LASER PEENING TECHNOLOGY

Laser peening is a rapidly developing surface treatment that puts the surface in a state of compressive residual stress to improve resistance to SCC.

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Laser peening is a process in which a laser beam is pulsed upon a metallic surface, producing a planar shockwave that travels through the workpiece and plastically deforms a layer of material. The depth of plastic deformation and resulting compressive residual stress are significantly deeper than possible with most other surface treatments.

This article describes some recent developments and applications of laser peening. First we summarize the history and process of laser peening. We then present test results from recent development efforts focused on new applications, describe recently commissioned commercial facilities, and discuss some production-related advances.

Recent progress

Recent dramatic progress in the commercialization of laser peening technology has been made possible by the unique contributions of three different entities: Metal Improvement Company (MIC), Lawrence Livermore National Laboratory (LLNL), and University of California, Davis (UC Davis). Chronologically, MIC funded a Cooperative Research and Development Agreement (CRADA) with LLNL. The CRADA was focused on applying to peening, the advanced solid state laser technology that was originally developed for military and other applications.

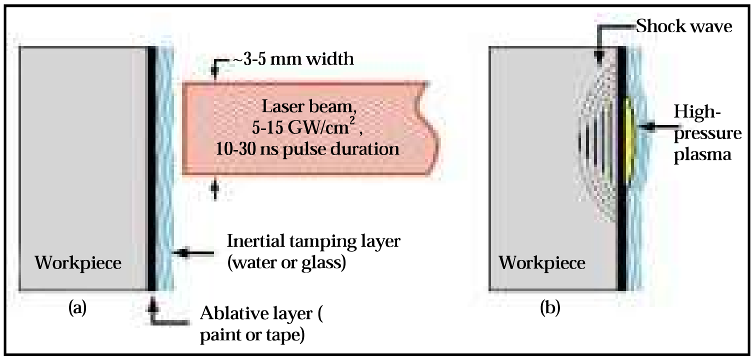

Fig. 1 — Description of laser peening process. (a) Workpiece is covered with a protective ablative layer and an inertial tamping layer. (b) Laser pulse forms high-pressure plasma on the surface of the part, causing a shock wave to travel through the depth and plastically deforming material in its wake.

The successful development of laser peening led to the commercialization of the process by MIC. The LLNL laser technology provides a reliable pulsed laser source that operates at a pulse-repetition rate more than ten times faster than previously available for laser peening. This increase in repetition rate significantly reduces the time required to apply the laser peening treatment, and therefore has increased throughput and reduced cost.

The group at UC Davis has developed key advances in residual stress measurement, and has applied this capability to better understand the effects of a variety of laser peening parameters. UC Davis has also provided mechanical testing, microstructural characterization, and structural modeling to the joint research and development effort.

Laser peening system

Laser peening is a rapidly developing surface treatment process that puts the surface in a state of compressive residual stress. Laser peening was first developed at Battelle Laboratory circa 1965, but was not commercialized for years due to the lack of a reliable, high repetition rate, high average-power laser. To the authors' knowledge, the first commercial application of laser peening was not until 1997 at GE Aircraft Engines (Cincinnati, Ohio) to mitigate foreign object damage on fan blade

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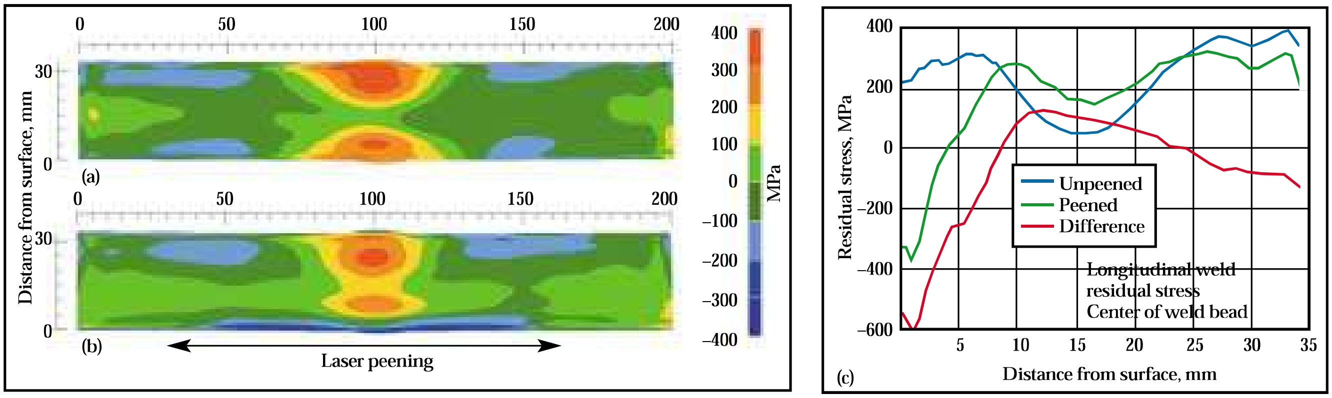

Fig. 2 — Longitudinal residual stress in a 33-mm thick Alloy 22 welded plate: (a) map of residual stress in unpeened weld; (b) map of residual stress in laser-peened weld; (c) line plot of residual stress versus depth at the center of the weld bead.

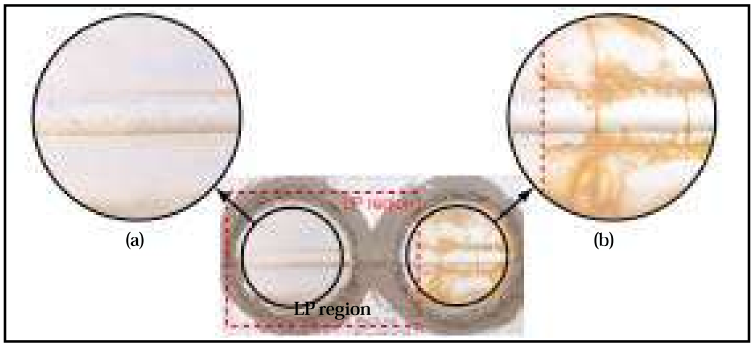

Fig. 3 — Photograph of 316 stainless steel weld tested in boiling $MgCl_2$ solution, showing (a) no SCC damage on the laser peened section, and (b) extensive SCC damage on the unpeened section, with crack arrest near the boundary of laser peening (red dashed line).

leading edges for a military aircraft turbine engine.

Production laser peening capability has grown enormously in the past two years. MIC's Laser Peening Division has recently commissioned two commercial laser peening systems, which are being used to treat turbine engine components.

The following description of laser peening has certain details that are specific to the LLNL-MIC laser peening system, but other recent commercial and research laser peening systems are not significantly different. The LLNL-MIC laser peening system is based on a novel Nd:glass slab, flashlamp pumped laser (Fig 1.)

- *System parameters:* The system has capability of 125 watts average power, a pulse width of 10 to 100 ns, a pulse energy to 20 J, a repetition rate to 5 Hz, and a nominally rectangular laser-spot profile. In general, the typical laser peening parameters are pulse width of 10 to 30 ns, pulse energy of 10 to 20 J, repetition rate of 3 Hz, and a laser spot size of 3 to 5 mm square.
- *Surface prep:* The laser source is directed at a prepared surface on a metallic workpiece. Consider a planar section through the workpiece, at the peening location. An opaque sacrificial "ablative layer" of paint or tape is applied to this surface prior to processing. A transparent "tamping layer" of laminar flowing water is also present, on top of the ablative layer.
- *Laser pulse:* A laser pulse is then directed at the workpiece surface. The photons in the laser pulse pass through the transparent tamping layer, and are absorbed by the ablative layer. This gives rise to a rapidly expanding plasma cloud that is tamped to the surface by the water layer. The tamped plasma expansion causes a pressure of 1 to 10 GPa to build up on the workpiece surface over 10 to 100 ns.
- *Plastically deformed surface:* A resulting planar shockwave then travels through the workpiece and leaves plastically deformed material behind. The high rate of deformation during laser peening produces a layer of plastically deformed material that is significantly deeper than possible with most other techniques.

Residual stress in Alloy 22 welds

A major effort is currently under way to design spent-fuel nuclear waste storage canisters capable of surviving thousands of years while interred at Yucca Mountain. The current designs have an outer corrosion barrier of Alloy 22 (UNS N06022), a nickel-based stainless steel that has excellent corrosion resistance.

Because the canisters will be sealed by welding, tensile weld residual stress will develop and may provide a driving force for stress corrosion cracking (SCC) over the extremely long service life of these canisters. The laser peening process is a leading candidate for mitigating the tensile weld residual stress in Yucca Mountain storage canisters, because our recent work has demonstrated that it produces compressive residual stress to great depths in Alloy 22 welds. Here we summarize some of these measurements and provide graphic evidence of the effect of laser peening on SCC.

- *Welded specimens:* Residual stress was measured in as-welded and laser-peened Alloy 22 butt-welded samples. These samples were removed from a long, continuously butt-welded plate fabricated in 33 mm thick Alloy 22 plate with two-sided, multi-pass GTAW on a double-vee preparation.

The original welded plate was 812 mm long and 200 mm wide, and was cut into four nominally identical 200 mm long specimens, two of which were tested during these experiments. An set of effective laser peening parameters was developed, based on parameter variations and residual stress measurements in small, 20-mm thick Alloy 22 coupons. Following these preliminary studies, laser peening was applied to a 100-mm square region on one side of one of the Alloy 22 weld samples.

- *Stress maps:* Two-dimensional maps of the longitudinal (weld-direction) component of residual stress in the peened and unpeened weld specimens were measured by the recently developed contour method. Stress distributions for the peened and unpeened specimens are shown as contour plots in Fig. 2a (unpeened) and Fig. 2b (laser peened), where the residual stress was determined in a single measurement over the entire width and thickness of the welded sample. Laser peening produces a deep layer of compressive stress throughout the entire treated region (100-mm wide region on the bottom edge of Fig. 2b).

- *Quantitative comparison:* To allow for quantitative comparison between the peened and the unpeened specimens, a line plot of the contour results was generated. A plot of residual stress versus depth from the bottom surface at the center of the weld bead (x = 102 mm) is shown in Fig. 2c. This plot clearly demonstrates the ability of laser peening to eliminate near-surface tensile weld residual stress.

At the center of the weld bead, laser peening produced compressive residual stress to a depth of 4.0 mm. Additional data interpretation shows even greater depths of compressive residual stress outside the weld bead. For example, compressive stress is found to a depth of 6.8 mm at a location 30 mm from the weld center.

- *Additional experiments:* Additional experiments have been carried out to investigate the SCC behavior of laser-peened welds, such as a partially peened 316 stainless steel butt-welded plate. Two sections of the plate were submerged in a boiling $MgCl_2$ solution for an extended period. One section was completely laser-peened, and another section was only partially laser-peened. Although no visible cracking was observed in the laser-peened region (Fig. 3a), extensive cracks developed throughout the unpeened region (Fig. 3b). Cracks that developed in the unpeened material were arrested when they reached the laser peened region.

Commercial applications

In May 2002, MIC commenced production laser peening in a dedicated facility incorporating LLNL laser technology. This facility was constructed in eight months, as MIC received a contract from an aerospace OEM to laser-peen a critical rotating titanium component for a commercial turbine engine in September 2001. Within four months of startup, the laser peening system was operating 24 hours per day and five days per week. The laser is currently firing at high power settings more than 100,000 times per day. Overall, the laser peening system has proven to be robust and reliable, meeting the requirements of the turbine engine industry and providing FAA and CAA certified laser peening treatment.

In mid-2002, as the result of the successful startup of its first production laser peening system, the same aerospace OEM committed to processing of additional rotating titanium components for other turbine engine models, and MIC committed to construction of three additional laser peening systems. The second laser peening facility achieved full power operation in March 2003, and the remaining laser peening systems are scheduled to be operational by September 2003.

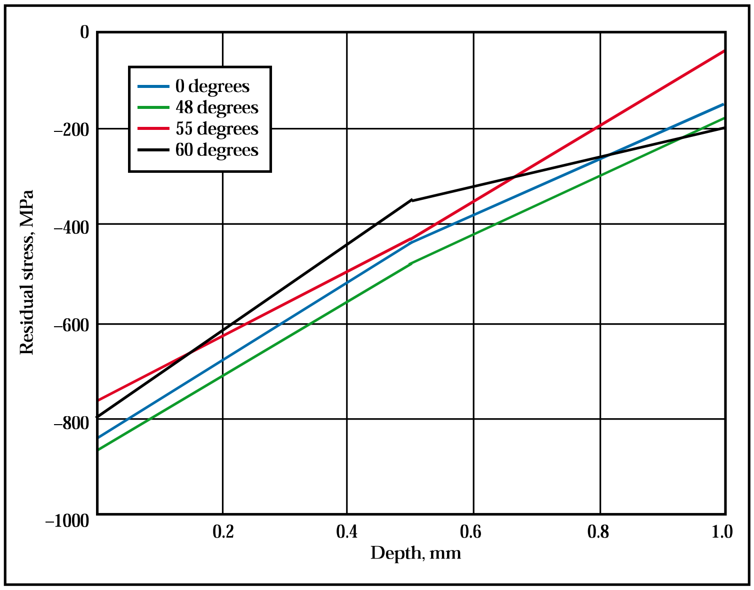

Fig. 4 — Residual stress profiles in laser peened Ti-6Al-4V specimens for various laser incidence angles (X-ray diffraction measurements).

To further develop production capability for titanium engine components, experiments have been conducted to investigate the residual stresses introduced in titanium under a variety of conditions. One such study looked at the effect of the incident angle of the laser beam on residual stress developed by laser peening. Small coupons of 8.73 mm thick Ti-6Al-4V (45 x 45 mm in plane) were laser-peened with incident beam angles varying from normal to the surface (0 degrees) to 60 degrees from normal.

Near-surface residual stresses (measured by X-ray diffraction with layer removal) were largely independent of the incident beam angle (Fig. 4). Because the plasma cloud applies pressure normal to the surface of the peened component (Fig. 1), not along the laser incidence angle, the results are not unexpected. Nevertheless, the results verify that peening may be applied at high incident angles, and this provides significant flexibility when peening components with complex geometry. ■

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Reprinted from the August 2003 issue of *Advanced Materials & Processes* magazine