LASER PEENING APPLICATIONS FOR NEXT GENERATION OF NUCLEAR POWER FACILITIES

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Abstract

Generation of electricity by nuclear power can assist in achieving goals of reduced greenhouse gas emissions. Increased safety and reliability are necessary attributes of any new nuclear power plants. High pressure, hot water and radiation contribute to operating environments where Stress Corrosion Cracking (SCC) and hydrogen embrittlement can lead to potential component failures. Desire for improved steam conversion efficiency pushes the fatigue stress limits of turbine blades and other rotating equipment. For nuclear reactor facilities now being designed and built and for the next generations of designs, laser peening could be incorporated to provide significant performance life to critical subsystems and components making them less susceptible to fatigue, SCC and radiation induced embrittlement. These types of components include steam turbine blades, hubs and bearings as well as reactor components including cladding material, housings, welded assemblies, fittings, pipes, flanges, vessel penetrations, nuclear waste storage canisters. Laser peening has proven to be a commercial success in aerospace applications and has recently been put into use for gas and steam turbine generators and light water reactors. An expanded role for this technology for the broader nuclear power industry would be a beneficial extension.

Introduction to Laser Peening

Enabled by advanced Nd:glass laser technology, laser peening was introduced to high volume commercial aircraft applications in 2002 and has continued expansion in aerospace, automotive, boiling and pressurized water reactors, and more recently conventional electric power generation applications.[1] The process extends the fatigue life and improves fatigue strength on a wide variety of metal alloys.[2,3] It is currently being utilized extensively by the commercial aviation industry to prevent foreign optic damage (FOD) fatigue and fretting fatigue of highly stressed rotating turbine engine components and more recently for gas and steam turbine electric power generation fatigue applications where the need for higher efficiency is requiring larger blades with greater stress loadings. In this paper we will present data on the fatigue benefits of laser peening applied to metals and will present specific data showing the benefits of Laser Peening to mitigate stress corrosion cracking (SCC) in metal alloys such as Alloy 600 and C22 as utilized in the Nuclear Power Industry.

It is has been shown 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 general corrosion [4,5]. Techniques such as shot peening (1), roller burnishing (2) and cavitation peening (3) have played important roles in extending the performance and lifetime of metal based systems. Each of these techniques has important applications but is limited as to the precision and areas that they can be applied and are nominally limited to the depth of compressive residual stress (RS) that they can achieve in the component without other deleterious effects such as high levels of cold work and/or a poor surface finish. In many applications a deeper level of compressive stress with low cold work and good surface finish is highly desirable.

Laser peening induces 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

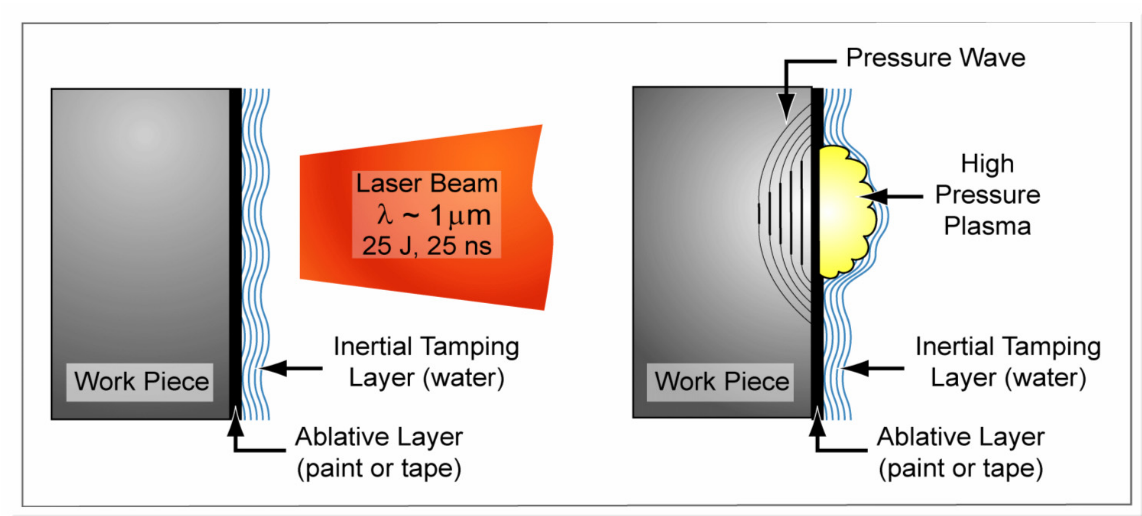

Figure 1*: A graphical representation of the laser peening process*

The laser light rapidly vaporizes a thin portion of the ablative layer, producing 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 8 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 typical surface roughness of 60 Ra in aluminum, titanium and steels.

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 Hz, making systematic treatment of multi-meter 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.

Stress corrosion cracking (SCC) is one of the major phenomena degrading the reliability of aged reactor components. As a preventive maintenance measure to avoid SCC, engineers in Toshiba have recently used laser peening to treat the inner surface of bottom-mounted instrumentation (BMI) nozzles of pressurized water reactors (PWR).[6] The same technique has also been applied to treat the weld lines on inlet nozzles and core flood lines of power reactor vessels (RV).

Laser peening could also be applied to mitigate irradiation assisted stress corrosion cracking (IASCC) in the next generation reactors. During the lifetime of operation, key internal components could potentially accumulate very high irradiation dose. Microstructure changes induced by neutrons are known to affect the mechanical properties of metals. Moreover, the intense radiation field will also induce radiolysis decomposition of the coolant, changing the environment to which key structure material is exposed. These effects may render IASCC failure in reactor parts. Laser peening of these parts will significantly extend the operating lifetime of advanced reactor components and enhance the safety of future power generation facilities.

Engineered Residual Stress for Electric Power Generation 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. Increased fatigue strength and lifetime is becoming more and more important as gas and steam turbine blades are being pushed to ever higher stress limits in an effort to improve conversion efficiency of steam energy to electric energy.

To analyze and engineer stress for a particular application, it is important to consider three elements of stress: 1) residual stress intensity and distribution resulting from manufacturing including machining and welding processes, 2) stresses resulting from applied loads and 3) engineered stress applied by processes such as laser peening. In the cases of all these stresses it is important to consider the multidimensional distribution of both the compressive and tensile components of the stress to determine the expected fatigue and corrosion cracking performance of a component.

In order to determine the intensity and distribution of manufacturing and imposed residual stresses, we routinely use x-ray diffraction techniques to determine residual stress on both the surface and in the subsurface of components. Additionally we use strain compliance techniques such as slitting (crack compliance method) [7] that provides excellent data on subsurface compressive and the deeper tensile components of stress) as well as fine hole drilling coupled with precision strain measurements. These techniques are in general applicable to a variety of materials.

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.

Control of Residual Stress in Steam Turbine Blades

Titanium steam turbine blades are being used in many higher performance steam turbines. Figure 2 illustrates the excellent level of control of residual stress that can be achieved in titanium alloys for example, by selection of laser peening parameters. Stresses as deep as 1.5 mm (0.060 inches) are achieved with excellent repeatability. The figure shows residual stress as a function of depth in 12.5 mm (0.5 inch) thick blocks of Beta Solution Treated and Overaged (BSTOA) Ti-6Al-4V 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 results of Figure 2 also show the effects of peening with a small spot (1 mm dimension vs. a more typical 3 mm spot). When the peening spot size is on the order of or smaller than the size of the desired depth, this small peening spot results in rarefaction of the shock wave as it propagates subsurface producing a Hertzian type force that results in low surface stress and less depth of compressive stress. Multiple hits of the surface required of the low energy also produce a more highly cold worked surface. This small spot size is a consequence of fiber optic based laser peening systems where transmitted peak power is limited by the optical damage limits of the fiber and consequently small (sub-millimeter) spot sizes are required to keep the laser fluence at the required multi-GW levels. In contrast, the surface laser peened with a high energy laser (~16 J) and the larger 3 mm size spot will typically be smoother than the mechanically peened surface, even with the same subsurface residual stress and display significantly less coldwork. 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.

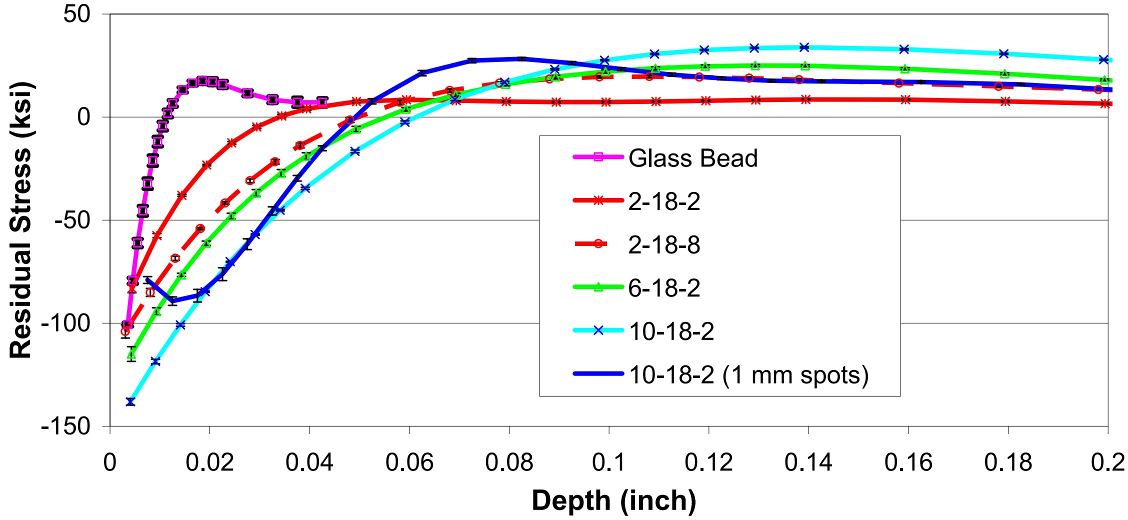

***Figure 2:** Residual stress versus depth data in BSTOA Ti 6-4 measured with the slitting method for a broad range peening parameters (100 ksi = 700 MPa)*

Geometries with fillet radii and other stress rising features are inevitable in steam turbine blade design. The combination of high stress loading from operation and the stress risers induced by geometry creates weak points susceptible to crack initiation and fatigue failure. In a geometry with 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 3 shows the results for a four-point bend specimen of corrosion resistant alloy, MP35N (nominally 20% Cr, 10% Mo, 35% Ni and balance Co), where a 6.3 mm (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 and growth of fatigue cracks.

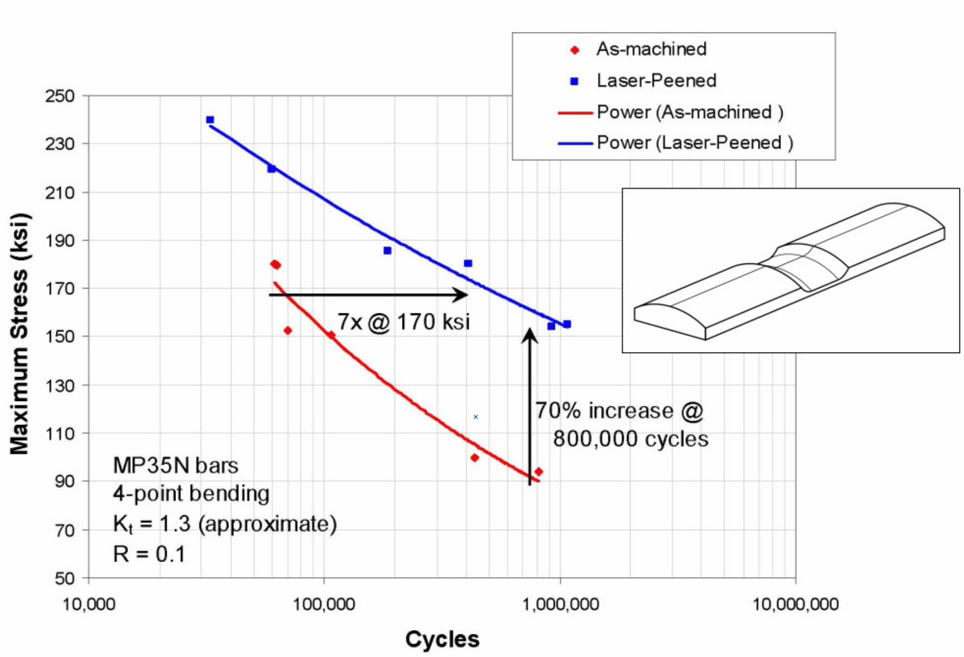

Figure 3: *Laser peened and unpeened fatigue data for four-point bend bars with Kt=1.3 manufactured from MP35N (170 ksi = 1190 MPa)*

As can be seen, the laser peening extends the fatigue lifetime at constant stress loading by roughly a factor of 7x. Equally important for highly stressed components such as steam turbine blades, the fatigue strength increases by roughly 70% allowing successful operation in a more highly stressed situation.

This is an excellent example of how residual stress can be engineered into a specific component with specific localized loading. Using an analysis of the applied loading and the local Kt factor of the geometry and specifying an applied stress treatment as explained by Figure 2, the design engineer can tailor the local stress under loading to optimize fatigue performance.

Improve Fatigue Lifetime of Welded Parts

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. As shown in figure 4, 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 12.5 mm (0.5 inch) deep, 60^o vee groove into the 19 mm (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 with three separate layers of peening each 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

60%, while maintaining the same fatigue life, or approximately an order of magnitude increase in life at a particular test stress.

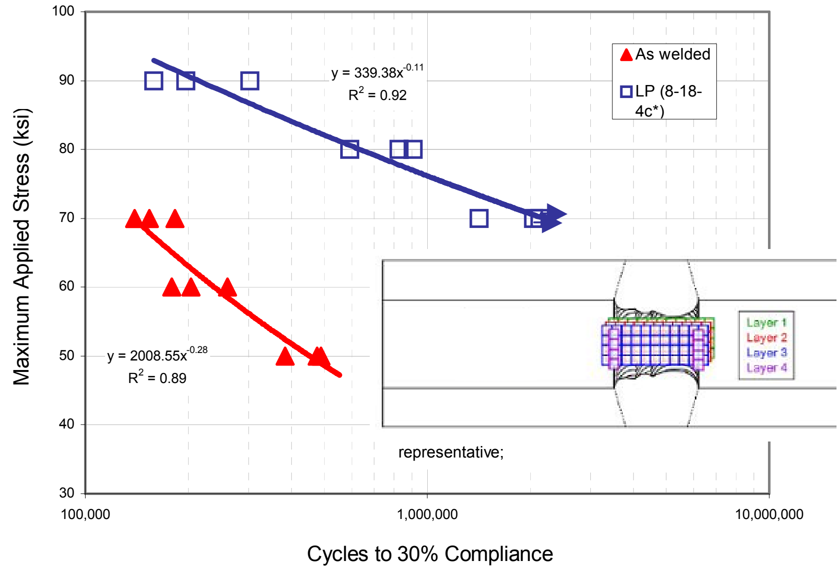

***Figure 4:** Laser Peened welded 4pt bend bars demonstrate ten times life enhancement compared to unpeened specimens (All testing was performed with R=0.1 and tests terminated at a 30% increase in specimen compliance) (60 ksi = 420 MPa)*

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Mitigating Stress Corrosion Cracking in Steels

Laser peening is also very effective in mitigating stress corrosion cracking. In order for stress corrosion cracking to initiate and propagate, three conditions are needed: the material needs to be susceptible to corrosion cracking, there needs to be a corrosive environment and the area in question needs to be under tensile stress. Because laser peening induces compressive stress, it is able to eliminate the tensile stress and thus greatly reduce the cracking. Because of the great depth of compression, the laser process is much more effective than processes such as shot peening which create a shallower compressive stress. Figure 5 shows an example of the benefits of the deep laser peened residual stress at applied to 300M high strength steel. These results were obtained from samples peened by MIC and tested by Theresa Pistochini and Prof. Michael R. Hill of UC Davis [8]. Three layers of laser peening were applied with a fluence of 10 GW/cm2 and laser pulse duration of 18 ns. In the accelerated corrosion testing of the three types of samples, the figure shows that the compressive surface stress induced by shot peening improves the lifetime by approximately a factor 2x but the laser peening shows lifetime improvement well in excess of 7x where the experiments were terminated after multiple samples did not fail.

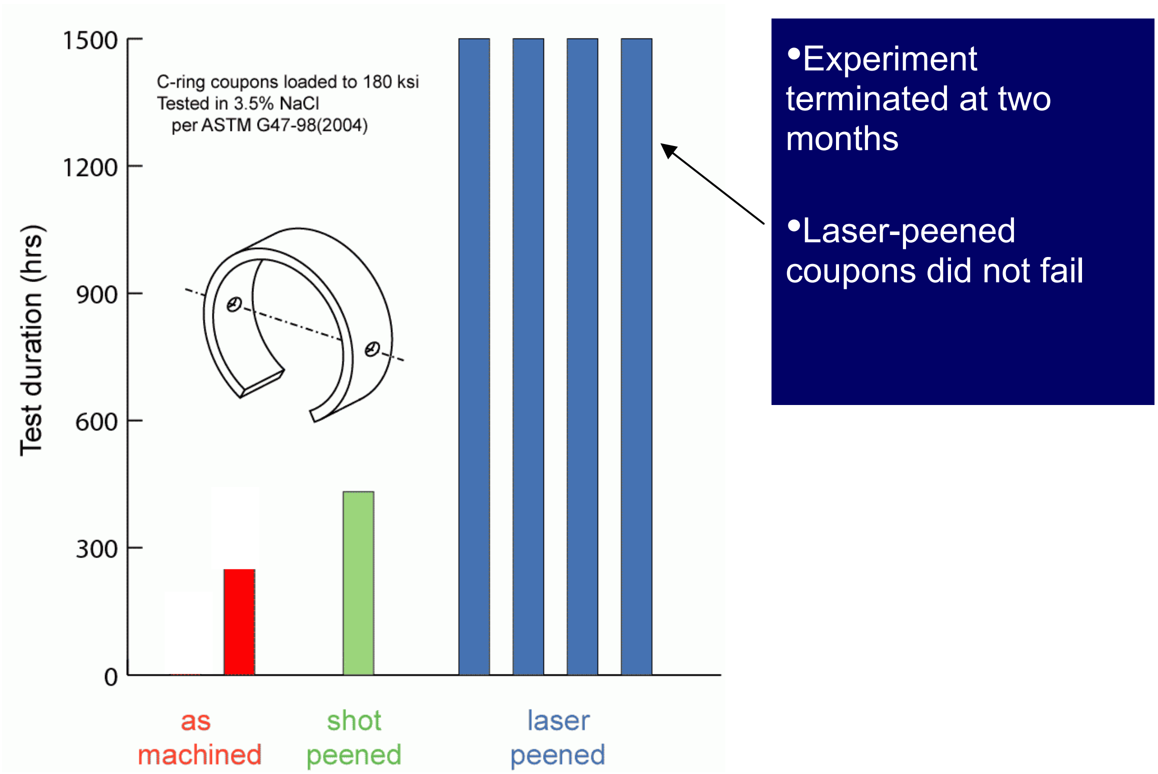

Figure 5: *Test results for stress corrosion cracking of 300M steel showing improvement in lifetime by applying residual compressive stress. Shot peening improves* lifetime by roughly 2x whereas laser peened samples would not fail after 7x lifetimes of as machined.

Figure 6 shows a qualitative example of the benefit of laser peening. In this example a 1 inch thick sample of 316 stainless steel was welded along the seam visible across the horizontal center of the sample. A region denoted by the dotted rectangle was laser peened and then two glass cylinders were epoxied to the sample each spanning the welded region. The cylinders were then filled with magnesium chloride kept at a temperature of 155 ^{o}C over a period of days. As the photograph clearly shows, stress corrosion cracks developed in the unpeened region both transverse to the weld and along the weld in the heat affected zone. The longitudinal cracks terminated upon reaching the compressive stress of the laser peened region. There is also general corrosion associated with the stress corrosion cracked regions. In contrast the laser peened areas, show a total lack of cracks and in general very little corrosion.

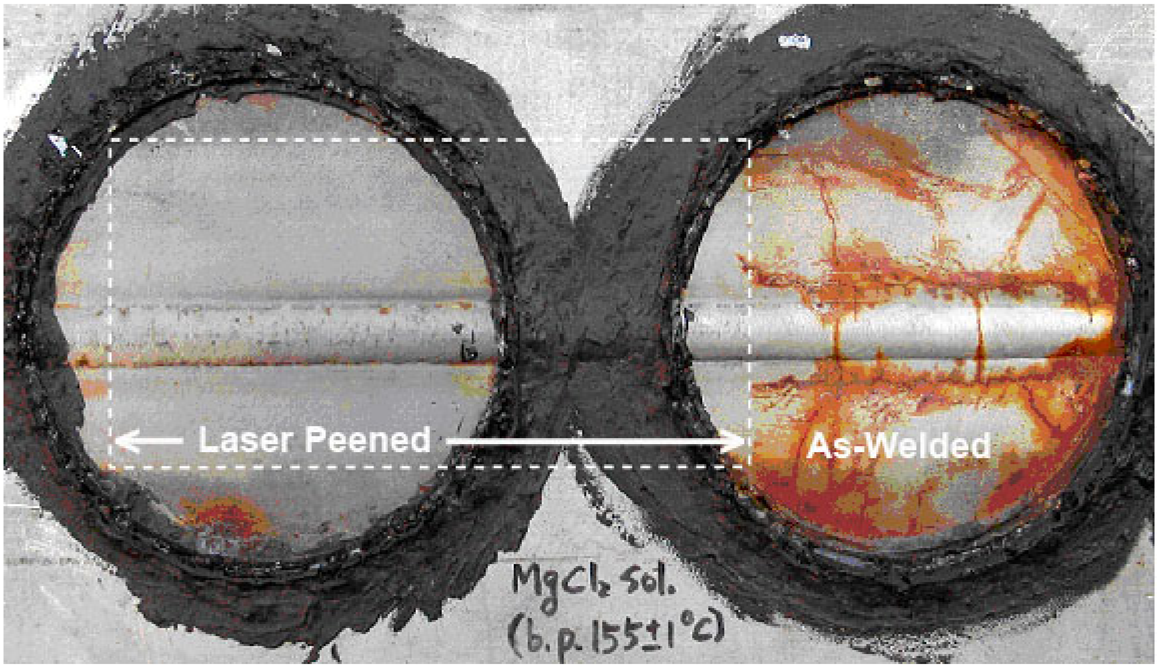

Figure 6: *One inch thick plates of 316 stainless steel were seam welded and then exposed to magnesium chloride at 155 ^{o}C to accelerate corrosion cracking. Dotted rectangle shows the laser peened region. In the non-laser peened region, transverse cracks appear across the weld and longitudinal cracks travel along the head affected zone but arrest when they reach the laser peened area. In contrast, the laser peened region shows no cracks and essentially no corrosion.*

Retarding SSC in Alloy 600 Inconel and 316L Stainless Steel

Material for nuclear reactors is specially chosen to be highly resistant to stress corrosion cracking. A particularly good material is Inconel Alloy 600. This material is a nickel-chromium alloy with good oxidation resistance at high temperatures and resistance to chloride-ion stress-corrosion cracking, corrosion by high-purity water, and caustic corrosion. As an evaluation of the potential benefits of laser peening for this alloy in nuclear reactor applications, we performed a demonstration experiment with results as shown in the photographs of Figure 7. Again the samples were comprised of U-bends loaded in tension, somewhat similar to that discussed in ASTM G47-98 (2004). SCC occurs due to the tensile stress in the presence of the thiosulfate solution. The photograph c shows significant cracking for a sample with no applied residual stress. In contrast the laser peened sample without pre-cracking showed no induced cracking and a sample pre-cracked and then laser peened showed no further growth of the cracking. In power plant applications, laser peening could be applied to create deep levels of compressive stress into welded areas and other areas loaded in tension so as to create greatly enhanced resistance to stress corrosion cracking.[8]

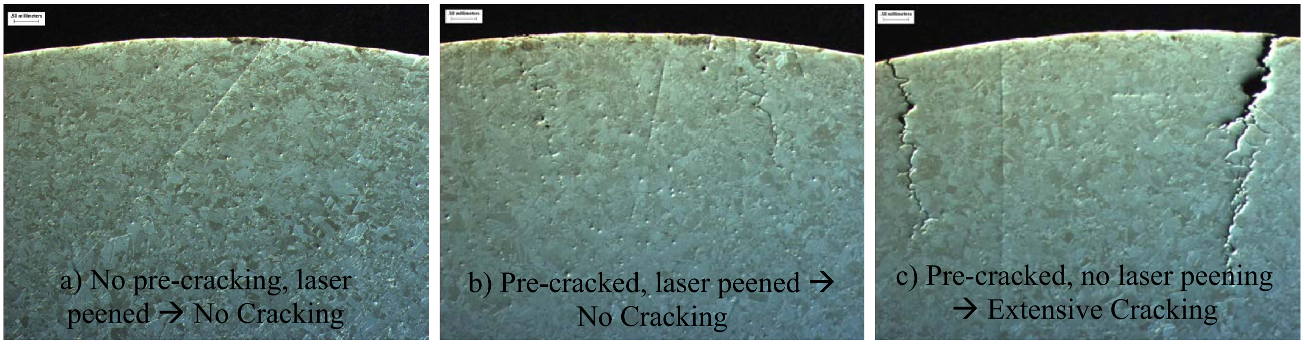

Figure 7: *Alloy 600 U-bends immersed in sodium thiosulfate solution for two days. Figure a) was laser peened then immersed in the thiosulfate solution. Figure b) was immersed in the thiosulfate solution to generate cracks, laser peened, then r-eimmersed in the thiosulfate solution. Figure c) was pre-cracked then re-immersed in the solution for comparison.*

As a final example, we demonstrate the potential of laser peening to help reduce the reaction potential of a surface potentially reducing corrosion and erosion. Figure 8 shows micrograph cross-sections of the surfaces of 316L stainless steel without and with laser peening after 400 hour exposure to liquid metal coolant (lead-bismuth). The laser peened surfaces showed much greater resistance to chemical interaction as opposed to the non-treated surfaces. A reduction in chemical activity of a treated surface has implications for a broad range of applications in nuclear power and conventional electric power generation. Highly advanced reactor designs could benefit by reducing reaction rates from exposure to liquid metal coolants. Current reactor designs could potentially benefit in areas where fluid flow or exposure to chemicals are an issue. Also, in current conventional electric power generation, erosion of leading and trailing edges steam turbine blades can be caused by chemical and mechanical interaction with the flowing steam and with water droplets injected into the steam. Reducing the chemical reaction rate and erosion potential on steel and titanium blades would be great benefit to extending the lifetime and potentially enabling design improvements leading to improved steam to electrical conversion efficiencies.

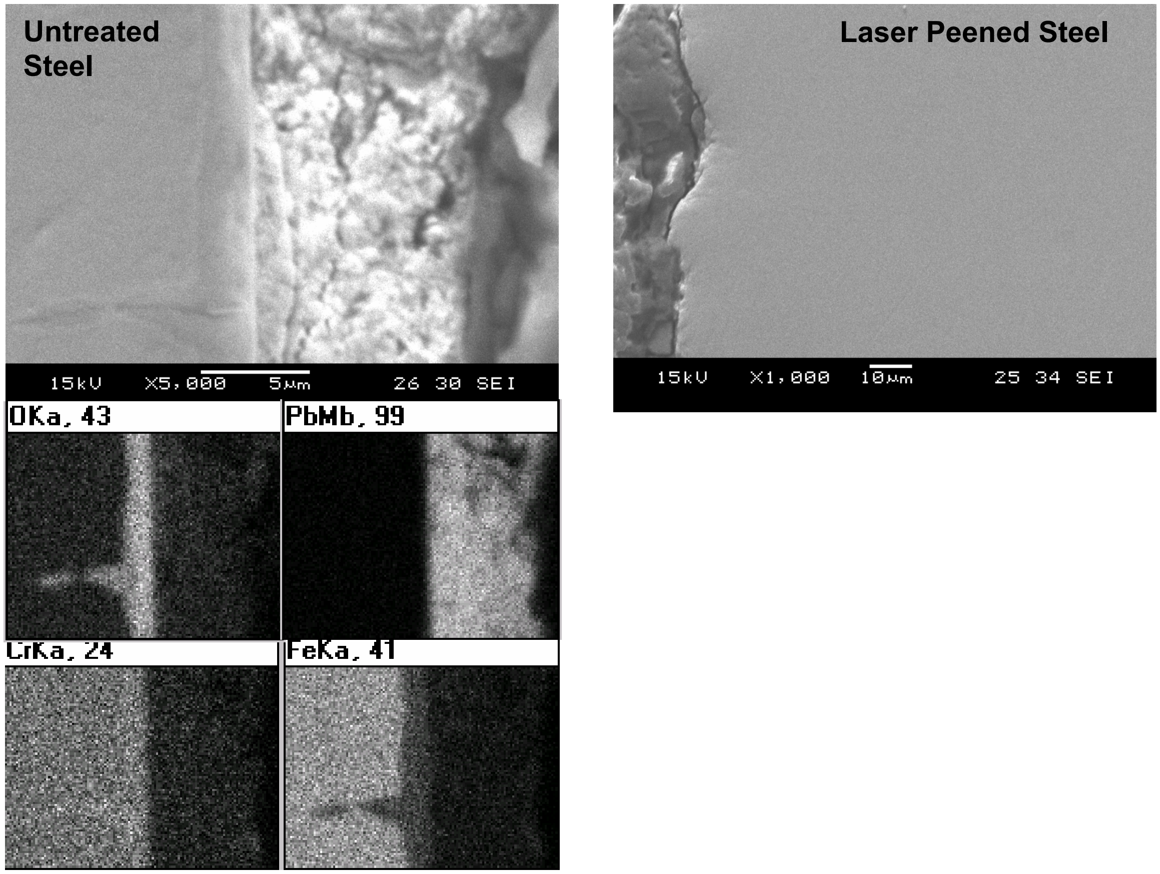

Figure 8: *Laser peened 316L shows no oxide layer formation after 400 h exposure to liquid metal coolant (lead-bismuth).*

Transportable laser technology

Many applications, such as work in nuclear power plants, require an ability to bring laser peening into a facility to work on large components in situ. With this in mind, the laser peening technology has been packaged into transportable trailers that allow production deployment with a peening laser stationed in or near but outside of a facility and the laser beam propagated inside simple tubes to a robotic system that is able to scan and peen the areas needing compressive stress. Transportable systems have been built as pictured in Figure 9. Moveable beam systems have been deployed in our shops for production processing and are being used for peening for steam turbines blades and for the large fan blades for the newest of commercial jet engines. A transportable system, UL certified as an approved system, with separation between the laser and processing area of over 150 feet has been set up in at a major commercial jet manufacturer for forming very large wing skin panels. Basically the technology that would be needed for working inside nuclear and conventional power plants is available and proven in production

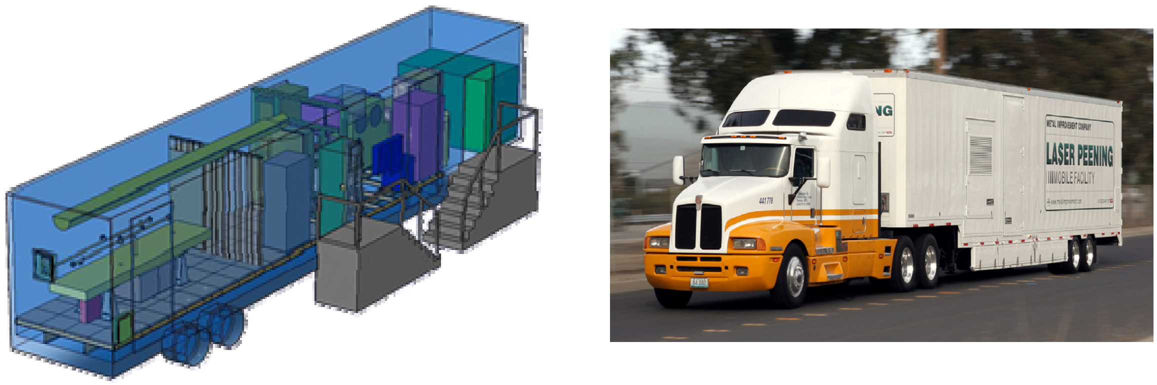

Figure 9: *Transportable laser peening systems have been built and put into production allowing consideration of on site processing at nuclear and conventional power generation facilities.*

Summary

Laser peening has become an accepted, reliable production tool for introducing deep levels of compressive stress into components. Major current applications include highly stressed components in aircraft engines, in motor sport engines, in light water power reactors and in electric power generation gas and steam turbine blades. This technology can be applied to engineering residual compressive stress to mitigate fatigue and stress corrosion cracking issues in conventional electric power generation systems and next generation nuclear power facilities.

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