E. NDE Development for Ceramic Valves for Diesel Engines

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Objectives

- Develop a laser-scattering nondestructive evaluation (NDE) method for detecting and characterizing subsurface defects/damage in silicon nitride ceramic valves; the NDE data can be used to determine the cost-effectiveness and reliability of ceramic valves for diesel engines.

- Identify strength-limiting flaws and failure mechanisms in silicon nitride ceramics due to machining and impact-induced damage.

Approach

- Develop an automated laser-scattering NDE system for fast scanning of entire valves and use the system to identify damage and failure mechanisms for ceramic valves from rig/engine tests.

- Correlate NDE data with detailed surface microstructure data to determine detection sensitivity for type, depth, and severity of defects/damage in different silicon nitride ceramics.

- Establish the correlation of NDE data with mechanical properties so the laser-scattering method may predict mechanical properties of ceramics.

Accomplishments

- Completed hardware and software development of an automated laser-scattering NDE system for scanning entire valves. This system was used to establish detection sensitivity for contact/impact damage and pre-spalls in several NT551 silicon nitride valves that were bench-tested for 100 hours.

- Established laser-scattering detection sensitivity for machining damage in cylindrical SN235P silicon nitride specimens. Machining-induced subsurface cracks were clearly identified in rough-ground rods, but they are not apparent in fine-ground rods.

- Characterized cyclic-impact damage in NT551 and SN235P silicon nitrides. The size, depth, and severity of detected impact damage (cracks) may be correlated with the impact load.

Future Direction

- Further increase data acquisition speed for the automated NDE system so an entire valve can be scanned within an hour. A fast detector such as a photomultiply tube will be implemented to replace the slower semiconductor detector used in the current system.
- Determine the detection sensitivity for failure-initiation damage in silicon nitride valves from rig/engine tests with more harsh conditions and longer operating durations.
- Develop theoretical models and image-processing methods for optimized and quantitative characterization of strength-limiting subsurface defects and damage in silicon nitride ceramics.
- Enhance the detection sensitivity on defect depth and establish a correlation of NDE data with data from destructive measurement of subsurface microstructure.

Introduction

Advanced ceramics are leading candidates for high-temperature engine applications that offer improved fuel efficiency and engine performance. Among them, silicon nitrides are being evaluated as valve train materials for diesel engines. For these ceramics, however, material defects and process-induced or operation-induced damage in the subsurface may significantly degrade reliability and performance. To detect and characterize these defects, Argonne National Laboratory (ANL) developed a laser-scattering NDE method for measurement of detailed subsurface microstructure in ceramics. The objective of this research is to demonstrate that this method can be used to assess/evaluate the cost-effectiveness and reliability of ceramic valves for diesel engines. The primary effort in FY 2003 was to develop an automated laser-scattering system for scanning entire valves and to investigate the detection sensitivity on material defects, machining damage, and contact/impact damage for candidate silicon nitrides (NT551 and SN235P) selected for fabricating into prototype valves. This research is being conducted in collaboration with Caterpillar, Inc.

Approach

The critical region of ceramic components for structural applications is the near surface (usually to a depth of <200 μm). The common types of defects in this region are mechanical, such as cracks, spalls, inclusions, and voids. Because ceramics are partially translucent to light (optical penetration depth for silicon nitrides is typically >0.1 mm in visible spectrum), a laser-scattering method based on cross-polarization detection of optical scattering originated from the subsurface can be used for noncontact, nondestructive measurement of subsurface microstructure in such materials. Scanning of the entire surface (flat or curved) of a ceramic component and construction of a two-dimensional (2D) scatter image can be used to readily identify subsurface defects, as they exhibit excessive scattering over the background, and analyze their type and severity. The resolution obtained using this method is typically one to two orders of magnitude better than that of conventional NDE methods such as ultrasound and X-ray. Previous studies at ANL showed that laser scattering can detect and identify strength-limiting flaws and flaw size distribution for several silicon nitride ceramics, and that NDE data can be correlated with machining conditions and mechanical properties. These investigations demonstrated the capability of the laser-scattering method for predicting material microstructural and mechanical properties for ceramic valves.

Results

The laser-scattering method was applied for detection and characterization of subsurface defects/damage in silicon nitride valves. An automated NDE system was developed to scan entire valves. Figure 1 is a photograph of the experimental setup. This system uses two rotation and two translation stages to align and focus the laser beam on the valve surface during the scan, and the resulting 2D scattering image data are used to identify the location, size, and relative severity of subsurface defects/damage. This system can therefore be used for inspection of the quality of manufactured valves and for evaluation of damage and failure mechanisms for ceramic valves from rig/engine tests.

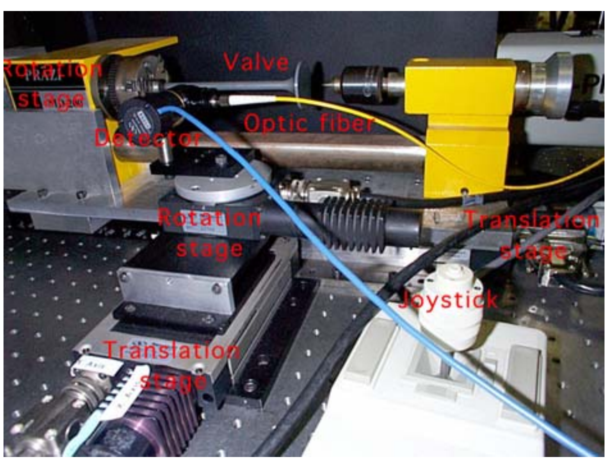


Figure 1. Automated laser-scattering system for scanning full ceramic valves.

Figure 2 is a photograph of a typical NT551 silicon nitride valve. While impact damage in the contact area (against the metal seat) is of interest, finite-element

Figure 2. An NT551 valve showing contact surface and laser-scattering scanned region.

modeling predicted that the maximum stress may occur at the fillet radius region, so subsurface microstructure within the entire valve-head surface should be examined. Laser-scattering scans were therefore performed for the entire valve-head surface, from the top of the contact area to the endof the fillet radius, as indicated in Figure 2. NDE data were obtained for several NT551 silicon-nitride valves that were bench-tested for 100 hours. Figure 3 shows a typical laser-scattering image of a valve-head surface. The scanned axial length is 19 mm (the top 4-mm region is the contact area) and is aligned in the vertical direction in the image. The image data in Figure 3 indicate no significant damage from the bench test except the wear scars (two darker horizontal stripes) within the contact surface. Most of the flaws (appearing as high optical-scattering spots) are within 50 μm in size, and they are likely natural porosity distributions in the ceramic material. A few larger flaws are observed near the top edge of the valve contact surface.

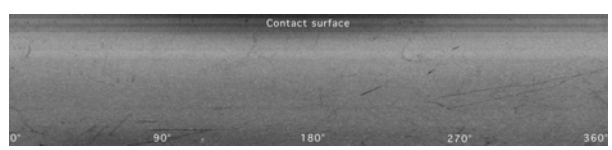
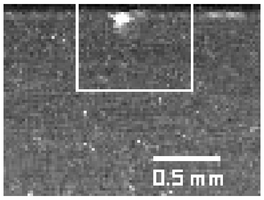
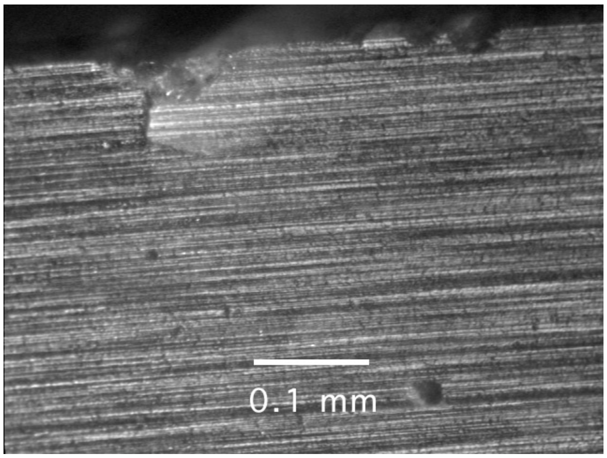


Figure 3. Laser-scattering images of valve-head section of an NT551 ceramic valve after 100-hour bench test.

Figure 4 shows a comparison of the detailed laser-scattering image and a photomicrograph of a typical flaw. The detected flaw is clearly seen from the photomicrograph as a pre-spall chip partially bonded at the edge.



(a)



(b)

Figure 4. Detailed laser-scattering image (a) and photomicrograph for a flaw at the edge of contact surface (b).

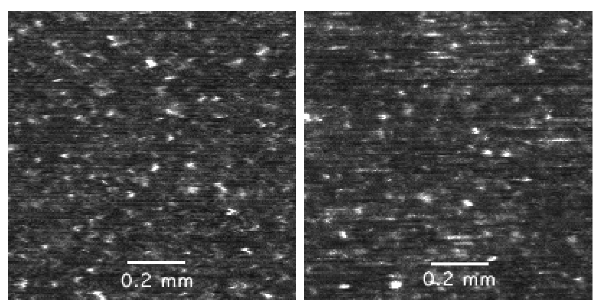
This type of flaw was probably generated during valve processing.

In addition to the material defects such as voids and pores that are distributed within the ceramic, machining and impact-induced damages are two major concerns for the cost-effectiveness and reliability of ceramic valves. Machining damage is represented by the formation of radial, lateral, and median cracks under the machined surface. The median cracks, which are parallel to the machining direction and perpendicular to the surface, are thought to cause the greatest strength reduction. Machining damage for cylindrical silicon nitride specimens was evaluated by the laser-scattering method. Figure 5 is a photograph of eight SN235P rods, four of them machined by fine grinding and four by rough grinding.

Figures 6a and 6b show typical laser-scattering images for the fine-ground and rough-ground rod, respectively. Material defects, likely subsurface pores appearing as

Figure 5. Photograph of four fine-ground and four rough-ground SN235P silicon nitride rods. Each is 75 mm long and 6 mm in diameter.

individual high-scattering spots, are seen distributed throughout the surfaces in both rods. Machining damage, the brighter horizontal marks along the grinding direction, is visible in the image of the rough-ground rod (Figure 6b). These machining marks are likely median cracks that may cause significant strength reduction. Machining marks are not apparent (indicating less damage) in the fine-ground rod (Figure 6a).



(a) (b)

Figure 6. Detailed laser-scattering images of (a) fine-ground and (b) rough-ground SN235P rods; note the grinding damage as bright horizontal lines in (b).

Impact damage was evaluated on NT551 and SN235P rectangular specimens that had been subjected to cyclic impact tests. Four loads were applied at four different locations on each test specimen: 2000, 2500, 3000, and 4000 Newton. The flat polished surfaces of the test specimens were loaded with a specialized polished silicon nitride sphere that had a radius of 3.18 mm. A constant load was applied for 10^6 cycles in order to assess the initiation of cracks and subsequent contact damage. The purpose of this investigation was to determine laser-scattering detection sensitivity on cyclic impact damage.

Figure 7 shows laser-scattering images for the surfaces of the impact-tested NT551 and SN235P specimens. For the NT551 specimen, Figure 7a, dendrite-like scattering structure is evident; this structure has been identified as the secondary or glassy phase. All impact regions for both specimens appear as rings, indicating the impact damage to be Hertzian in nature. The size of the impact region

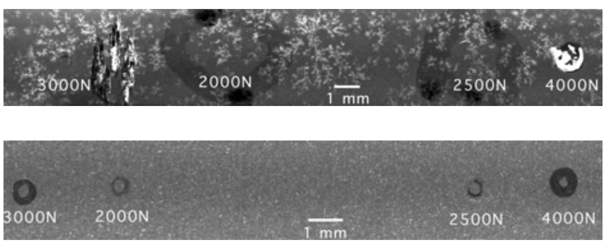
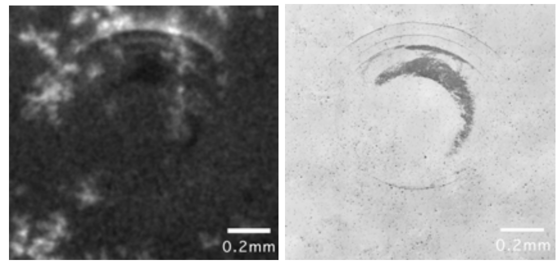


Figure 7. Laser-scattering images of (a) NT551 and (b) SN235P specimen surfaces; each was tested with cyclic impact at four indicated loads.

increases with increasing load, as evidenced from the plastic deformation. When the scattering images are compared with photomicrographs, (Figure 8), impact-induced cracks with higher scattering intensities are identifiable in the scattering images, suggesting that these cracks have different depths and severities. In contrast, the extent of subsurface damage cannot be predicted from the suface photomicrographs.

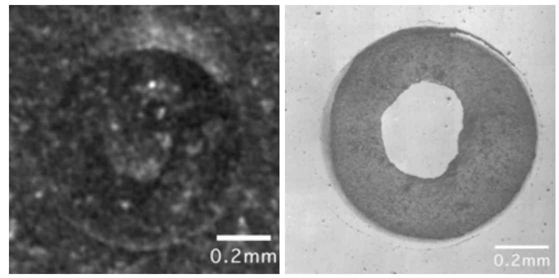
Conclusions

An automated laser-scattering NDE system was developed to scan entire valves. This system uses two rotation and two translation stages to align and focus the laser beam on the valve surface during the scan; and the



(a)

Laser scattering image Photomicrograph



(b)

Laser scattering image Photomicrograph

Figure 8. Comparison of laser-scattering images and photomicrographs for 3000N-load impact spots in (a) NT551 and (b) SN235P specimen.

resulting 2D scattering image data are used to identify the location, size, and relative severity of subsurface defects/damage. Laser-scattering images were obtained for several NT551 silicon nitride valves that were bench-tested for 100 hours. These NDE results established the detection sensitivity for two types of defect/damage: contact/impact damage and pre-spalls due to valve processing.

Machining and impact-induced damages, two of the major concerns for the cost-effectiveness and reliability of ceramic valves, were evaluated by laser scattering for cylindrical and rectangular NT551 and SN235P silicon nitride specimens. The machining damage in rough-ground SN235P rods can be clearly detected; it likely consists of median cracks that may cause significant strength reduction. Detection and characterization of machining damage may help to improve and optimize machining conditions for valve manufacturing. The impact damage was characterized on NT551 and SN235P rectangular specimens that had been subjected to cyclic impact tests. By comparing the laser scattering images with photomicrographs, it was shown that the laser-scattering method can identify impact-induced cracks having different depths and severities. Therefore, the NDE data may potentially be used to determine the failure probability and reliability of ceramic valves that are operated under periodic impact stress in diesel engines.