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Laser Science and Technology Program

Laser Peening—A Processing Tool To Strengthen Metals or Alloys

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Laser Peening—A Processing Tool to Strengthen Metals or Alloys to Improve Fatigue Lifetime and Retard Stress-Induced Corrosion Cracking

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Laser peening is an emerging modern process that impresses a compressive stress into the surfaces of metals or alloys. This treatment can reduce the rate of fatigue cracking and stress corrosion cracking in structural metals or alloys needed for aerospace, nuclear power plants, and military applications. Laser peening could also be used to form metals or alloys into precise shapes without their yielding, leaving their surfaces in a crack resistant compressive state.

Introduction

When metal is bent, the surface of the outer radius is stretched into a tensile state. Under tension, any flaw or microcrack will grow in size with each flexure until the crack spreads through the entire strip, breaking it into two pieces. Flexure of metal components occurs in most applications. The teeth of transmission gears strain at the root as they deliver torque in a vehicle. Springs and valves flex every time they transfer loads. The process of metal forming and welding can also cause tensile stress that allows defects to grow into cracks and accelerate corrosion. If fatigue or stress corrosion cracking (SCC) failures from loads or vibration occur in aerospace components and nuclear power plants (such as turbine fan blades ane reactor vessel closure head nozzles and bolts), significant loss of assets and potential loss of human life can occur.

Laser peening, better than any other surface treatment technique, has proven to extend the fatigue lifetime of metal and alloy components. In the laser peening process, a high-energy laser beam creates an intense pressure wave (of about 1 million pounds per square inch) on the surface of the metal, straining the metal and leaving a residual compressive stress both on the top and inside of the metal surface. If the compressive stress is intense and deep enough, when the component flexes under a load, the surface remains in compression, and a micro-crack or flaw on the surface cannot grow.

The first laser peening experiments took place more than 30 years ago at the Battelle Institute in Ohio. However, it was only recently (1996)—with the advent of high-power solid-state lasers (see Figure 1) at higher repetition rates and better beam quality—that this method began to compete with traditional shot-peening methods, which employ small metal or ceramic particles to deliver the impact. While shot peening and other

Figure 1. LLNL's laser peening system.

mechanical surface treatment techniques are only capable of producing compressive stress down to depths of a few tenths of a millimeter, depths of compressive residual stress induced by laser peening are typically on the order of several millimeters or more.

Laser Peening Process

Laser peening employs high-energy laser pulses from a solid-state laser to create intense shock waves in a material. The basics of the laser peening process are described in Figure 2. A high-intensity laser beam with peak power greater than 1 GW is imaged to a spot size of about 5 mm × 5 mm and illuminates the metal substrate to be peened. The energy density of the laser is typically in the range of 50 to 200 joules per cm^2 and the duration of the pulse is 5 to 30 nanoseconds (ns). Laser peening is applied in a spot by spot manner with typical irradiance (power per unit area) on the order of 2 to 10 GW/cm^2. A laser system appropriate for peening at the industrial level requires an average power in the multihundred watt to kilowatt range and pulse energy of around 20 to 100 J.

Prior to laser irradiation, the area to be treated is locally covered with two different layers of material. First, a protective layer is applied to the surface; this is called the ablative layer because its surface is ablated off during treatment. Typical ablative layer materials include 1- to 2-mils-thick plastic or metal foil tape or paint, although in many applications where the surface finish is not a critical issue, the metal surface to be peened can act as the ablative layer. Next, a transparent inertial tamping layer is applied over the ablative layer, which acts as a tamper to confine the expansion of the high-pressure plasma to be generated by a laser pulse. Typical materials for the tamping layer include glass or water (1–2 mm thick). After these two surface layers are in place, the laser peening process can be carried out.

When the laser beam illuminates the surface, it is absorbed and rapidly forms high-intensity plasma. The plasma is confined by the tamping layer and builds to a pressure of roughly a million pounds per square inch (75 kbars). Although the tamping layer is very thin, during the very short 20-ns duration of the laser pulse, its inertia keeps it from moving more than a few microns, and thus it very effectively confines the pressure. This short duration

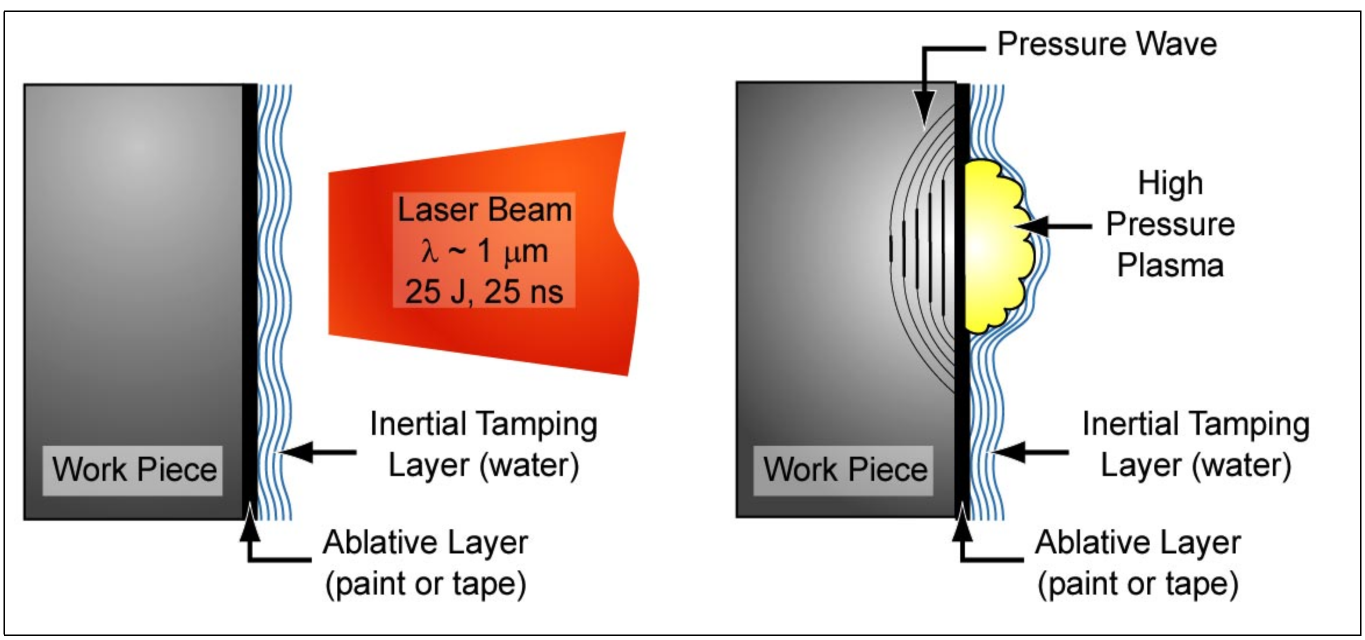

Figure 2. Laser peening process description.

pressure pulse causes a shock wave to travel through the material and leaves plastically deformed material in its wake. The plastic deformation (or density dislocation) caused by the shock wave gives rise to compressive residual stresses that can extend to several millimeters in depth, making the material more resistant to fatigue and stress corrosion cracking. To induce a residual compressive stress into the material, one must tailor the laser intensity to GWs level to generate a surface pressure that is greater than the dynamic yield strength (Hugoniot) of metal.

Using an optical delivery system, the peening pulses can be rapidly applied, uniformly covering the full desired area. The laser peening technology was commercialized by industry in 2002 and is now treating parts 24 hours a da0y, five to six days per week, at peening rates of nominal 1 squared meter per hour.

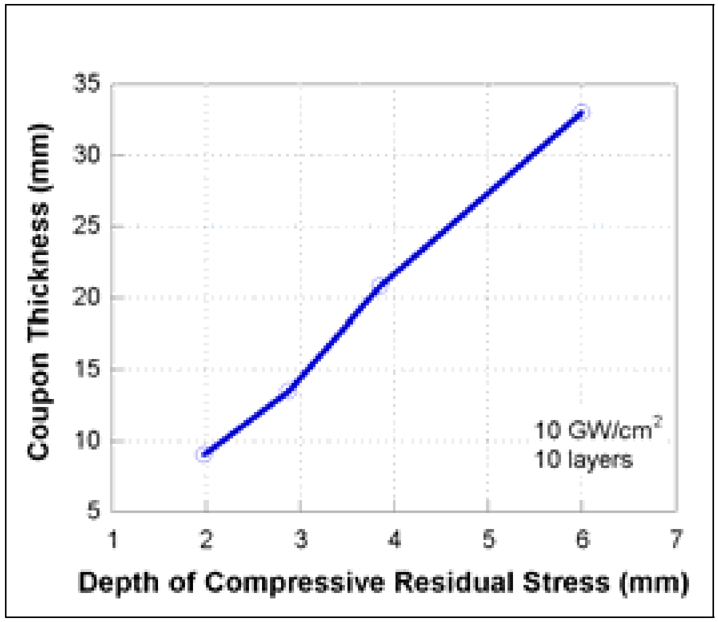

Figure 3. Laser peening produced residual compressive stress to a depth of 20% of the thickness of an Alloy 22 base metal.

Laser Peening Induces Deep Compressive Stress in Metal

Laser peening can very effectively convert tensile stresses in the metal to strong and relatively deep compressive stresses. Residual stress induced by laser peening can be made deeper and with significantly greater stressed volume than conventional shot peening. Depth of residual compressive stress reaching 20% of the part thickness has been achieved in Alloy 22 base metal (see Figure 3). Laser peening was found to produce residual stress to a depth of 3.8 mm in 20-mm-thick Alloy 22 base material. A residual stress profile for applications requiring very deep residual stress is shown in Figure 4. The depth of residual stress was found to have a significant dependence on the number of peening layers and a slight dependence on the level of irradiance.

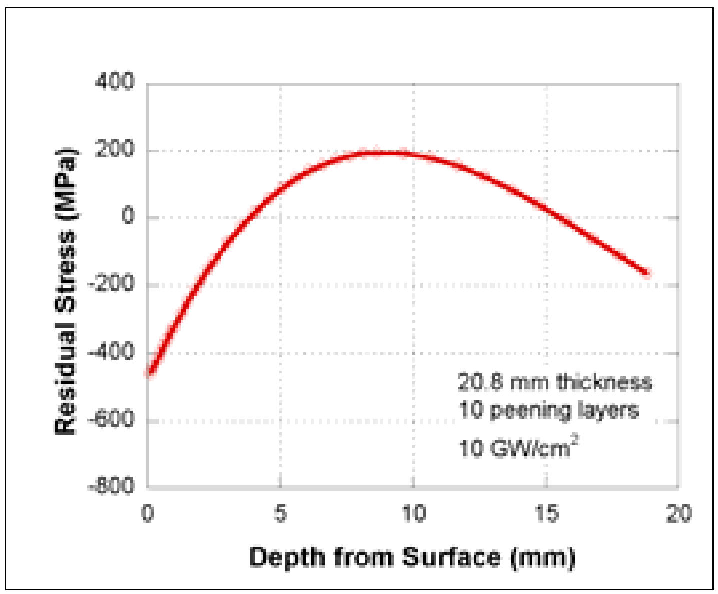

Figure 4. A residual stress profile for applications requiring very deep residual stress.

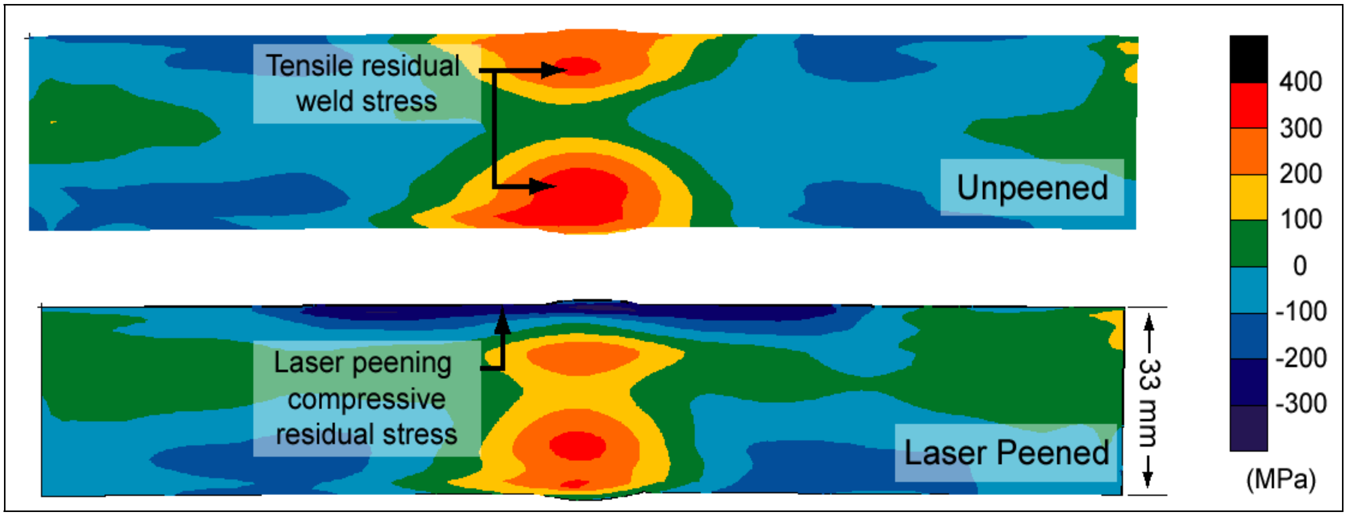

Figure 5. Laser peening generates extremely deep compressive residual stress in alloy 22 weldment.

One of the recent laser peening successes is the production of compressive residual stress to depths on the order of 5 mm in Ni-base alloy (Alloy-22) weldments and base material. As a result of this accomplishment, laser peening will be used to remove tensile stresses on metal canister closure lids induced by the welding process. Figure 5 shows the contours of residual stress field measured in two identical 33-mm-thick welded Alloy-22 plates with and without laser peening. Tensile stresses typically observed at the center of the weld bead were converted into compressive stresses after laser peening. The contour plot of residual stress in the laser-peened sample shows a region of large and uniform compressive stress within the peened area.

Laser peening produces very little amount of cold work (a few percent) on parts because only a single or a few deformation cycles are required. After treatment, it leaves a relatively uniform surface with an rms surface finish of 50 microinches (see Figure 6). There is evidence that the stress induced by laser peening has very low thermal relaxation rate and remains much more effective in parts operated at high temperatures.

Compressive Stress Improves Fatigue Lifetime

Laser peening imparts a compressive residual stress to metal surfaces. With a compressive residual stress effectively pushing the atoms on the metal surface together, small surface cracks and flaws that could easily grow into larger destructive cracks are prevented from growing. This arrest of crack growth results in a significant enhanced lifetime against fatigue failure.

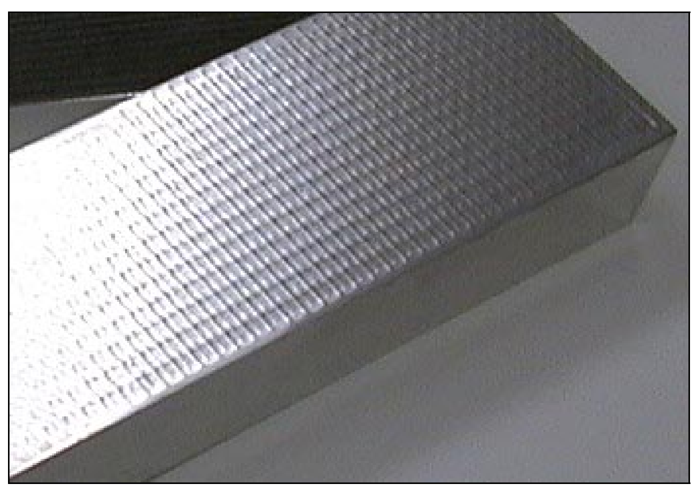

Figure 6. Laser peening induces deep compressive stress in metal.

Tests on structural aluminum components under heavy load are showing 10- to 15-times lifetime improvements. As shown in Figure 7, recent fatigue tests on 6061 T6 aluminum under various stress load conditions show more than 50 times improvement in fatigue lifetime for structural aluminum test plates when compared to unpeened (control) components and 10 times improvement when compared to conventionally shot-peened components. Shot peening is widely used in industry to improve lifetime and resist corrosion. However, the residual stress imparted by shot peening is not nearly as deep as that achieved with laser peening, and consequently, laser peening achieves a much greater lifetime improvement. This lifetime extension can have dramatic importance for the performance and reliability of field systems and an even greater effect on the maintenance costs to keep field systems operating.

Laser peening of root area of gears increases bending fatigue strength and lifetime for high-cycle fatigue (see Figure 8). Recent testing has demonstrated significantly improvement in high-stress component lifetimes: 2 to 6 times in automotive and helicopter gears and up to 10 times in bearing lifetime after laser treatment.

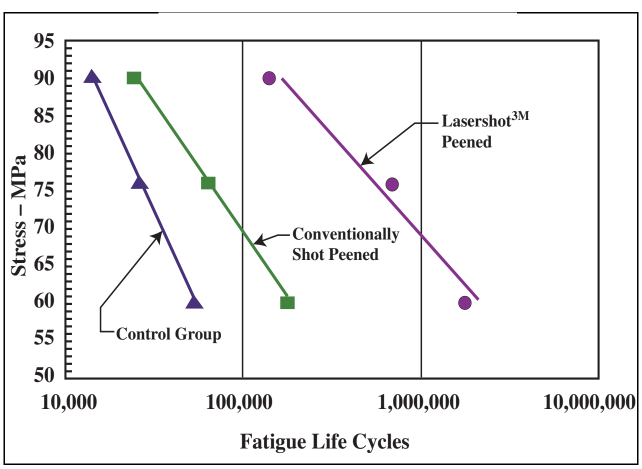

Figure 7. Laser peening significantly extends the fatigue lifetime of metal components

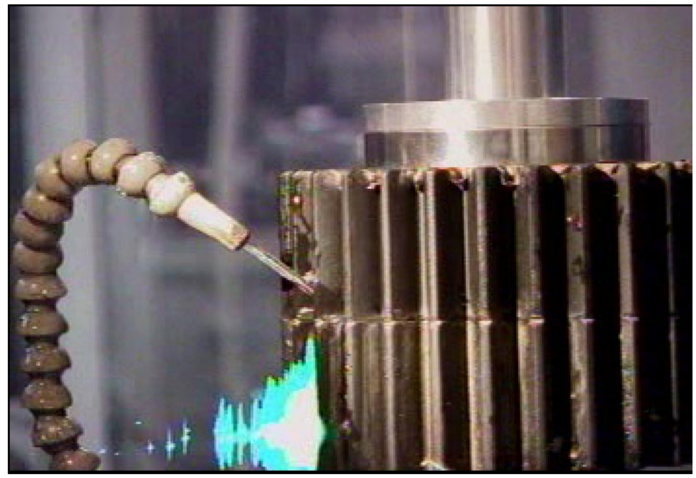

Figure 8. Laser peening increases bending fatigue strength of gears.

Laser peening was introduced this past year into commercial production by industry to eliminate fatigue failure in high value commercial jet engine fan blades. In rigorous tests of laser peening, jet engine fan blades that used to develop fatigue failure cracks after 500 flights are now able to achieve 10,000 flight operations without failure. The process was developed, tested, and certified by the Federal Aviation Administration and then immediately brought into production to solve the serious problem. Since commercial introduction, aircraft worth several tens of billions of dollars are now in service with laser-peened blades—saving millions of dollars per month in aircraft maintenance and blade replacement costs, while also greatly enhancing safety.

Retards Stress-Induced Corrosion Cracking of Metals

Recent experiments at LLNL have also shown that laser peening can virtually eliminate occurrence of stress corrosion cracking in metal. During an accelerated stress corrosion cracking experiment in an aqueous solution of $MgCl_2$ at high temperature, we measured the lifetime of type 304 stainless

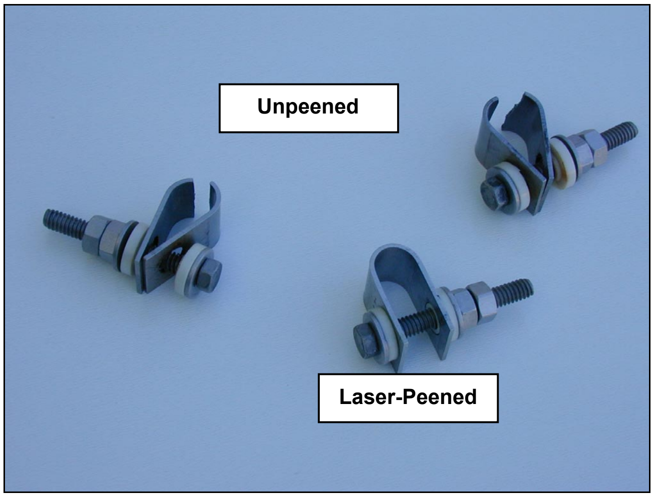

Figure 9. Peened U-bend shows no sign of cracking.

steel U-bends under high-stress conditions. The unpeened U-bends broke into two pieces within two hours, while the laser-peened U-bends showed no signs of cracking after more six days (see Figure 9).

Test treatments of the laser processing show it to be very effective in reducing corrosion and eliminating stress corrosion cracking. Figure 10 shows graphically how the laser peening process reduces corrosion and stops stress corrosion cracking. The photo shows the results of a test on stainless steel type 316 where two sections of metal are welded together; the area on the left was laser peened and the area on the right was not.

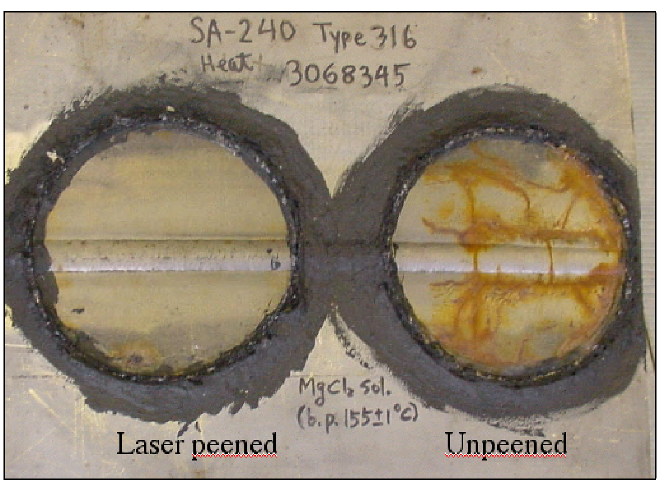

Figure 10. Laser peenng retards stress corrosion cracking and overall corrosion in stainless steel 316.

Then the surface was subjected to a highly corrosive environment of a 40% solution of boiling magnesium chloride. As can be seen, the unpeened area has several critical cracks running transversely through the welded section, and the test area has a highly corroded surface appearance. In contrast, the laser-peened area is free of stress corrosion cracks and is shiny and free of rust. The application of laser peening is clearly making a significant improvement to the corrosion lifetime of the stainless type 316 metal.

In another convincing test, a welded section of 1-inch-thick stainless steel is peened in selected areas and then subjected to the harsh magnesium chloride environment. As seen in Figure 11, a stress corrosion crack, extending through the entire one-inch thickness of the material began to run longitudinally along the weld (along the right-hand side). However, when it encountered the laser-peened area, the compressive stress imparted to the surface effectively prevented the crack from propagating into the laser-peened area.

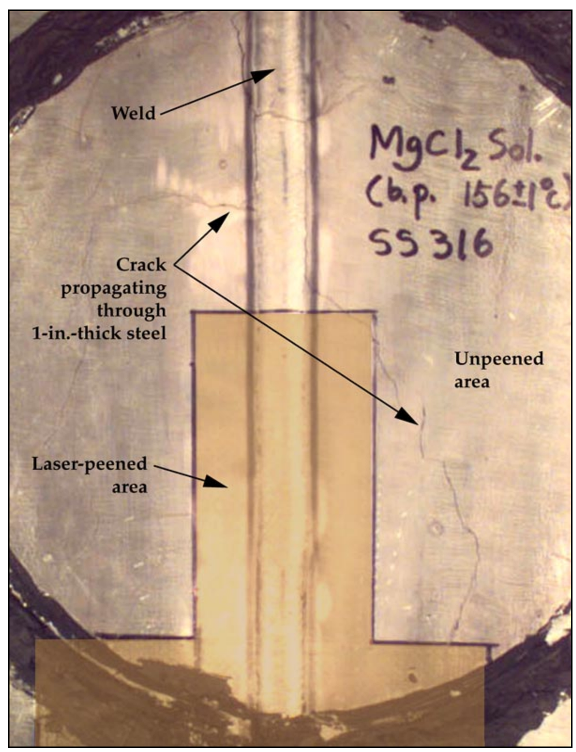

Figure 11. Laser peening significantly reduces stress corrosion cracking in welded 316 stainless steel.

The crack made a turn, continuing through unpeened area and eventually was arrested when it encountered the larger laser-peened area. The peening of the surface has clearly demonstrated a dramatic effect on the crack resistance of the metal.

For the Department of Energy's Yucca Mountain Nuclear Waste Disposal Program, stress corrosion cracking is a primary concern in the design of the storage canisters since tensile residual stresses will be left behind by the closure weld. Alloy 22 is a nickel-based stainless steel that is particularly resistant to corrosion; however, there is a chance that stress corrosion cracking could develop giving the right environmental conditions. Laser peening is an emerging surface treatment technology that has recently been identified as an effective tool for mitigating tensile residual stresses in the storage canisters. These canisters, which will be buried in Yucca Mountain, Nevada, need to remain intact for 10,000 years. Figure 12 is a schematic of the storage canister. After the canisters are loaded with radioactive waste, the lids are welded on. Stress corrosion cracking of the outer barrier lid weld has been identified as a critical failure point. Laser peening is a leading candidate to convert the residual weld stress from tensile to compressive, eliminating stress corrosion cracking on storage canisters.

Forming Metals with Greater Curvature and High Surface Finish

The compressive residual stress selectively induced by the laser peening process can also be used to cause the metal to curve in a precisely controlled fashion. Now for the first time, large metal panels up to 1 inch thick can be formed to tight radii (see Figure 13) and to difficult contours. During the forming process, laser peening impresses a deep level of residual stress into selected surfaces of the metal. The strain associated with the compressive stress causes the treated surface to elongate, effectively bending the metal within the processed area. When applied to aircraft structural sections such as panels,

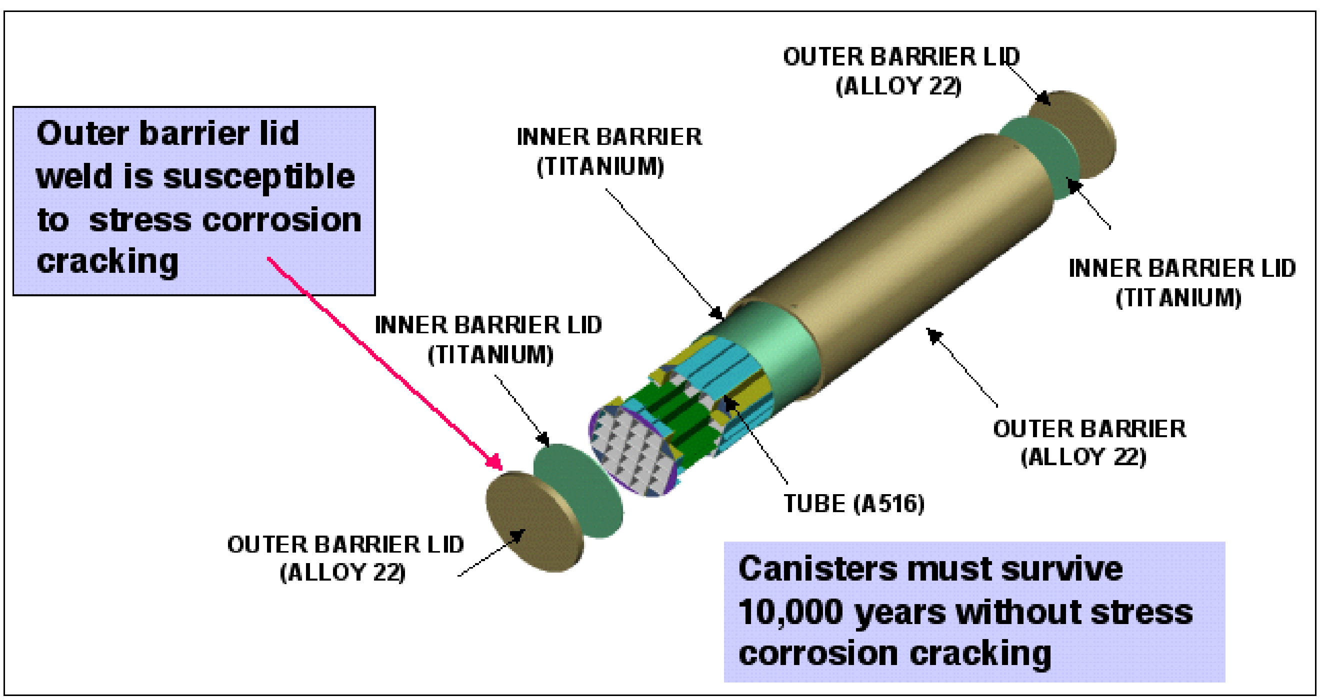

Figure 12. Waste storage canister for use in the Yucca Mountain Nuclear Waste Disposal Program. Eleven thousand canisters filled with nuclear waste will be buried in the Nevada mountain.

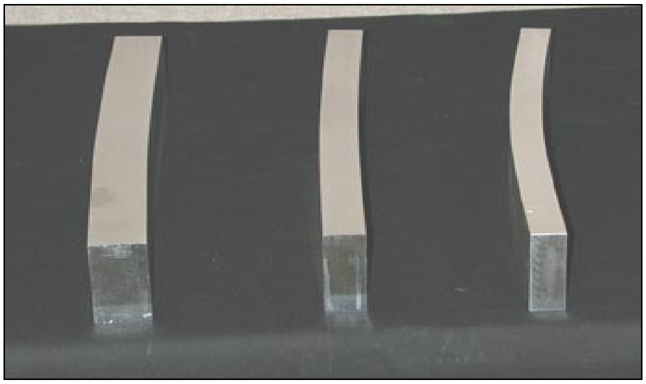

Figure 13. Laser peen-forming can form tight radii in thick material with high accuracy and repeatability.

vertical stabilizers, and rudders, the laser process creates highly precise curvatures (<160-inch radius) and contours even in very thick (1-inch-thick and greater) section material.

The laser peen-forming process leaves a beneficial compressive stress on both front and back surfaces, making the shaped sections highly resistant to stress corrosion cracking and fatigue failure. This process will dramatically change aircraft manufacturing by introducing a new capability for designing and forming thick section components. Component sections can be made larger, reducing the number of joints and allowing lighter weight panels. This will translate directly into increased payload and fuel efficiency for the transportation industries.

Laser Peening is a Developed Process —Enhancing Fatigue Lifetime and System Safety

Laser peening was introduced into commercial production by industry in May 2002. This peening system was deployed to solve an important fatigue failure problem in high-value commercial jet engine fan blades and discs. Since initial deployment, multiple applications and aircraft worth billions of dollars are now in service with laser-peened parts—saving millions of dollars per month in aircraft maintenance costs and millions more in parts replacement costs, all the while greatly enhancing safety (see Figure 14).

Laser peening is already having an important impact in preventing the failure of jet engine fan blades. The high-stress and high-cycle loading of these components has led to failures. Led initially by the U.S. Air Force, research showed that laser treatment of the leading edge of blades against foreign object debris damage significantly extends the fatigue lifetime and allows even a highly damaged but laser-peened blade to have better fatigue lifetime than unpeened new blade. An even greater-magnitude application has been the treatment of wide cord fan blades for commercial engines to prevent fretting fatigue failure.

The manufacturing industry can now apply the laser peening technology to improve the safety, reliability, and operational life of the next generation airplanes, ships, nuclear power plants, fighter jets, and military vehicles so that they will have longer service life and lower operating cost.

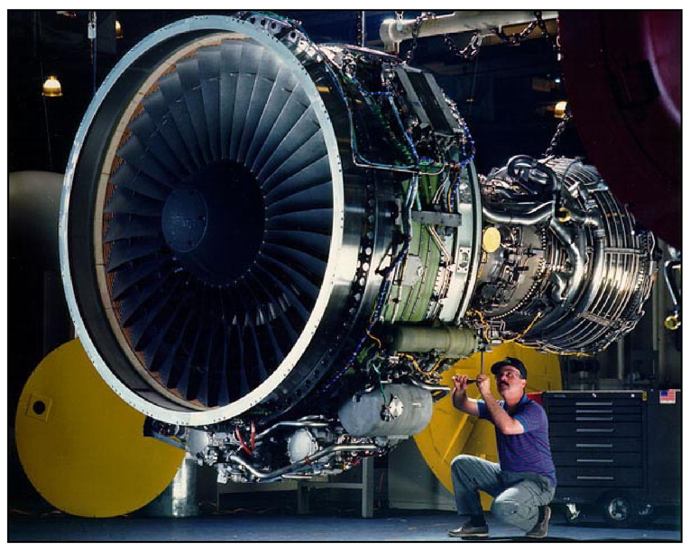

Figure 14. Production laser peening has arrived. It will increase the lifetime of parts, improving reliability and safety.

For further information, please contact:

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