Laser-Based Optical Scattering Detection of Surface and Subsurface Defects in Machined Si₃N₄ Components *

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LASER-BASED OPTICAL SCATTERING DETECTION OF SURFACE AND SUBSURFACE DEFECTS IN MACHINED Si$_3$N$_4$ COMPONENTS

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ABSTRACT

It is known that surface and subsurface defects in ceramic components may significantly affect component strength and lifetime. An elastic optical scattering technique that uses a low-power He-Ne laser, special optical components, and digital image processing has been developed to provide two-dimensional-image type data for the detection of surface or subsurface defects in machined Si$_3$N$_4$ components. The technique has been used to analyze diamond ground Si$_3$N$_4$ specimens that were subjected to various machining conditions. The laser scattering results were processed to obtain statistical data on machining-induced damage and were correlated with machining conditions.

INTRODUCTION

Silicon nitride (Si$_3$N$_4$) ceramics are considered the primary materials of choice to replace metals in many structural applications because of their mechanical and physical properties, such as high stiffness, corrosion and wear resistance, and greater thermal stability. For such applications, the most critical portions of a ceramic component, i.e., those under greatest stress during operation, are the surface or near-surface (usually to depths of <200 µm) regions. The most common types of defects in these critical regions are mechanical, e.g., cracks, spalls, inclusions, voids, etc., and they can be induced by either machining or operation.

Machining of engineering ceramic surfaces is conducted by various material removal processes. The finish of the machined surfaces depends upon the demanded end use and this, in turn, directs the type of machining operation used. During the machining of ceramics, material directly in the path of an abrasive particle encounters high stresses and temperatures and, as a result, is broken and/or deformed. Material adjacent to the abrasive particle is placed in compression. After the particle passes, this material rebounds and causes tensile stresses that lead to the formation of radial, lateral, and longitudinal cracks. Neither the radial nor lateral cracks are thought to significantly reduce the strength of the ceramic. Longitudinal (sometimes called median) cracks are parallel to the direction of grinding and perpendicular to the surface and, therefore, are thought to cause the greatest strength reduction.
It is known that a high cost value is added to the final product by machining operations.\textsuperscript{1,2} Any machining-induced damage that leads to part rejection is to be detected as early in the process as possible. An on-line method to determine the amount of surface and subsurface damage imparted to a ceramic is, therefore, desired. An on-line detection method could optimize machine tool feed rates and contact pressures during machining to obtain the highest material removal rates without adversely affecting the mechanical or tribological properties of the ceramic.

Because Si$_3$N$_4$ ceramics are partially translucent to visible (and IR) light, we developed an elastic optical scattering method for detecting surface and near-surface defects in Si$_3$N$_4$ ceramics. For many Si$_3$N$_4$ (and other) ceramics, the optical penetration depth is $>100$ μm in the visible spectrum, depending on grain size, second-phase composition, and material absorption.\textsuperscript{3} Thus, elastic optical scattering can be used as a noncontact, nondestructive method for detecting surface and near-surface defects in Si$_3$N$_4$ ceramics.\textsuperscript{4,5} In an effort to apply this technique to on-line inspection of machining of ceramic components, we have examined machined ceramic specimens to detect and characterize machining-induced damage and obtained two-dimensional (2-D) scatter images. The images were analyzed further to obtain statistical information about the damage.

ELASTIC OPTICAL SCATTERING SYSTEM

The experimental arrangement of the optical scattering system is illustrated in Fig. 1. A vertically polarized laser beam is directed through a polarizing beam-splitter (PBS) cube onto the specimen surface. Light reflected from the component surface will not undergo change in polarization unless the surface is extremely rough; therefore, all surface-scattered light will again be reflected in the PBS and directed back toward the laser. However, any light that is scattered from the subsurface material undergoes several reflections and refractions at the grain boundaries; each of these serves to alter the polarization of the light. The net effect of this behavior is to randomize the polarization of the subsurface scattered light and make the scatter completely diffuse. Thus, half of the subsurface-scattered light will also be reflected by the PBS and directed back to the laser. However, the other half of the subsurface-scattered light will be transmitted by the PBS into the detection train. The back-scattered light that passes through the surface-illuminating PBS is incident on a second PBS, through which it also passes. It is then directed through a quarter-wave plate, imaged by a positive lens onto a polished stainless steel pinhole aperture (=100 μm in diameter), and is recorded by Detector A. Any light that is scattered from the subsurface directly beneath the incident spot passes through the aperture and onto Detector A. The remaining light that is scattered from the area around the illuminating spot is reflected back through the lens and quarter-wave plate. In this case, its polarization has been rotated to horizontal, and it is reflected by the detecting PBS and directed to a 50/50 beam splitter. One side of the 50/50 beam splitter is imaged by a positive lens onto Detector B, while the other side is imaged onto a CCD array to monitor the scattering surface.
The total back-scattered intensity can be measured by monitoring the sum of the outputs of Detectors A and B, i.e., $A + B$. This sum will be most indicative of lateral defects. As the laser illumination is rastered across the specimen surface, these sum values are assembled into a gray-scale image of the surface, hereafter called the "sum" image. However, if the ratio of outputs from Detectors B and A, i.e., $B/A$, is computed, we obtain an indication of the degree of lateral spread of the subsurface scatter. This value is primarily sensitive to median defects. Again, as the specimen is scanned, these ratio values are assembled into a gray-scale image hereafter called the "ratio" image. Note that most real defects will have some orientation between median and lateral, and will therefore provide an indication in each image, though one orientation will often dominate the other.

RESULTS

Figure 2 shows the total optical transmission (including all scattered light) of various Si$_3$N$_4$ ceramic specimens at various depths. The data were obtained with an integrating sphere and calibrated step wedges of each material. As shown, there is a wide distribution of optical transmission among the various Si$_3$N$_4$ specimens. Sensitivity to subsurface cracks, whose signal strength is dependent on the amount of light that reaches the crack, and hence depends on the depth of that crack, will be highly dependent on the material.

An NBD-200 specimen with back-surface drilled holes was used to simulate a material with subsurface pores. A schematic diagram of the specimen configuration is shown in Fig. 3a. Examination of the specimen with the 2-D laser scatter scanning system produced the sum image shown in Fig. 3b, which shows that both simulated pores are clearly detected, with the shallower pore being more prominent.
Fig. 2. Optical transmission as a function of specimen thickness at wavelength of 0.6328 µm. Lines are best-fit approximations to $e^{-\alpha t}$, where $t$ is thickness, and values of $\alpha$ are given parenthetically in the legend.

Fig. 3. NBD-200 specimen with simulated subsurface pores: (a) schematic diagram (not drawn to scale, hole diameters are =1 mm), and (b) subsurface laser scatter.

To evaluate the sensitivity of the system to median-type defects, which are more likely to be induced during machining, a known median crack was generated with Vickers indents in an NT164 flexure bar. The specimen was then subjected to laser scatter inspection and inspection by advanced dye penetrant methods. The dye penetrant image and the laser scatter sum and ratio images are shown in Fig. 4.
Fig. 4. Images of Vickers indent showing (a) dye penetrant image in 0.5 mm square, and elastic optical scattering (b) sum, and (c) ratio images in 1 mm squares.

Several characteristic features are clearly evident from Fig. 4. The elastic optical sum image (b) shows two types of cracks: lateral cone-type cracks (indicated by a brighter halo around the indent), which emanate beneath the surface from the indent; and median cracks that can be seen extending from the corners of the indent, with the crack in the lower right being most severe, because the cracks are not perfectly straight and exhibit a lateral component. The presence of both of these features is supported by the dye penetrant image. In addition, the actual surface indent is visible in the sum image as a darker region near the indent center. By comparison, the elastic optical ratio image (c) shows no indication of the lateral defects, and is almost completely insensitive to the actual surface indent itself. Rather, it only indicates of the presence of the median cracks that extend from the corners of the indent.

Two diamond-ground GS-44 coupons were analyzed by elastic optical scattering for machining-induced subsurface defects. The surface area of the coupons was ≈25 mm (1 in.) square; the machining conditions that were used are listed in Table 1. Specimen 10102 was ground with a coarse grit at low grinding speed, whereas specimen 10202 was ground with a finer grit at high grinding speed. Six 1.28 x 6-mm surface areas of each specimen were scanned with a resolution of 10 μm. Sample elastic optical scattering ratio and sum images are shown in Figs. 5 and 6 for specimens 10102 and 10202, respectively. The machining (or lay) direction is vertical in these images. In the sum images, the white speckles represent surface regions with excessive light scattering that is due to subsurface defects or cracks. Correspondingly, the damaged regions are shown as dark speckles in the ratio images. As described above, the ratio and sum images are sensitive, respectively, to median and lateral cracks in the specimen subsurface.

<table>
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<th>Coupon ID</th>
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Fig. 6. Elastic optical scattering images of GS-44 coupons 10202: (a) ratio image; (b) sum image.

Two types of machining-induced damage are visible in these images. First, machining marks are represented by vertical lines, darker lines in ratio images and whiter lines in sum images; these marks are most likely median cracks generated when the grinding particles pass through the specimen surfaces. Second, individual damaged areas, or individual speckles, are distributed throughout the specimen subsurfaces. The scattering images in Figs. 5 and 6 show different speckle patterns for the two specimens. The frequency of these speckles can be found from Fast Fourier Transforms (FFTs) of the images. However, because it is difficult to extract quantitative information from FFT images displayed in gray scales, only the central horizontal and vertical profiles of the 2-D FFT images are plotted and shown in Fig. 7. The plotted profiles are the averaged FFT profiles from the scattering ratio images at all six locations on the two specimens. The horizontal direction is across the lay
and the vertical is along the lay on the specimen. The central spikes at pixel 64 in the profiles represent the zero frequency and the frequency increases toward both sides. The figures show that lower frequency components are generally dominant. The speckles across the lay direction in specimen 10102 have a dominant spatial period (inverse of frequency) at \( \approx 213 \) \( \mu \)m, whereas those in specimen 10202 have a dominant spatial period at 320 \( \mu \)m.

A comparison of the horizontal and vertical profiles in Fig. 7a reveals that the 213-\( \mu \)m period exists only in the horizontal direction (across the lay). Similarly, in Fig. 7b, the 320- and 107-\( \mu \)m periods are present only in the horizontal direction. If we assume an isotropic distribution of the individual speckles, these periods then correspond to those of the machining marks. The additional characteristic frequencies that are present in both the horizontal and vertical profiles can likely be attributed to the distributed individual speckles. Therefore, by analyzing the FFTs of the scattering images, the differences of the suspected machining-induced damage in the two directions may be characterized.

The intensities of the scattering images may be examined through histograms. Figure 8 shows gray-scale histograms of the scattering ratio images shown in Figs. 5a and 6a for the two specimens. For specimen 10102, a characteristic cut in intensity is present at a low gray scale (corresponding to dark speckles in the scattering ratio images), with a higher intensity above the cut. This characteristic feature may indicate a certain strong defect pattern, probably the machining marks, that appears repeatedly in the image. On the other hand, the histogram of ratio images for specimen 10202 (Fig. 7b) is relatively symmetrical.
CONCLUSION

A novel, noncontact, nondestructive elastic optical scattering technique has been developed to detect defects and/or damage in the surface and subsurface of ceramic materials. The technique is based on the unique property of ceramics to partially transmit visible (and IR) light into a subsurface. Using polarization techniques, we could separate the effects of surface and subsurface defects to depths of several hundred micrometers. The detection system developed at Argonne National Laboratory is versatile, can operate at high speed, and is sensitive to both lateral and median type defects in the material subsurface. Through the application of a 2-D scanning system, we can generate conformally mapped images of a scattering surface or subsurface with specified resolutions.

This laser scattering inspection technique was applied to detect defects and/or damage in test specimens and in actual machined components of various Si₃N₄ ceramic materials. The results indicate that the laser scattering technique may detect and identify various types of surface and subsurface defects that are critical to component strength and lifetime. Thus, the laser scattering method holds promise for automated inspection and qualification of ceramic components.

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