LASER PEENING FOR PREVENTION OF FATIGUE FAILURES

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ABSTRACT

Laser peening is an innovative commercially-available surface enhancement process for increasing the fatigue life of metal components. The process produces deep residual compressive stress into treated surfaces, typically five to ten times deeper than conventional metal shot peening. These deep compressive residual stresses inhibit the initiation and propagation of fatigue cracks. Laser peening has been particularly effective in increasing the resistance to fatigue crack propagation initiated from foreign object damage in titanium alloy fan and compressor blades of aircraft gas turbine engines. [1,2,3,4] However, the potential application of this process is much broader, encompassing automotive parts, orthopedic implants, tooling and dies, and others. Significant progress has been made to lower the cost and increase the throughput of the process, making it affordable for numerous applications. This paper reviews the status of laser peening technology, material property enhancements, and potential applications.

KEYWORDS Laser shock peening, fatigue, life, residual stress, surface, enhancement

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 to be treated. The opaque overlay serves to protect the 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; paint, dry or wet, black tape, adhesive-backed metal foils, and metal foils have all been used with varying, but nominally equivalent results in terms of the pressure pulses generated.

A transparent overlay, i.e., transparent to the laser beam, is placed over the opaque overlay. The transparent overlay serves to confine the plasma generated at the surface of the opaque overlay against the surface being treated. The transparent overlay can be any material transparent to the laser beam. The simplest and most cost-effective material and method of application is water flowing 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 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.

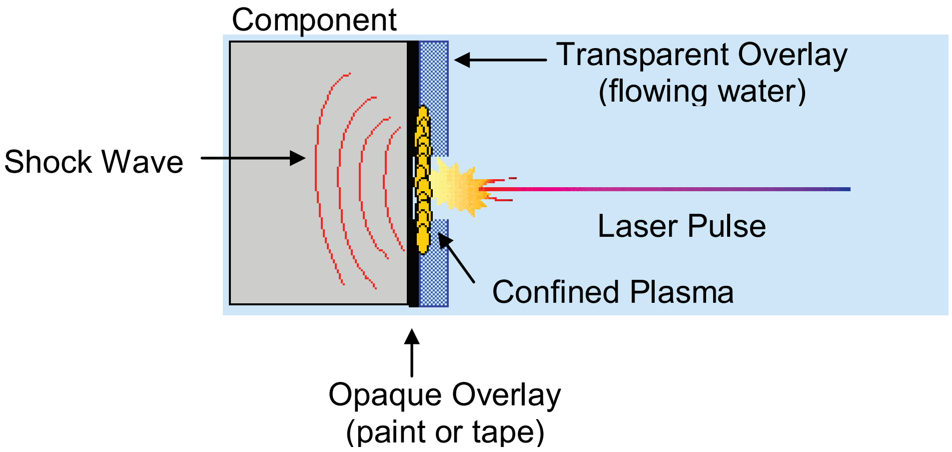

Figure 1 Schematic of the laser peening process.

With the 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 opaque overlay, and outward through the transparent overlay material.

In practice, the laser system is located next to a peening cell in which the parts are held and the part is positioned with a robot 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, for example, 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 in the plane of the surface. 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 than 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 residual stresses achieved in two titanium alloys versus the shallower compressive stress profiles when conventional shot peening was used. The compressive residual stresses produced by laser peening extend in excess of 1.0 mm deep into the surface depending upon the processing conditions and material, whereas the compressive stresses for conventionally shot peened samples are present to a depth of about 0.2 mm.

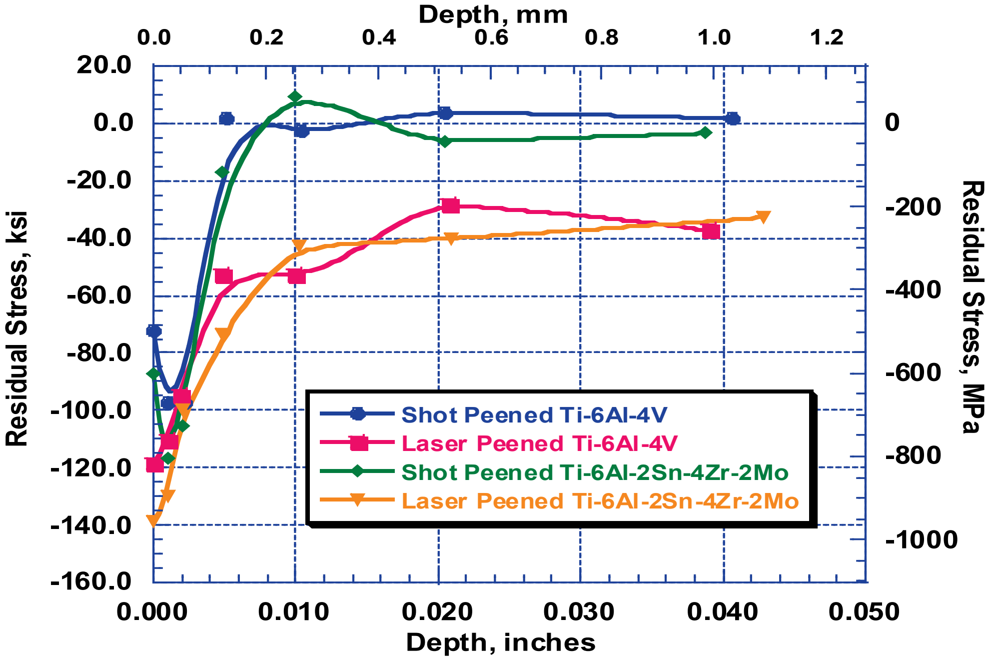

Figure 2 Residual stress profiles for laser peened and shot peened titanium alloys.

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, the residual stresses 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. After these anneals, the residual stress profiles were measured. The results, in Figure 3, show that after four hours there is no recovery of the residual stress. [7]

Fatigue

The key benefit achieved with by laser peening for most applications is a significant increase in fatigue life and fatigue strength. The most dramatic increases in fatigue strength are achievable in thin sections for through-thickness cracks propagating into the structure from a stress riser 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 laser peening and shot peening fatigue properties for 7075-T7351 aluminum. [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 30-50 percent increase in notched fatigue strength and an increase in fatigue life by 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 106 cycles at 70 ksi. The notched, untreated blades failed at 20 to 30 ksi. The estimated average failure stress for the dual intensity shot peened blades was 35 ksi, and for the high intensity peened blades, 45 ksi. By comparison, the failure stress of the laser shock peened blades averaged about 100 ksi for the chisel notch, well above the failure stress of the undamaged blades, and at about the same level as the undamaged blades for the EDM notch. These results indicated that laser shock peening would enable a blade to continue to operate safely, although damaged by FOD at some level above that previously viewed as cause for removal and repair of the blade.

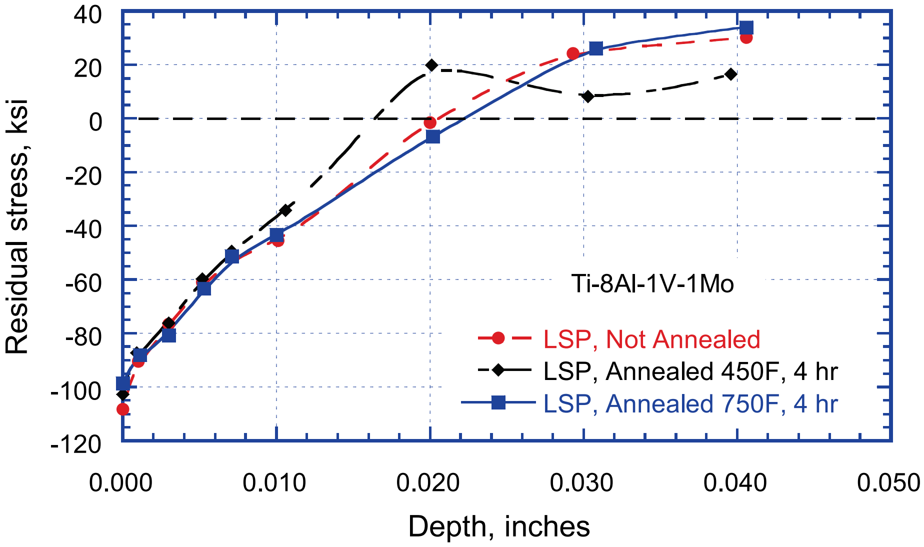

Figure 3 In-depth residual stress profiles after annealing Ti-8Al-1V-1Mo for 4 hours at elevated temperatures.

PRODUCTION APPLICATIONS

Production applications of laser peening have focused initially on aircraft engine parts such as turbine engine airfoils because of the enormous benefits of preventing fatigue failures and improving damage tolerance for these critical parts. Laser peening is used in production to process first stage airfoils for the F110-GE-129 engine (used on the F-16 C/D Falcon), 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 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.

Beginning in 1991, the B-1B Lancer's F101 engine began experiencing failures of titanium turbine blades due to foreign object damage (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.

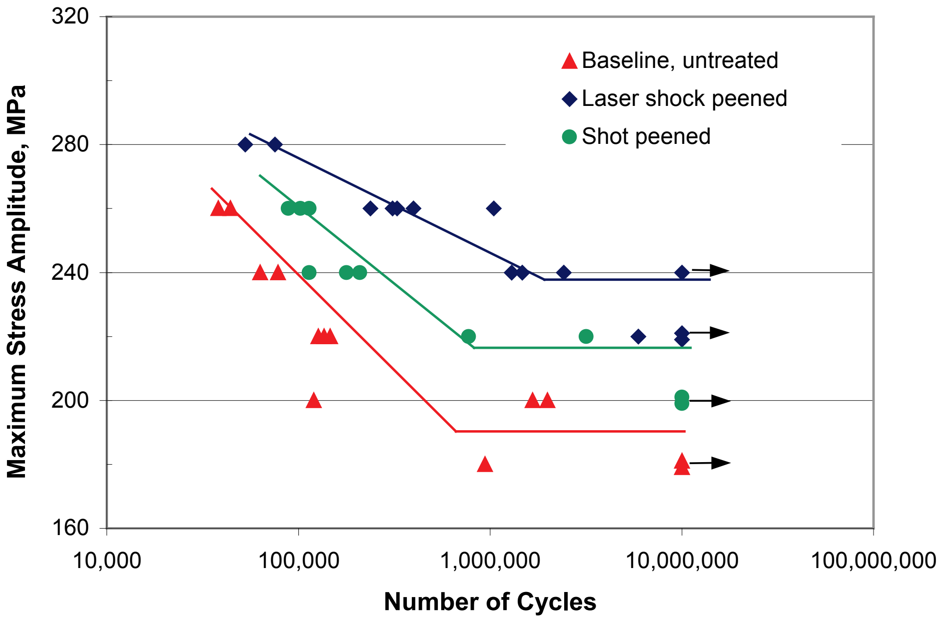

Figure 4 Comparison of laser peening and shot peening fatigue properties for 7075-T7351 aluminum.

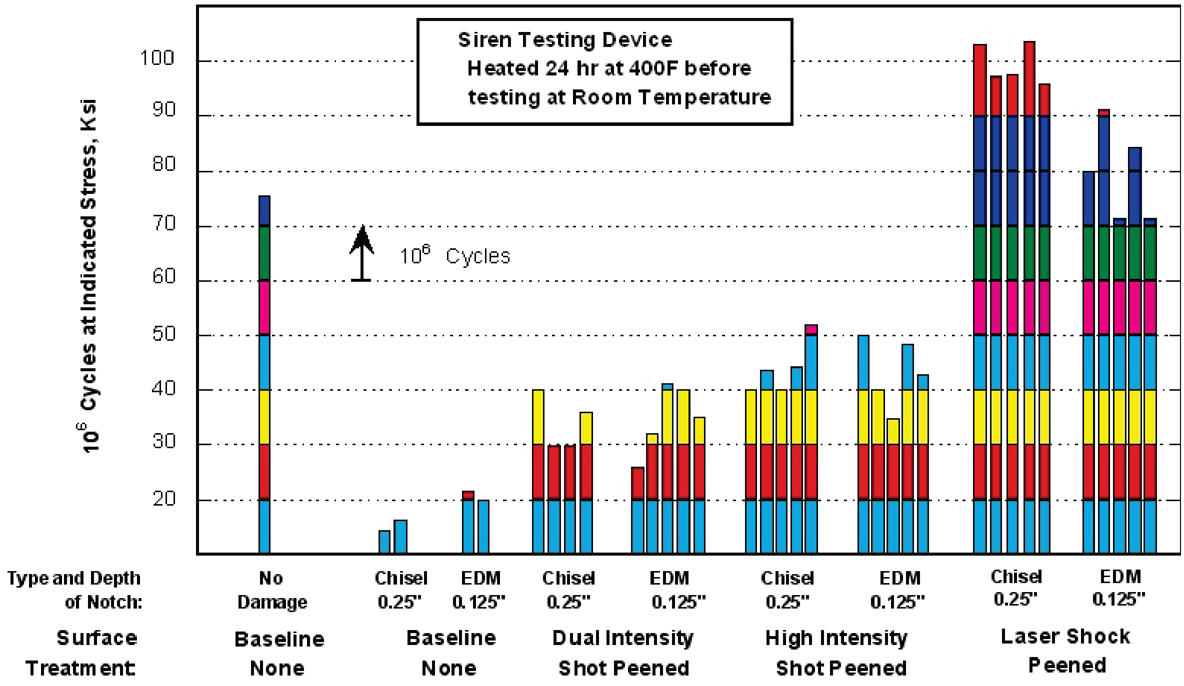

Figure 5. Comparison of the effect of the laser peen process on the leading edge of the F101-GE-102 1st fan blades.

Corrosion

In limited studies, some laser peened materials have been shown to have 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. [10]

THE FUTURE FOR LASER PEENING

The future of laser shock processing is one of continuing advancement in production applications, technology development, and scientific research. 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 been supported by the Air Force's AFRL 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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