Laser Peening to Mitigate Stress Corrosion Cracking of Nuclear Power Facilities

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Abstract

Nuclear power is experiencing a rebirth with new materials and technologies offering the potential to reduce issues of reactor safety and reliability. Laser Peening is a mitigation technology introduced to advanced production in 2002, providing high volume, cost effective processing. It is being used for aircraft, automotive and conventional electric power generation applications. The technology has been made transportable for deployment at aircraft hangers, marine shipyards and nuclear power facilities. We describe hardware and new approaches for peening inside of pipes and other confined or hard to reach areas. We present data on the fatigue and SCC benefits of laser peening in metals, including Alloy 600 and C22 as utilized in the nuclear industry.

1. Introduction to Laser Peening

High pressure, hot water and radiation contribute to operating environments in the nuclear power industry where Stress Corrosion Cracking (SCC) and material erosion can lead to component failures. For current and next generation of nuclear reactor facilities it would be a significant advantage if the critical subsystems and components could be made less susceptible to these failure mechanisms. These types of components include piping and tubes, cladding material, welded assemblies, fittings, flanges, vessel penetrations, nuclear waste storage canisters; and even the non-radioactive subsystems, such as the airfoils of highly stressed rotating steam turbine components.
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 and more recently conventional electric power generation applications.[1] The process extends the fatigue life and improves fatigue strength of 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. Military applications include extending the lifetime of components loaded beyond yield stress limits such as aircraft arrestment hook shanks.

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 typically much deeper than conventionally available processes.. 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 depending on the yield strength of the material being peened, is most often directed on to a sacrificial ablating material placed on the surface of a component to be treated. In some applications where placement of an ablative layer presents a complication, the peening can be done on the metal surface itself, omitting the ablative layer.

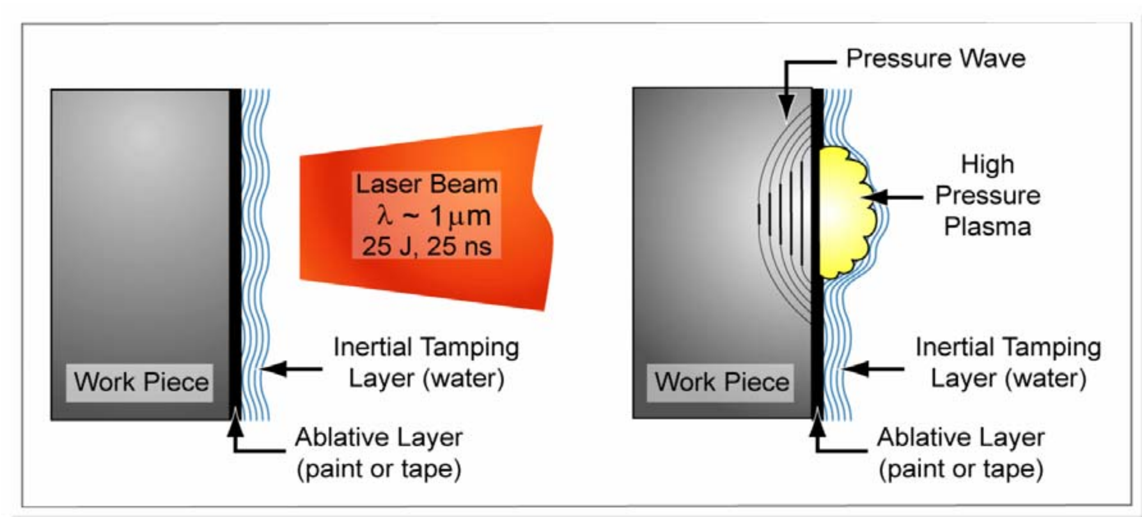

Figure 1**:** A graphical representation of the laser peening process

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 propagates into the part. This shock wave creates 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, thus enabling treatment rates as great as 1 square meter per hour. 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. When an ablative layer is not used in the processing, a recast layer of metal is formed on the surface to a depth of about 10 microns. This layer, although of reduced compressive or even tensile stress, can be easily removed or in some application left in place with no deleterious result.

2. Applications to Conventional and Nuclear Electric Power Generation 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). The system described herein and built by Metal Improvement Company, is also well suited to these types of applications and offers the great advantage of requiring only single to two shot per unit area application with its more powerful laser output and thus affording much faster processing.

Laser peening with relatively low energy laser systems, less than 1 Joule per pulse, and systems with round beams of Gaussian profile generated lower depths of compressive stress due to the relatively rapid expansion of the shock wave as it propagates into the material. The small spot size and normal type of intensity profile also creates a Hertzian type of impact leaving a reduced surface residual stress. Results of measuring residual stress from a 1 mm spot size are shown in Figure 2. In contrast the figure shows deeper levels of compressive stress and greater surface stress when 10 GW/cm2 laser irradiance is employed but using a much larger 3 mm spot size. 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. .

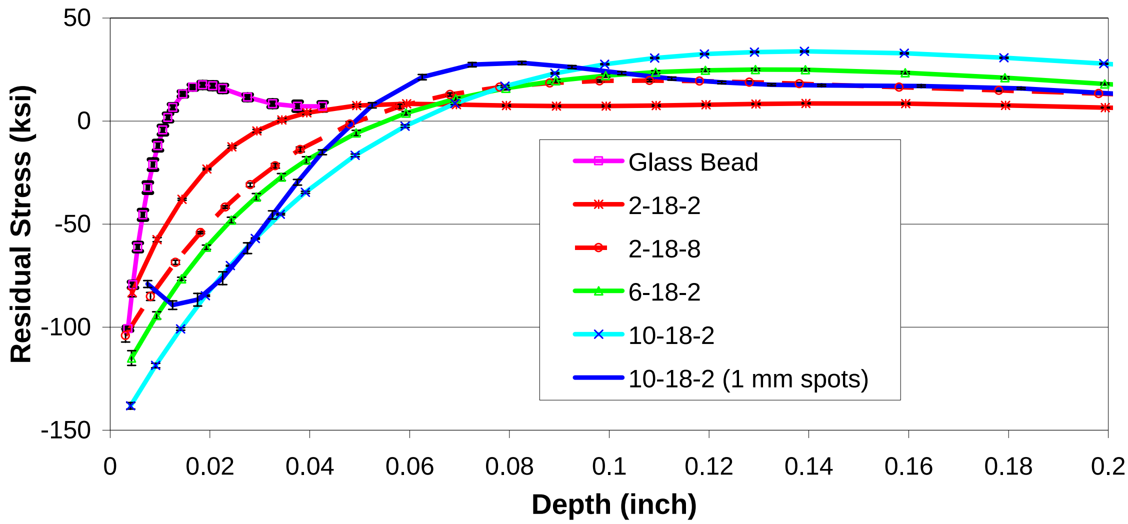

Figure 2: Residual stress versus depth data in BSTOA Ti 6-4 measured with the slitting method for a broad range peening parameters (100 ksi = 700 MPa)

3. Laser peening inside of pipes and tubes

Many of the failure problems in power plant operation occur with pipes and tubes. This includes stress corrosion cracking and erosion where water chemistry and flow create the environment for failure. Consequently is it important for the laser treatment process to be able to access the inside regions of pipes to add compressive stress to the impacted regions. These regions can include the interior areas of welds as well as those regions in the water flow where corrosion/erosion occurs due to fatigue from collapsing bubbles. We have consequently developed an approach to reach into moderate sized pipe and tubing (4 inch to larger diameter) to apply laser peened compressive stress on the interior.

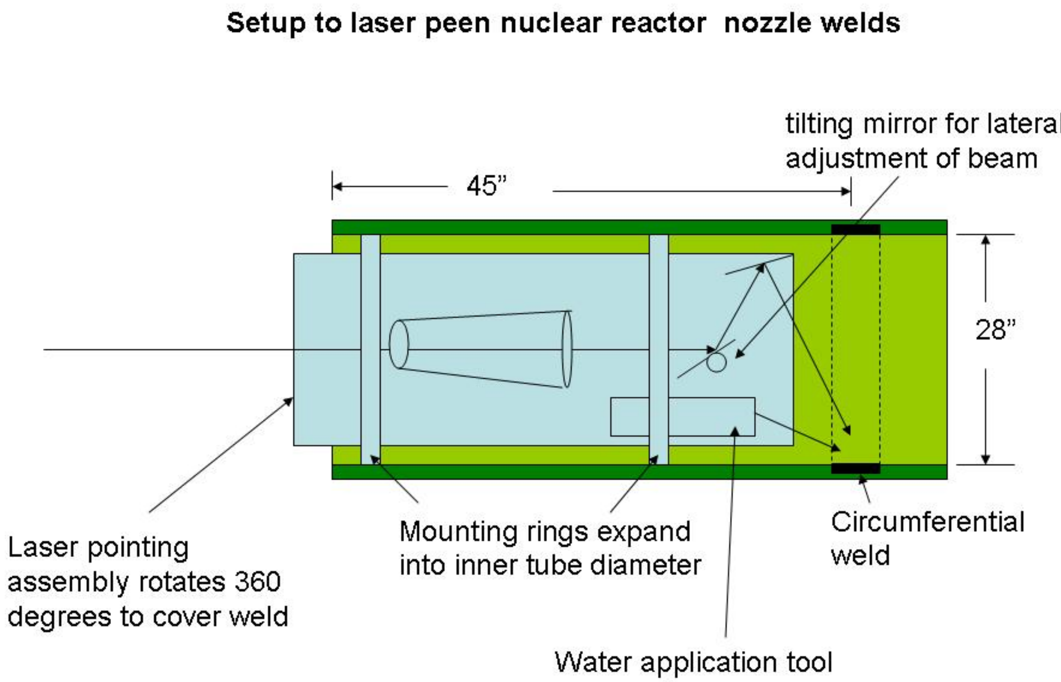

Figure 3: Approach for laser peening inside of pipes

Figure 3 shows a schematic drawing of our approach for directing the laser beam into a tube and then manipulating the beam about the interior for processing. In the approach, an optical system is mounted within a cylinder that slides into the pipe up to the area to be laser peened. Mounting rings extend from the cylinder to grip the interior wall and secure the cylinder in place. The high power laser is then fed into the input end of the cylinder with its pointing controlled by an optical control system similar to that deployed in our production moveable beam systems. Control optics within the cylinder direct the beam on to the weld or other area needing peening. A separate water application tool provides the tamping water for the shock generation. Remembering that laser peening can be applied at angle up to 70 degrees off of normal incidence, the beam can reach out from just in front of the cylinder to an further distance approximately 1.8 times the pipe diameter and by rotating the cylinder around the entire diameter of the pipe can be laser peened. The cylinder can then be repositioned for the next section of inner pipe to be laser peened. For example, for a 28 inch inlet water nozzle, a band 50 inches wide around the entire pipe diameter can be peened with a single positioning of the laser peening cylinder. The significant ability of laser peening to arrest stress corrosion cracking is discussed in the next section of this paper.

4. Retarding SSC in Alloy 600 Inconel, 316L and High Strength Steels

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 4. 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]

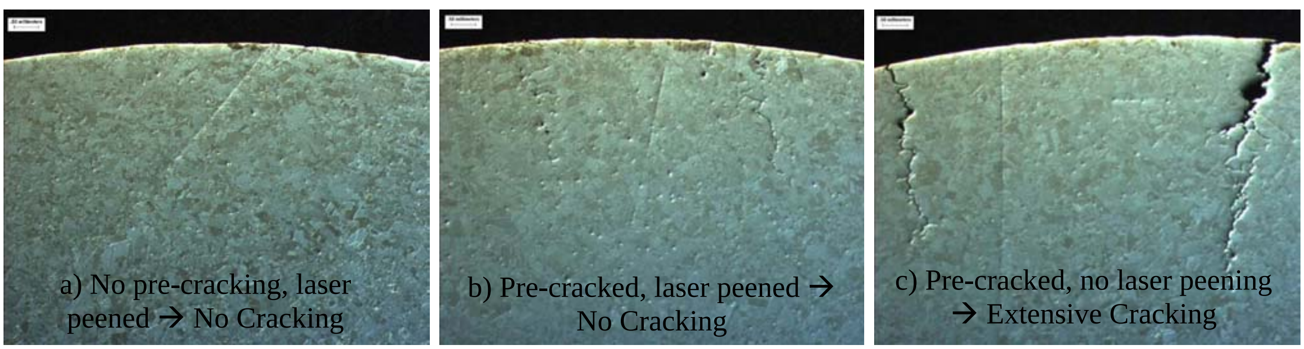

Figure 4: Alloy 600 U-bends immersed in sodium thiosulfate solution for two days. Figure a) laser peened then immersed in the thiosulfate solution. Figure b) immersed in the thiosulfate solution to generate cracks, laser peened, then r-eimmersed in the thiosulfate solution. Figure c) pre-cracked then re-immersed in the solution for comparison.

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.

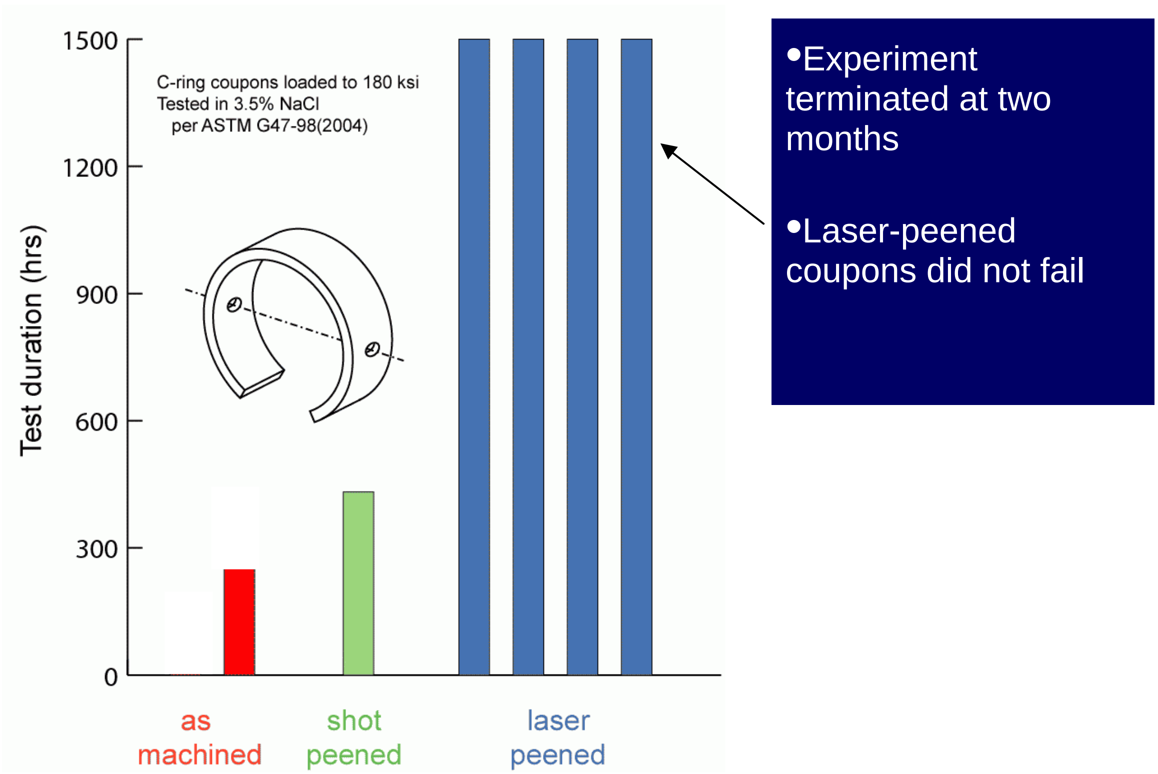

Figure 5: Test results for stress corrosion cracking of 300M steel showing improvement in lifetime by applying residual compressive stress. Shot peening improves lifetime by roughly 2x whereas laser peened samples would not fail after 7x lifetimes.

5. 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 6, 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 of Figure 6 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.

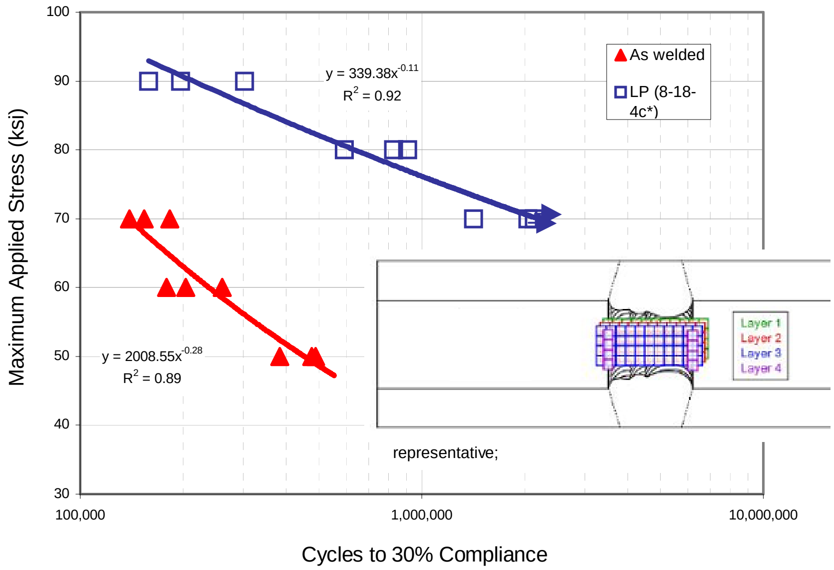

Figure 6: Laser Peened welded 4pt bend bars demonstrate ten times life enhancement compared to unpeened specimens (All testing was performed with R=0.1 and tests terminated at a 30% increase in specimen compliance) (60 ksi = 420 MPa)

6. Transportable laser peening systems

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 7. 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

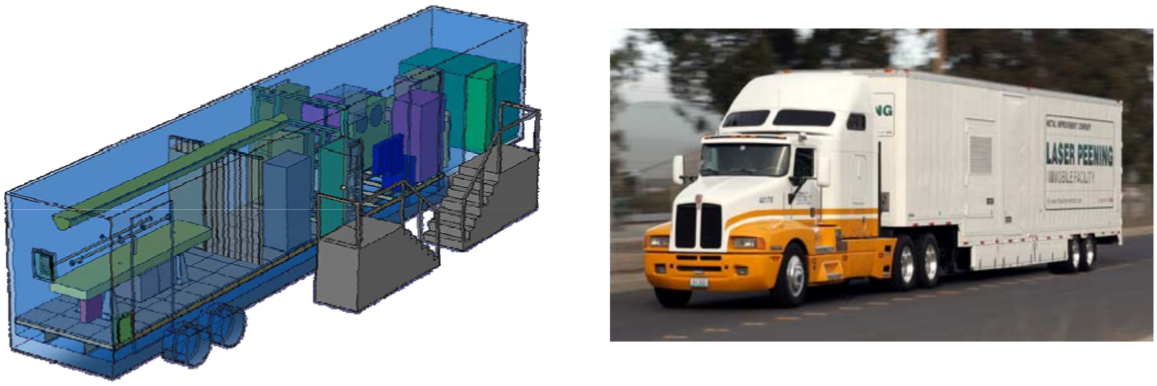

Figure 7: Transportable laser peening systems have been built and put into production allowing consideration of on site processing at nuclear and conventional power generation facilities.

7. 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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