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Optimization of Neutron Tomography for Rapid Hydrogen Concentration Inspection of Metal Castings

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ABSTRACT

Hydrogen embrittlement describes a group of phenomena leading to the degradation of metal alloy properties. The hydrogen concentration in the alloy can be used as an indicator for the onset of embrittlement. A neutron tomography system has been optimized to perform nondestructive detection of hydrogen concentration in titanium aircraft engine compressor blades. Preprocessing of backprojection images and postprocessing of tomographic reconstructions are used to achieve hydrogen concentration sensitivity below 200 ppm weight. This paper emphasizes the postprocessing techniques which allow automated reporting of hydrogen concentration.

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I. INTRODUCTION

This paper describes the neutron tomography system at the McClellan Nuclear Radiation Center (MNRC) with emphasis on the automated procedures for quantitative determination of hydrogen concentrations in metal components. The system was developed as a result of the need to obtain hydrogen concentration data for aircraft engine compressor blades. The hydrogen concentration can be used as an indicator for the loss of mechanical properties, embrittlement, which can occur in metals after exposure to hydrogen[1]. The requirements for the system include the evaluation of large parts (tens of cm) with small features (< 1 cm) at a rate of several per hour. Additionally, hydrogen concentrations must be detected accurately from 200 ppm weight to several thousand ppm.

The tomography system consists of a neutron source, object turntable, scintillator screen, mirror, CCD camera, and computer support[2] and is similar to McFarland, et. al.[3]. The neutron source is a 2 MW TRIGA thermal reactor. The neutron beam is approximately 50 cm in diameter at the scintillation screen with a thermal flux of 10^7 n/cm²s. The system can acquire 180 images with 0.057 cm resolution in one hour. The tomographic reconstruction algorithm calculates the spatial distribution of the macroscopic neutron cross section in an object from the attenuation of the neutron beam as it passes through the object at different angles. The hydrogen content has been calibrated against the increase in the macroscopic cross section. Besides reconstruction with the filtered backprojection method[4], preprocessing of backprojection images as well as postprocessing of tomographic reconstructions are used to achieve the required hydrogen concentration sensitivity and spatial resolution.

II. IMAGE PREPROCESSING AND HYDROGEN SIGNAL

Before the backprojection images are given to the reconstruction routine, preprocessing is required to ensure that the beam intensity in the images is an accurate representation of the attenuation caused by the objects imaged[5]. The procedures are detailed in a recent article[2], and only a summary will be presented here.

A dark charge image is taken and subtracted automatically during image acquisition. The images are then divided by the unobstructed beam image to remove beam spatial inhomogeneities. The average flux from the MNRC reactor has some fluctuation with time. The average intensity of the beam in each normalized image determines the correction coefficients for reactor fluctuations. A relatively uniform background noise signal was also measured. This background signal is due to scattered light from the scintillation screen and scattered neutrons from the beam stop and other structures in the radiography bay. The background noise and any object neutron scattering signals are determined from the intensity behind a borated-poly strip which is placed between the object and the beam. This strip is opaque to the neutron beam so any signal behind the strip is subtracted from each image's intensity.

The tomographic reconstruction algorithm calculates the spatially dependent attenuation coefficient from the line integrals in the backprojection images. Since the neutron beam of the MNRC reactor is not monoenergetic, line integrals found assuming exponential attenuation of the beam will result in beam hardening errors[2]. The beam hardening errors are corrected by using a table of attenuation length versus intensity. The table was initially calculated from measurements of intensity behind titanium alloy samples of known thickness. Measurement of test samples also provides the attenuation coefficient corresponding to particular densities of hydrogen. Over a wide range of concentrations the attenuation coefficient for 100 ppm hydrogen relative to the attenuation coefficient of titanium is 0.02. The results of the preprocessing is demonstrated in the reconstruction of a Ti6Al4V disk. Figure 1a and b are cross sections of the results without and with image corrections. The elimination of the beam hardening artifacts is obvious in the corrected image reconstruction.

III. TOMOGRAPHIC RECONSTRUCTION POSTPROCESSING

The size of detectable defects in tomographic reconstructions is limited by the spatial resolution and number of the initial backprojection images. For objects centered at 10 cm from the scintillation screen, resolutions of approximately 0.06 cm were found. For the detection of a low amounts of

hydrogen in small or thin objects, postprocessing procedures become necessary. The procedure chosen is to align the reconstruction of an object being tested with a standard object. The standard object is the same as the test object in composition and shape except the standard has little or no hydrogen. More than one object can be defined in an image, and the software aligns each object separately. After alignment the standard object image is subtracted from the test object image. The result is an image which contains only the hydrogen signal plus any data noise. Any systematic errors such as reconstruction aliases should be removed. The procedure results in improved detection capability for the small hydrogen signal as well as data which can be more easily interpreted in an automated fashion.

Consider the images resulting from the tomographic reconstruction of a test object and a standard object. The objects are assumed to be vertically aligned so only one 2-D slice is postprocessed at a time. The postprocessing algorithm creates object templates, aligns the objects' centers of mass, rotates the test object, generates a difference image, and reports the difference in attenuation coefficient. The first task is to determine the extent of objects in the images. Since we already know the effective attenuation coefficient of the object, we can set a cutoff value which is some fraction of the coefficient (usually 0.8). A template array is generated for each image by setting the value of pixels with attenuation coefficients above the cutoff to one, and the value of pixels with attenuation coefficients below the cutoff to zero. These template arrays delineate the pixels inside the objects. Of course, edge spread will limit the accuracy of determining which pixels are inside objects.

The test object image is then translated so that its center of mass is coincident with the standard object center of mass. Since the test object pixels are no longer at integer locations in the standard object coordinate system, the intensities are linearly weighted to the grid. After the test object has been translated, the test object template is updated.

Once the center of masses are coincident, the test object can be rotated to complete the alignment. For an object of unknown shape a method is necessary to define its orientation. The ellipsoid of inertia provides the required information[6]. The angle of the principal axes with respect

to the coordinate axes can be matched for the test and standard objects. It is assumed that the test and standard object orientations are within $\pm 90^\circ$ since the ellipse is symmetric about its axes. Otherwise this spatial degeneracy could result in a 180° misalignment of the object orientations. This is not a problem since the objects and turntables are always started as close as possible to the same initial position. The orientation of the principal axes is found as follows. The moments and product of inertia (I_x , I_y , and I_{xy}) are determined at the center of mass for each object in the template images. The principal axes of inertia are found from

$$I_p = .5 \left[I_x + I_y \pm \left[(I_x + I_y)^2 - 4(I_x I_y - I_{xy}^2) \right]^{1/2} \right]. \quad (1)$$

The angle between the principal axes and the coordinate axes is given by

$$\theta = \arctan \left(\frac{I_x - I_p}{I_{xy}} \right). \quad (2)$$

Given these object orientations the test object can now be rotated to the same angle as the standard object. The rotation is centered at the center of mass. After rotation a new test object template, center of mass, and angle are calculated. These characteristics can be used to determine the effect of the linear weighting on the test object as well as the accuracy of the alignment.

The intensity values of the standard object images are now subtracted from the intensity values of the test object image for each individual pixel. The result should be only the hydrogen signal except for data noise and edge spread artifacts. Edge artifacts could arise due to slight differences in the objects' shapes, linear weighting effects, variation in object orientation in the original backprojection images, etc. Since the attenuation coefficients drop off sharply at the edges, large spurious difference signals could occur. To reduce the chance for such spurious signals, the templates for the test image and the standard image are multiplied together. The difference image is then multiplied by the combined template. Pixels which are not included in both objects (test and standard) are removed from the resulting images.

By using the image comparison (subtraction) technique, we hope to preserve the surface signal as much as possible. Nonetheless, if hydrogen concentrates solely on the surface with no significant diffusion to thicknesses greater than a pixel width (0.57 mm), we will have a significantly limited

ability to achieve accurate detection. With the high diffusivity of hydrogen in metals it is unlikely that only an extremely thin surface layer of hydrogen will be the normal condition; therefore, we are confident in the detection capability of our present method.

IV. RECONSTRUCTION RESULTS

The reconstruction of a set of three compressor blades is shown in figure 2a. Some radial artifacts are evident due to the finite number of backprojection images. The interior regions of the blades do not suffer too badly from these artifacts. The density is 1.009 ± 0.008 which represents a variation of only ± 50 ppm hydrogen. This signal is so low that we cannot be certain if it is due solely to noise or if there is some hydrogen signal present. In figure 2b the difference image generated by the alignment algorithm for one of the blades is shown. The alignment of objects caused a loss of approximately 3% of the pixels in the templates of the test objects. The average signal found in the difference images was equivalent to 33 ppm hydrogen with a standard deviation of 70 ppm. The signals are very small and may be due to small differences in the physical size of the blades as well as system noise. We can conclude that the algorithm adequately aligns the blades and has sufficient sensitivity to report low hydrogen concentrations in images where three blades are present.

Two plates of Ti6Al4V were loaded with hydrogen. According to gas fusion and Cold Neutron Prompt Gamma Activation Analysis (CNPAA), plate 115 had 115 ppm hydrogen, and plate 175 had 175 ppm hydrogen[7]. Since the plates are thinner than the blades, the plates were reconstructed from 360 backprojections. The postprocessing decreased the test object, plate 175, size by 1.7%. The standard object, plate 115, had 20% fewer pixels than the test object. Measurements of the plate thicknesses indicated the plate 175 is 4% thicker than plate 115. This may in part account for the difference in the number of pixels defined as being inside each object. The density of hydrogen found in the difference image was 78 ppm which is near the CNPAA determined value. The standard deviation is 108 ppm. The fluctuations are probably due to a combination of image noise, reconstruction aliases, and hydrogen density variation. As a whole the results show

sensitivity which is better than the required 200 ppm for thin objects.

V. CONCLUSION

The tomography system has demonstrated the capability to detect hydrogen in titanium components to levels of 100 ppm weight with an acquisition time of 60 minutes. This is accomplished by correction of the backprojection images before reconstruction and comparison of standard and test objects after reconstruction. The resulting neutron tomography system is applicable to a wide range of NDE tasks where rapid evaluation of low Z impurity concentrations is needed.

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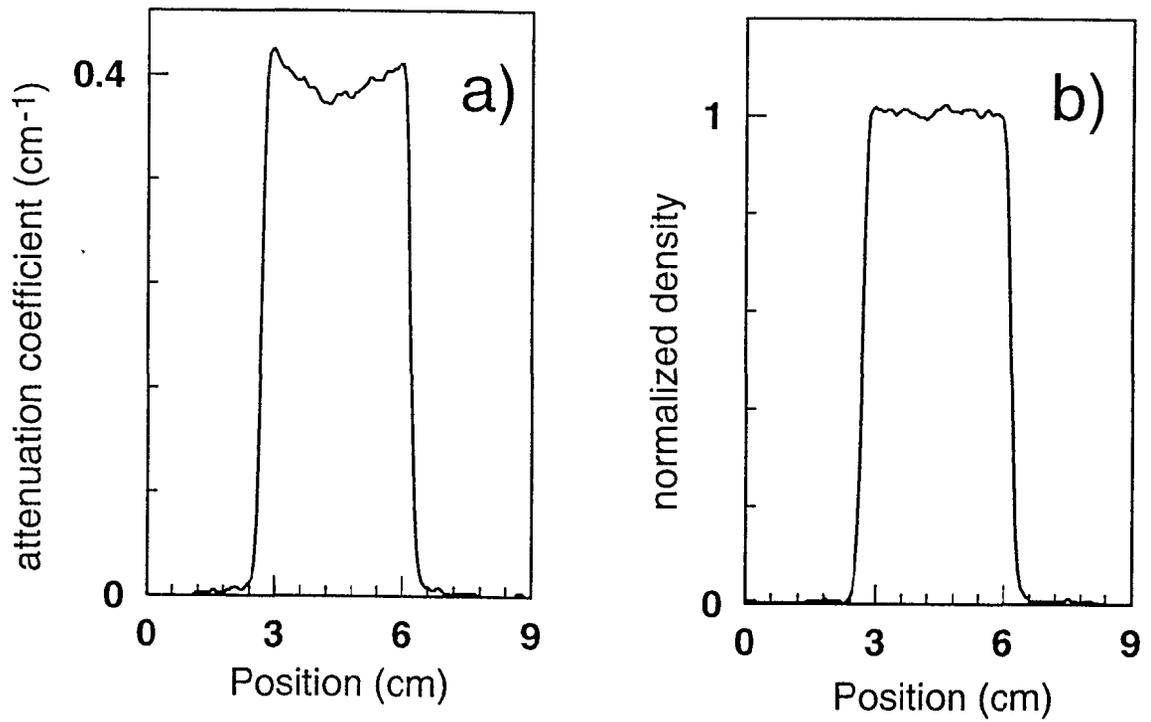


Figure 1: Cross section of a Ti6Al4V disk reconstruction where a) backprojection preprocessing was not performed, and b) preprocessing was performed.

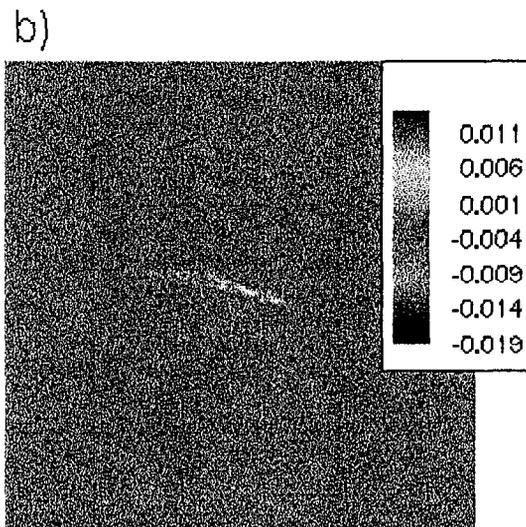
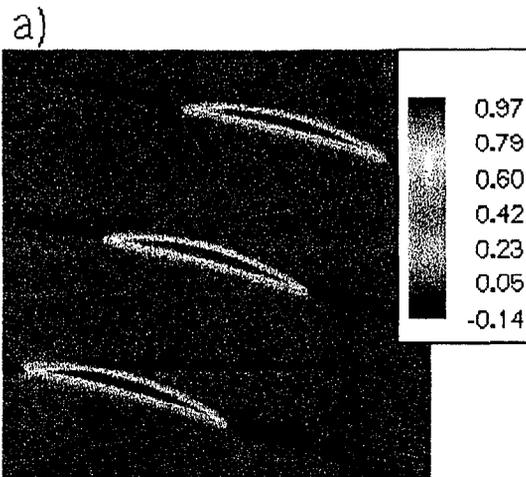


Figure 2 Images of a) the tomographic reconstruction with three engine compressor blades and b) the difference in reconstructions for one of the blade positions.

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