LASER-BASED NDT OF TITANIUM AIRCRAFT ENGINE COMPONENTS

J. Doyle Jr and M. J. Brinkman
Laser Techniques Company, LLC, Bellevue, USA

Abstract: Assuring the integrity of high-energy rotating parts in aircraft engines is of utmost importance to manufacturers and end users. Because of their complex shapes and unique material properties, some titanium components are quite difficult to inspect using conventional NDE methods(1). Features such as small diameter, high length-to-diameter (L/D) bores, for example, are particularly difficult to inspect for machining-induced flaws such as microstructural anomalies, inclusions, smearing and cracks. However, flaws of this type can cause a severe reduction of fatigue life, particularly when occurring on highly stressed aircraft engine parts. Visual inspection methods rely on the operator's ability to clearly see sometimes very subtle changes in surface color or reflectivity. Mirrors, borescopes and other optical devices are often used to inspect difficult-to-access surfaces, but they can produce distorted or otherwise inadequate images. In addition, a human observer may miss positive indications for a number of reasons, such as awkward viewing angles, poor contrast, inattentiveness or fatigue. A study was conducted for MANHIRP to investigate the feasibility of employing automated laser-based NDE methods to improve the process by which safety-critical aircraft engine components are inspected. The study demonstrated that by employing state-of-the-art laser-based NDE technology, automated, high-resolution laser-based sensors can be employed on difficult-to-inspect features such as small diameter tubes and high L/D bores. These sensors can be integrated with existing conventional NDE methods, such as eddy current, to eliminate operator subjectivity and human error. They can rapidly scan up to 100% of the surface, providing quantitative results that can be used to confirm, document and track the integrity of safety-critical components.

Introduction: Over the past several years, the use of laser technology has steadily increased in the field of NDE. Laser Techniques Company (LTC) specializes in the development of laser-based NDE technology for a variety of high-value, safety-critical applications, including nuclear steam generator tubes, high-performance gun barrels and rocket thrusters. A unique benefit of this technology is the fact that sensors can be manufactured in very small packages (Figure 1) and are well suited for inspection of difficult-to-inspect features such as small diameter tubes and bores. Laser-based profiling sensors help to eliminate operator subjectivity and human error by scanning up to 100% of the surface and providing quantitative results that can be used to confirm and document the integrity of safety-critical components.

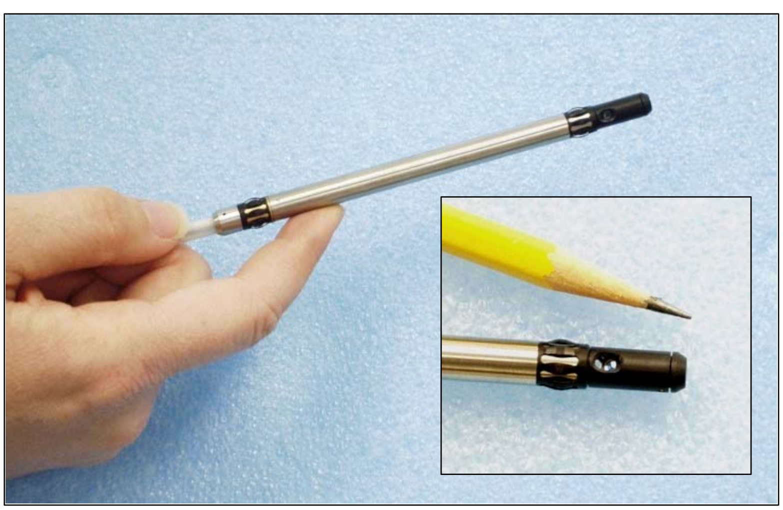

Figure 1. Laser-based sensors can be configured in very small packages.

Volvo Aero Corporation (Sweden) and MTU Aero Engines GmbH (Germany) recently contracted with LTC to conduct a preliminary feasibility study (2) for adapting its laser-based sensor technology to the inspection of titanium aircraft engine parts. In particular, the objective of this study was to evaluate the possibility of employing laser-based scanning technology for automatically inspecting high L/D holes in gas turbine rotor disks. The disks had been treated with the Blue Acid Etch (BAE) process and included flaws such as smearing, lapping, scoring, and effects from excessive overheating.

Background: The inspection of high L/D bores is often conduced using visual methods, which are subject to a variety of limitations. In addition, many features are difficult to detect using conventional NDE methods such as eddy current and ultrasonics. LTC has developed laser-based NDE methods that may eliminate these problems through the use of an optical scanning process that is well suited for application to cylindrical surfaces.

Laser-based profiling sensors are used to detect a wide variety of geometric defects such as deformation, corrosion and pitting. In addition to generating a proximity-related signal, laser-based sensors generate a signal that is associated with the manner by which light scatters from the part surface. By employing advanced optical imaging, filtering and processing techniques, sensors can be used to detect non-geometric metallurgical anomalies as well. Features such as small scores and scratches, variations in surface roughness, and even discoloration can be located and mapped using laser-based NDE technology.

Over the past several years, efforts have been undertaken to adapt conventional fiber-optic imaging probes and endoscopes (often with a right-angle mirror) to inspect small bores. These devices, however, have several drawbacks. They have limited resolution, often produce optically distorted images, and are not well suited for automated inspections. Most importantly, these visual inspection methods are dependent on the visual acuity, attentiveness and judgment of the operator.

Laser-based sensors have a number of advantages over visual inspection methods because they can:

- be adapted for mapping difficult-to-access areas such as small diameter, high L/D bores;
- automatically scan and process data in near real time;
- produce undistorted maps of the surface reflectivity variations of complex surfaces;
- measure the variations in surface reflectivity for one or more individual laser wavelengths; and
- generate quantitative results for analysis, documentation and archival.

Theory of Operation: The problems associated with visual inspection methods may be eliminated through the use of automated, laser-based scanning methods. Rather than flooding the inspection area with divergent white light that is then imaged onto a miniature CCD photodetector, the laser scanning sensor projects a highly focused (less than 0.025 mm diameter) spot of monochromatic laser light onto the target surface. The sensor's receiving optics collect the diffuse light that is scattered from the surface and image it onto a single-element photodetector that is optimized for the laser scanning wavelength (3). Figure 2 illustrates this approach.

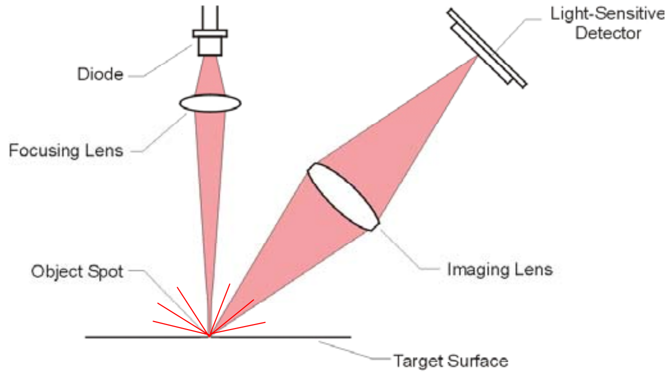

Figure 2. Basic components used in laser-based NDE sensor.

As the sensor is scanned through the bore of a test part, a series of signals are generated, processed, and displayed in near real-time, which can be used to detect anomalies. These data can also be used to produce high-resolution images and three-dimensional profiles of the inner surface of the bore. Inspection results are viewable using a software program that provides quantitative color plot images. Operators can accurately measure feature geometry, print out hard-copy images, archive and export data for future analysis and documentation. Moreover, these data can be processed in near real-time for use in manufacturing process control. The ability to rapidly and automatically scan small diameter, high L/D bores and achieve automated flaw detection is a significant departure from and improvement over conventional visual inspection methods. LTC refers to the data associated with this type of laser-based NDE as LaserVideo™ images (LVI). When the laser spot size is sufficiently small and the sampling density is sufficiently high, these images can take on near photograph quality, as shown in Figure 3.

Figure 3. Laser-generated LVI images of coins.

The application at hand includes two basic types of features, geometric and chromatic. Geometric features create high contrast (e.g. resulting from a parent metal smear, scratch or crack). Chromatic features are distinguishable by their preferential reflection of unique wavelengths of light (e.g. resulting from overheating and BAE treatment). When the target surface contains more than one type of feature, a single-wavelength LVI sensor generates an image that may reveal all of the features, but cannot distinguish one type of indication from another. For example, a single wavelength (red) sensor is capable of detecting the features but has difficulty distinguishing the nature (or cause) of the features. The image would simply show a contrast between the background and the features. A similar effect would happen if the laser wavelength were in the blue or violet range. However, by implementing a dual laser wavelength approach, differentiation can be made between geometric features and chromatic features.

This Preliminary Feasibility Study was directed toward the application of the LVI method for the detection of metallurgical anomalies such as parent metal smearing (re-deposition), lapping and metallurgical changes that have been highlighted using the blue acid etch process. All of these features create unique scattering of light and/or preferential reflection of certain optical wavelengths. For example, Figure 4 shows a photograph of a sample (provided by Volvo) that clearly has three types of features: blue, dark grey and an edge from a smear or lap.

Figure 4. Photograph of inner surface of sectioned titanium sample

Experimental Setup: Spectroscopic reflectance analysis of the samples provides helpful insight into the spectral properties of the machined surface. Tests were conducted to determine the comparative reflectance of the blue features (from overheating and BAE) and the background as a function of wavelength. The results are shown in Figure 5 below. The grey background of the samples reflects consistently over a wide range of wavelengths, but the blue features reflect more strongly for short wavelengths (350-450 nm) than for long wavelengths (>600 nm). This analysis suggests that a two-wavelength approach could result in high contrast for differentiation of blue features from those generated by laps, scratches or smears.

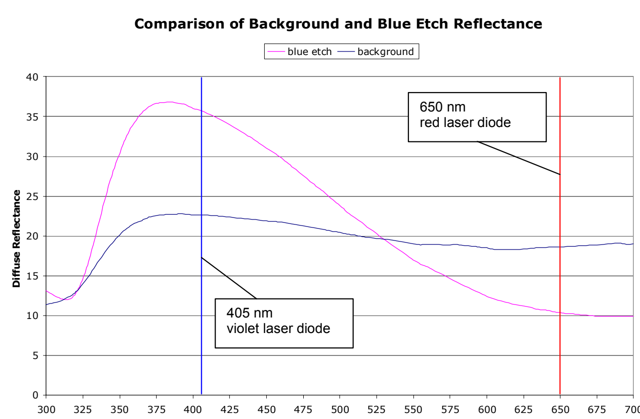

Figure 5. Spectroscopic analysis of titanium sample.

A prototype LVI sensor was built that was capable of scanning the inner surfaces of 11 mm diameter bores. The sensor was designed to accept two different laser diode light sources, one emitting at 405 nm (violet) and the other at 650 nm (red). Automated motion control equipment was used to rotate the LVI sensor while translating the sample axially — enabling full 360° raster scanning of the sample bores. A series of scans were taken with the 405 nm diode laser source and then with the 650 nm source, each with a projected laser spot size of approximately 0.025 mm. The sampling resolution used for all scans was 0.025 mm per sample, in both circumference and axial pitch. The setup is detailed in a block diagram of the laboratory data acquisition setup (Figure 6) and a photograph of the scanning apparatus (Figure 7) and the prototype LVI sensor (Figure 8). A series of scans were performed on several test samples with varying types of indications. The results from Sample #3 are discussed below.

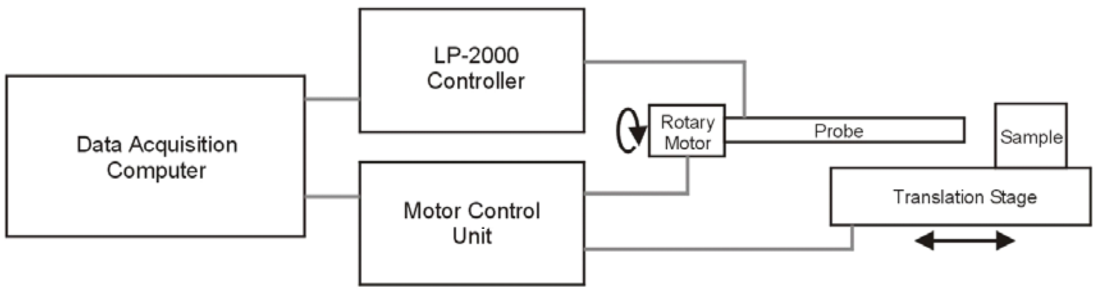

Figure 6. Block diagram of test setup.

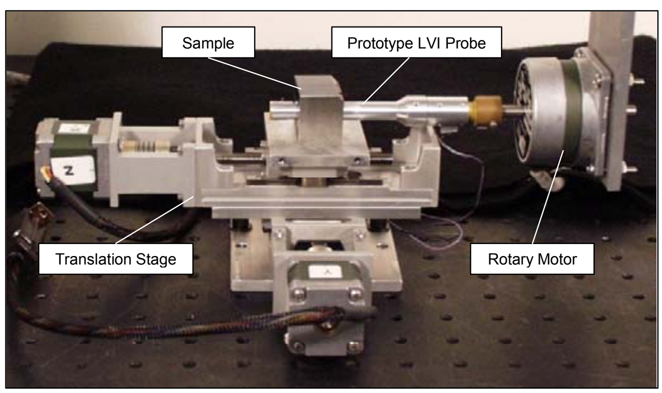

Figure 7. Photograph of prototype laser sensor and scanning fixture.

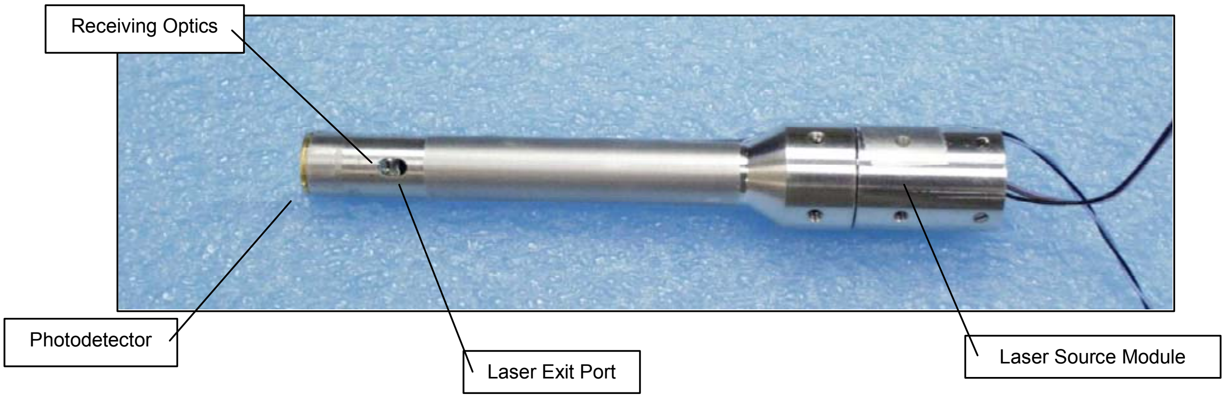

Figure 8. Photograph of prototype laser sensor.

Results: A total of four different samples were scanned using the above-described method. These samples ranged from a reference sample — with no flaw indications — to an aggressively machined sample (sample #3) with several types of flaws, including:

- Excessive surface roughness
- Smearing
- Tool scoring and scratches
- Discoloration and BAE indications

Figure 9 shows the results of the scans of the Sample #3. The image on the left is from a single laser wavelength (650 nm) scan. The sample was then scanned with a 405 nm laser. These data were post-processed to generate the image on the right, highlighting the blue indications from the BAE treatment.

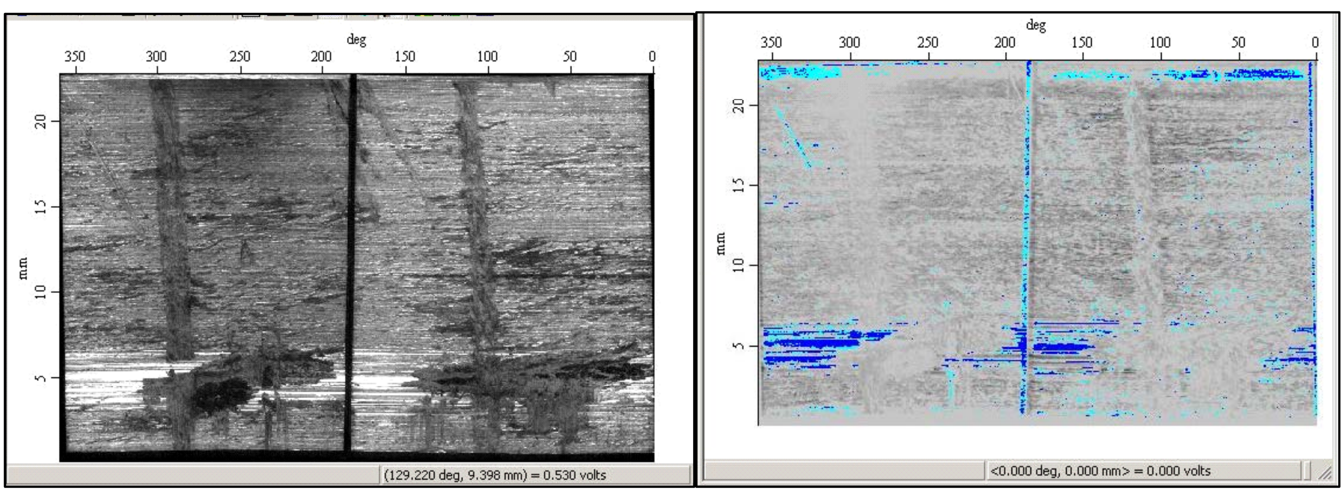

Figure 9. Single wavelength scan (left) and dual-wavelength post-processed scan (right).

Discussion: Both laser sensor wavelengths (red and violet) generated high-resolution results that clearly indicated the presence of features such as laps, inclusions, fine surface scratches and even tool point grooves. Surface reflectivity variation over the entire bore of each sample was also detectable. The shorter wavelength violet laser (405 nm) scan results provided exceptional resolution. In some cases, these scans generated near-photographic quality images. These scans were particularly detailed because of the highly focused laser footprint, enabling detection and mapping of surface-disrupting features such as fine scratches, laps and gouges.

It is interesting to note that the vertical tool marks seen in Figure 9 are almost indistinguishable in the photograph (Figure 8). Although these indications may have been missed with a visual examination, they were easily detectable using a highly focused laser scanning sensor. In addition, differences in general surface roughness was detectable on all samples.

By post-processing the two laser wavelength results, chromatic indications were also clearly distinguishable. As shown in Figure 9 (right) the blue indications are separated from the geometric indications shown on the left.

Conclusions: This Preliminary Feasibility Study clearly indicates that by employing laser-based scanning sensors with multiple wavelengths a variety of both geometric and chromatic flaw indications can be located and accurately mapped in machined titanium engine components. When fully implemented, this new approach to NDE technology holds the promise of providing high-resolution quantitative inspection results in a compact and automated format. Individual bores can be scanned in a matter of seconds, with results available in a variety of formats, ranging from simple go/no-go displays, to full-color computer-graphic images. Sensors can be provided in packages less than 7 mm in diameter; allowing operators to obtain virtually 100% surface coverage on small diameter high L/D holes.

An important aspect of this new NDE method is its potential ability to provide information that may allow operators to detect possible problems before they develop into flaws. The highly focused laser sensor can detect even slight changes in surface roughness. By monitoring the condition of the bore surface roughness as part of the normal NDE process, operators may be able to detect the initial signs of tool wear, coolant degradation or other factors before they cause damage to the part. The net result of this innovation in NDE technology will be improved quality, reduced scrap and improved reliability of components. Most importantly, it will result in higher confidence in safe operation of high energy, safety-critical rotating engine parts.

References

(1) NTSB Report NTSB/AAR-98/01, **Uncontained Engine Failure – Delta Flight 1288**, July 6, 1996

(2) J. Doyle: **Laser-Based Inspection of High L/D Bores in Titanium Aircraft Engine Components**, December, 2003 (MANHIRP-Programme internal report)

(3) Johnson, R. F., Doyle, J. L., and Bondurant, P. D. (1995) **Laser-Based Profilometry Using Point Triangulation,** American Society for Nondestructive Testing, Second Edition Volume 9, *Special Nondestructive Testing Methods,* Section 3 Part 4, pp. 141-157.