Production Laser Peening of High Strength Metals

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Abstract

Laser peening technology has matured into a fully qualified production process that is now in routine and reliable use for a range of metal alloys. The technology is capable of extending the fatigue life and stress corrosion cracking life of components, and will enable designers to consider higher stress levels in certain life limited designs. Engineered residual compressive stress has been strategically applied by Metal Improvement Company to critical component areas in the processing of over 14,000 wide chord fan blades and blade hubs for operation in high performance commercial jet engines. The process facilities have been FAA/JAA certified or ISO 9001 approved. A broad range of materials are in production or development, including but not limited to Ti 6-4 (alpha and beta and BSTOA), 300M and 9310 steels, Al 7050, and Al 2024 and MP35N and C22 corrosion resistant alloys. Enhancement to the life of components with complex geometries and welds has been demonstrated. The processing capability is being extended with the introduction of a transportable laser peening system and a system with a moveable beam that can treat very large or heavy components. Authors will describe the system and present processed materials performance data with a special emphasis on high strength corrosion resistant materials for marine environments.

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Introduction

It is well known that placing residual compressive stress into the surface of metals provides performance benefits including increased fatigue lifetime, increased fatigue strength, resistance to stress corrosion cracking and fretting related failures. Techniques such as shot peening have played an important role in extending the performance and lifetime of metal based systems. Shot peening is utilized in many important applications; however it is sometimes limited by the potential of high levels of cold work and a rougher surface finish. In many applications a deeper level of compressive stress with low cold work and good surface finish is highly desirable.

Laser peening has emerged in the past 3 years as an industrial quality technology for inducing compressive residual stress that is as deep or deeper than conventionally available processes, while simultaneously inducing very low cold work, producing a good surface finish and being rapidly and precisely controlled in a production environment. The process is illustrated in Figure 1; an intense beam of laser light with an irradiance (power per unit area, typically measured in units of gigawatts per square centimeter) in the range of 2 to 10 GW/cm^2, is directed on to a sacrificial ablating material placed on the surface of a component to be treated

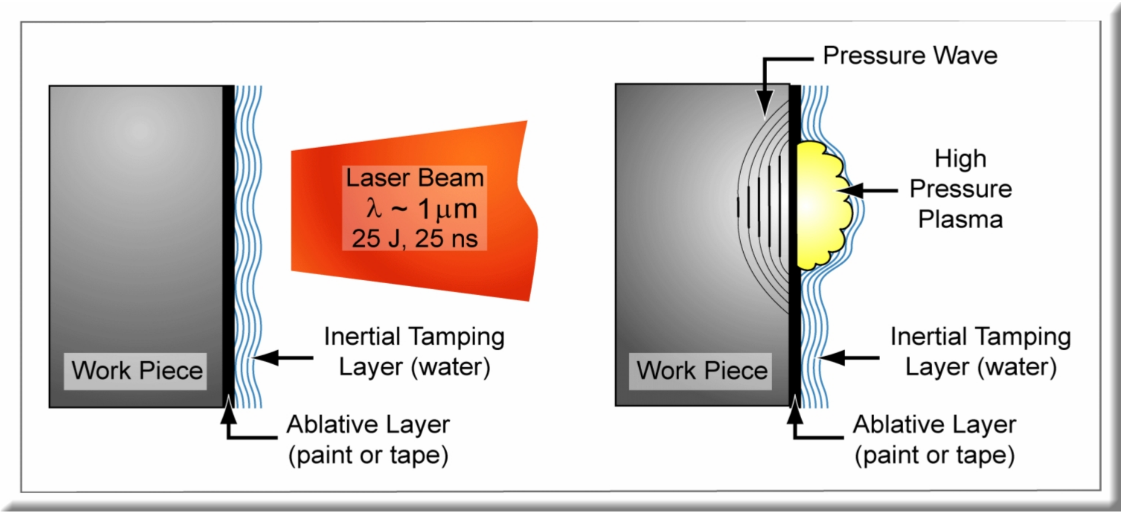

Figure 1: A graphical representation of the laser peening process

The laser light rapidly vaporizes a thin portion of the ablative layer, producing a plasma that is confined by a thin laminar layer of water (~1 mm thick) flowing over the surface of the material. In response to the rapidly expanding plasma, a shock wave with a peak pressure on the order of 100 kbar is generated in the part. This shock wave runs locally into the material, creating a plastic strain that results in a residual stress field with highly controllable depth and magnitude. The process is purely mechanical, with essentially no heating of the part due to the extremely short time scales involved. Laser peening typically results in residual compressive stress that penetrate to a depth of 1 mm to 4 mm with near surface magnitudes of 50-100% of the elastic yield strength, depending on the material, part geometry, and the processing parameters. These deep compressive residual stresses delay crack initiation, and retard crack growth, resulting in enhanced fatigue lifetime and improved resistance to stress corrosion cracking. Surface finish of treated parts is quite good, with visible witness marks and a surface roughness of xxx microinch in aluminum, titanium and mild steels, and almost no visible effect on higher strength alloys (figure?).

The area treated with each pulse of the laser is between 9 to 100 mm^2 depending on specific peening parameters. The laser can fire at rates up to 5 Hertz, making systematic treatment of large areas feasible. Multiple layers of peening can be applied to achieve even deeper levels of stress and the intensity and depth of induced residual stress can be faded in or out through control of laser spot size and layers of coverage. Laser peening technology has found important applications for commercial jet engine and electric power generation components and is expanding into applications in aircraft structures and landing gear as well as uses in military, automotive, medical and other energy systems.

Engineered residual stress through laser peening

By providing reliable, controlled high speed processing, laser peening offers engineers in the design, maintenance and overhaul phases of a component's life the ability to place compressive residual stress into key areas to retard crack initiation and growth, resulting in increased fatigue strength or service life. It is effective for both fatigue and corrosion cracking applications.

A critical part of applying laser peening effectively is understanding what residual stress is developed in a particular material and geometry of interest. We have used the slitting (crack compliance) method extensively to determine residual stress in a variety of materials, under varying laser peening treatments. Slitting relies on measuring the strain changes on the surface of a sample as the unknown residual stress inside is mechanically released (typically through the introduction of a slit via wire EDM). Using this strain as an input to an inverse elastic solution yields the residual stress in the component prior to slitting. The method has been shown to be very effective in determining relatively minor variations in residual stress as a function of peening parameters.

Figure 2 illustrates (need corrected figure with proper glass bead result) the excellent level of control of residual stress that can be achieved by selection of laser peening parameters. The figure shows residual stress as a function of depth in 0.5 inch thick blocks of BSTOA Ti 6-4 measured with the slitting method. The key identifies the individual results where the numbers x-y-z represent respectively the laser power density (GW/cm^2), the laser pulse duration (held constant at 18 ns for this work) and the layers of coverage (2 equals 200% coverage). Higher power densities and higher percentage of coverage produce higher magnitude surface stress and a greater depth of compressive stress. A relatively low power treatment can be used to emulate the residual stress resulting from glass bead peening. The laser peened surface will typically be smoother than the mechanically peened surface, even with the same subsurface residual stress. The wide range of residual stress fields available with laser peening gives the designer the ability to precisely define a local treatment based on component geometry, applied loading, or environment.

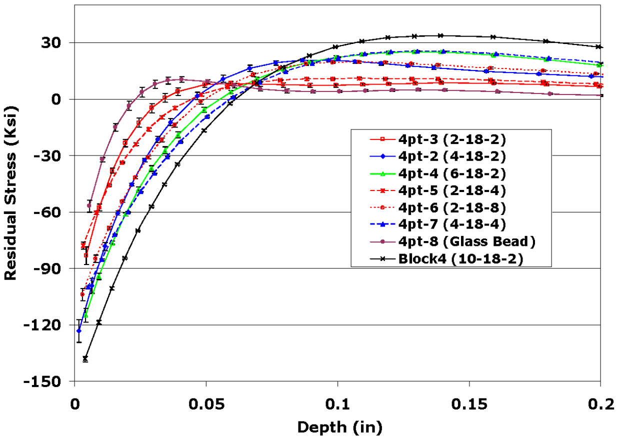

Figure 2: Residual stress versus depth data in BSTOA Ti 6-4 measured with the slitting method for a broad range peening parameters

Figure 3 shows laser peened residual stress in a high strength nickel alloy, MP35N (nominally 20% Cr, 10% Mo, 35% Ni and balance Co). A similar control of the processing also results in selectable levels of residual stress.

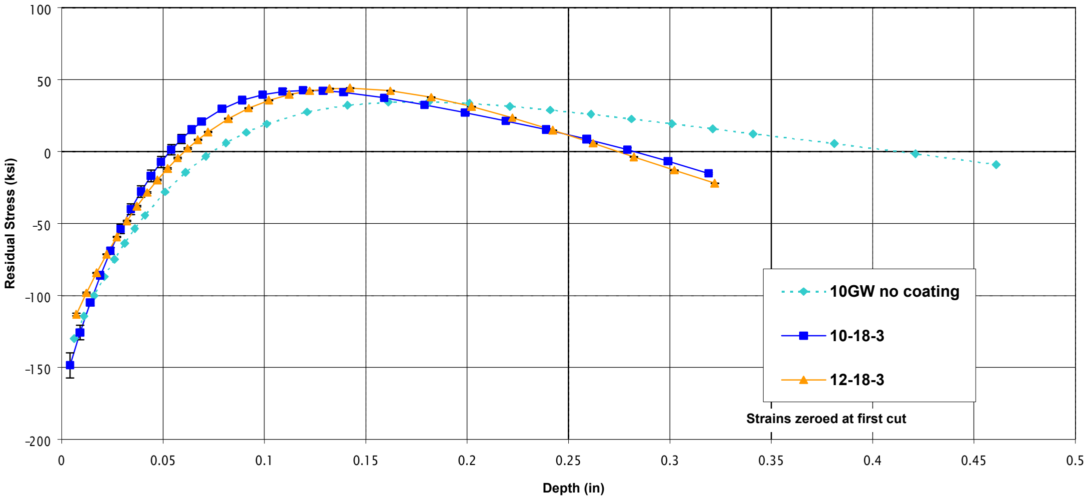

Figure 3: Residual stress versus depth data in MP35N measured with the slitting method

In contrast to the data presented above, Figure 4 shows laser peening induced residual stress in a relatively low strength, lightweight metal, 7050 T7451 Aluminum. Due to the much lower yield strength of this metal, a lower laser irradiance (and hence lower shock pressure) of 2 GW/cm^2 to 4 GW/cm^2 was used for the peening. As with the higher strength metals, relatively higher irradiance or greater percent coverage leads to a greater depth of compressive residual stress. Thus in titanium, nickel alloys, aluminum and steels, the design or overhaul engineer can choose the magnitude and depth of stress required for each area of an application.

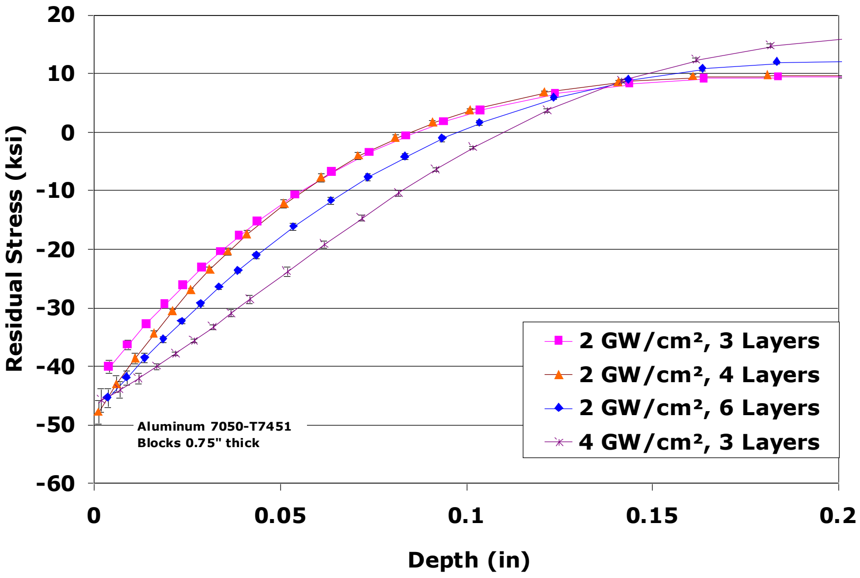

Figure 4: Residual stress versus depth data measured with the slitting method in Al 7050-T7451 blocks laser peened with various parameters

Fatigue enhancement

Compressive residual stress introduced into a component through laser peening improves fatigue performance, either through extended fatigue lifetime at a particular test stress, or increasing the allowable stress for a particular desired life. Figure 5 shows fatigue data for BSTOA Ti 6-4 in laser peened, glass bead peened, and etched base metal conditions. Etching was performed for all coupons to eliminate near surface residual stress and marking from the coupon fabrication. The samples were smooth ($K_t = 1$) bars fatigue tested in four-point bending. Laser peening was performed at 10 GW/cm^2, 18 nanosecond pulses and 300% coverage. The residual stress due to peening in this material for similar parameters is shown in Figure 2. Note that the data plotted in Figure 5 are not the raw fatigue results, but the results of a Weibull analysis. For a given lifetime, the allowable stress for a laser peened coupon is increased by approximately 25% compared to the etched base material.

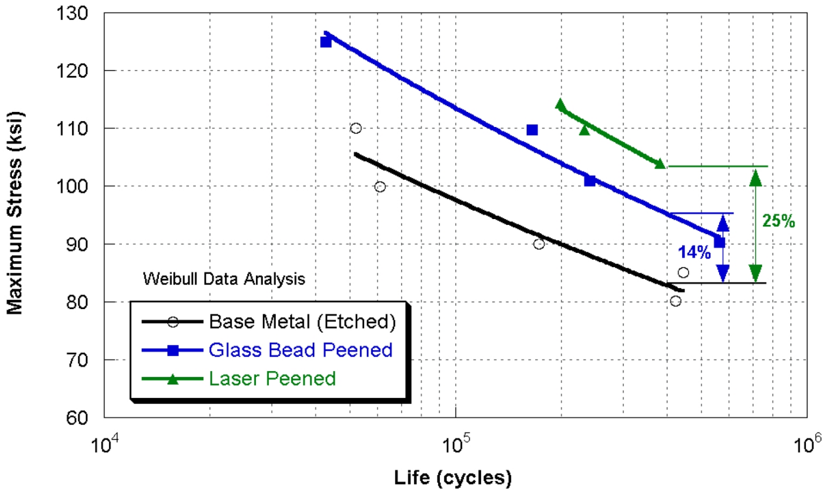

Figure 5: A Weibull data reduction from a fatigue study with BSTOA Ti 6-4 etched, glass bead peened and laser peened, smooth four-point bend bars

The benefits of laser peening can be even greater when the influence of realistic geometry is considered. In a notched geometry with a stress concentration factors greater than unity, the benefit of deep residual stress becomes even greater as resistance to crack growth becomes a dominating factor. Figure 6 shows the results for a four-point bend specimen where a notch with a 0.25 inch radius (K_t=1.3) was machined into the high stress region to simulate a stress riser present in an actual component of interest. The greater K_t factor emphasizes the value of surface compressive residual stress in the notch area for impeding the nucleation of fatigue cracks.

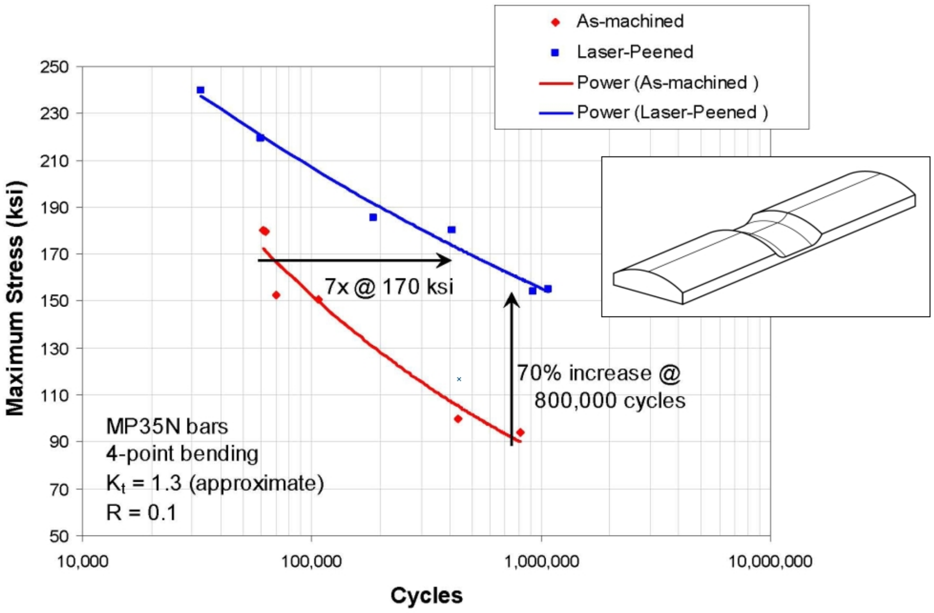

Figure 6: Laser peened and unpeened fatigue data for four-point bend bars with Kt=1.3 manufactured from MP35N

Laser peening has also been effectively used to improve fatigue performance of weldments, where the weld is both a geometric stress riser, and the material is left in an undesirable tensile residual stress state from the welding. Four-point bend coupons were fabricated from ASTM A656 Grade 1 steel (minimum yield strength of 80 ksi) with a weld running transverse to the stressed direction. The weld was made by machining a 0.5 inch deep, 60° vee groove into the 0.75 inch thick parent plate and re-filling with a multi-pass automated process. The weld reinforcement was left unimproved, which resulted in a stress concentration at each toe. Laser peening was applied as shown in the inset in Figure 7, with three layers covering the entire weld width, and a fourth layer of spots applied at each weld toe. The fatigue data shows that in this load range laser peening gives an increase in allowable stress of more 20%, while maintaining the same fatigue life, or approximately an order of magnitude increase in life at a particular test stress.

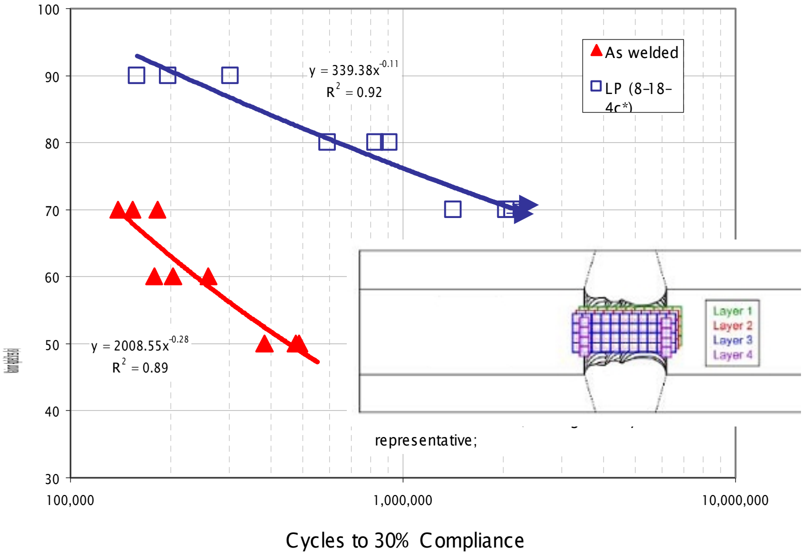

Figure 7: Fatigue data for welded four-point bend coupons with and without laser peening

Mitigating environmental effects - Stress corrosion cracking and foreign object debris

In real world applications, components are subjected to environmental effects that can dramatically impact service life. Two important environmental conditions are foreign object damage (FOD) and stress corrosion cracking, (SCC).

To quantify the effects of laser peening on these environmental factors, fatigue testing was performed on four-point bend bars made from 300M, a high strength steel used in aircraft landing gear components. The material was heat treated to a hardness of 54 HRC and a yield strength of 240 ksi. The laser peening parameters employed were 10 GW/cm^2 and 300% coverage, and were selected by residual stress measurements and iterative fatigue testing. FOD was simulated by machining a triangular notch 0.005 inch wide (in the stressed direction) by 0.080 inch long and 0.020 inch deep on the high stress surface of the bend bars. The machining was performed after the laser peening was completed for the LP+FOD coupons. For the corrosion tests the environment was created by taping a piece of gauze soaked in a 3.5% salt solution to the gage section of the bend bars, per ASTM standard G52-00.

Fatigue data for all conditions is shown in Figure 8. Laser peening in the nominal condition (no FOD or salt environment) results in a 59% higher allowable stress for the same lifetime, compared to as-machined samples. With the introduction of FOD or a corrosive environment, both the laser peened and the unpeened coupons experience a performance detriment, but all laser peened coupons still exceed the performance of the as-machined coupons. LP+FOD and LP+Salt allowable stress was 19% and 29% higher respectively than as-machined (no FOD or salt).

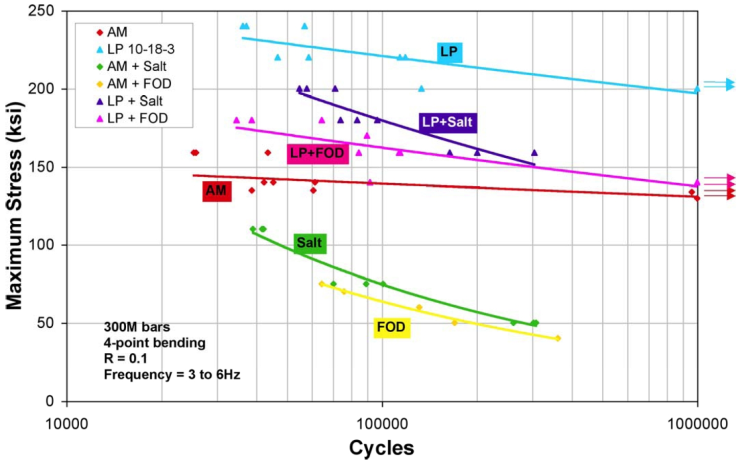

Figure 8: Fatigue data for high strength 300M steel in smooth, damaged (FOD), and corrosive environments, with and without laser peening

Production quality laser peening enables use as an engineering tool

The concept of laser peening has existed almost since the invention of the laser in the 1960s. However laser technology capable of producing the required peak power in the range of 1 GW and useful repetition rate with sufficiently good beam quality were not available. In 1997 the first production applications began to mitigate FOD induced cracking on the fan blades of GEAE F101 and F110 jet engines.

This processing was relatively slow but the resultant residual stress was highly beneficial to the engines and thus aircraft safety. Subsequently, in 2002, a laser technology employing a multipass slab laser amplifier and wavefront phase conjugation was introduced. This enabled much higher repetition rates and thus higher surface coverage rates. Wavefront control provides uniform and controlled illumination of the target at all repetition rates and all operational scenarios, a factor critically important for delivering millions of laser shots in a production environment. This advanced technology introduced commercial high volume laser peening that has proven to be repeatable and reliable. The spot patterns are controlled with precision robots and laser processing parameters and robot positions are recorded for each laser shot. The laser peening systems are FAA and JAA approved for peening aircraft components and meet ISO 9001 production standards. In production use, including 3 shift / 6 day per week operation, system availability exceeds 97%. To date over 12,000 wide chord commercial jet engine fan blades and discs have been laser peened with high levels of quality control at each step. In short, laser peening processing has matured for use in a broad range of engineering applications.

Summary

Laser peening can provide very deep levels of compressive stress in a highly reliable manner and at the high throughput rates required for commercial production. The residual stress induced by the process is shown to enhance fatigue life of components, resist stress corrosion cracking and enhance tolerance to environmental effects such as foreign object damage. The reliability and repeatability of the process and the acceptance by engineering authorities enables the use of applied residual stress in the initial design and overhaul of components and systems.