E. NDE Development for Valve-Train Components for Diesel Engines

Jiangang Sun
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
630-252-5169; fax: 630-252-4798; e-mail: sun@anl.gov

DOE Technology Development Area Specialist: James J. Eberhardt
(202) 586-9837; fax: (202) 586-1600; e-mail: james.eberhardt@ee.doe.gov
ORNL Technical Advisor: D. Ray Johnson
(865) 576-6832; fax: (865) 574-6098; e-mail: johnsondr@ornl.gov

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Objectives

- Develop laser-scattering and other nondestructive evaluation (NDE) methods for detection and characterization of surface and subsurface defect/damage in diesel-engine valve-train components made from advanced materials such as ceramics and intermetallics.
- Develop quantitative NDE analysis tools to identify strength-limiting flaws and failure mechanisms, evaluate damage evolution and growth, and predict mechanical properties for advanced materials.

Approach

- Develop fast and reliable automated laser-scattering NDE systems for surface/subsurface inspection of ceramic and intermetallic valves.
- Inspect valve surfaces to determine the level of machining damage and accumulated damages from bench or engine tests.
- Correlate NDE data with microstructure and strength of silicon-nitride specimens for prediction of fracture initiation defects and mechanical properties.

Accomplishments

- Successfully implemented a photomultiply tube (PMT) detector coupled with an optical fiber in a NDE valve-scan system. The PMT detector is more sensitive and more than six times faster in scan speed so it allows for fast NDE inspection of a large number of valves to meet the engine test schedule.
- Evaluated 25 finish-machined SN235P silicon nitride valves. Verified significant improvement in machined valve surfaces especially at keeper groove where a severe machining damage had caused a premature valve failure in a rig test.
- Inspected machined surfaces of 11 as-processed TiAl valves.
- Completed analysis and correlation of NDE data with microstructure and strength for cylindrical SN235P specimens machined at various conditions.

Future Direction

- Establish laser-scatter NDE detection sensitivity and characterization capability for surface damage in TiAl intermetallic specimens.
- Complete NDE evaluation for damage accumulation in prototype SN235P and TiAl valves by periodic inspections of these valves during planned engine duration tests.
- Develop quantitative image-processing methods for prediction of strength-limiting subsurface defects/damage in silicon nitride ceramics.

Introduction

Advanced ceramics and intermetallics are leading candidates for high-temperature engine applications that offer improved fuel efficiency and engine performance. Among them, silicon nitrides (Si_3N_4) and titanium aluminide (TiAl) are being evaluated as valve-train materials for diesel and natural gas engines because of their lighter weight and high strength and corrosion resistance at elevated temperatures. However, these materials are brittle so microscopic defect/damage near the surface may significantly degrade their mechanical properties. Material damage in the subsurface may be induced by machining or from service due to impact, wear, and corrosion. For silicon nitrides, material strength may also be limited by inherent defects such as voids and porosities within subsurface. To detect and characterize these defects, Argonne National Laboratory (ANL) developed a laser scattering NDE method to measure detailed surface/subsurface microstructure for these materials. The objective of this research is to demonstrate that this method can be used to assess/evaluate the cost-effectiveness and reliability of valve-train components manufactured from advanced ceramic and intermetallic materials for diesel engines. The primary effort in FY 2005 was to develop a fast NDE valve-scan system and to inspect finish-machined SN235P silicon nitride valves to determine the improvement in machined surface quality from their initial rough machining conducted in FY 2004. Another effort was directed on analysis and correlation of NDE data with microstructure and strength for cylindrical SN235P specimens machined at various conditions. This research is collaborated with Caterpillar, Inc.

Approach

The critical region for brittle ceramic and intermetallic components in structural applications is near surface. The common types of defects in this region are mechanical, such as cracks, spalls, inclusions, and voids. The size of the defects that limits the component strength is generally small, say ~100 μm. To detect these defects, a laser-scattering method based on cross-polarization detection of optical scattering originated from surface and subsurface microstructure can be used for noncontact, NDE of these materials. Because ceramics are partially translucent to light, optical penetration can reach the subsurface to directly interact with the subsurface defects. For metallic or intermetallic materials, optical penetration is not possible. However, using the cross-polarization detection approach, optical scattering from rough surface or open cracks can be significantly enhanced against the smoother background. By scanning the entire surface (flat or curved) of a component and constructing a two-dimensional (2-D) scatter image, surface/subsurface defects can be readily identified as they exhibit excessive scattering over the background, and their type and severity may be analyzed. To apply this technology for NDE of Si_3N_4 and TiAl valves, an automated laser-scatter system was developed by ANL for scanning the entire valve surface at high spatial resolutions. This system utilizes two-rotation and two-translation stages to align and focus the laser beam on the valve surface during the scan, and the resulting 2-D scattering image data are used to identify the location, size, and relative severity of subsurface defects/damage. Analysis of the NDE data can determine the statistical properties of the component surface, which can be correlated with machining or service conditions. Development of quantitative image-processing methods may lead to automated identification of strength-limiting defect/damage for prediction of mechanical properties.

Results

Development of a Fast Valve-Scan NDE System

Prototype silicon nitride and titanium aluminide valves have been planned for engine duration tests in FY 2006. Because of a large number (24) of valves to be used and a tight schedule for intermittent valve evaluation, the NDE system must be able to scan each valve at a fast speed to meet the engine test schedule. The previous valve-scan system was limited by the speed of a silicon detector; a photomultiplier tube (PMT) was therefore selected to replace the silicon detector for detection of back-scattered signal. The PMT detector has a data acquisition speed up to 20 kHz with 16-bit dynamic range, which is more than six times faster and more than five times higher in detection sensitivity than the silicon detector.

Figure 1 is a photograph of the new automated laser-scatter system. The system utilizes a multi-mode optical fiber to collect and deliver the back-scattered light to the PMT detector. A long translation stage was used to allow for scanning of entire valve surface (head and stem) within one pass. In addition, data acquisition software was modified to improve synchronization between data acquisition and stage motion along the valve profile. The improved system can scan the complex valve-head surface in an hour.

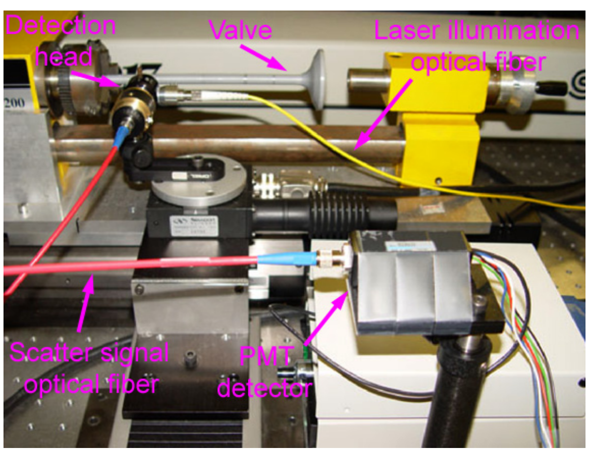

Figure 1. Photograph of automated laser-scattering NDE system.

Evaluation of Finish-Machined SN235P Valves

Twenty-five finish-machined SN235P silicon nitride valves were evaluated by the automated laser-scatter system. They are natural-gas intake and exhaust valves to be used by Caterpillar Inc. in an engine duration test. These valves were initially machined in FY 2004. Because of a process error, most of the valve head and keeper-groove surfaces were rough machined, resulting in significant machining damage on these surfaces.[1] NDE data of the finish-machined valves were compared with those of initial machined to verify improvement in machined surfaces.

Figures 2 and 3 show, respectively, laser-scatter images of SN235P natural-gas intake valve No. 8 at before and after the finish machining. Spatial resolution in both scan directions was ~10 μm. In Figure 2, significant machining damage can be found on the entire valve head surface except the stem surface near the bottom of the image. These damages are seen as bright lines (of higher scattering intensities) along the machining direction, as shown in the detailed image in Figure 4(a). The lengths of the machining damage are typically near 1 mm. In

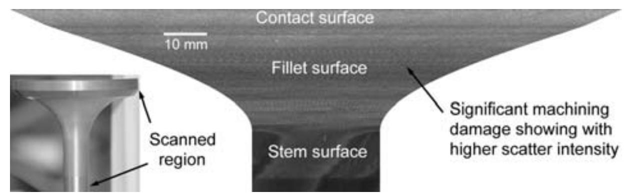

Figure 2. Laser-scatter scan image of SN235P valve 8 after initial rough machining.

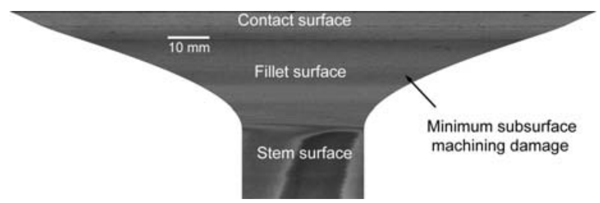

Figure 3. Laser-scatter scan image of SN235P valve 8 after finish machining.

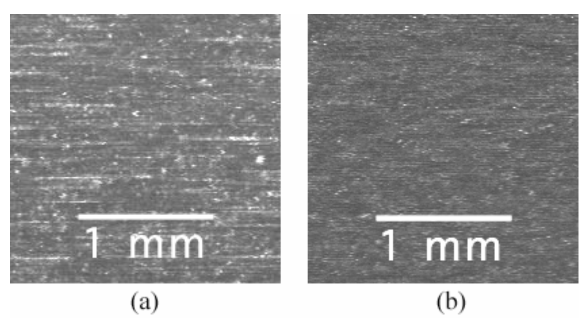

Figure 4. Detailed laser-scatter images in contact surface of SN235P valve 8 after (a) initial rough machining and (b) finish machining.

addition, the overall optical scatter intensity of the valve-head surface is high, indicating a higher level of overall damage. In comparison, the finish-machined surface shows minimum machining-damage indications as seen in Figure 3 and the detailed image in Figure 4(b). The higher scatter-intensity spots in Figures 4(a–b) come from material inherent defects such as porosities with sizes typically smaller than 50 μm. Therefore, it is apparent that the finish machining essentially removed all machining damages induced in the initial rough machining of these SN235P valves.

Laser scattering scan was also conducted in the keeper groove region of the SN235P valves. Before the finish machining, a severe machining damage was found around the entire circumference of the keeper-groove edge, which caused premature failure of a SN235P valve in a rig test.[2] In the finish-machined valves, this damage was also removed. However, because the edges are still sharp, some chip damage can be detected along the keeper-groove edges. Figure 5 shows detected edge chips in a laser-scatter image and photomicrographs.

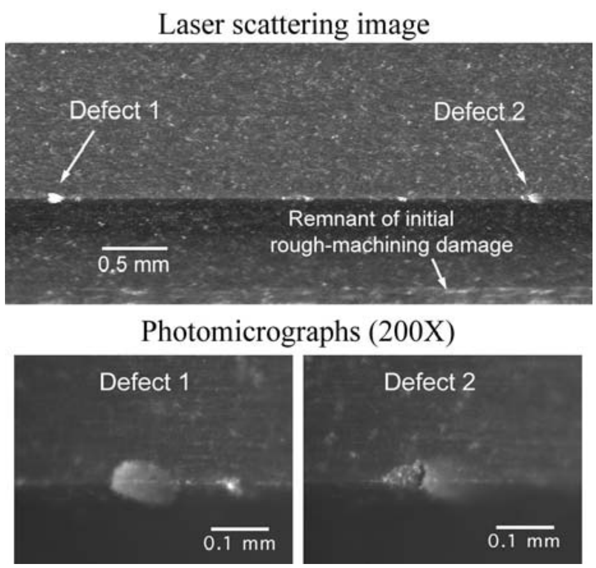

Figure 5. Detailed laser-scatter image and photomicrographs of chip flaws at keeper groove edge of a SN235P valve.

Inspection of As-Processed TiAl Valves

Eleven as-processed TiAl intermetallic valves were inspected by the valve-scan NDE system. Figure 6 shows a laser-scatter image of a typical TiAl valve-head surface. Spatial resolution in both

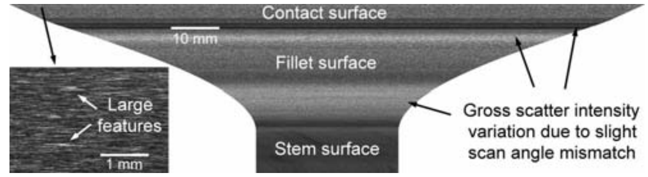

Figure 6. Laser-scatter scan image of an as-processed TiAl valve.

scan directions was ~10 μm. Because intermetallic surface is highly reflective to light and the surface mismatch during the scan can cause gross change in measured scatter intensity, especially at regions with sharp curvatures as seen in Figure 6. The enlarged image in Figure 6 shows machining marks; the nature of these marks will be further investigated.

Laser scatter scans were also performed for the joint region between the TiAl stem and the titanium alloy (Ti-6V-4Al) stem. Figure 7 presents a typical scan image of the joint surface, which shows clearly the joint line and no apparent defect. The image also shows axial stripes along the machining direction in this region; the nature of these stripes will be further studied.

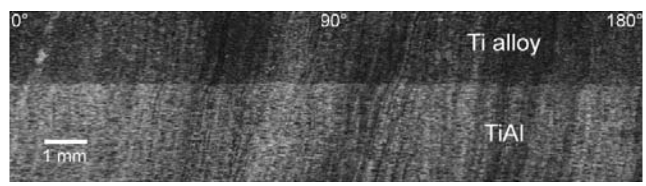

Figure 7. Laser-scatter scan image of joint surface of a TiAl valve.

Correlation of NDE Data with Microstructure and Strength

Three sets of 32 cylindrical SN235P silicon nitride specimens machined by two vendors at various conditions were initially examined by laser scatter in FY 2004. After fracture test, eight specimens were further studied for correlation of the NDE data with material microstructure and strength. In the microstructure study, fractographic examinations were performed to identify the fracture sites on the fracture surfaces. These fracture sites were then mapped into the tensile (or cylinder) surface to locate the fracture initiation positions. As expected, each fracture initiation position corresponds to a defect detected in the laser scatter NDE data. The results for all eight SN235P specimens are summarized in Figure 8, which shows the fracture strength of each specimen and its corresponding fracture

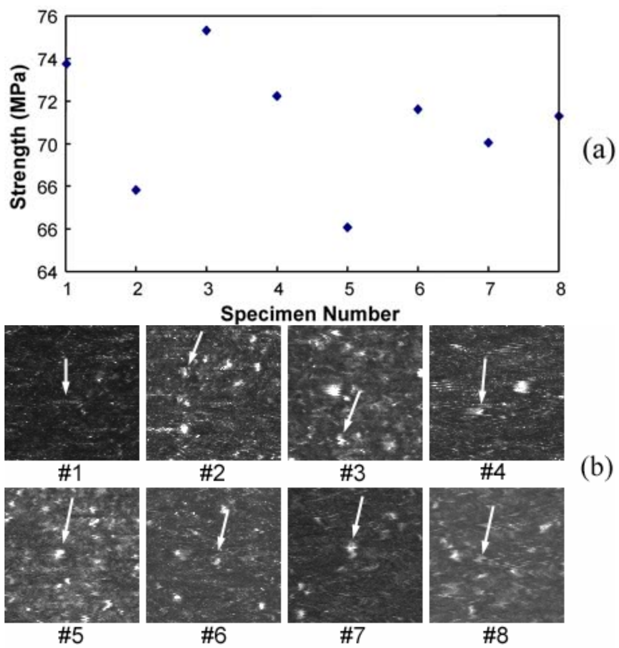

Figure 8. (a) Fracture strength and (b) corresponding fracture origins in scattering images (image size is 0.5 mm × 0.5 mm) of eight ground rods.

origin in the scanning image. It is clear that all specimens fractured from inherent material flaws (high-porosity defects), except specimen 1, which fractured from a machining damage (likely a lateral machining crack). The lowest fracture strength occurred in specimens 2 and 5. For specimen 2, there are a group of material flaws along the fracture line, which may explain its low fracture strength. As for specimen 5, its fracture origin is more intensive (likely deeper flaw) and slightly bigger (~35 μm) than those of the other specimens (~25 μm); therefore, its strength is lower.

Statistical parameters of laser scatter data were correlated with fracture strength. These statistical parameters include standard deviation, skewness, skewness/standard deviation, and coefficient of variance Cv (standard deviation/mean). Figure 9 shows fracture strength as functions of statistical parameters for the eight specimens. The standard deviation and skewness in Figures 9(a–b) generally correlate well with the fracture strength. Both show a similar trend, that is, strength decreases with the increase of standard deviation or skewness. These results are physically reasonable. Because standard deviation represents the second-order and skewness the third-order difference of local scatter intensity from the

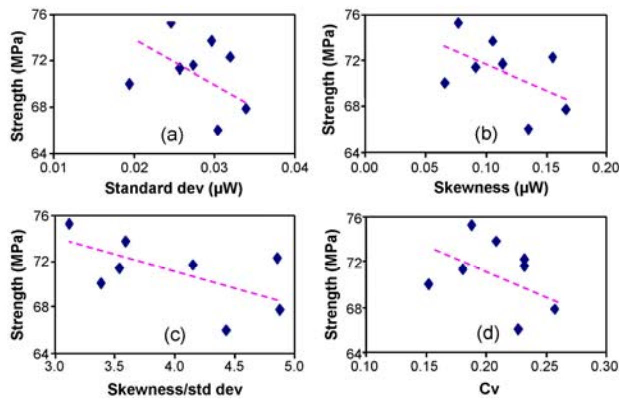

Figure 9. Correlation of fracture strength with statistical parameters processed from laser-scatter data around fracture regions.

background, a higher standard deviation or skewness indicates the presence of severe subsurface damages/defects that generate higher scattered light intensity above the background. Note that the nondimensional parameters skewness/standard-deviation and Cv in Figures 9(c–d) also show the same trend. These nondimensional parameters can be good candidates for predicting the fracture strength.

Conclusions

A high-speed automated laser-scatter system was developed. It utilizes a PMT detector coupled with an optical fiber for collecting and delivering scatter signal. The PMT detector is more sensitive and more than six times faster in data acquisition than a silicon detector. With this new system, scanning of a complex valve-head surface will be reduced to about an hour, which allows for fast NDE inspection of large number of valves to be evaluated in engine duration tests scheduled for FY 2006.

Twenty-five finish-machined SN235P silicon nitride valves and eleven as-processed TiAl valves were inspected by the valve-scan system. The SN235P valves had been rough-machined in FY 2004, which induced significant machining damage on the valve surface. In particular, a severe damage at keeper groove caused premature failure of a valve in a rig test. Laser-scatter examination verified that there is a significant improvement in the surface quality of these finish-machined valves, that is, most rough-machining damages were removed although minor chip damages were detected on the edges of keeper grooves. For the as-processed TiAl valves, because intermetallic surface is highly reflective to light and the surface scatter is weak, it was challenging to align the laser-scatter system with the valve profile during the entire scan. Nevertheless, laser scatter images were obtained for the valve-head and stem-joint surfaces for these valves, and machining marks and material variation can be readily observed. However, correlation of NDE data with surface microstructure for TiAl materials need to be further investigated.

Laser scatter measurements were conducted for three sets of 32 cylindrical SN235P silicon nitride specimens that were machined at different conditions. After fracture test, eight of these specimens were delivered to ANL for correlation of NDE data with microstructure and strength. In microstructure study, fractographic examinations were performed to identify the fracture sites that were then correlated with NDE data to locate fracture initiation defects on tensile surfaces of the specimens. The correlation allowed for direct determination of the size, severity, and type of defect/damage that caused the fracture. The fracture strength was also correlated with statistical parameters of laser scatter NDE data. These statistical parameters included standard deviation, skewness, skewness/standard deviation, and coefficient of variance (standard deviation/mean). It was found that strength decreases as these parameters increase; which is physically meaningful because these parameters become larger when the number or severity of defects increases.

References

1. J. G. Sun, "NDE Development for Ceramic Valves for Diesel Engines," *Annual Report for FY 2004, Heavy Vehicle Propulsion Materials Program*.
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Presentations and Publications

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J. M. Zhang, J. G. Sun, M. J. Andrews, A. Ramesh, J. S. Trethewey, and D. M. Longanbach, "Characterization of Subsurface Defects in Ceramic Rods by Laser Scattering and Fractography," paper accepted for publication in the *Proceeding of the 32nd Annual Review of Progress in Quantitative Nondestructive Evaluation, Bowdoin College, Brunswick, Maine, July 31–August 5, 2005*.