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# VISUALIZATION OF FLAWS WITHIN HEAVY SECTION ULTRASONIC TEST BLOCKS USING HIGH ENERGY COMPUTED TOMOGRAPHY

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# VISUALIZATION OF FLAWS WITHIN HEAVY SECTION ULTRASONIC TEST BLOCKS USING HIGH ENERGY COMPUTED TOMOGRAPHY

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## Abstract

The feasibility of high energy computed tomography (9 MeV) to detect volumetric and planar discontinuities in large pressure vessel mock-up blocks was studied. The data supplied by the manufacturer of the test blocks on the intended flaw geometry were compared to manual, contact ultrasonic test and computed tomography test data. Subsequently, a visualization program was used to construct fully three-dimensional morphological information enabling interactive data analysis on the detected flaws. Density isosurfaces show the relative shape and location of the volumetric defects within the mock-up blocks. Such a technique may be used to qualify personnel or newly developed ultrasonic test methods without the associated high cost of destructive evaluation. Data is presented showing the capability of the volumetric data analysis program to overlay the computed tomography and destructive evaluation (serial metallography) data for a direct, three-dimensional comparison.

## Introduction

X-ray computed tomography (CT) is a radiographic method that produces cross sectional images of a component, perpendicular to the incident beam of radiation. This technique, unlike conventional radiography, presents an image free from the interference of superimposed projected features [1]. CT can complement alternate nondestructive inspection methods such as ultrasonic, eddy current and radiographic testing. In an industrial sense, X-ray computed tomography has been used to characterize high value parts: advanced composite materials, electronic components, castings and machined forgings [2,3].

Computed tomography has shown the potential to reduce, or sometimes eliminate, the costly and time-consuming task of destructive evaluation (metallographic sectioning, polishing and photographing). Destructive evaluation (DE) is required to determine "truth" against which ultrasonic test (UT) results are compared. When fully qualified, CT can be used in place of destructive techniques as a means to qualify newly developed test techniques and personnel.

To obtain the maximum benefit from CT imaging, a quantitative method of three-dimensional image analysis must be employed. Disconnected features that appear in two-dimensional images may be connected in three-dimensional space. Static renderings show the three-dimensional (3D) connectivity of flaws within a component, but these images are slow to construct and cannot highlight more than one side of a flaw at a time. The novelty of the current effort is an interactive 3D data display for the same purpose.

The use of CT and volumetric imaging has been extended to steel components of up to eleven inches thick in maximum radiographic chord length. Penetrating such thick sections requires the use of a linear accelerator as found at

Hill Air Force Base. This system's high intensity X-ray flux enables scan times as fast as three minutes. CT test data obtained from mockup blocks with embedded volumetric and planar flaws is presented below. This data is compared to manual, contact UT data, the intended flaw geometry information supplied by the block manufacturer, and DE data when available. Finally, a full three-dimensional representation of selected flaws is given, superimposed upon destructive evaluation data.

## Materials and Equipment

Five cladded carbon steel (A533) blocks containing a total of eight planar and six volumetric flaws were interrogated with CT (see Figure 1). The 9 MeV linear accelerator was employed at Hill Air Force Base to collect the raw CT images. Image reconstruction was done on a MicroVAX with an array processor. The volumetric image compilation was performed with Lockheed Martin developed visualization software on a Silicon Graphics Inc. RE$^2$.

| **Block Number** | **Block Dimensions (A x B x C) in inches** | **Flaw Number** | **Throughwall Depth (D) in inches** | **Width (E) in inches** | **Length (F) in inches** |
|---|---|---|---|---|---|
| 1 | 20 x 6 x 3.6 | 1 | 1.20 | n/a | 3.55 |
| 2 | 20 x 6 x 3.7 | 1 | 0.80 | n/a | 2.04 |
| 3 | 20 x 6 x 10.5 | 1 | 1.00 | n/a | 3.11 |
| 4 | 20 x 4 x 4 | 1 | 0.54 | 0.8 | 0.51 |
| | | 2 | 0.44 | 0.01 | 1.10 |
| | **Intended Flaw Dimensions** | 3 | 0.13 | 0.01 | 0.38 |
| | | 4 | 0.37 | 0.20 | 0.49 |
| 5 | 20 x 8 x 8 | 1 | 0.11 | 0.19 | 0.39 |
| | | 2 | 0.10 | n/a | 0.38 |
| | | 3 | 0.20 | n/a | 0.66 |
| | | 4 | 0.16 | n/a | 0.64 |
| | | 5* | 0.13 | n/a | 0.51 |
| | **Destructively Evaluated Flaw Dimensions** | 6 | 0.13 | 0.19 | 0.50 |
| | | 7* | 0.14 | n/a | 0.49 |

*Not detected with CT

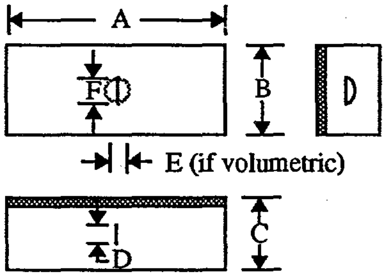

*Figure 1. Table of flaw dimensions and block sizes (shown top), drawing of flaw orientation (shown bottom).*

## Experimental Procedure

A digital radiograph was used to obtain approximate flaw locations within each mockup block. The computed tomography images were then taken with a 0.06 in. X-ray source spot size, 9.2 ft source-to-detector distance, 0.04 in. slice thickness and 0.04 in. detector aperture. Reconstructions were performed on the raw sinogram data using an ARACOR proprietary filtered backprojection method. Measurements from the two-dimensional images were manually collected, while 3D information was selected based upon trial threshold levels described below.

Ultrasonic test data were collected on the mockup blocks using 45 and 70 degree refracted longitudinal waves generated and displayed on a USM-3S or equivalent ultrasonic oscilloscope. A test frequency of 3.5 MHz was used. A full width at one-half maximum amplitude sizing technique established the length of the flaw, while calibrated timing measurements determined the throughwall dimension using reflectors at known depths.

The stacked CT slices were merged into one volumetric data set. Isosurfaces, or surfaces of constant density, were created with a marching cube algorithm [4]. A density value of the flaw volume corresponding to the maximum gradient with respect to the nominal base metal density was chosen as the boundary of the isosurface. Topological connectivity was used to segregate flaws from one another and from background noise. A coordinate transformation of the DE data into the CT data space enabled a direct volumetric comparison of the results.

## Discussion of Results

Computed tomography successfully detected the three planar and four volumetric flaws in blocks 1 through 4. In addition, two volumetric and three planar defects were found in block 5 (two planar cracks of approximate size 0.45 x 0.15 in. were not detected). The planar flaws were detected at 75% confidence, while volumetric flaws were detected at greater than 99% confidence. The confidence bands were established from feature size versus contrast curves as described in standard practice methods [5]. Planar flaws such as cracks or lack-of-fusion welding defects are difficult to image due to their small volume. Volumetric flaws such as oxide inclusions (slag) are more readily detected due to higher contrast. Figure 2 provides a correlation of the height (or throughwall depth) of the flaw found through CT to the intended, or destructive evaluation data when it exists. This height is the smallest dimension of each flaw, and is the most challenging to correctly size. Data points in Figure 2 were selected visually from a video display.

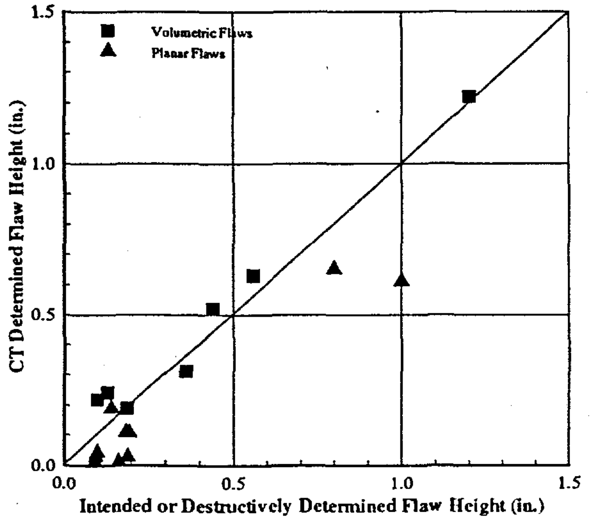

*Figure 2. Comparison of results obtained by CT to intended flaw dimensions and DE data.*

As a further test of the ability of CT to size the volumetric flaws, a 3D overlay plot was constructed as shown in Figure 3. The shape of the volumetric flaw shown in Figure 3 matches well with the CT data isosurface created based upon a maximum gradient value. The DE data is naturally oversized since a bounding box was used to establish flaw dimensions within each metallurgical grind plane. Much of the data interpretation is lost in the two-dimensional flat figure, the true benefit lies in the ability to interactively assess the regions of data intersection. Further work is necessary to optimize the volumetric analysis program allowing for flaw composition, morphology and noise. Although not presented here, the visualization program has the capability to overlay multiple data sets (DE vs. UT, UT vs. CT, etc.).

Ultrasonic test data collected on blocks 1 through 4 were extracted from an interlaboratory round robin examination (multiple inspectors, multiple facilities). An absolute comparison to DE data is not available; however, the correlation between the intended flaw size, the ultrasonic test data and the computed tomography test data can show if any of these measurements agree (see Table 1).

*Table 1. Correlation Coefficients of Intended, Ultrasonic and Computed Tomography Flaw Geometry*

| | Flaw Length Dimension | Throughwall Dimension | Distance to Top of Flaw |
|---|---|---|---|
| UT vs. CT | 0.813 | 0.772 | 0.990 |
| CT vs. Intended | 0.993 | 0.884 | 0.999 |
| Intended vs. UT | 0.851 | 0.876 | 0.989 |

By comparing and contrasting the above tests, CT and UT measured data correlate well with the manufacturer's predicted flaw geometry. In addition, CT provides complete volumetric information, not only the maximum defect throughwall, length and orientation.

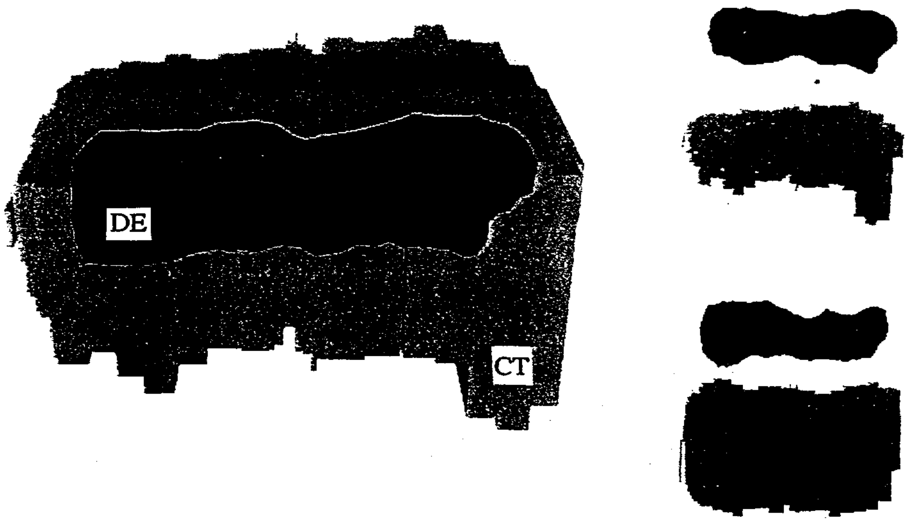

*Figure 3. Volumetric data comparison between destructive and CT data on a volumetric flaw.*

## Conclusion

High energy computed tomography has shown the potential to detect embedded planar and volumetric defects in pressure vessel mock-up blocks. Sufficient density variations exist between the flaw and the host base metal to enable calculation of the flaw geometry. Good correlation was found among ultrasonic test data, the manufacturer's intended size and computed tomography data. A volumetric comparison of the computed tomography and the destructive evaluation data was performed and showed the potential to provide additional information as compared to slice-by-slice data analysis. Further investigation will yield a quantitative understanding of the measurement uncertainty of the volumetric image analysis techniques.

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[2] Frock, B. et al, "Research on Advanced NDE Methods for Aerospace Structures" Wright Laboratory Technical Report WL-TR-95-4012, November 1994

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[5] Standard Practice for Computed Tomographic (CT) Imaging ASTM E1570-93.