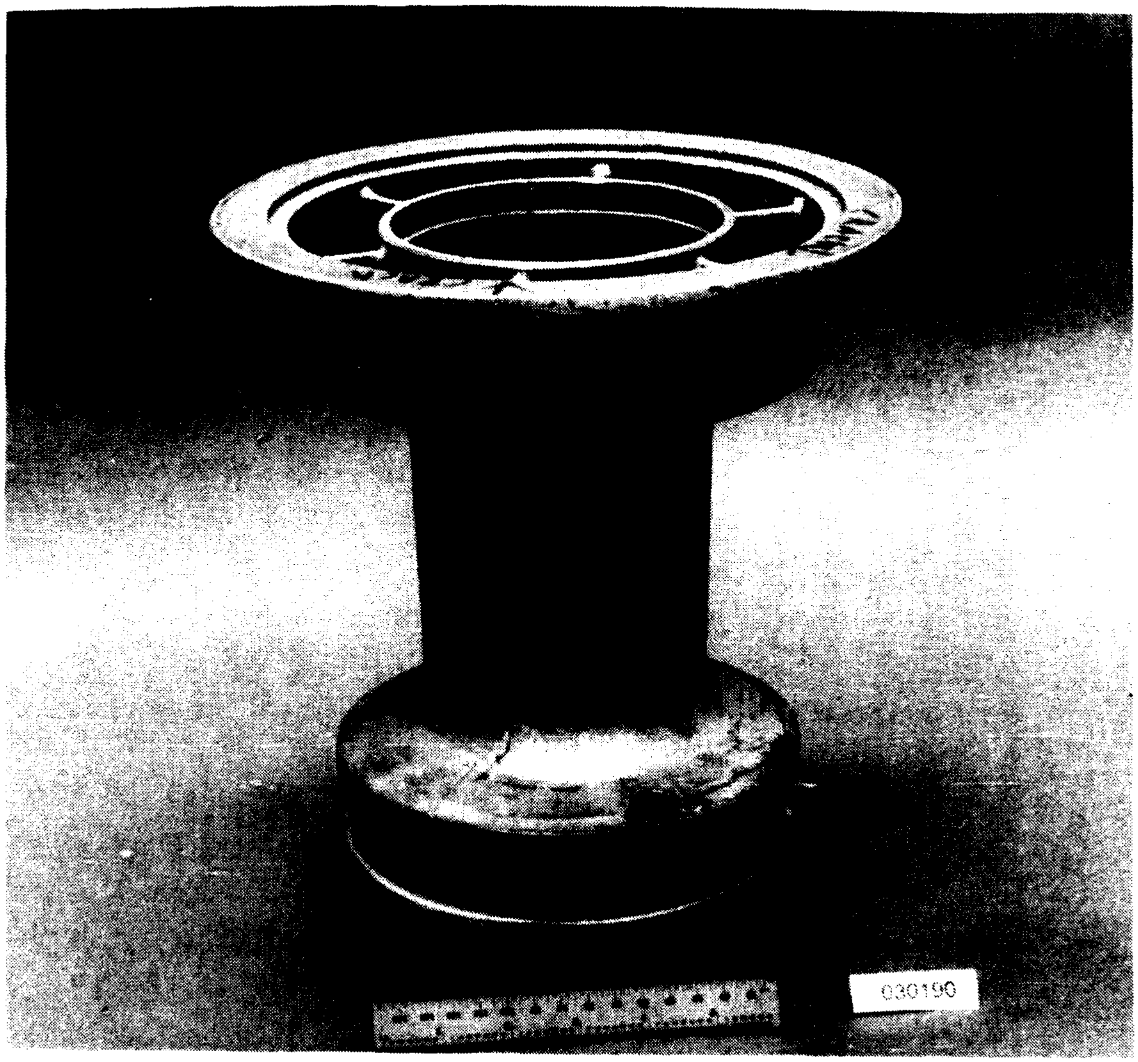


Figure 3.1.2-2 Photograph of the B-17 tail wheel.

At the time of purchase, visual and penetrant inspection of this wheel indicated two cracks on external webs. Film radiography of the tail wheel could barely detect one of the cracks and could not provide any estimate of extent. X-ray CT was then applied to determine the extent of the cracks and assist the evaluation of their potential effect on wheel performance. Successive CT slices perpendicular to the cracks revealed that one crack extended less than 4 mm into the fin. The other crack extended less than 1 mm into the fin, and was essentially a surface defect. Figure 3.1.2-3 is one of the CT images taken to evaluate the cracks. Reproduction in print form limits the detail that can be presented. The evaluation of the CT image on the CT system monitor provides greater sensitivity. Based upon the information in the CT images, it was determined that the cracks were not threatening to the performance of the wheel over the expected service conditions.

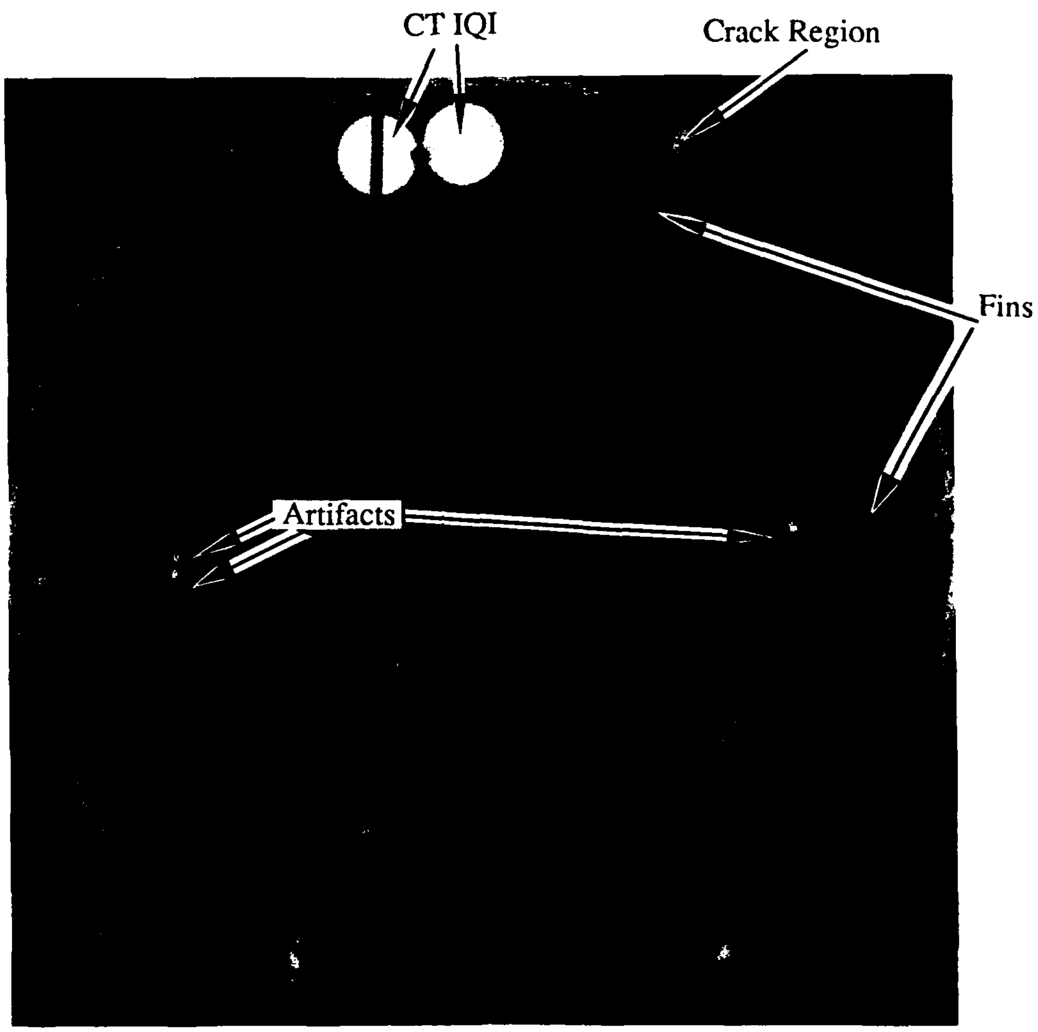


Figure 3.1.2-3 CT image of B-17 tail wheel.

During the scanning, high levels of porosity were discovered in several sections of the wheel. A slice through the diameter of the central narrowest portion of the wheel is shown in Figure 3.1.2-4. Porosity is clearly indicated, especially in the lower and left-hand portions of the wheel, from about "5 o'clock" to about "11 o'clock."

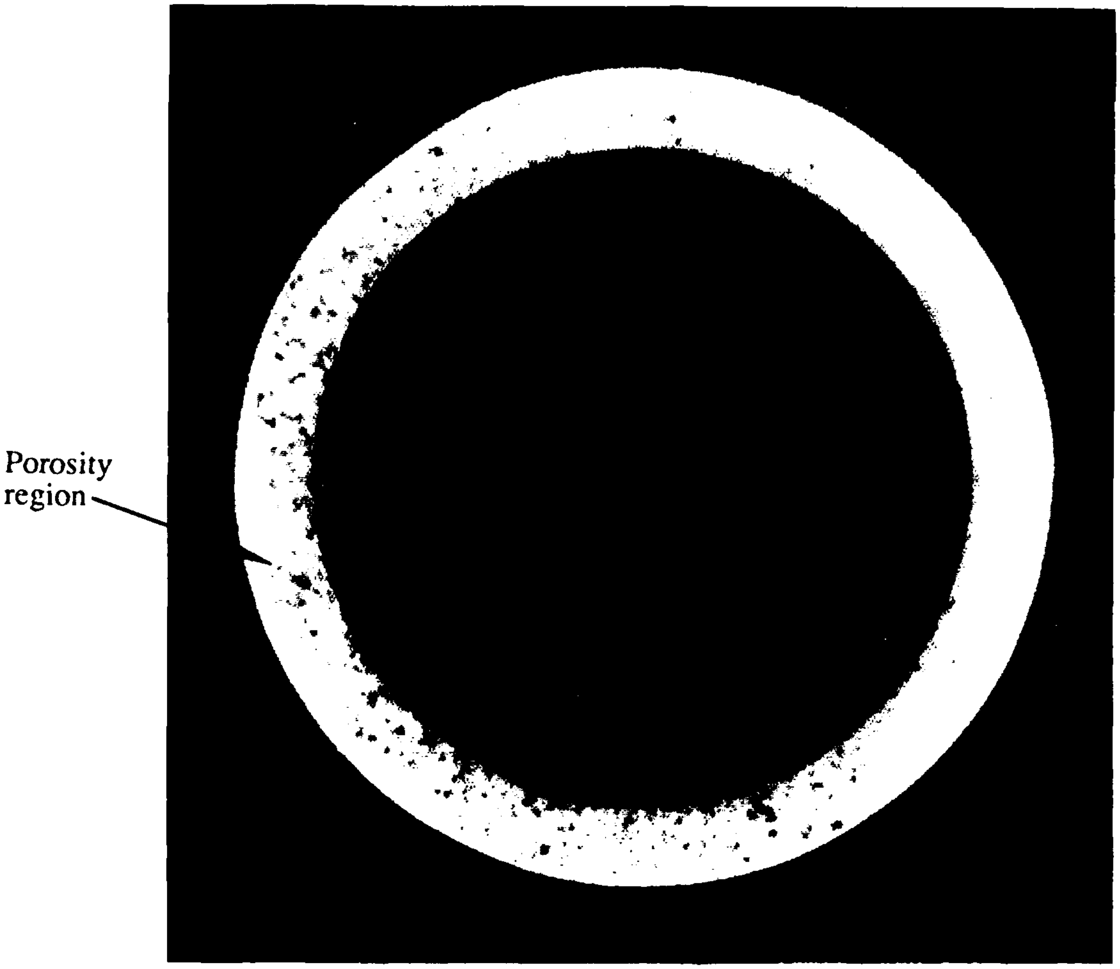


Figure 3.1.2-4 CT image of B-17 tail wheel showing porosity.

The wheel was expected to see only limited loading, so it was determined that the porosity levels were acceptable. It is interesting to note that the wheel has more than likely seen thousands of hours of service, but contains porosity which would certainly have caused it to be rejected by today's radiographic specifications for castings used on aircraft.

3.1.3 Crack Detection

While CT has been shown to be an excellent tool for detecting porosity in castings, the question of crack detection is of interest. In the above B-17 tail wheel example, the crack in the tail wheel was found with CT, but was difficult to see in the reproduced images. An example of using CT for crack detection and measurement is shown in a forging, rather that a casting. The test part is a portion of a forged aluminum wheel mounting plate. Figure 3 1.3-1 shows the part mounted on a medium resolution (1 lp/mm) CT system. Visual and penetrant methods had revealed a crack which was estimated to be very narrow.

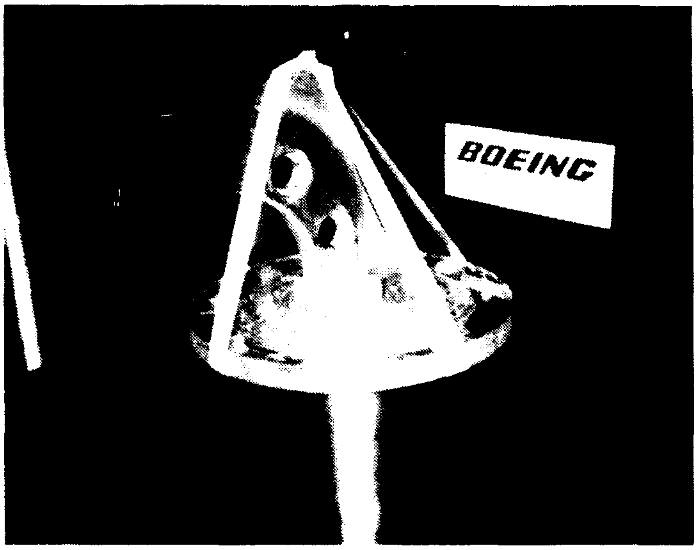


Figure 3.1.3-1 Aluminum forging containing a crack mounted on a CT system for examination.

The scanning was performed using 420 kV energy. A CT image is shown in Figure 3.1.3-2. This scan clearly reveals the crack, which goes from the top of the image down most of the way through the part. The part was subsequently sectioned, and the crack was observed as indicated by the CT image. A photograph of the cut surface in a region near but not identical to the CT slice position is shown in Figure 3.1.3-3, with the crack enhanced for visualization. The crack does run from one side of the part to about 90 percent of the way through to the other side. Figure 3.1.3-4 is a photomicrograph of the crack at 100X magnification near the surface of the part. The crack width was estimated to be about 0.012 mm (0.0005 inch).

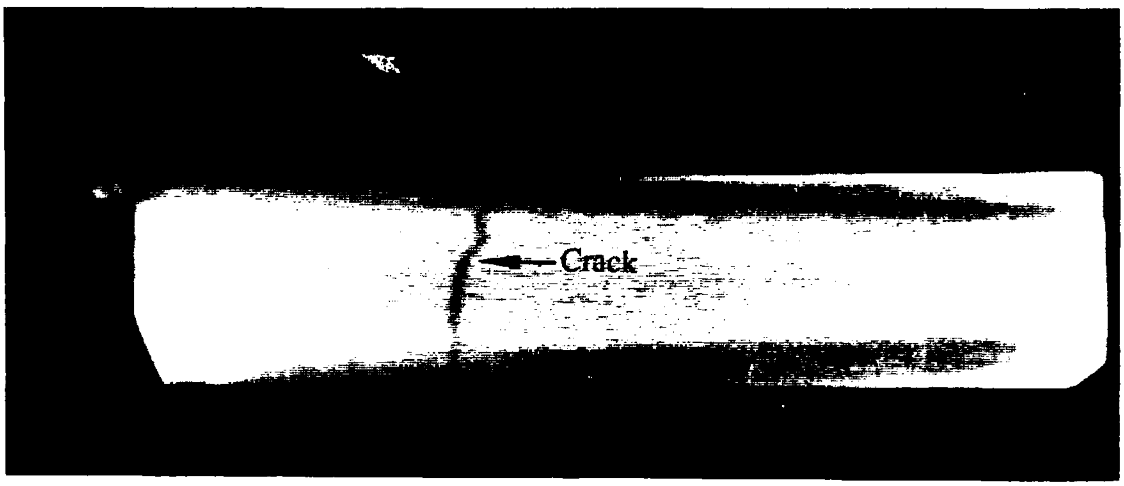


Figure 3.1.3-2 CT image showing crack in an aluminum forging.

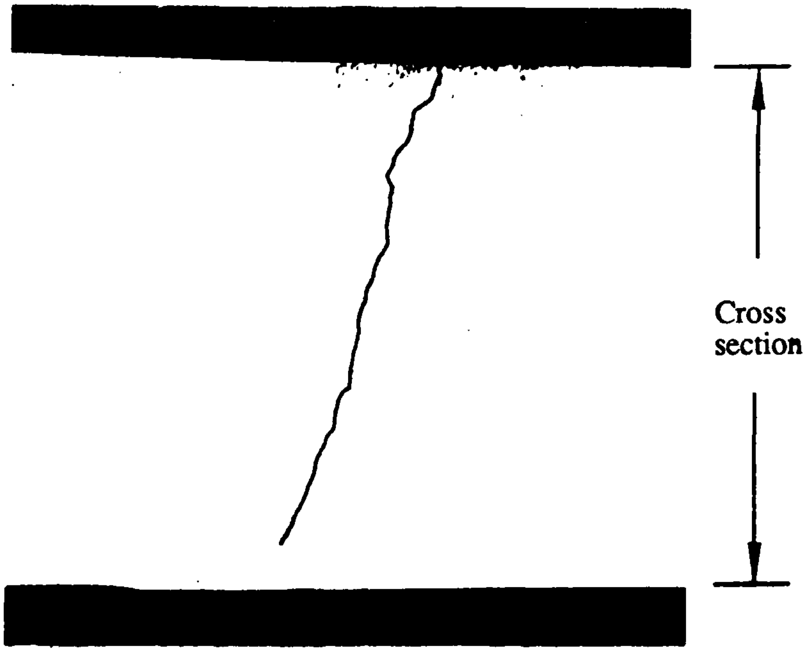


Figure 3.1.3-3 Photograph of cut surface with the crack enhanced for visualization.

Figure 3.1.3-4 Photomicrograph (100X) of the crack at the part surface.

This is an excellent example of the ability of CT to detect very small features. Although CT is a volumetric feature detection NDE methodology, there is sufficient volume in even very fine cracks that allows detection with X-ray CT technology.

3.2 Process Evaluation

3.2.1 Kruger Flap Hot Isotatic Processing

In an earlier CTAD report [13], CT was found to be a useful measure of the effect of hot isostatic processing (HIPping). Based on the results, the CT measurements were applied to a cast part that is considering the addition of HIPping to the process to reduce defects. Figure 3.2.1-1 is a photograph of an aluminum cast Kruger flap for aircraft. This flap had been used in service but also contained defects.

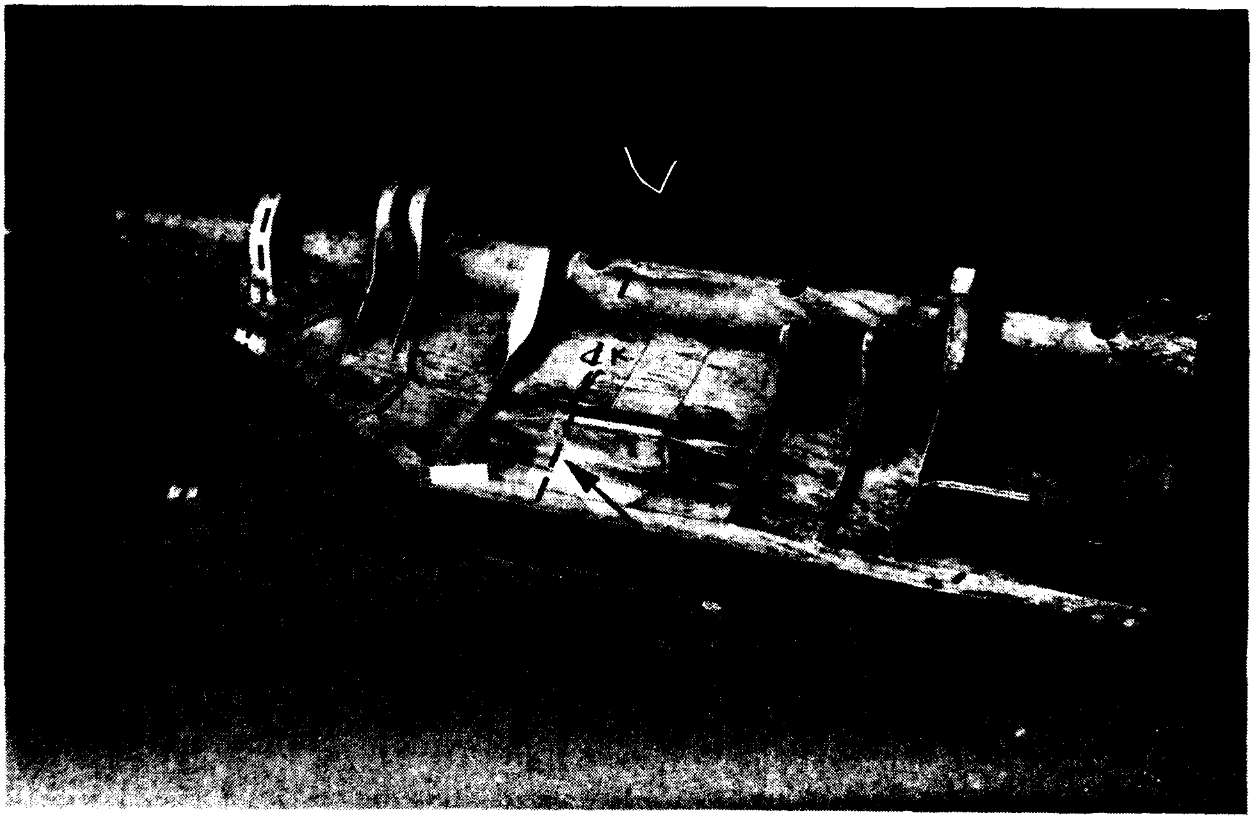
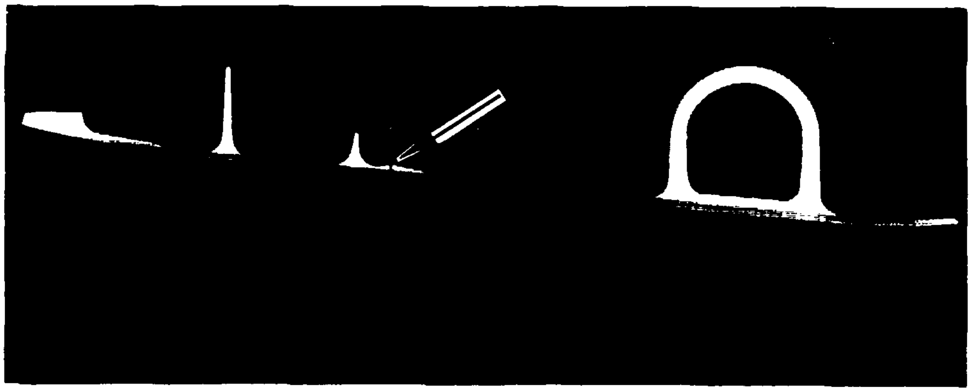


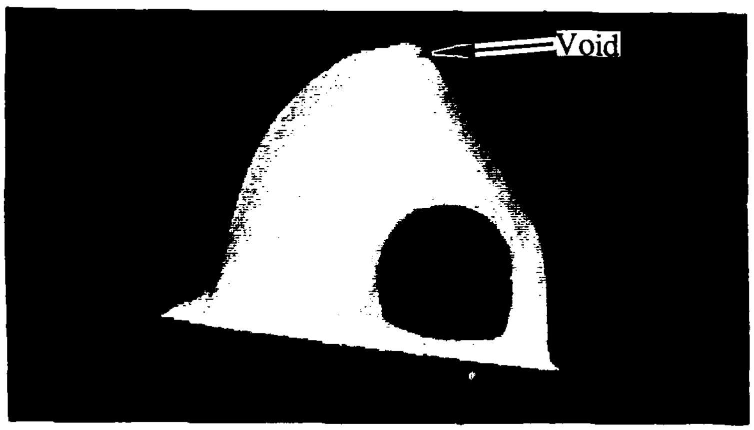
Figure 3.2.1-1 Photograph of a cast aluminum Kruger flap.

Figure 3.2.1-1 is a CT slice of the Kruger flap through a defect at location "A" in Figure 3.2.1-1. Figure 3.2.1-3 shows a CT slice a location "B," which indicates a void in the casting. Following CT examination, the flap was HIPped. A CT image, after HIPping, at the same location as Figure 3.2.1-3 is shown in Figure 3.2.1-4 indicating that the void has been removed due to the HIPping. Measurements at various locations along the flap indicated that the post HIPped condition was superior to the before HIPped condition for porosity presence in the flap.



Slice location "A"

Figure 3.2.1-2 CT image of defect in cast aluminum Kruger flap.



Slice location "B"

Figure 3.2.1-3 CT image showing void in Kruger flap before HIPping.

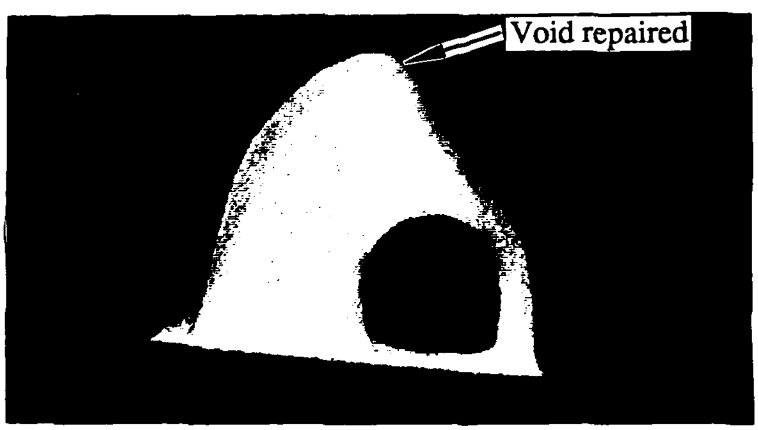


Figure 3.2.1-4 CT image of region of Figure 3.2.1-3 indicating that HIPping removed the void.

3.2.2 Selectively Reinforced Castings

The use of selective reinforcement in casting offers the potential for improvements in the performance of castings by increasing properties at critical locations. The use of metal matrix composites (MMC) as the reinforcement provides a cost effective use of the expensive MMC and improves the characteristics of the casting. This processing technology is still in the early stages of development. The placement and condition of the MMC and the casting material surrounding it are critical to the success of the final product. CT technology can aid in the assessment of the insert and cast material condition during process development and, eventually, may be the final inspection technique of choice.

Figure 3.2.2-1 shows a selectively reinforced titanium casting test sample with a Ti MMC insert. The sample cross section is 100 mm x 17 mm (4 inches x 0.7 inches) with a 19 x 5 mm (0.75 x 0.2 inch) insert. The MMC is 0.14 mm (0.0056 inch) diameter SiC fibers in a titanium matrix. The MMC insert consists of 24 plies of MMC fiber and matrix sheets in three 8-ply stacks. Each 8-ply stack has a molybdenum coating for protection. The group of three 8-ply stacks also has a 0.025 mm (0.001 inch) tantalum layer placed around the outside and spot welded. The MMC insert was placed in a mold and titanium cast around it.

The test sample was CT examined and a CT slice is shown in Figure 3.2.2-2. In this sample, the insert is well placed and the surrounding casting material shows no indications of defects. Figure 3.2.2-2 is a CT slice which includes an image quality indicator (IQI). The IQI was discussed in an earlier task assignment report [7]. The indicator shows that CT would be sensitive to a 0.5 mm diameter hole, 0.25 mm tall (2-2T for 13 mm (0.5 inch)) titanium. The CT images show the tantalum outside layer and unevenness at the corners due to the welding. The molybdenum between the 8-ply, SiC fiber stack is detected.

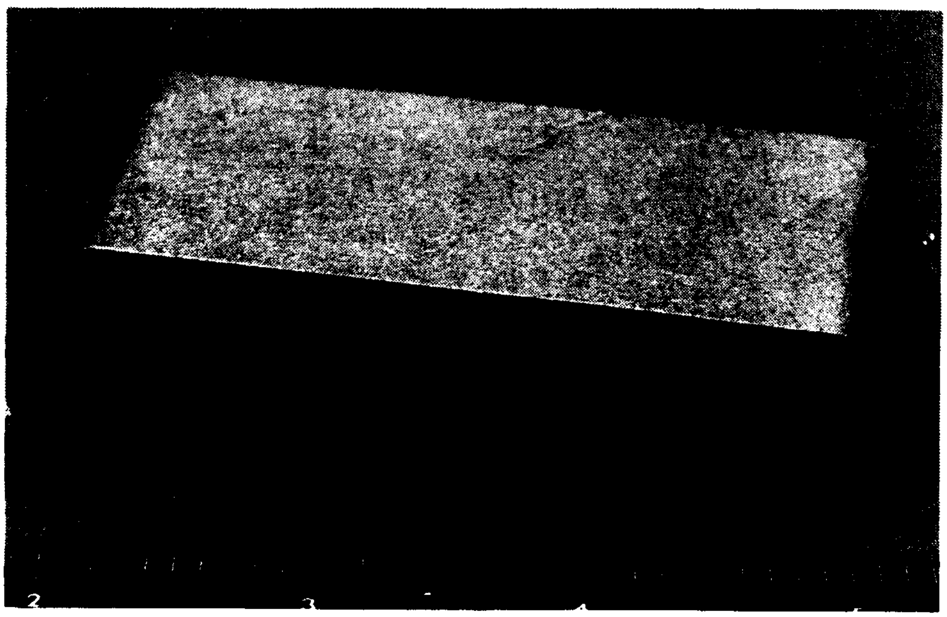


Figure 3.2.2-1 Photograph of a selectively reinforced titanium casting.

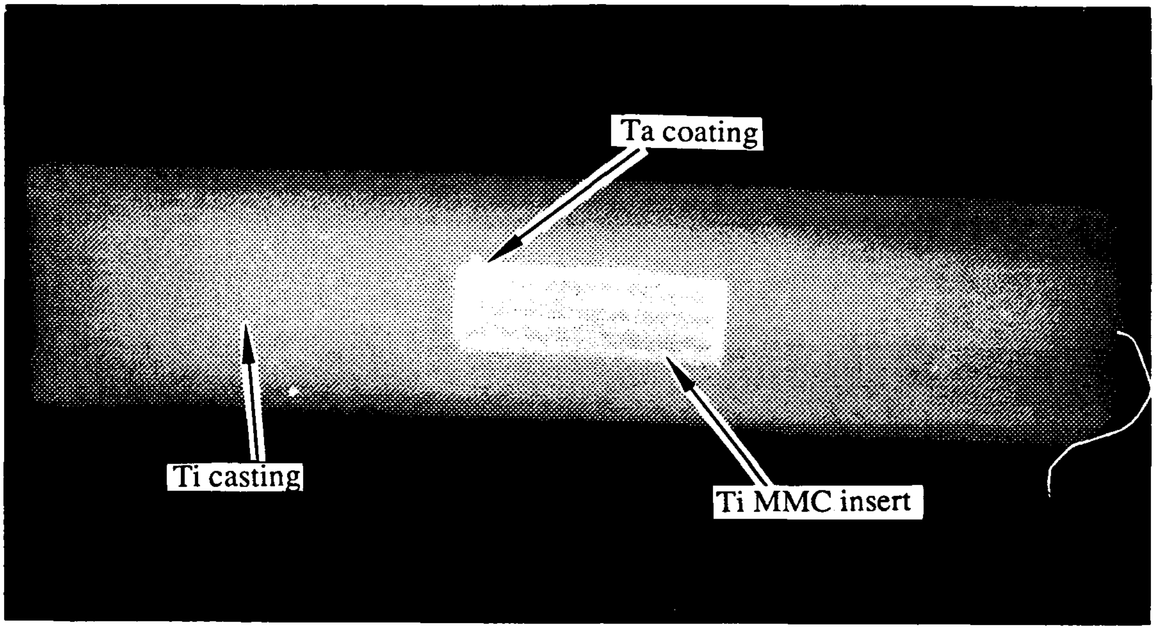


Figure 3.2.2-2 CT image of selectively reinforced titanium casting.

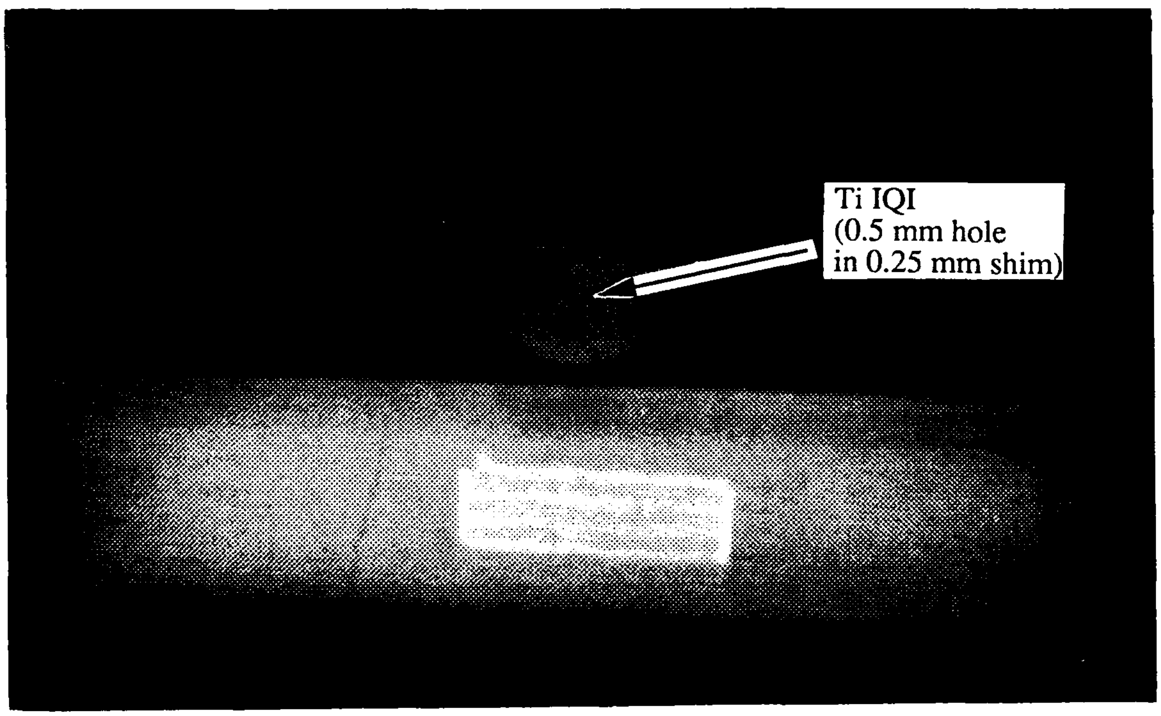


Figure 3.2.2-3 CT image through IQI and selectively reinforced titanium casting.

4.0 CONCLUSIONS

X-ray computed tomography provides information that has economic benefit for the casting industry in several areas using presently available technology, and should see increasing application as advancements in CT capability at lower cost are developed. Figure 4.0-1 summarizes conclusions from the studies of CT for castings. CT provides flaw characterization capability in critical regions that is not available with conventional casting NDE methods. This capability allows the evaluation of regions which tend to have defects in the developmental stages of a casting process, and can assure material quality in the same region during production. When only partial coverage of the part is needed with a few CT slices, it allows a quick and inexpensive means of evaluating the material quality in critically stressed regions, which often cannot get thorough coverage with radiography. By using CT on "just cast" parts, valuable information is provided which can reduce costs through early screening or repair planning. The "dead end" costs associated with completing the manufacturing steps on castings that will ultimately be rejected by radiography can be reduced or eliminated. A more significant payback, however, is in the ability of CT to demonstrate that an anomaly such as a void is non-critical, and to provide exact locations for repair when required, therefore saving an otherwise scrap part. This is particularly advantageous on high value parts where CT costs are a small fraction of the casting value.

CT of Castings

- Superior quality measure than radiography

  more reliable
  complex castings
  critical regions

- Critical for nondestructive dimensional measurements

  internal and external geometry acquisition
  better than 0.05 mm (0.002 inch) accuracy
  3D digital format
  transferable to CAD/E (reverse engineering)

- Valuable data for engineering assessment

  material review board
  finite element analysis
  material property correlation
  model verification

- Cost effective for foundries

  new products
  critical regions
  dimensional measurements

Figure 4.0-1 Casting conclusions.

CT evaluation provides internal dimensional measurements in castings that are as good or better than destructive sectioning. Dimensional measurements to better than 0.050 mm (0.002 inch) are fairly easy to achieve with the CT system configurations tested. Using appropriate techniques, measurements that have previously been considered to be beyond the inherent resolution of the CT system can be made. Dimensional measurements should provide accuracies on relatively large parts that are in the range of 1 part in 10,000. The relative cost of the CT dimensional measurement depends on the number and difficulty of the measurement, but appears to be very competitive with destructive sectioning, particularly if many measurements are desired. If the casting is within dimensional tolerance, the use of CT saves the cost of the component. For foundries with high value components such as jet engine castings, the direct cost benefits of CT in saving the casting from destructive sectioning or other difficult measurements can justify the cost of CT system acquisition.

The three dimensional location capability of CT allows CT data to be converted to CAD/E workstation files. CT can be effectively used to acquire casting geometry in drawing formats (reverse engineering) and reconstruct components for visualization as part of the engineering analysis. This geometry acquisition capability can also allow drawings to be made of components in their as-built condition or of components for which drawings do not exist. If the definition of flaws, obtained from CT evaluation of castings, is included in the CAD/E data, the information can be input to finite element engineering models to analyze the performance as a function of the casting condition. The most likely and cost effective application of CT data transfer to CAD/E workstations will be for "software gauging," where first articles and production test articles are compared to the design models for verification of internal and external dimensions. CT can compete with coordinate measuring machines for complex external measurements and is the only technique for nondestructive internal measurements.

The quantitative nature of CT allows an engineering evaluation of castings based upon a correlation with performance. This study has shown that CT can provide a measure of porosity and voiding which correlates with the level at which casting strength begins to degrade and to shift out of the distribution of normal mechanical properties for tensile specimens. This can greatly reduce the current number of "good" castings which are rejected based upon the qualitative assessments from presently employed NDE techniques. The high scrap rates associated with subjective inspection methods for castings can be reduced through the implementation of CT. CT provides the link in the inspection methodologies to engineering evaluation that can allow the engineer to design and utilize castings with greater confidence. CT sensitivity to anomaly sizes has been measured by the use of image quality indicators. In thick sections (> 0.12 mm) CT imaging may be more sensitive to volumetric defects than radiographic inspection, with respect to MIL-STD-453 requirements.

Although presently available CT capability and inspection specifications currently prevent realization of potential cost benefits for general inspection of aerospace/aircraft castings, there are categories of casting manufacture for which CT is optimally suited. CT is an excellent enabling technology for castings. It can be used today for new product development and for specific areas of production inspection to reduce scrap. The analysis of the CT testing in the CTAD program indicated that there is currently a technical and economic benefit to using CT in new product development, early screening, complex geometries and critical region inspection. This is particularly true for castings that are being developed with greater internal complexity, including inserts. The foundry in which CT will be economically viable will have one or more of the following characteristics: sufficiently large production, a requirement for internal dimensional measurement capabilities, high production of complex castings, or material review board authority.

In the near future, CT system speed and image resolution should continue to increase, and costs will continue to decrease, making CT a cost effective inspection methodology for 100 percent coverage of castings. High throughput CT, such as cone beam CT, will become very cost effective for casting inspection, provided required sensitivity to critical defect size is achieved. As CT system and operating costs decrease, CT will compete with radiography in most areas of casting inspection. Digital radiography and CT can be implemented in combination to allow a rapid DR evaluation followed by selective CT scanning at critical locations.

Although CT is technically applicable to many foundry needs, for it to become universally economic, CT results must be acceptable (and perhaps even required) by specification and called out on casting drawings. It will also be necessary to modify existing inspection specifications for castings to allow for CT examination to be used in the accept/reject mode of current aircraft/aerospace practice. This change will involve considerable effort and education. However, the opportunity exists to make a significant economic and technical impact in some areas by changing from contemporary qualitative, subjective inspections with radiography to quantitative CT evaluations. This will allow castings to be designed and accepted based on performance criteria.

It is recommended that engineers be educated in the application of CT to castings and that they incorporate its use in the casting inspection criteria using critical defect size and location analysis as a fundamental approach to casting design. The Air Force CTAD reports, showing example stories, have been successful in increasing awareness and possibilities of applying CT. Future growth in CT applications to castings will depend on the ingenuity of design, casting and NDE engineers seeking improvements to performance and productivity through superior nondestructive evaluation technology.

5.0 REFERENCES

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APPENDIX: Task 12 Casting Cost Benefits

Casting Cost Benefit Summary from the Task 12 report, "X-Ray Computed Tomography for Casting Development," WL-TR-92-4032, September 1992.

CT can serve as a cost effective evaluation tool for the development of new castings. The areas in which CT can be of technical and economic value are internal dimensional measurement, flaw characterization, performance prediction, and geometry acquisition for engineering and design. Although any one of these areas may provide a specific cost benefit for a particular foundry condition, it is the overall cumulative impact of CT that provides the best payback. This is also the most difficult to quantify.

A.1 Internal Dimensional Measurement

Cast aluminum discharge fittings can serve as a baseline example for the cost benefits of CT for dimensional measurements. The fittings were estimated to cost approximately $450 a piece to manufacture in small (<20 piece) lots, once the engineering and patterning have been established. For a component of this complexity, the development costs of casting engineering, patterning and first article evaluation exceeded $10K. The cost of CT examination of the first article on the high resolution industrial CT system was over $2000, which is a large fraction of component development expense. The medical CT costs were less than $500 for a single fitting. This is a significant cost, but not prohibitive. The destructive sectioning and measurement of the first article performed in this study actually cost $240. Although CT is twice the cost, if the first article had been acceptable, and could be used, then CT would save the $450 value of the part and be the most cost effective approach. The use of CT will depend the foundry operation and whether "good" parts are actually scrapped for internal dimensional measurements.

Costs of CT analysis can often be greatly reduced through simultaneous scanning. Such cost effective use of CT can compete with the costs of destructive sectioning. Figure A.1-1 shows a graph of the projected costs of measurement for the destructive sectioning and CT examination when more than one fitting can be examined at a time. These data were calculated and extrapolated from actual costs of examining the first discharge fitting. If a fitting is measured by CT, but is out of tolerance and must be rejected, the cost of scrapping the fitting ($450) is added to the scanning cost. This possibility is shown by a separate curve. If all the fittings measured by CT are "good," the cost per fitting would follow the lower curve. There can be an economic incentive to use CT over destructive sectioning depending on the requirements for and number of units that are sectioned. Qualitatively, the CT scanning will ensure a quality product delivered to the customer. The economic use of CT for dimensional measurements by a foundry will depend on a number of particular factors in the value of the part, the first article development costs and the difficulty of obtaining the number of required measurements destructively.

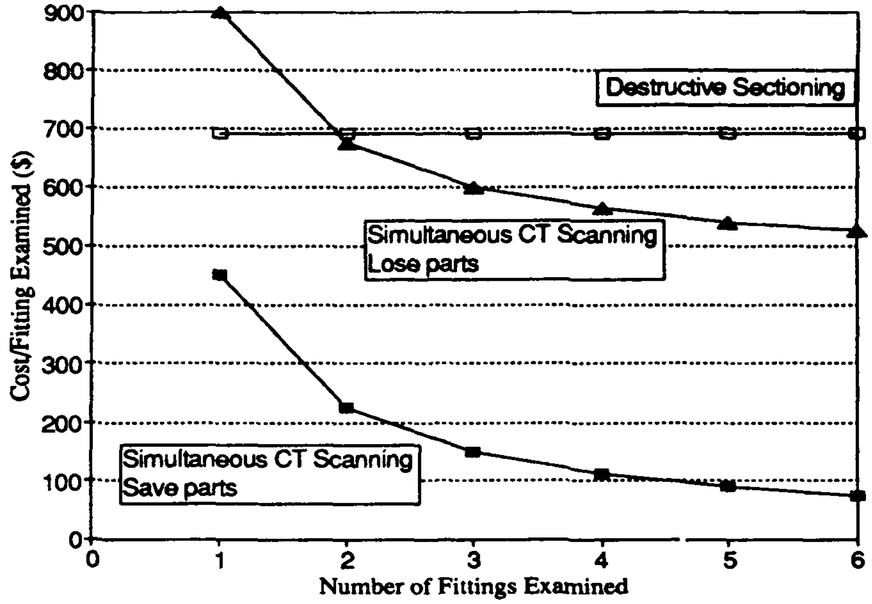

Figure A.1-1 Graph of the economic benefit CT when multiple castings must be examined for dimensional measurements.

A.2 Flaw Characterization

The wall thickness in a small tube of an aluminum manifold casting was found to be out of tolerance using CT. The evaluation was performed when the casting had just been poured and saved the additional costs (approximately $100) associated with the manufacture of this casting: grounding, sand blasting, and HIPping. The "dead end" costs associated with completing the manufacturing steps on castings that will ultimately be rejected by another method can be reduced or eliminated. If CT evaluation (for example, for internal dimensional measurements) is performed on every casting, the cost of CT will need to be a fraction of the value of each of the castings, that is, less than the scrap rate, for CT evaluation to be cost effective. The use of CT in "early screening" would probably provide a relatively small amount of savings in a few special cases.

In many cases, a casting containing a flaw can be repaired, or even passed, if the flaw size can be quantified and the wall thickness is shown to meet specification. CT provides three-dimensional density data that allow one to determine the size, shape, and location of the defect. This information enables flaw assessment and intelligent repair. If every casting is CT scanned for flaws, the effect on casting costs can be estimated from Figure A.2-1. The figure is based on CT scanning costing a fraction of the casting manufacturing. For example, if CT scanning of the casting were to cost only 10 percent of the original manufacturing cost of the casting itself, a benefit will be realized when 13 percent or more of the castings in the lot are saved through acceptance or repair. This would most likely be applicable for new processes that are not yet under control. The curves assume that CT costs can be obtained at 10 or 20 percent of the casting value. This would be true for very high cost castings or for a very low cost CT system. An average of 10 percent of the casting value is assumed to allow for cost of repair if required.

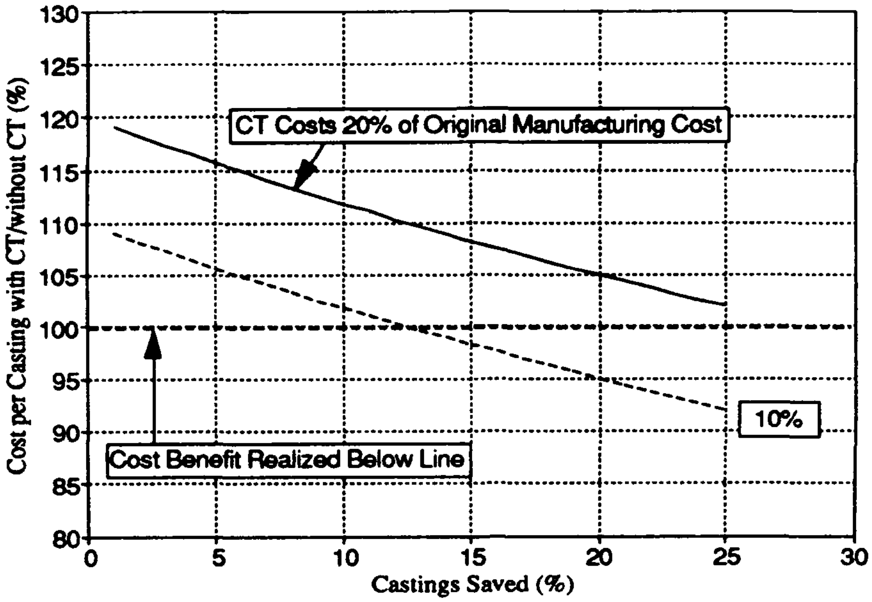

Figure A.2-1 Graph of the economic benefit CT for repair or passing of castings with flaws.

The savings that are due to the reduction or elimination of other NDE methods are not included in Figure A.2-1. This savings amount could be substantial, depending on the inspection requirements for the particular casting. Casting inspection with film radiography is normal for castings used in the aerospace industry. The radiographic inspection costs can vary widely depending on the casting and contract requirements. In some cases, all castings require radiographic inspection, in others only a small percentage require inspection. Assuming a radiographic cost of 10 percent of the total manufacturing costs (a conservative estimate in some cases and too large in others) could be eliminated by using CT, new cost curves, which are shifted down 10 percent from Figure A.2-1, are shown in Figure A.2-2. In this case, CT could be 20 percent of the original manufacturing cost, and begin to show a cost benefit if 13 percent or more of the castings are saved. In general, the cost of casting manufacturing could actually go down if CT evaluation could be performed within the cost of present radiographic evaluation because CT provides superior information for decision making on the casting process and control than radiography.

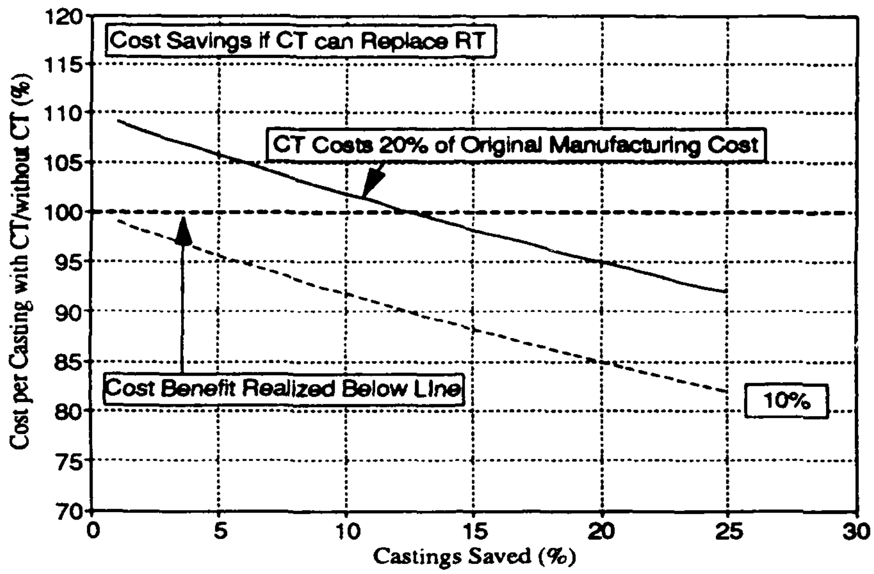

Figure A.2-2 Graph of the economic benefit CT for repair or passing of castings with flaws when RT is eliminated.

The economics for flaw characterization are different if only initially rejected castings are CT scanned rather than all of them. Figure A.2-3 shows how rapidly the average cost per casting decreases when all rejected castings that are scanned can be repaired or accepted. An average of 10 percent of the casting value is assumed as the cost for repair. This curve shows an immediate payback with CT evaluation for this scenario. There is a payback whenever the cost of CT evaluation plus repair, as a fraction of the value of each casting, is less than the fraction of the castings that are saved.

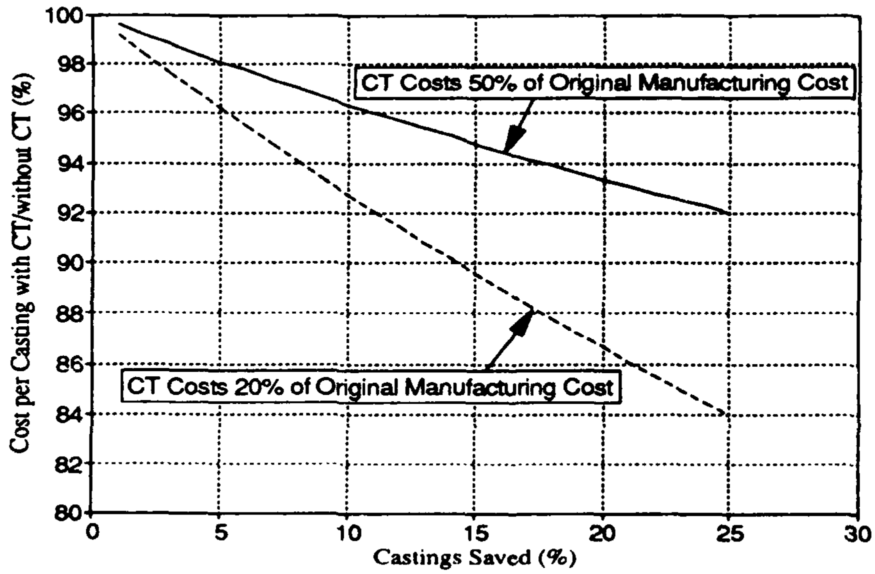

Figure A.2-3 Graph of the economic benefit CT for repair or passing of rejected castings.

The use of CT for flaw characterization is most applicable in critically stressed regions. In such cases or in regions which tend to have defects it may be possible to use CT for only a portion of the entire casting. CT can be used in conjunction with the digital radiography (DR) available as part of the CT system; full coverage of the part is possible with a DR, and critical regions or anomalous indications can be fully evaluated with CT. In this case, CT can be more economical than film radiography, providing characterization of any flaws. This approach has been demonstrated by General Electric in the development of the X-ray Inspection Module (XIM) system for cast turbine blade examination. The XIM has both CT and DR capability; DR is used routinely, and CT when needed in particular regions.

A.3 Performance Prediction with Mechanical Testing

CT allows an engineering evaluation of castings based upon performance, and can reduce the number of "good" castings which are rejected based upon a qualitative assessment. The CTAD program found that CT data correlated with tensile strength in samples that contained very high levels of porosity. In a study of tensile specimens, CT criteria might have allowed acceptance of 90 percent of the specimens, while rejecting the 10 percent which actually showed a reduction in strength. The other methods, dye penetrant (before removal of the coupons) and film radiography, would have rejected 100 percent and 50 percent, respectively, of the specimens based on normally applied criteria.

Normal rejection rates for radiographic and penetrant evaluation of castings during manufacturing are often in the range of 5 to 20 percent or more. However, the evidence from the mechanical studies indicate that these rejections do not necessarily correlate to a reduction in the mechanical strength. The quantitative evaluation of internal condition of the castings should create a superior criteria for acceptance or rejection, with subsequent economic benefit. Figure A.3-1 shows the curves for the cost effect of using CT on casting production when CT is used to replace radiography, if quantitative criteria for performance is considered. If CT costs were 20 percent of the casting value and twice the cost of radiography, then CT would show a savings if 11 percent in a lot could be saved from rejection based on an improved CT based evaluation criteria.

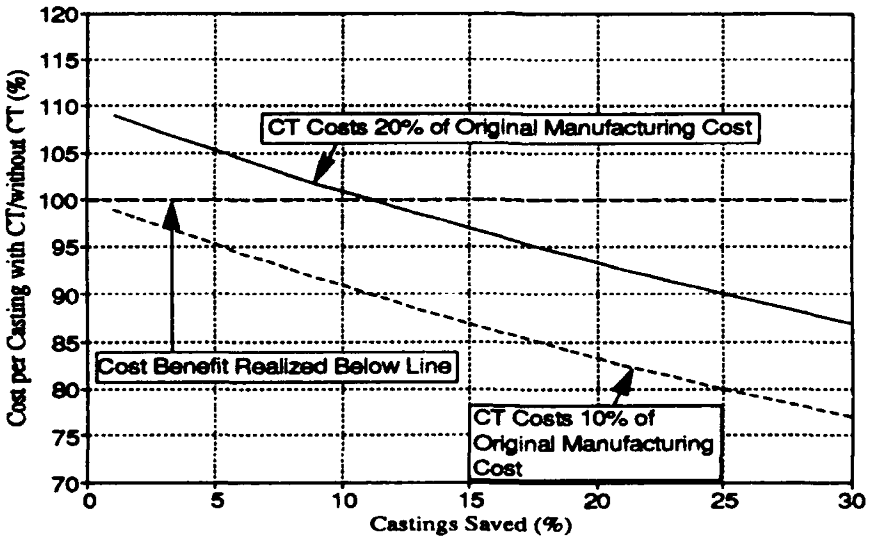

Figure A.3-1 Graph of the economic benefit of CT for evaluation of castings instead of radiography using a quantitative acceptance criteria.

The curve in Figure A.3-1 is very similar to Figure A.2-2 but does not include the cost of repair. In fact, the actual application of CT would hopefully involve both a new criteria for acceptance of castings and also provide information to allow better repair. If the CT cost is less than or equal to the RT cost to inspect a casting, a manufacturer would see the greatest savings by using CT instead of RT for all castings.

The cost benefit of using CT to replace RT, versus evaluating RT rejected castings, will primarily depend upon the cost of CT relative to RT. For example, if CT is significantly greater than the cost of RT, it would be most economical for a manufacturer to purchase CT scanning services only for RT rejected castings. However, if CT costs (using a CT system with DR capability) could be implemented in an evaluation scheme at nearly equal to the cost of RT, the manufacturer would save by replacing RT with CT. This is shown graphically in Figure A.3-2.

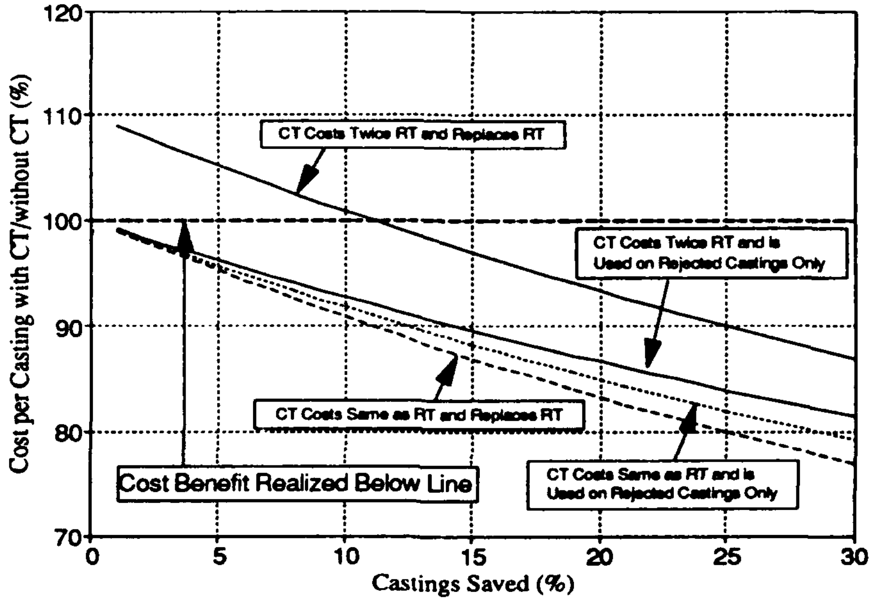

Figure A.3-2 Graph of the economic benefit CT for evaluation of castings using a quantitative acceptance criteria.

The casting factors and high scrap rates associated with subjective inspection methods for castings can be reduced through the implementation of CT. Casting weight and scrap savings which could come from a performance based criteria should be substantial. This, however, will remain speculative until specifications are modified to actually allow the implementation of CT in this type of analysis.

A.4 Geometry Acquisition

Defining ergonomically designed or complex shaped components digitally for input into CAD models for engineering design and assessment can be done using CT at a faster rate and at a lower cost than conventional methods.

The cost of defining a flight control wheel using an optical surface measurement approach can be quite high compared to using CT. In one case, 450 labor hours of engineering (estimated to be comprised of 200 hours dealing with the type and sparseness of the measuring machine data, and 250 hours to fully develop the surfaces of the wheel) and 120 shop hours (for measuring of the surface at approximately 200 discrete pre-selected points) were required for a symmetric (right/left mirror image) control wheel. CT geometry acquisition provided a 200-engineering hour and a 100-shop-hour savings. (The 250 hours to fully develop the surfaces of the wheel are still required with the CT data set.) Additionally, the conventional method only provided definition of the external surfaces of a hollow cast part (where the hollow portion is used for routing control wiring), while CT could define interior surfaces as well. CT geometric acquisition represents a 300 out of 570 hours (53 percent) savings.

For the non-symmetric wheel, there would be a potential 600-hour savings for the total process by using CT for the geometry acquisition because both of the horns would be obtained directly by the CT data acquisition but each would require significant engineering effort in the optical acquisition case. Although a 600 hour savings is significant in cost, the 7- to 14-calendar-week schedule required to do the work is often of more concern. The turnaround time for the CT geometry acquisition process was 1 calendar day after receipt of the model (the availability of the CT facility scheduled in advance). This included the time required to have the data reduced and ready to load into the CAD workstation.

CT shows tremendous cost savings potential as a tool for geometry acquisition for a variety of ergonomically designed or complex shaped components.

A.5 Overall Benefit

The above sections have broken down the use of CT into various areas and attempted to assess an economic payback. In some cases, the payback is more obvious than others. And, depending on the particulars of the casting and foundry, the economics may in many cases be marginal at best. The curves of the previous sections indicate that higher value castings are most likely to benefit from CT evaluation. The fixed costs of CT operation will determine to a first approximation the minimum costs that CT can be performed; the casting program will need to be worth at least 5 times that amount.

However, the examples of the use of CT in casting development demonstrated a significant economic potential that cannot be directly quantified. In the case of a discharge fitting, the casting engineer, who manufactured the fitting commented that had CT been required in the original specification for the casting purchase, the risk in the product development would actually have been reduced. A result of this could have affected a lower original bid for the discharge fitting program.

A key incentive for moving CT into broader foundry applications will be the development of low cost CT systems. Low cost CT may come in terms of higher throughput of existing designs or entirely new designs. For casting evaluation, a system with volumetric data acquisition would have considerable value. The ability of CT to reduce or eliminate radiographic film by virtue of digital radiography and/or CT slices is an important economic factor. Although there are certainly cases where CT could provide a benefit on its own evaluation merit, the overall economic benefit of CT in the casting industry will require specification changes. The implementation of these changes will have a positive effect on the bottom line costs in the casting industry.

U.S. GOVERNMENT PRINTING OFFICE 750-113