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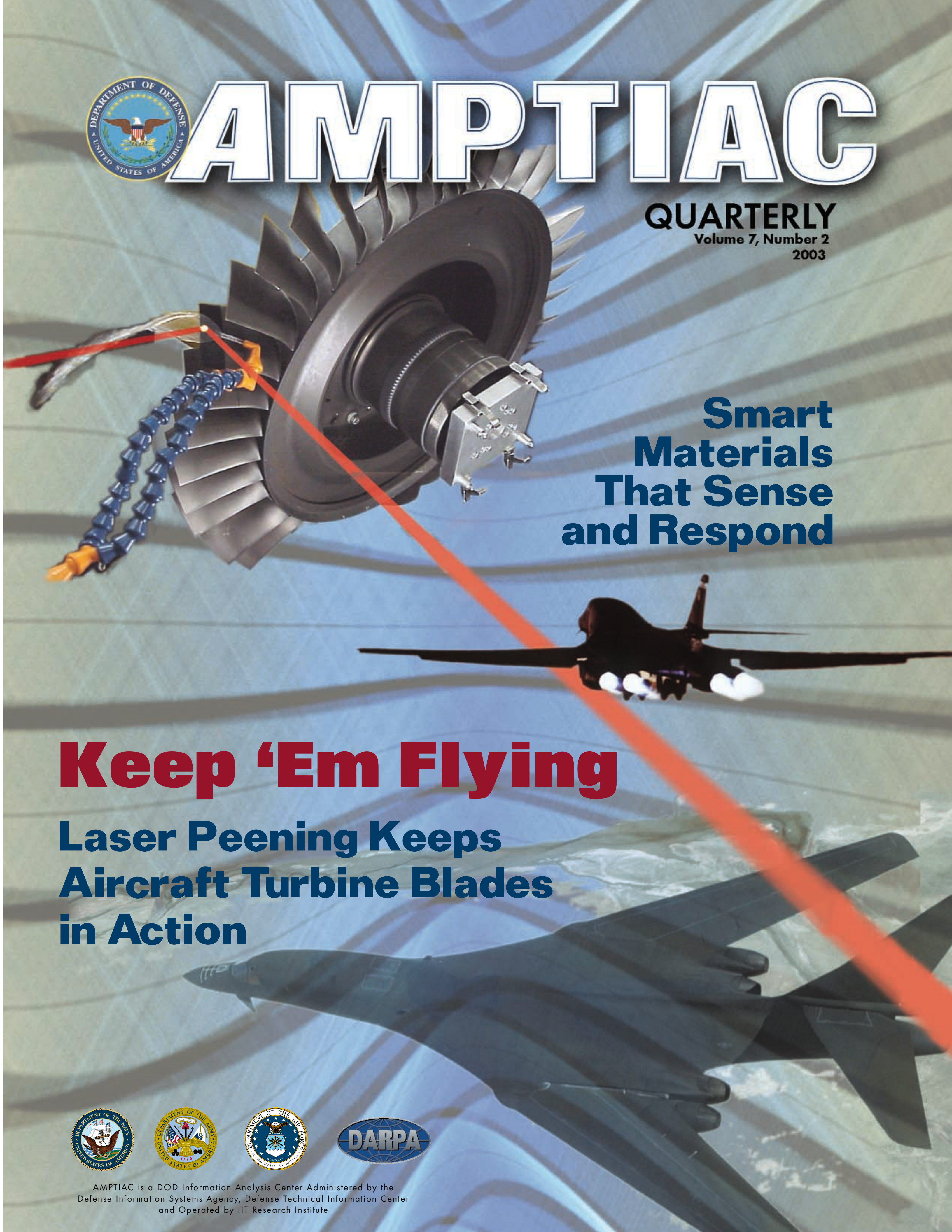

Smart Materials That Sense and Respond

Keep 'Em Flying

Laser Peening Keeps Aircraft Turbine Blades in Action

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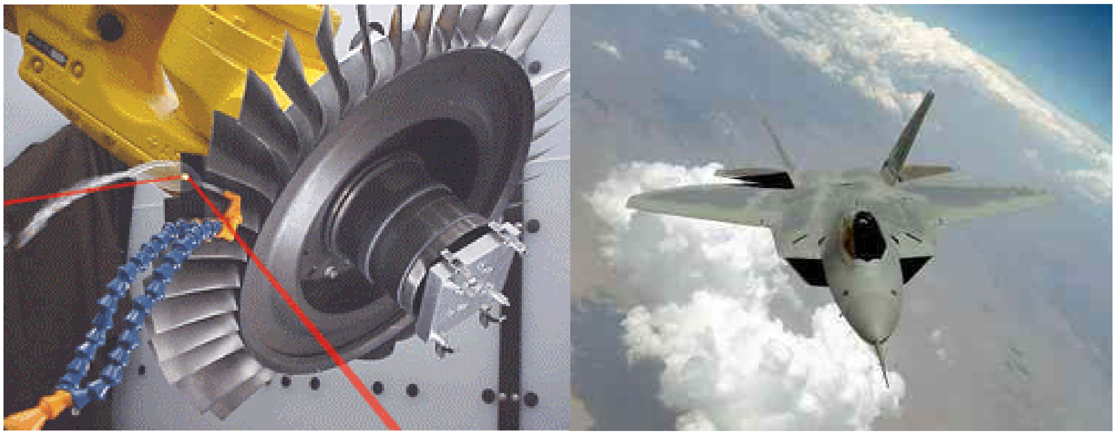

Production use of the LaserPeen® process on the fourth stage Integrally Bladed Rotor (IBR) of Pratt & Whitney's F119-PW-100 engine for the F/A-22 Raptor commenced at LSP Technologies, Inc. in March 2003. LaserPeen® processing increases the damage tolerance and enhances the fatigue performance of this IBR.

*** The LaserPeen® process is a registered trade name of LSP Technologies, Inc.**

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UNITED STATES AIR FORCE

Pratt & Whitney
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LSP
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About the Cover:
An integrally bladed rotor is undergoing the laser shock peening process featured in our lead article. (Red laser beams are added graphics; the actual infrared laser beams are invisible to the human eye). This technology has increased the readiness of B1 bombers significantly.

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Preventing Fatigue Failures with Laser Peening

ACKNOWLEDGEMENT

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INTRODUCTION

Laser peening is an innovative surface enhancement process used to increase the resistance of aircraft gas turbine engine compressor and fan blades to foreign object damage (FOD) and improve high cycle fatigue (HCF) life. [1,2,3,4] The process creates residual compressive stresses deep into part surfaces – typically five to ten times deeper than conventional metal shot peening. These compressive surface stresses inhibit the initiation and propagation of fatigue cracks. Laser peening has been particularly effective in aircraft engine titanium alloy fan and compressor blades, however the potential application of this process is much broader, encompassing automotive parts, orthopedic implants, tooling and dies, and more. Significant progress has been made to lower the cost and increase the throughput of the process, making it affordable for numerous applications from gas turbine engines to aircraft structures, land vehicles, weapon systems, as well as general industrial use. Laser peening may also be referred to as laser shock processing (LSP), and various other commercial trade names. This paper reviews the status of laser peening technology, material property enhancements, and potential applications.

How Laser Peening Works

Laser peening drives a high amplitude shock wave into a material surface using a high energy pulsed laser. The effect on the material being processed is achieved through the mechanical "cold working" effect produced by the shock wave, not a thermal effect from heating of the surface by the laser beam.

The laser system is a high-energy, pulsed neodymium-glass laser system having a wavelength of 1.054 μm. The laser peening system produces very short laser pulses, selectable from 8 to 40 nanoseconds, with a pulse energy of up to 50 joules. The laser spot is typically 5-6 mm in diameter. The laser peening parameters are typically selected to achieve a power density or laser irradiance of 5-10 GW/cm^2. [5]

To prepare a part for laser peening, an overlay opaque to the laser beam is applied to the material surface being treated. An additional layer, transparent to the laser beam, is placed over the opaque overlay. With the two overlays in place, the laser pulse is directed through the transparent overlay and interacts with the opaque overlay as shown in Figure 1. The interaction consists of the laser energy being absorbed in the first few micrometers of the opaque overlay surface, vaporizing the material and forming a plasma. The plasma temperature rises rapidly through further heating from the incoming laser beam, but thermal expansion of the plasma is limited by the transparent overlay material. The pressure in the confined plasma increases rapidly, causing a shock wave to travel into the material through the remainder of the opaque overlay, and outward through the transparent overlay material.

The opaque overlay serves to protect the part's surface from direct thermal contact with the laser-induced plasma, and provides a consistent surface condition for interaction with the laser beam, independent of the actual material being treated. Direct contact of a metal surface with the plasma will, in most cases, form a thin melt layer on the surface of the metal, ranging from a surface discoloration to a surface melt layer up to 15 to 25 μm thick, depending on the laser irradiation conditions and metal properties. Opaque overlays can be of a variety of forms; dry or wet paint, black tape, metal foils, and adhesive-backed metal foils have all been used with varying, but nominally equivalent results in terms of the pressure pulses generated.

The transparent overlay serves to confine the plasma generated at the surface of the opaque overlay against the surface being treated and can be any material transparent to the laser beam. The simplest and most cost-effective method is to flow water over the surface from an appropriately placed nozzle. The water is not used to cool the part but serves the key function of confining the plasma generated when the laser beam interacts with the opaque overlay surface. The confinement increases the

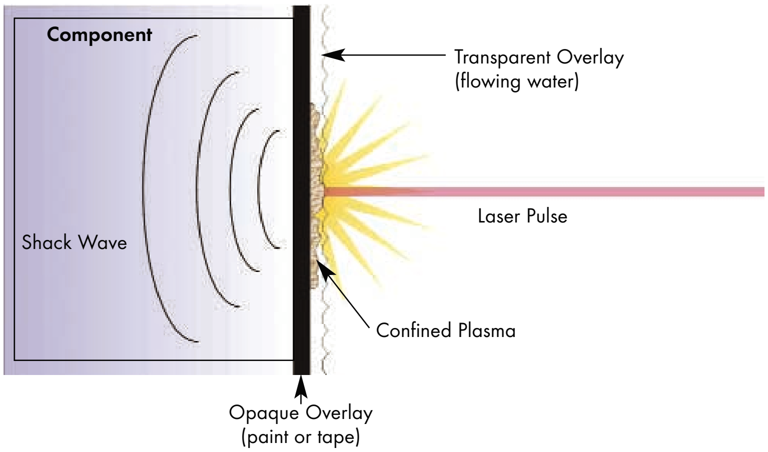

Figure 1. Schematic of the Laser Peening Process.

pressure developed by the plasma on the surface up to 10 times over the surface pressure developed if the plasma is unconfined and allowed to accelerate away freely from the material surface.

In practice, the laser system is located next to a peening cell in which the parts are robotically positioned during processing. The size of the area to be treated depends on the part design and service conditions. Sometimes, a part requires that only a small area be treated and a single treated spot will suffice. Examples might include around small bolt holes, or at the root of a notch in the side of a thin section[6]. In other instances, the areas requiring treatment will be larger, such as a patch on a turbine blade, crankshaft fillet, or gear. In these cases, successive spots are overlapped until the desired region is completely covered.

The shock wave traveling into the material being processed is the means for enhancing material properties. If the peak pressure of the shock wave is above the dynamic yield strength of the material, it will cause dynamic yielding as it travels into the material. The yielding of the material introduces tensile plastic strain in the plane of the surface, creating a residual compressive stress. As the peak pressure of the shock wave decreases with distance into the material, the total plastic strain associated with the shock wave decreases. This plastic strain gradient gives rise to the compressive stress gradient below the surface. Because the plastic strain produced by the shock wave extends much deeper then that produced by conventional shot peening, the compressive residual stresses produced by laser shock peening also extend deeper into the material. The deeper residual stresses, in general, provide much more substantial property benefits.

MATERIAL PROPERTY ENHANCEMENTS

Residual Stress

Laser peening produces a number of beneficial effects in metals and alloys. Foremost among these is increasing the resistance of materials to surface-related failures, such as fatigue, fretting fatigue and stress corrosion cracking. Numerous metals and alloys have been laser peened successfully, including titanium alloys, steels, aluminum alloys, nickel-base superalloys, cast irons, and a powder metallurgy iron alloy.

The material property enhancements are derived from the deep compressive residual surface stresses imparted by laser peening. Figure 2 shows an example of the deep compressive stresses achieved in two titanium alloys versus the shallower compressive stress profiles when conventional shot peening was used. Stress profiles were determined by standard X-ray diffraction measurements. The compressive residual stresses produced by laser peening extend in excess of 1.0 mm deep into the surface, whereas the compressive stresses for shot peened samples are present to a depth of about 0.2 mm.

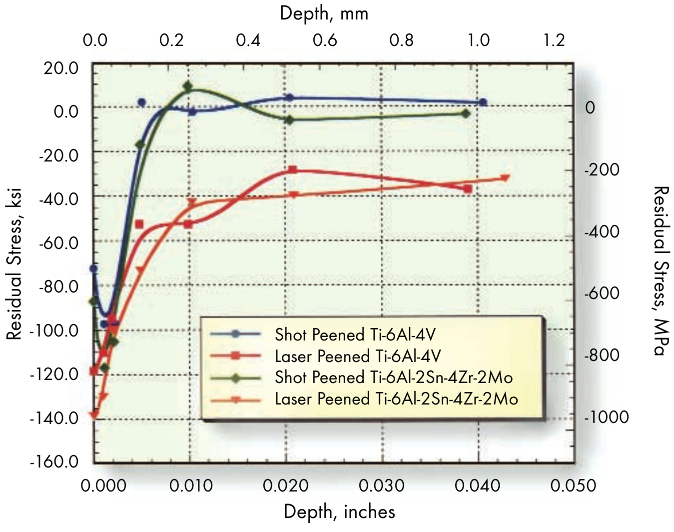

Figure 2. Residual Stress Profiles for Laser Peened and Shot Peened Titanium Alloys.

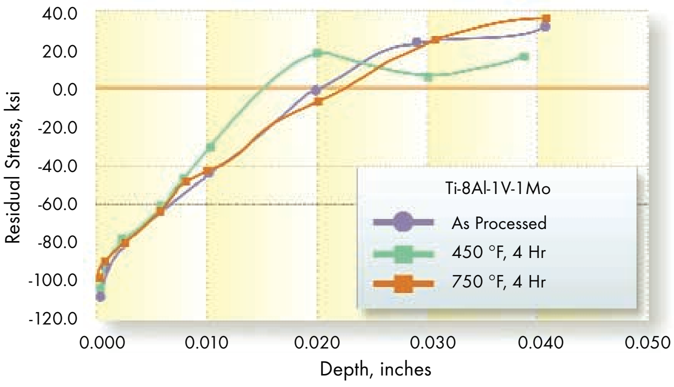

Figure 3. In-depth Residual Stress Profiles after Elevated Temperature Exposure of Laser Peened Ti-8Al-1V-1Mo for 4 Hours.

Thermal Stability of Residual Stresses

In service conditions involving elevated temperatures, the thermal stability of the residual stresses becomes an important issue. To retain the benefits of the residual stresses at higher service temperatures, they must be resistant to thermal recovery. A titanium alloy, Ti-8Al-1V-1Mo, was laser peened, then held at elevated temperatures in the service temperature range of interest, for four hours. Afterwards, the residual stress profiles were measured. The results shown in Figure 3 demonstrate that after four hours at elevated temperature residual stress recovery near the surface is minimal. [7]

Fatigue

The key benefits achieved in most applications with laser peening are significant increases in fatigue life and fatigue strength. The most dramatic increases in fatigue strength are achievable in thin sections for through-the-thickness cracks propagating into the structure from a stress concentration associated with an edge, be it a hole, notch, corner, inclusion or other feature. Substantial increases in fatigue strength are also achieved in thicker structures laser peened on a single surface in the area of a stress riser or stress concentration. Figure 4 shows a comparison of fatigue properties for 7075-T7351 aluminum specimens subjected to laser peening and shot peening. [8] The notched fatigue specimens were tested in 3-point bending, using test conditions of R=0.1 and K_t=1.68. The data illustrate the typical fatigue enhancement of laser peened parts, including a 30-

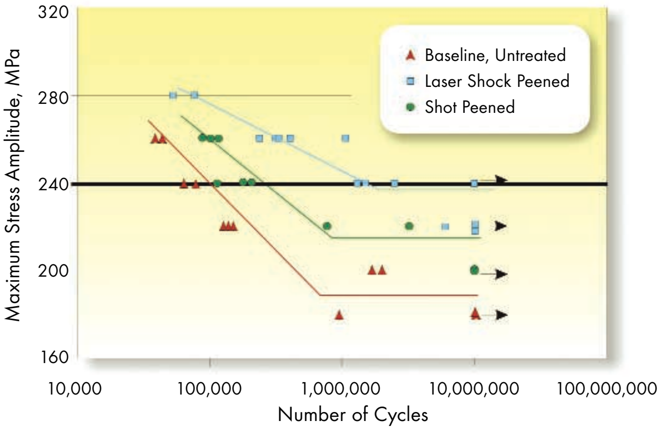

Figure 4. **Comparison of Laser Peening and Shot Peening Fatigue Properties for 7075-T7351 Aluminum. (Data points with arrows indicate tests halted with no failure.)**

50 percent increase in notched fatigue strength and an increase in fatigue life of about an order of magnitude.

The earliest investigation of the effect of laser peening on the fatigue behavior of thin sections was performed on F101-GE-102 aircraft gas turbine engine fan blades. [9] In this investigation, the effects of shot peening and laser peening surface treatments on increasing the resistance of the airfoils to foreign object damage (FOD) were compared. The results of the fatigue testing are shown in Figure 5. The baseline, undamaged blades failed within 10^6 cycles at 70 ksi. The notched, untreated blades failed at 20 to 30 ksi. The estimated average failure stress for the dual intensity [10] shot peened blades was 35 ksi, and for the high intensity [11] peened blades, 45 ksi. By comparison, the failure stress of the laser shock peened notched blades averaged about 100 ksi, well above the failure stress of the undamaged blades. Even the laser peened blades with electro-discharge machined (EDM) notches averaged around 75-80 ksi. These results indicated that laser shock peening would enable a blade to continue to operate safely, even with FOD at some level above that previously viewed as cause for removal and repair of the blade.

Corrosion

In limited studies, some laser peened materials have shown increased resistance to corrosion and stress corrosion cracking (SCC). In 2024-T351 aluminum, for example, potentiodynamic tests showed anodic current density shifts after laser peening, indicating enhancement of pitting resistance for both initiation and propagation. There was also a reduction of the passive current density on laser shock peened surfaces, indicating increased corrosion resistance. [12]

PRODUCTION APPLICATIONS

Beginning in 1991, the B-1B Lancer's F101 engine began experiencing failures of titanium turbine blades due to FOD caused by ice and hard objects ingested into the engine. Chunks of blades that broke loose, in some cases, did irreparable damage to the rest of the engine. To avoid grounding the B-1 fleet, the Air Force required a manual inspection of all the fan blades before each flight. The time-consuming leading edge inspections involved rubbing the leading edge with cotton balls, cotton gloves and even dental floss. If a single snag was detected, the blade was replaced prior to the next flight. In 1994, over one million man-hours at a cost of $10 million per year were required to complete the engine inspections and keep the B-1 flying.

GE Aircraft Engines (GEAE) investigated laser peening as a potential solution to increase the durability of titanium fan blades and decrease their sensitivity to FOD. The improvement to high cycle fatigue performance was remarkable. Damage to an F101 blade can reduce the fatigue strength from about 75 ksi to less than 20 ksi, which is less than half of the design requirement. However, when laser peened blades are comparably damaged, they retain a fatigue strength of 75-100 ksi. Thus, laser peening restores the structural integrity of damaged fan blades. Sensitivity to FOD defects up to 0.25 inch in F101 blades was virtually eliminated.

In 1995, the US Air Force authorized the production development of laser peening, bringing this technology out of the lab and into a production environment. LSP Technologies, Inc. (LSPT) was founded in 1995 to provide laser peening equip-

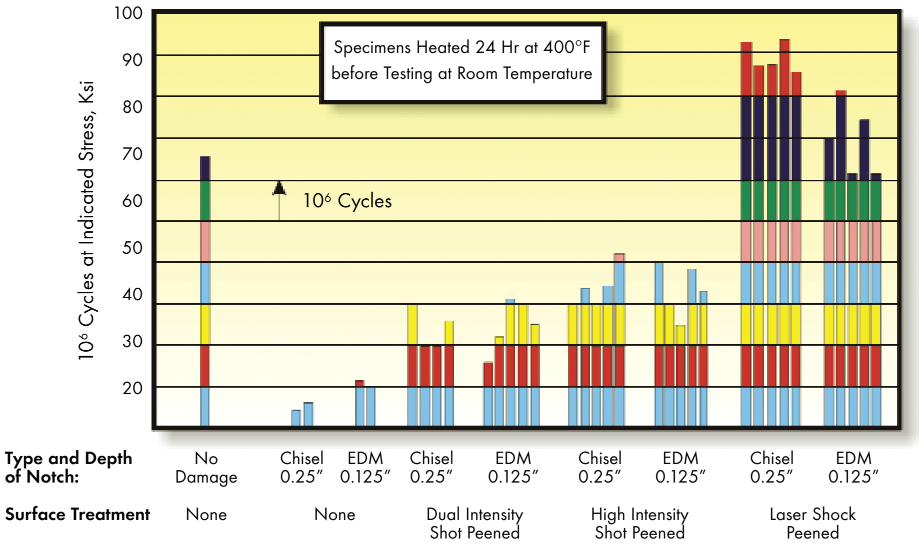

Figure 5. **Comparing Effects of Laser Peen and Shot Peen Processing on the Leading Edge of F101-GE-102 Fan Blades.**

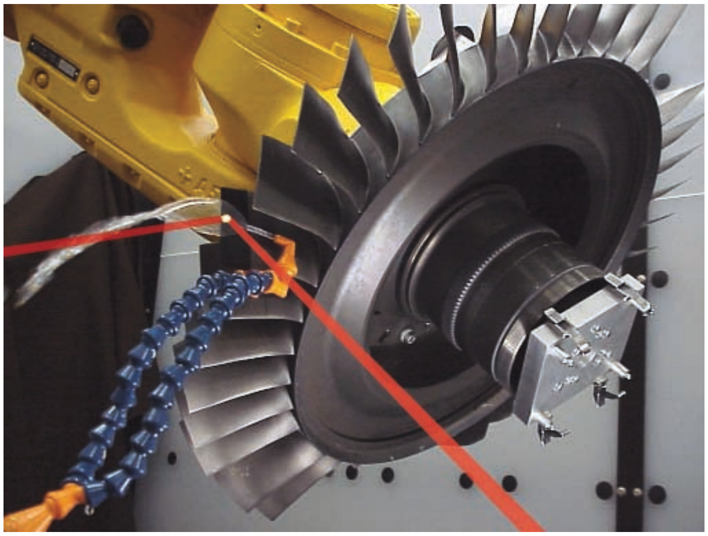

Figure 6. Laser Peening of an IBR for the F-119-PW-100 Engine.

ment and services to industry and the US military. By 1997, GEAE had proven the beneficial effects of laser peening and began production application to F101 blades, using four laser peening systems designed and built by LSPT.

Application of laser peening avoided over $59 million in blade replacement costs, secondary damage engine repair costs, and cost avoidance from airfoil failures. Avoiding catastrophic engine failures over the remaining life of the B-1B/F101 program is estimated to save another $40 million. Due to this success, laser peening was applied to solve similar problems for the F110-GE-129 engine (used on the F-16 C/D Falcon), and the Air Force estimates cost savings similar to the B-1B/F101 program. The process has also been implemented in the F110-GE-100 engine (used on the F-16 A/B Falcon), and the F101-GE-102 engine (used on the B1-B Lancer). In March 2003, production laser peening also commenced on an integrally bladed rotors (IBR) for Pratt & Whitney's F119-PW-100 engine, used on the F/A-22 Raptor. The production use of laser peening has been a notable success story for these military engine applications. Overall, the potential savings from laser peening are estimated to approach $1 billion when calculating this impact over all engines in the Air Force fleet.

Figure 6 shows the application of the LaserPeen™ (Trademark of LSP Technologies, Inc.) process to an integrally bladed rotor used in Pratt & Whitney's F119-PW-100 engine for the F/A-22 Raptor. Note that the red laser beams were added schematically to illustrate the process. The actual laser peening pulses are in the infrared spectrum (not visible to the human eye).

EMERGING APPLICATIONS

Much progress has been made at decreasing the cost and increasing the throughput of laser peening, making the process affordable for many new applications. Further progress is expected as production applications of laser peening expand. Numerous applications are under development or are good candidates for improvement using this technology.

In addition to engine components for the Air Force, numerous applications for airframe structures exist, including:

- Fatigue-critical components such as F-16 bulkheads, wing attachments, flight control mechanisms, wheels, brakes, landing gear,
- Welded titanium and aluminum components for improved reliability,
- Welded aging aircraft parts for improved reliability,
- Fasteners and fastener holes to combat fatigue, fretting fatigue and stress corrosion cracking,
- Cost-effective, high reliability castings to replace forgings, and
- Mobile laser peening for deployment at repair depots for treatment of large structures and detection of exfoliation corrosion.

For the Army, numerous opportunities exist for laser peening enhancement of fatigue prone helicopter parts such as transmission gears and other drive train components. Laser peening will enable the development of lightweight drive trains capable of higher horsepower loads than present generation helicopters (Figure 7). Laser peening can also improve the performance and reliability of rapid cycling firearms and artillery, as well as toughen support systems and vehicle components in tanks and armored vehicles.

The US Navy, US Marines, and the Royal Air Force (RAF) have interest in laser peening for improving the reliability of the Pegasus engine for the Harrier. Another potential application includes stress relief of nuclear propulsion system parts such as tube/sheet welded assemblies in nuclear submarine and surface ship vessels for improved resistance to stress corrosion cracking (SCC) and crevice corrosion. Other candidates include fatigue prone catapult and tail-hook arrest mechanisms, ship drive gears and bearings, and prevention of stress corrosion cracking (SCC) in welded components found on vehicles such as HUMVEES.

Applications for laser peening are not limited to military parts. As the process has become affordable, numerous industrial applications are emerging. Opportunities exist to apply laser peening for weight reduction, increased reliability, and improved fuel economy in automotive and truck parts such as transmission gears and axles, rotating engine parts, and impellers. Medical applications include treatment of orthopedic implants to improve the fatigue performance of hip and knee replacement joints and spinal fixation devices. Laser peening is also expected to find applications in power generation equipment for land based and nuclear power systems.

THE FUTURE FOR LASER PEENING

The future of laser shock processing is one of continuing advancement in new production applications and technology development. The biggest barrier to wider application of laser peening in manufacturing has been the relatively high cost, and to a lesser extent, the slow throughput of the process. This situation has improved rapidly with the availability of robust, production-ready laser peening systems and advances in processing technology such as LSP Technologies' RapidCoater™ system for automating the application and removal of the process overlay coatings. Much of this recent manufacturing-oriented development for increasing throughput and decreasing cost has

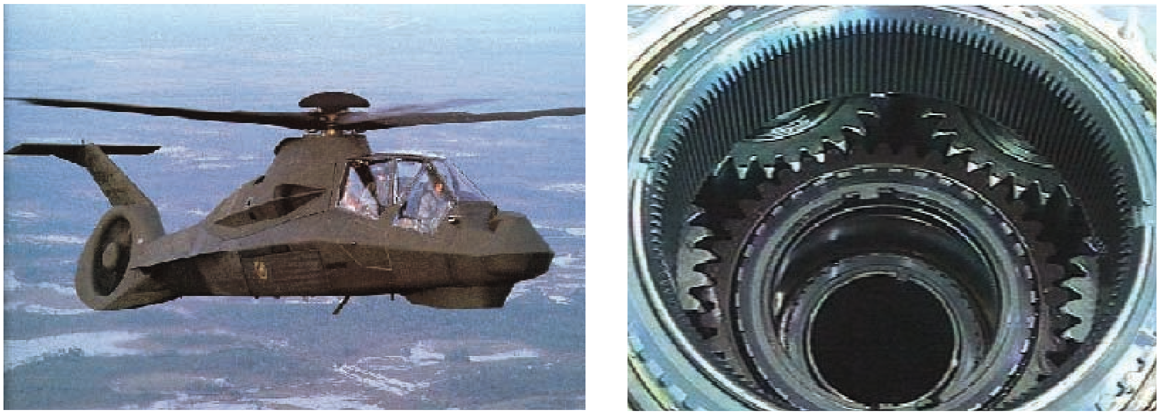

Figure 7. Comanche RAH-66 Helicopter and Helicopter Drive Train Gears.

been supported by the Air Force Research Laboratory's Materials and Manufacturing Technology Directorate. The variety of applications being evaluated for potential production applications continues to increase. From several production applications at present, this number is expected to expand rapidly over the next five years.

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[10] Dual intensity peening processes involve peening a part at one intensity level, then specifying an additional peening step at a lower intensity level. The purpose of the first peening intensity is to impart deep compressive residual stresses into the part, and shot peening at the second lower peening intensity smoothes the surface.
[11] High intensity peening involves peening a part at a very high level of bead size, bead velocity, and/or peening duration to achieve severe stress inducement. High intensity peening may also severely damage the surface of a part.
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