

Laser Shock Processing Increases the Fatigue Life of Metal Parts

Laser shock processing (LSP) produces a surface compressive residual stress in the metal part being treated that can significantly improve those properties which are affected by the initiation and propagation of surface cracks. The properties of greatest interest are fatigue life and fatigue strength. But the process also can reduce fretting fatigue and stress-corrosion cracking as well as strengthen thin sections. The potential advantages of LSP include the possibility of direct integration into manufacturing production lines with a high degree of automation, use on machined surfaces, increased quality assurance, treatment of localized fatigue critical areas without masking, and the ability to make design changes that would not be possible using alternative methods for increasing fatigue resistance. Among the applications that have been identified are the manufacture of blades, disks, and vanes for aircraft gas turbine engines; gears, connecting rods, and crankshafts for automotive engines; and medical implants.

As developed at Battelle, where it was invented, the process works by directing a high energy pulsed laser beam onto the surface of the part being treated. First a dual-component overlay is applied to the surface over the area being processed. This consists of a thin film of material opaque to the laser beam, which is placed directly on the part's surface, and a second, thicker film, transparent to the laser beam, which is placed over the opaque film. When the laser beam strikes the material, it passes through the transparent film and is absorbed by the opaque film, causing a thin layer of material on the surface of the opaque film to vaporize. The rapidly expanding, heated gas is confined on the surface of the metal part by the transparent overlay, creating pressures of 6 GPa or more. This surface pressure propagates into the part as a shock wave, plastically deforming the material just below the surface and producing a high residual surface compressive stress.

An important feature of this residual stress is that it extends 0.5 to 1 mm or more below the surface, which is deeper than can be obtained by shot peening. Another feature is that there is little or no visible effect on the surface. After LSP, the surface of hard steels is essentially unchanged, while impressions of only 25 to 50 μm deep occur on soft aluminum alloys. However, even with soft alloys the laser conditions can be controlled to minimize the impressions to less than 5 to 10 μm . Thus, for many applications the process can be used on machined surfaces.

The size of the laser spot used can be varied depending on the intensity of the treatment required and the size of the laser, but typically it is about 1 cm in diameter. The distribution of the residual stress across the treated spot is relatively uniform, as indicated in figure 4, which shows the residual stress from the center to the outside of a laser treated spot on a 7075-T6 aluminum plate 6 mm thick, measured using x-ray diffraction. The residual stress around the exterior of the treated region changes to tension, requiring that this region be kept outside of the fatigue-critical region. Figure 5, a typical depth profile for the residual stress, shows that the compressive stress reaches a depth of over 1 mm in 2024-T3 aluminum. In some materials the stress oscillates within 50 to 100 μm of the surface, that is, it peaks in some sections of the subsurface before it gradually decreases with depth.

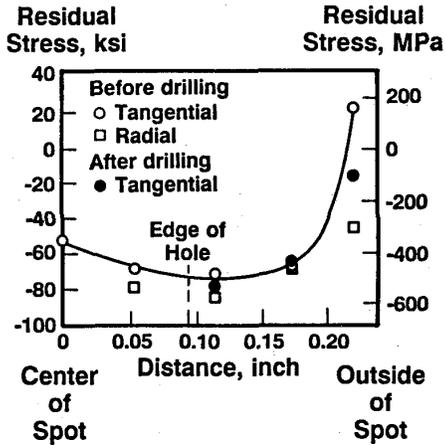
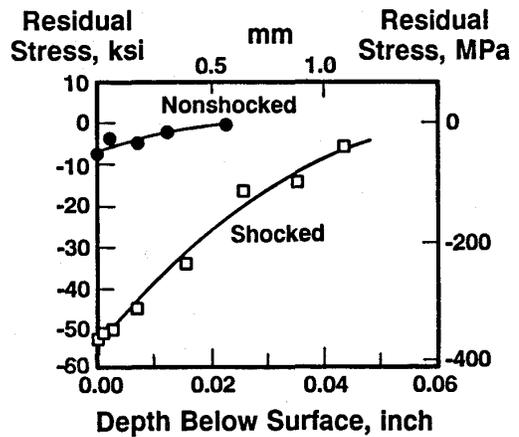


Figure 4 The stress distribution across a laser shock processed area of 7075-76 aluminum is relatively uniform.

Figure 5 The depth of the residual stresses in 6-mm thick 2024-T3 aluminum.



Areas larger than 1 cm in diameter are treated by using overlapping spots. There is a relatively uniform distribution of the stress across the regions of the overlap, which indicates that there should be little or no degradation of the properties when larger areas are treated. When residual stresses in the overlap region in 1026 steel and ductile cast iron were investigated, no indication of tensile residual stresses in the overlap regions was found. The tensile fatigue life of welded 5456 aluminum alloy specimens at stress amplitudes of 138 and 158.7 MPa (20,000 and 23,000 psi) was increased at least tenfold by using overlapped spots to treat the entire weld and heat-affected zones. (See also M&PR Vol.5 No.11 pp.3-4 for a report of work in France on laser shock treatment to densify porous materials and Ni-based superalloys.)

The chief interest in the effects of these residual stresses is how they affect fatigue properties. Several examples are shown here, all for 2024-T3 aluminum alloy. Figure 6 shows that the number of cycles to failure (N) was increased fortyfold in a specimen containing a hole after LSP with a solid spot. And even when an annular-shaped spot was used, thus enabling a crack to start and propagate for a short distance before it encountered the laser shocked zone, the specimen's fatigue life was still increased by 3 times.

More significant effects can be obtained if the laser shocked region extends beyond the crack. Figure 7 shows an example in which a crack was first initiated in a specimen followed by laser shocking the region ahead of the crack. This approach can increase the fatigue life of a cracked specimen by as much as 4 to 6 times compared with an uncracked, untreated specimen.

LSP can also increase fretting fatigue resistance. When specimens of fastened joints of 7075-T6 aluminum were treated around the fastener hole, the fretting fatigue life was increased by orders of magnitude at 96.6 MPa (14,000 psi) stress amplitude and doubled at 110.4 MPa (16,000 psi).

Figure 6 Increased fatigue life in 2024-T3 aluminum after laser shock processing around a hole using either a solid spot or an annular shaped spot. Left = specimen configuration and laser shocked region shape. Right = fatigue life and crack length dependence on the number of cycles.

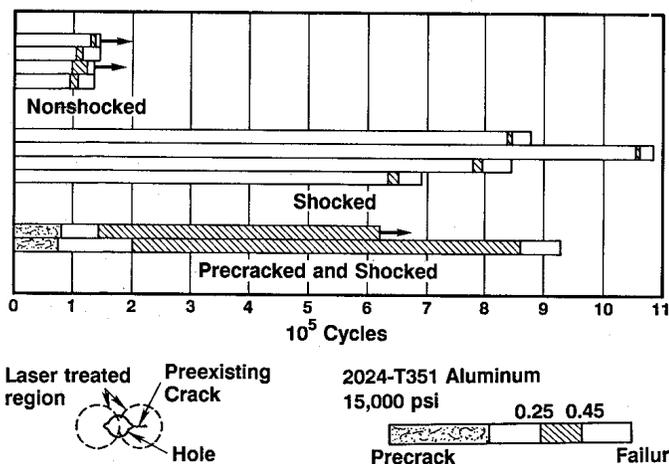
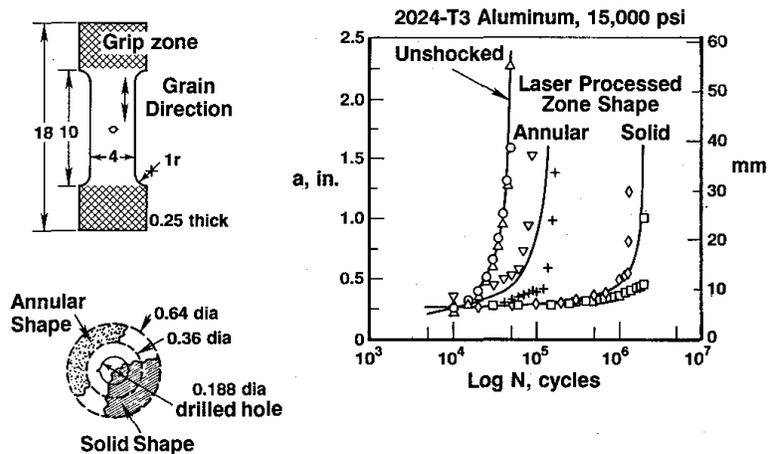
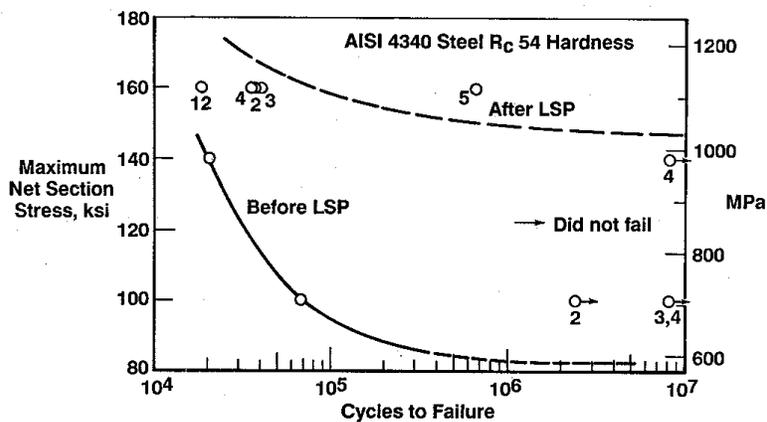


Figure 7 Laser shock processing increases the fatigue life of precracked specimens. Left = laser shock process pattern. Right = fatigue life.

The ability of LSP to increase fatigue strength is shown in figure 8, by the results both with and without LSP of tensile fatigue tests of thin (1.5 mm thick) AISI 4340 steel (heat treated to a Rockwell hardness of 54). The specimens are designated by the numbered data points. For example, specimen 4 was tested at 140 MPa (100,000 psi), at 966 MPa (140,000 psi), and at 1,104 MPa (160,000 psi) without failing. Overall, the fatigue strength was increased 60 to 80%, from 552 MPa-612 MPa (80,00-90,000 psi) to 966 MPa-1,035 MPa (140,000-150,000 psi).

Figure 8 Fatigue improvement in 4340 steel after laser shock processing.



LSP was first patented by Battelle in 1974, with additional patents filed subsequently. To commercialize the process, Battelle has granted an option for an exclusive license for its use with metals to Wagner Laser Technologies (Decatur, Illinois). As a critical step toward commercialization, a prototype laser with the small size, flexibility, and pulsing rate suitable for use in a manufacturing facility was designed, constructed, and is operating at Battelle for Wagner Laser Technologies.

The continued development of LSP is now focused on broadening the processing data base and optimizing the process. This technology is expected to be widely applicable for improving the fatigue properties of metals and alloys, particularly those that show a positive response to shot peening. The deeper residual stresses of LSP should offer even greater improvements than shot peening. Wagner Laser Technologies is actively seeking commercial applications for this process, and has been processing laboratory specimens and actual parts for interested companies to determine the feasibility of LSP for specific applications.