DEVELOPMENT OF METROLOGICAL NDE METHODS FOR MICROTURBINES CERAMIC COMPONENTS*

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ABSTRACT

In this work, X-ray computed tomographic imaging technology with high spatial resolution has been explored for metrological applications to Si_3N_4 ceramic turbine wheels. X-ray computed tomography (XCT) data were acquired by a charge-coupled device detector coupled to an image intensifier. Cone-beam XCT reconstruction algorithms were used to allow full-volume data acquisition from the turbine wheels. Special software was developed so that edge detection and complex blade contours could be determined from the XCT data. The feasibility of using the XCT for dimensional analyses was compared with that of a coordinate-measuring machine (CMM). Details of the XCT system, data acquisition, and dimensional comparisons will be presented. Comparison between XCT and CMM dimensions shows that the 3D XCT data have an accuracy of ± 0.2 mm in all three axis whereas the CMM data have an accuracy of ± 0.5 mm in the horizontal plane and ± 0.025 mm in the vertical plane.

1 INTRODUCTION

Microturbine electric power generating systems using ceramic turbine wheels are estimated to have efficiencies of ~30% to >40% over similar systems that use metal wheels. However, reliable production volumes have yet to be demonstrated for the ceramic turbine wheels. Important factors in volume production are the reliability of as-produced dimensions and the detection and measurement of internal defects. Determination of the size, shape, and specific location of various aspects of a component with a complex shape can be time-consuming and thus very expensive. For components of turbine engines such as blades, vanes, or integral blisks, dimensions are usually verified with a coordinate-measuring machine (CMM). However, if critical internal-cooling channels or other internal shapes are complex, CMM devices cannot be used because there is no access to the area to be measured. The X-ray computed tomographic image has been used for many years in the medical and industrial communities to determine the quality of components and to provide information about processing of new materials (Mohr and Little, 1995, Illerhaus and Thomson, 1999, and Flisch et al., 1999). More recently, because of high quality industrial X-ray computed tomography (XCT) systems, it is now possible to make detailed geometric measurements on industrial components (Yancey et al., 1995 and Little and Janning, 1998). In fact, the American Society of Mechanical Engineers has established a special committee, B-89, to address the development of standards for XCT metrology.

The objective of XCT-aided metrology (XCTAM) is to obtain geometrical information about a scanned object from a point-cloud function or an edge function of XCT reconstruction. Ideally, the XCT reconstruction process should produce clear, sharp images that correlate closely with object density. If high-quality XCT images are generated, density and wall thickness can be measured from the reconstructed images, and various edge detection algorithms can be used to determine the boundary of the object from the reconstructed images (Thirion, 1994). In reality, however, several factors, such as pixel noise of a detector, combine to degrade the reconstructed images by blurring the edge of the images and producing reconstruction artifacts. This results in the degradation of the images, and then in the distortion of the edge detection. Currently, industrial XCT systems utilize calibration procedures and image compensation algorithms to minimize image artifacts and thus enhance images to acquisition of metrological data.

This paper, which describes one application of XCTAM to determine the dimensions and shapes of Si_3N_4 turbine wheels, includes edge-detection, metrological measurements, and a comparison of XCTAM and CMM methods.

2 X-RAY CT RECONSTRUCTION

In this work, the selected test specimen was an available injection-molded T-3 Si_3N_4 rotor (Fig.1) that was developed for automotive turbocharger use.[1] XCT data were obtained with an X-320 CT scanner, which consists of a 320-kVp TFI Gemini-III X-ray source and a

[1] A full-size electric power microburbine wheel was not available. However, the methods and results are applicable to microturbine rotors.

detector system that is an X-ray-image intensifier (XII) coupled to an ordinary 8-bit CCD camera. The X-320 scanner has a focal spot size of ≈300 µm and produces a maximum power of ≈6 kW. The tri-field XII has a 20-cm-diameter input screen that is coated with CsI scintillator powder, and a 2-cm-diameter output lens. The CCD camera coupled to the XII contains a 568 x 480-pixel active area, with a unit-pixel size of 9 x 9 μm^2 and an 8-bit dynamic range. For this work, projection images were obtained with the X-ray source operating at 170 kVp/1.4 mA.

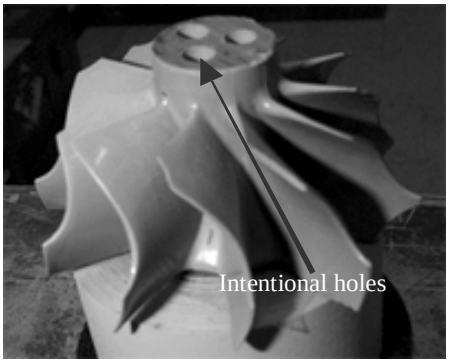
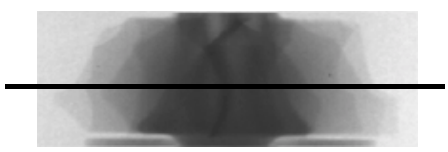
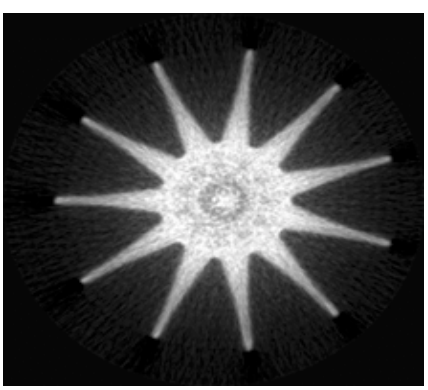


Fig. 1. Injection-molded, T-3 Si_3N_4 rotor developed for automotive turbocharger use.

During the XCT scan, 360 frames of two-dimensional (2-D) projections were captured over a rotation of 360° and saved into a CT-scan file, which would be input for three-dimensional (3-D) cone-beam reconstruction (Barker et al., 1996). Figure 2a shows a typical X-ray-projection image with a size of 450 x 180 $pixels^2$; a pixel corresponds to a physical size of 200 x 200 μm^2. Figure 2b shows a reconstructed image at the level indicated in Fig. 2a. Reconstructed-image data such as that shown in Fig. 2b were used to develop edge detection methods.



a)



b)

Fig. 2. X-ray images: (a) Typical X-ray projection image of part of rotor. (b) Typical XCT-reconstructed image with 170-µm-thick slice.

3 EDGE DETECTION

The goal of edge detection from XCT images is to determine the boundary of an object. Here, our approach is to apply on the reconstructed images threshold values that are determined by image contrast. In this method, pixel intensities are determined by producing a line profile on the reconstructed images. In our work, the boundary of the object was defined with a specified reference threshold value based on 50% image contrast. The pixel deviation from the boundary was measured from pixel positions at 30 and 70% of the maximum image contrast.

Threshold-based edge detection works well when image quality is high. However, beam hardening and penetration-related artifacts, which selectively alter absolute image intensity, may contribute significant errors to edge location. In general, all artifacts increase with object size so the magnitude of edge errors increases with part size. In this work, the image-analysis codes were locally written in LabView user interface software. Assuming that the core body of the rotor has a circular symmetry, as shown in Fig. 3, we obtained an intensity profile along a circular arc with a radius of 100 pixels, which is the distance from the center of the core. The edge profiles were obtained on eight slices, with a five-slice interval for estimating an average threshold value.

As shown in Fig. 4a, the image of the object edge was extracted from the original reconstructed image shown in Fig. 2b. Figure 4b, which is an image of the original reconstruction superimposed on the edge image, shows the accuracy of the edge detecting method previously mentioned. A sequential series of edge images were merged along the rotational axis, allowing construction of a point-cloud function, which is a 3-D edge image of the object and is used for metrological analysis of the object.

4. METROLOGY

Rotors, in general, have symmetrical core bodies and identical blades that are evenly spaced around the core. This arrangement leads to consideration of the shape and position of blades for metrological analysis. Special software was developed locally to determine the complex blade contours from the XCT-reconstruction data. From the reconstruction data, the center of the rotor was determined and one of blade was selected as a reference to develop the calculated/interpolated contour of each blade tip. The contours were expressed in terms of radius and angle, according to Eqs. 1 and 2

$$R(z) = a + bz + cz^2 + dz^3 \qquad (1)$$

$$\theta(z) = e + fz + gz^2 + hz^3 + \theta_o \,, \qquad (2)$$

which are third-order polynomials of the z (i.e., vertical) position along the axis of rotation, where θ_o represents the angle of shift for each blade from the reference blade. Four slices of the reconstructions were selected to develop the polynomial functions for the contour of the reference blade. Based on these polynomials, the contours of all the blades were developed by simply adding a shift in angle.

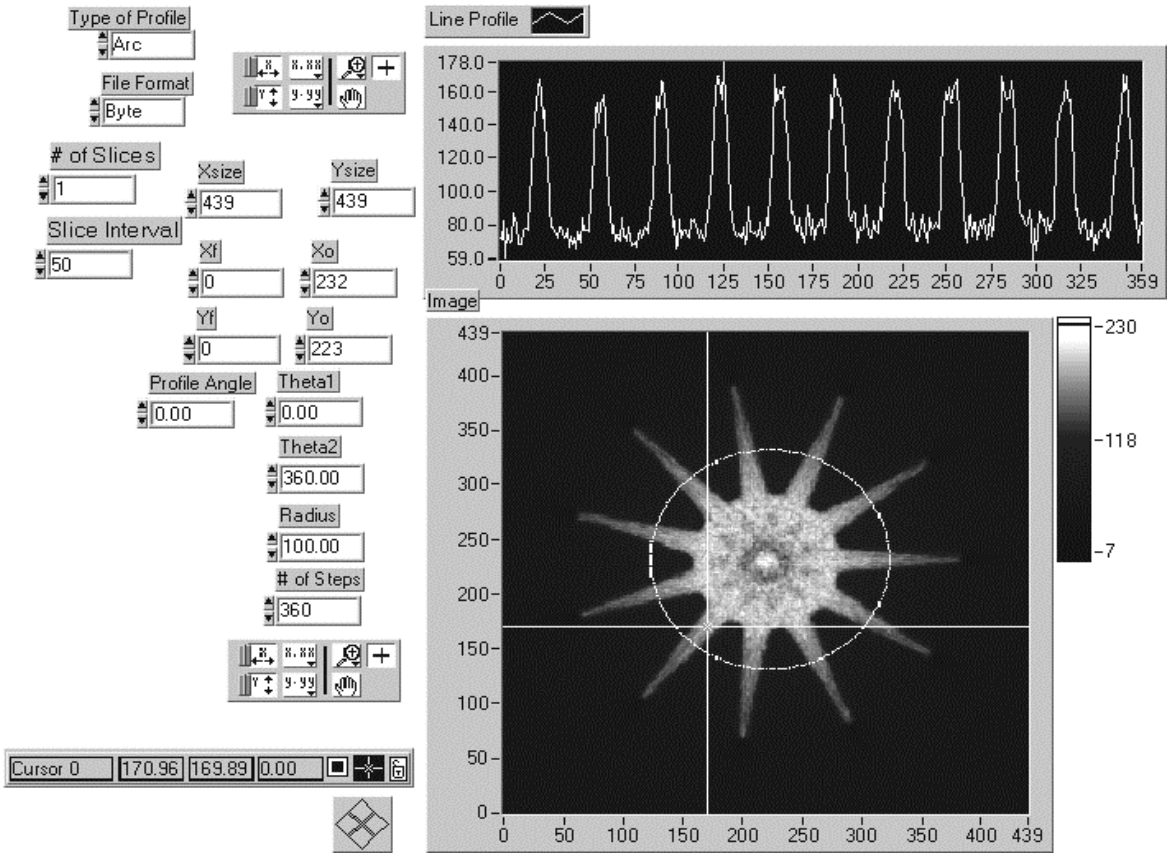
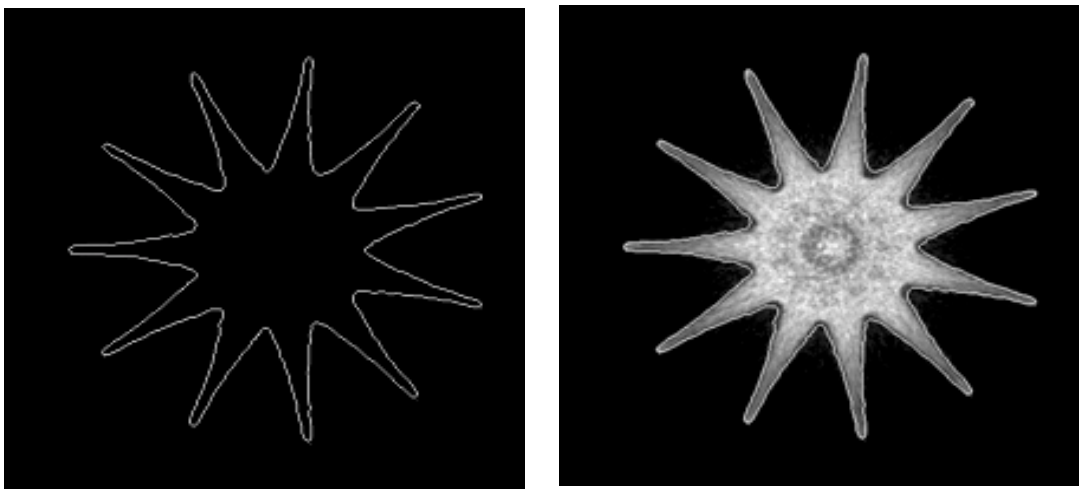


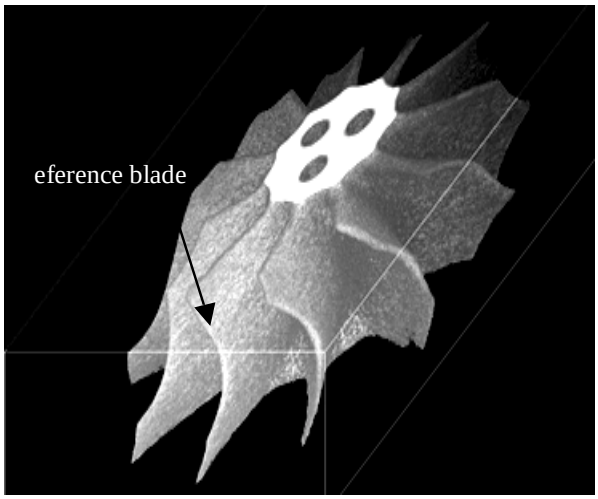
Fig. 3. Screen-captured image of LabView code for intensity profile



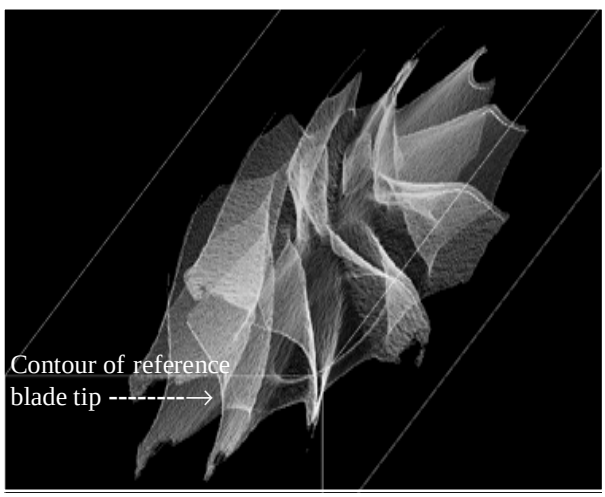
(b)

Fig. 4. Accuracy of edge detecting method: (a) Edge image of reconstructed image shown in Fig. 2b. (b) Image of reconstructed image superimposed on edge image.

Figure 5 shows a surface-rendered image of the 3-D reconstruction of the rotor and a point-cloud function of the rotor; the latter includes the contours of the blades in 3-D space. The contours were interpolated from the polynomials and inserted into the point-cloud function. By doing this, we can obtain metrological information about the rotor, i.e., the separation distance between blades, position of blades, etc.. As shown in Fig. 5b, the contour of the reference blade is well matched with the shape of the blade, but the other contour positions shifts a little off the tip of the blades. With the method we have described to this point, manufacturers may be able to examine and verify production of rotors.



(a)

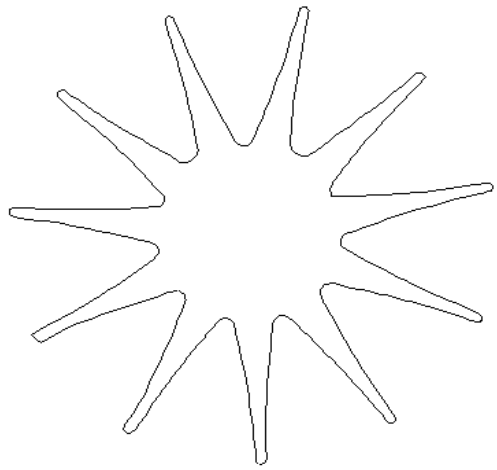


(b)

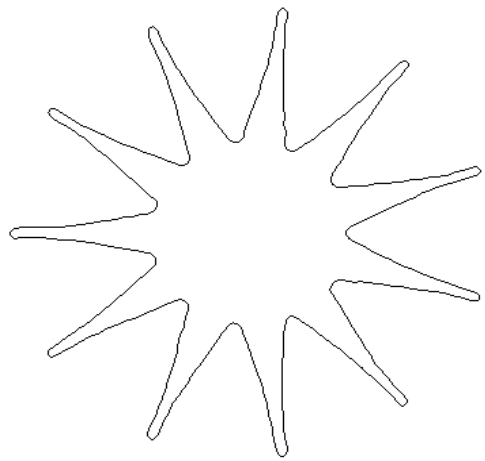
Fig. 5. Surface renderings generated from edge-detected files. (a) Surface rendering developed from reconstruction data. (b) Point-cloud function with blade tip contours.

4. COMPARISON OF XCTAM AND CMM TECHNIQUES

To compare the XCTAM with the CMM method, we used the Argonne National Laboratory CMM machine, which is a Brown & Sharpe, Model EXCEL 7-10-7. Figure 6 shows the edge-detection images generated by both methods. (However, the edge images could not be superimposed on each other for comparison because they were developed by different software with different scales and orientations.) The CMM method generated one 2-D edge image of the rotor after a 4-hour developing procedure because the turbine was complex. The accuracy of this measurement was ±0.5 mm in the vertical direction and ±0.025 mm in the horizontal direction. In comparison, the XCTAM shows an accuracy of ±0.2-mm in both directions. This accuracy corresponds to the spatial resolution of the reconstructed images and provides the entire 3-D point-cloud function from the 3-D reconstructed image in <1 minute.



(a)



(b)

Fig. 6. Edge detection images of Fig. 2b generated by (a) CMM, and (b) XCTAM.

6 SUMMARY

An initial metrological comparison has been made between results obtained from a CMM machine and those obtained from one approach to XCTAM when used to acquire geometrical information about a ceramic microturbine. An XCT scan was performed on an injection-

molded, T-3 Si_3N_4 rotor by utilizing an X-320 CT scanner. With the CT-scan data, we developed a 3-D-reconstructed image with a spatial resolution of 200 µm. From this 3-D image, we generated a point-cloud function by applying a threshold technique. The boundary of the object was defined with a specified reference threshold value based on 50% image contrast. The point-cloud function, which is an edge function of the XCT reconstruction was used to obtain geometrical information about the scanned object. The blade-tip contour was determined from the point-cloud function, in which the XCTAM shows ±200-µm accuracy and a fast dimensional analysis within <1 min. In the future, we must verify the precision of the XCTAM, which depends on various factors, such as the number of projections, which is determined by the complexity and size of an object, and the threshold values that must applied to develop an edge detection image.

ACKNOWLEDGMENT

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