X-RAY CT FOR QUANTITATIVE CASTING MATERIAL EVALUATION

Gary Georgeson and Richard Bossi
Boeing Defense & Space Group
Seattle, WA 98124

INTRODUCTION

Casting is an economical way to manufacture parts. However, castings are rarely used as primary structure in aircraft because of the large safety factors that are required for design allowables. This conservatism in utilization is due, in part, to the traditional limitations in evaluation technology for castings. The safety factor increases the overall weight of the casting, which defeats the cost and weight savings that castings offer. Significant gains in casting utilization are possible by a combination of control of the casting microstructure and proper nondestructive evaluation (NDE) of the product. The presently applied NDE criteria for accepting castings involves a comparison to a qualitative standard and has very little to do with their ability to provide operational service. Computed tomography is an enabling technology whose measurements can be used to quantify the product quality level and improve the consistency of casting manufacture.

Computed tomography (CT) measures the transmitted X-ray intensity from many angles about an object to reconstruct cross sectional images of the object interior [1,2]. The images are two dimensional maps of the X-ray linear attenuation coefficient for small volume elements in the object defined by the effective X-ray beam size. The quantitative measurement capability of X-ray CT provides a technically superior approach for casting evaluation over presently applied penetrant or film radiography techniques. The CT measurements of feature dimensions and material density uniformity allow quantification of casting porosity, voids, and inclusions on a sub-millimeter scale.

DISCUSSION

Computed tomography has been shown to be useful for dimensional measurements on castings, particularly in interior regions [3,4,5]. CT is also excellent for detecting internal defects such as voids, porosity and/or cracking. In some cases, it can provide a more reliable assessment of critical regions in castings than radiography [6]. Most recently, CT has been applied to the evaluation of aluminum tensile test specimens and hot isostatic processed castings.

Aluminum Tensile Test Specimens

The measure of the X-ray linear attenuation in volume elements of a casting does not physically relate to the microstructural strength of the material. However, the attenuation does correlate to material uniformity and will correlate to strength measurements that are dependent on material macrostructural conditions, such as porosity or voids.

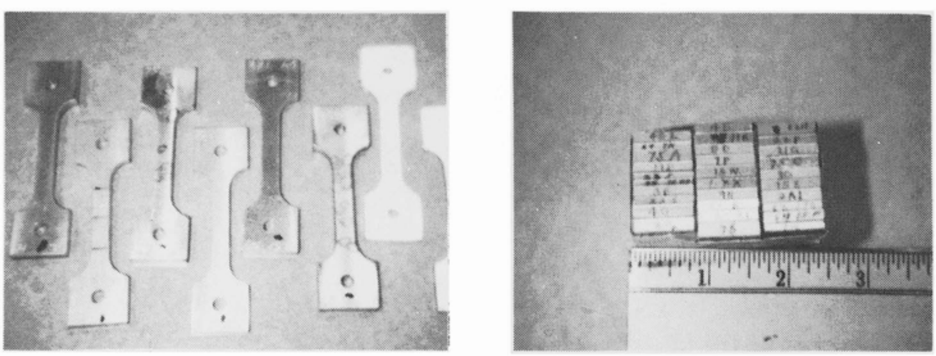
Review of Progress in Quantitative Nondestructive Evaluation, Vol. 12
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1993

CT can be used to assess the material quality of a casting by quantifying features such as inclusions, macro-porosity, or voids. For feature sizes down to about one millimeter, CT can provide valuable information on size, shape, orientation and location of a defect. With CT data, however, complete definition of features is not always required, because the data lends itself to statistical analysis. For example, the CT value mean and standard deviation are useful for defining the extent of micro-porosity, even when individual bubbles are too small to be imaged. Because micro-porosity, as well as macro-porosity has been shown to dramatically affect the mechanical properties of some aluminum alloys [7,8], a non-destructive means of quantifying it is crucial for performance prediction in those alloys.

Castings have experienced significant rejection levels in manufacturing due to dye penetrant inspections. However, it has been suggested that the rejections are not indicative of the ability of the casting to actually maintain strength in its design application. This hypothesis was examined as part of an evaluation of a number of tensile specimens taken from aluminum sand castings manufactured by various foundries using standard process specifications. One hundred and fifty-five tensile test specimens were selected from regions of various castings of alloys 356-T6, A356-T6 and A357-T6, which showed rejectable dye penetrant indications.

After machining the tensile specimens from the castings, reinspection with penetrant indicated that only 53 of the tensile specimens showed penetrant indications. And, of the original 155 tensile specimens, only 16 were identified by film radiography of having an ASTM quality level less than grade A. Of these 16, 15 of the specimens were a subset of the 53 specimens that showed penetrant indications. The other specimen contained an inclusions identified by film radiography. The 15 specimens that were identified with film radiography as having defects were combined with an additional 12 specimens that were considered good radiographically and with penetrant, and 3 specimens that were considered good radiographically but had penetrant indications, to form a set of 30 specimens for CT evaluation. Figure 1 shows the specimens and how they were stacked together for scanning purposes.

The center 25 mm of the specimens were scanned on a CT system, with a slice taken every 1 mm. Figure 2 is a CT image of one of the scans showing the variation in density across the various specimens at that location. Measurements of the CT mean value and standard deviation were made in a region-of-interest box in each specimen on the CT system. Graphs of the mean and standard deviation of the CT values across the test section of three of the specimens are shown in Figures 3 and 4. These graphs show that each specimen has a distinct response range and the values will vary depending on the presence of voids or porosity. In Figure 3 there is a correlation between the position of drops in the CT value and visual observation of voids in the corresponding CT image.



(a) (b)

Figure 1. Photograph of the tensile specimens a) several individual specimens and b) the 30 specimens assembled for CT examination.

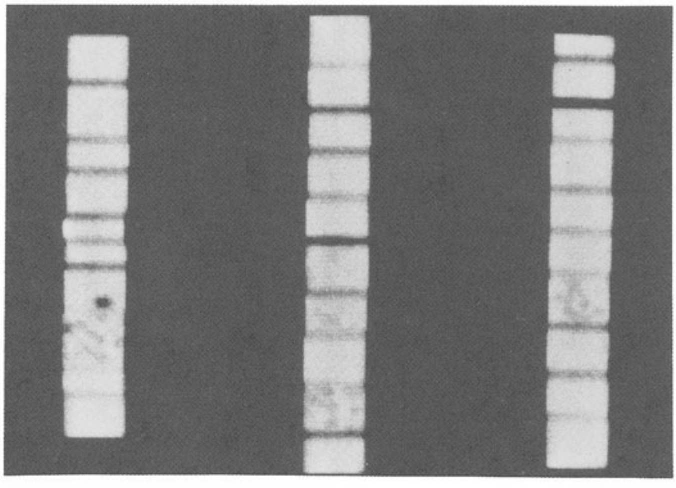


Figure 2. CT image of tensile test samples.

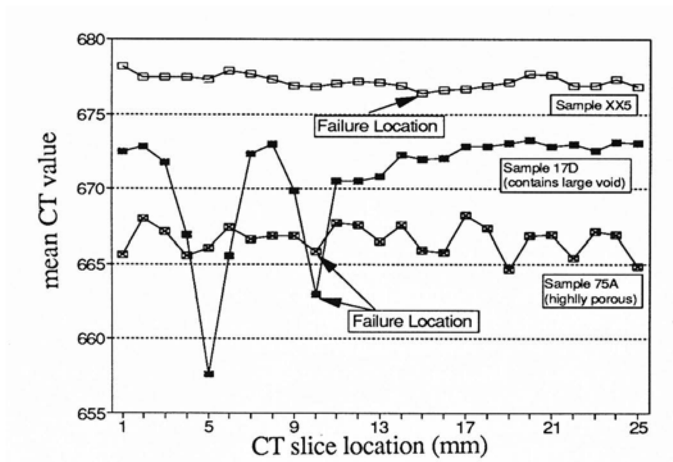


Figure 3. Mean CT value versus position across 3 tensile specimens.

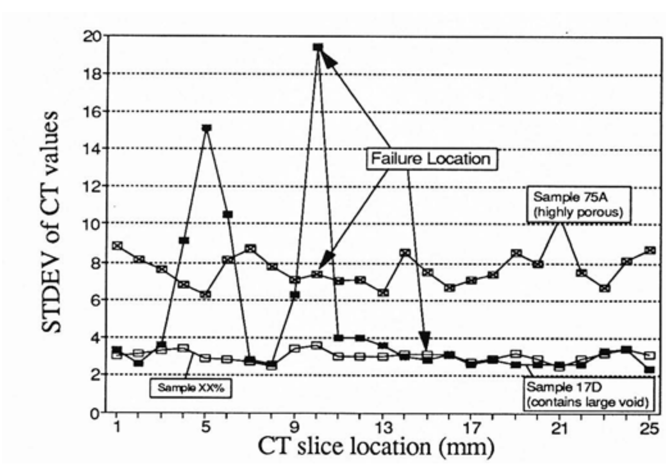


Figure 4. Standard deviation of CT value versus position across 3 tensile specimens.

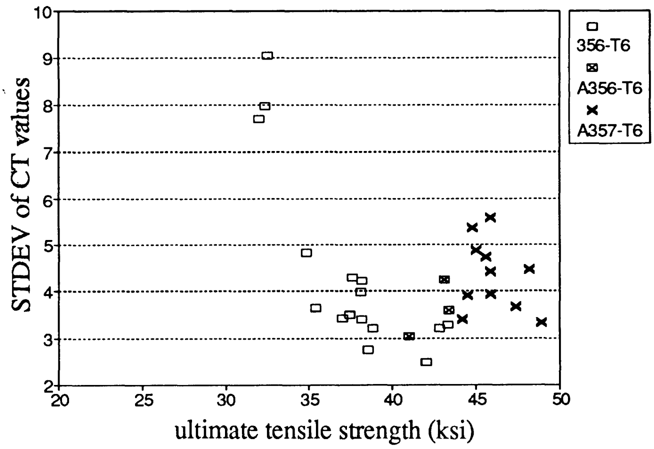


Figure 5. CT standard deviation versus ultimate strength.

All the specimens were pulled to failure in tension while measuring the yield strength, ultimate strength, and percent elongation. A graph of the results, plotting standard deviation of the CT values against ultimate strength, is shown in Figure 5. The three specimens which are out of family for having high CT standard deviation also demonstrated the poorest mechanical properties. CT measurements, of course, would not be expected to directly measure mechanical strength because CT is primarily a density measurement, not a microstructure measurement. However, the most porous specimens showed a clear reduction in strength and were clearly identified as different from the other castings by CT.

Figure 5 shows that A357 castings have higher ultimate strength than 356 and A356. The A356 shows some indication of higher strength than 356. At CT standard deviation values below 5 units (roughly 0.7%) there is significant variability. Thus no clear correlation of the CT measure and strength can be defined. But the very high standard deviation samples, greater than 7 units (>1%), do show lower ultimate strength.

The CT standard deviation was also plotted against yield strength (at .2% offset) and percent elongation. The correlation was not as strong for the yield strength as it was for the ultimate strength, but it was similar. And, although there is a trend that high CT standard deviation was related to lower elongation, it did not show a strong enough correlation to be used in performance prediction.

Table 1 summarizes the specimen measurement results from the three NDE methods and the material properties. The table shows that fifteen of the specimens would have been rejected on penetrant indications. Radiographically, ten specimens, the C and D grades, would have been rejected on quality. With CT, the data would indicate that only three specimens were significantly different and that a quantitative value could be used to establish a criteria. These specimens are also the three given radiographic D grades. The material properties of all the others with radiographic grades A, B, and C, are such that there is no meaningful reason not to utilize the material.

The mechanical testing results indicate that there is considerable room for modification of the approach for the rejection of castings based on nondestructive evaluation data. All of the originals samples were taken from castings that were rejected by penetrant examination. However, the performance of the 30 tensile specimens indicates that the mechanical properties were not necessarily compromised in the samples that had penetrant indications. In an associated study [9], a correlation between all the 155 specimens that showed penetrant indications and a reduction in mechanical properties was found and depended on the alloy and treatment. This correlation was not evident in the smaller 30 sample set employed in the CT study.

Table 1. NDE correlation to material properties in cast aluminum

Specimen	NDE Method				Material Properties		
	Dye Penetrant	Film Radio-graphy	CT Mean	CT STDEV	TYS (.2%)	UTS	Elong-ation
		Grade			(ksi)	(ksi)	(%)
356-T6							
75A	Reject	D	666.6	7.69	26.7	32.0	1.60
75B	Reject	D	663.9	7.98	29.4	32.4	0.99
75C	Reject	D	660.1	9.05	28.3	32.5	1.42
65B		A	674.6	3.22	32.3	42.8	5.71
21C	Reject	C	671.1	3.65	29.4	35.4	1.70
2A-1		A	674.7	3.50	32.1	37.4	1.47
2E		A	687.3	2.74	30.8	38.5	3.43
4S		A	678.6	3.40	32.1	38.2	1.84
4E2		A	683.0	2.48	33.7	42.0	4.40
4G	Reject	C	677.9	3.98	32.8	38.1	1.32
9H		A	669.0	3.21	31.1	38.8	3.50
17C	Reject	B	677.0	4.22	32.8	38.2	1.46
17D	Reject	B	670.8	4.83	31.0	34.8	0.76
3B	Reject	B	674.3	3.42	30.4	37.0	2.17
3C	Reject	B	670.2	4.29	31.2	37.6	2.28
5D	Reject	B	670.3	3.28	31.6	43.3	15.0
A356-T6							
XX-1		A	668.8	4.26	32.0	43.1	7.65
XX-5		A	677.2	3.03	30.9	41.0	4.72
ZZ-5		A	671.3	3.60	31.1	43.4	11.0
A357-T6							
7N		A	678.0	3.32	41.5	48.9	4.50
7P	Reject	C	661.2	5.37	39.2	44.8	1.65
7S		A	680.3	3.41	38.5	44.2	1.74
7W		A	685.7	4.89	42.5	45.0	3.93
22N		A	682.0	5.60	42.1	45.9	1.00
22P	Reject	C	676.8	4.47	42.3	48.2	2.37
22Q-1		A	677.4	3.93	41.9	45.9	1.35
15W	Reject	B	664.4	3.90	42.0	44.5	0.69
15X	Reject	B	672.2	3.66	42.9	47.4	1.11
15AB	Reject	B	673.2	4.74	41.8	45.6	0.93
15F		A	681.7	4.42	40.8	45.9	2.06

Figure 6 is a graph of the ASTM E-155 numbers for radiographic inspection for porosity versus the CT standard deviation for the specimens containing indications. The CT data correlate with the radiographic evaluation of the specimens, but provides a quantitative measurement of the porosity in each one.

These results demonstrate that current NDE methods of inspection are suspect with respect to correlating to static strength properties in aluminum castings. The vast majority of tensile specimens excised at dye penetrant indications on the surface of the castings were defect free (no penetrant or radiographic indications) once they were machined to shape, and showed no degradation in tensile properties. Although the sample size was small, the results indicate that quantitative CT might very well be used to dramatically reduce the number of rejected castings. The study needs to be repeated on a larger sample and also needs to be performed with fatigue specimens, so that a correlation with fatigue strength in castings can be explored.

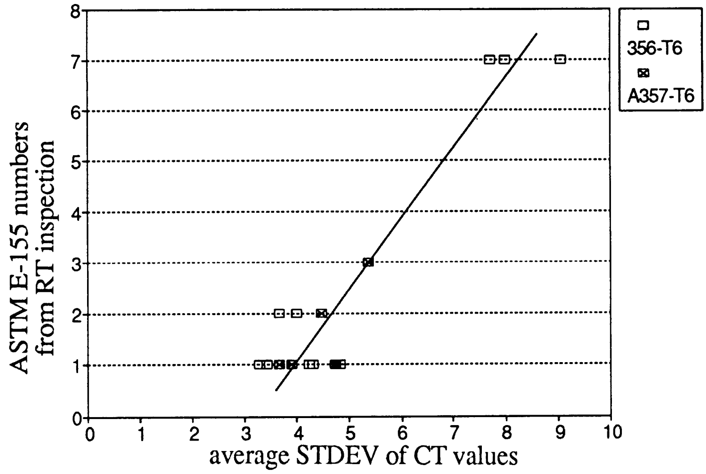


Figure 6. CT standard deviation versus ASTM Number.

Hot Isostatic Processing of Castings

Hot isostatic processing (HIP) is a high pressure heat treatment that is used for powder consolidation, diffusion bonding, and healing of castings [10]. When a casting is subjected to HIP, both the material consolidation and the mechanical properties can be improved [11]. An aircraft cast aluminum hydraulic manifold is an example of a casting in which HIP is part of its manufacture. Because it channels fluid under pressure, the manifold must not contain connected porosity or voids which might allow leaking. A photograph of a manifold is shown in Figure 7.

Three manifolds were CT evaluated before and after being subjected to HIP. Ten contiguous 2 mm thick slices were taken to obtain CT data in a 20 mm thick critical section (the location is noted in the photograph of Figure 7). The mean and standard deviation of the CT values (relative linear X-ray attenuation coefficients) before and after HIP in all three manifolds were calculated at each CT slice. These values were measured by taking region-of-interest statistical measurements of the CT values in the area between the large passageways (area where the porosity was identified in the pre-HIP'ed castings). The level of the mean indicates how dense a casting is at the location scanned, and the standard deviation is a measure of the uniformity of the density at the same location. A highly porous material will have a low mean CT density and a high standard deviation. A comparison of the pre- and post-HIP data reveals that HIP greatly reduced the porosity in the region analyzed, increasing the average density by 2 to 5%.

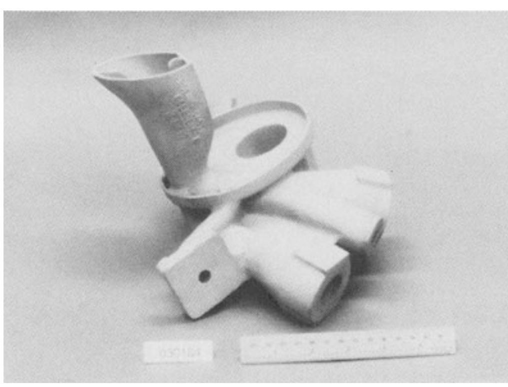


Figure 7. Photograph of a cast aluminum hydraulic manifold.

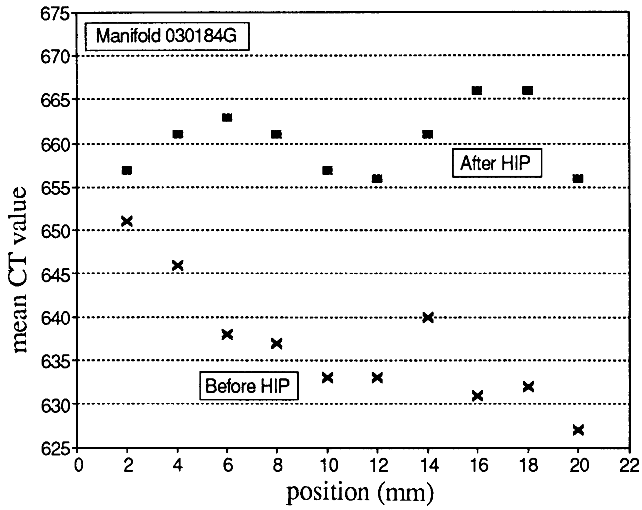


Figure 8. Graph of CT value versus position in a manifold.

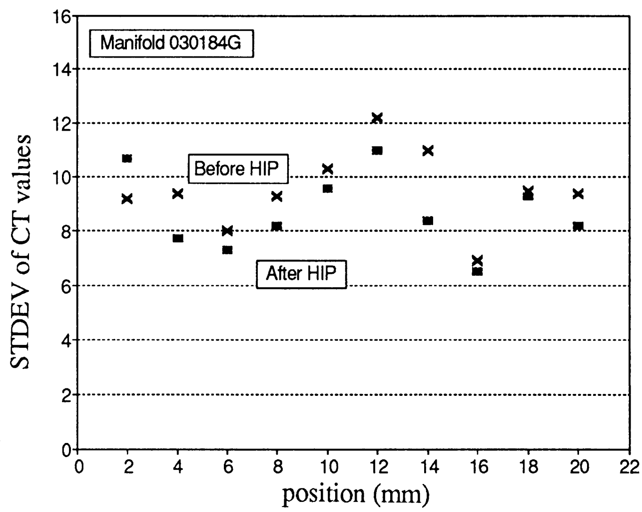


Figure 9. Graph of CT standard deviation versus position in a manifold.

Figures 8 and 9 show the results in graphic form for one of the three castings. The results were very similar for the other two castings analyzed. In general, the mean CT value increases and the standard deviation of the CT values decreases due to HIP. It is important to note that the width of each casting (and therefore the amount of material at that location) decreases from left to right on each graph. The increase in density (reduction in porosity) was greater for the thinner areas than the thicker.

The CT data obtained before and after HIP allows the examination of the migration of porosity due to this process. Besides measuring the mean and standard deviation in regions of interest on each CT slice, each set of images were evaluated before and after for qualitative changes. In one manifold, HIP reduced the overall porosity in the region examined, but produced a single, larger void. A CT image of the post-HIP'ed casting contained the void, which was not seen in the CT slice (or adjacent slices) of the pre-HIP'ed casting. This void is most likely due to the reprecipitation of hydrogen gas during post-HIP treatments which can coalesce into gas bubbles in the aluminum [12]. This void is located near a thin wall where it could be of concern.

Several general trends are clear from these CT results, (a) HIP of these castings significantly reduces their porosity (increase of 2-5% in overall material density in the region examined) and increases their uniformity, (b) the effectiveness of HIP is inversely proportional to the amount of material at any given location (since HIP produces diffusion of gas bubbles out of a casting under high temperature and pressure, one would expect it to be thickness dependent), and (c) if the pores are filled with a gas that does not dissolve easily in the alloy, HIP can cause the coalescence of small voids into larger ones or produce the migration of voids.

SUMMARY

The utilization of CT for quantitative material evaluation has been demonstrated in a study aimed at correlating NDI methods to tensile strength in aluminum sand castings. The results from the strength tests indicate that many structurally sound castings are being rejected under the present qualitative NDI criteria. CT measurement and analysis has shown potential to increase the yield of "good" castings through quantitative interpretation of casting quality based upon voids and porosity. CT has also been demonstrated as an effective tool for quantifying and evaluating hot isostatic processing (HIP) currently used for improving properties in high quality castings. The reduction or movement of porosity and voids caused by the HIP can be measured with CT at any location in the casting.

ACKNOWLEDGEMENT

This work was sponsored by the Wright Research and Development Center, Materials Laboratory, Nondestructive Evaluation Section through the "Advanced Development of X-Ray Computed Tomography Applications Program." Charles Buynak is the technical monitor.

REFERENCES

1. M. J. Dennis, "Industrial Computed Tomography," *Metals Handbook*, Ninth Edition, Vol. 17 "Nondestructive Evaluation and Quality Control" ASM, Metals Park, OH, (1989).
2. "Standard Guide to Computed Tomography (CT) Imaging," E144-91, ASTM, (1991).
3. E. Segal, A. Notea and Y. Segal, "Dimensional Information Through Industrial Computerized Tomography," *Materials Evaluation*, 40 (1982).
4. P. D. Tonner and G. Tosello, "Computed Tomography Scanning for Location and Sizing of Cavities in Valve Castings," *Materials Evaluation*, 44, No. 2 (1986).
5. R. H. Bossi and G. E. Georgeson, "X-ray Computed Tomography Analysis of Castings," Light Metals 1992, Edited by E. R. Cutshall, TMS Warrendale, PA (1991).
6. G. E. Georgeson, A. R. Crews and R. H. Bossi, "X-ray Computed Tomography for Casting Development," WL-TR-92-4032, September, 1992, pp. 17-21.
7. F. V. Lawrence, Jr. and W. H Munse, "Effects of Porosity on the Tensile Properties of 5083 and 6061 Aluminum Alloy Weldments," Welding Research Council Bulletin 181, New York, February, 1973.
8. F. V. Lawrence, Jr. W. H Munse and J. D. Burke, "Effects of Porosity on the Fatigue Properties of 5083 Aluminum Alloy Weldments," WRC Bulletin 206, New York, June 1975.
9. Private communication with Wes Graham of Boeing, Seattle.
10. H. D. Hanes, D. A. Seifert and C. R. Watts, *Hot Isostatic Processing*, Battelle Press, Columbus Ohio, 1979, p.1.
11. Ibid., p. 55.
12. A. H. Claner, K. W. Weiners and C. B. Boyer, "Hot Isostatic Processing," HCIC Report, Metals and Ceramics Information Center, Columbus, OH, September, 1982, p. 143.