LASER SHOCK PEENING FOR

FATIGUE RESISTANCE

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Abstract

Laser shock peening produces a compressive residual stress in the surface of metallic materials, which significantly increases fatigue life in applications where failure is caused by surface-initiated cracks. Laser shock peening is applied by using a high energy pulsed laser to create a high amplitude stress wave or shock wave on the surface to be treated. This stress wave propagates into the material, causing the surface layer to yield and plastically deform, and thereby, develop a residual compressive stress. Where comparisons have been made to shot peening, the magnitude of the residual stresses at the surface are similar, but the compressive stresses from laser peening extend much deeper below the surface than those from shot peening. The resulting fatigue life enhancement is often greater for laser peering than it is for shot peening. In addition to fatigue strength improvement, laser peering can also locally strain harden thin sections of parts or strain harden a surface.

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Introduction

Laser shock peening (LSP) or laser peening generally increases the resistance of metals and alloys to fatigue and fretting fatigue. It does this by using a high energy pulsed laser to produce residual compressive stresses and strain hardening into the surface of a laser peened part. The residual compressive stresses from laser shock peening extend deeper below the surface than those from shot peening, usually resulting in a significantly greater benefit in fatigue resistance after laser peening. Laser peening can also be used to locally strain harden thin sections of parts, and, if the part is thin enough, it can be strain hardened through the section thickness.

Applying LSP

LSP can be applied to the finished surface of a part, or just prior to the final finishing step. On machine components, tooling and other parts, application to external surfaces and internal surfaces with line-of-sight access is straightforward. Application to internal surfaces without line-of-sight access is quite possible, but the method used is application specific and requires some development for each application.

LSP works by exerting a *mechanical force* on the part surface; the surface is not affected thermally. However, process options can be selected which have a limited thermal effect and offer potential cost benefits. The effects of the mechanical force on the surface itself are minimal. In softer alloys, a very shallow surface depression occurs, which decreases in depth in harder materials. For example, in aluminum alloys, the depression is about 250 µinches (6 µm) deep, but on machined surfaces of harder alloys, it is difficult to see where the surface was laser shocked. The depth of the depression increases with increasing intensity of treatment.

With LSP, treating just the fatigue critical area(s) on a part without masking the area around it is easily accomplished. This enables localized treatment around holes, and in and along notches, keyways, fillets, splines, welds, and other highly stressed regions.

The intensity of LSP can be easily controlled and monitored, allowing the process to be tailored to the specific service and manufacturing requirements demanded by the part. The flexible nature of the process accommodates a wide range of part geometries and sizes. It can also be used in combination with other treatments, e.g., shot peering or coatings, to achieve the most beneficial property and cost advantages for each application.

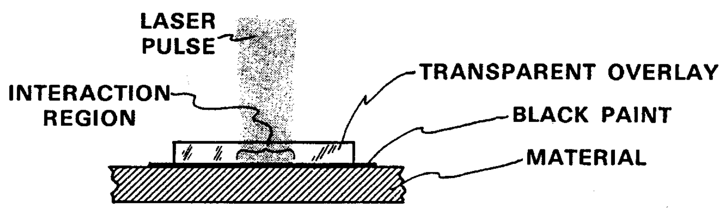
Laser Shock Peening

Laser shock peering is a mechanical process for treating materials, not a thermal process. The laser is a high-energy, pulsed neodymium-glass laser, producing a very short pulse, 15 to 30 nanoseconds long, having a wavelength of 1.06 µm, with an energy per pulse of 50 joules or more. The laser beam is directed from the laser through an optical chain of mirrors and lenses onto the surface of the part being treated (1).

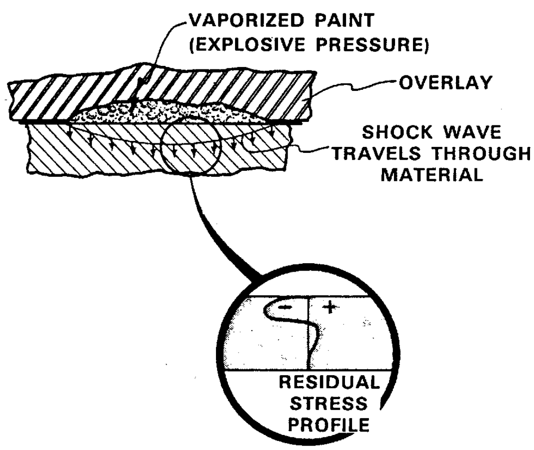
Description of the Process

A schematic of how the process works is shown in Figure 1. The area to be treated on a part is locally covered with two types of overlays: an opaque overlay, opaque to the laser beam, placed directly on the surface of the part, and over this a transparent overlay, transparent to the laser beam (Figure la). The opaque overlay can be any material opaque to the laser beam; a black coating is commonly used. The transparent overlay can be any material transparent to the laser beam; water is commonly used.

When the laser beam is directed onto the surface to be treated, it passes through the transparent overlay and strikes the opaque overlay. As shown in Figure 1b, when the laser beam strikes the surface of the opaque overlay, it immediately vaporizes a thin surface layer of the overlay. This vapor then absorbs the incoming laser energy, rapidly heating and expanding against the surfaces of the workpiece and the transparent overlay.



a. Surface area to be laser shocked, showing the laser beam and overlays.



b. Effect of laser beam at the overlay-workpiece interface.

Figure 1 - Schematics of how the laser shock process works (2).

The transparent overlay traps the thermally expanding vapor and plasma against the surface of the workpiece, and consequently causes the pressure to rise much higher than it would if the transparent overlay were absent. The sudden, high pressure against the surface of the workpiece causes a shock wave to propagate into the material. If the peak stress of this shock wave is above the dynamic yield strength of the material, the material yields and plastically deforms. As the stress wave propagates deeper into the material, the peak stress of the wave decreases, but deformation of the material continues until the peak stress falls below its dynamic yield strength. This plastic deformation caused by the shock wave gives rise to strain hardening and compressive residual stresses at the surface of the workpiece (Figure 1b). This is one of the most useful effects produced by laser shock peening.

The shape of the laser treated spots is generally round, but other shapes can be used, if necessary, to provide the most efficient and effective processing conditions. The size of the area treated in one pulse depends on a number of material, laser and processing factors. The spot size can range from about 25 mm to about 2.5 mm in diameter. A typical spot size is about 6 mm to 9 mm or larger. Future, higher power lasers will be capable of larger spot sizes.

Parts are set up for laser shock processing in either of two ways. For thicker sections, nominally 12 mm thick or more, a single beam is directed onto the surface of the area being treated. To minimize distortion of the part in thinner sections, the laser beam is usually split into two beams of equal intensity, and these beams strike the part on the opposite surfaces simultaneously. Alternatively, thin sections can be treated from one side only, if desired, by using a back-up support.

The size of the area to be treated depends on the part design and service conditions. Sometimes, a part requires that only a small area be treated and a single treated spot will suffice, e.g., around small oil, pin or bolt holes, or at the root of a notch in the side of a thin section. In other instances, the areas requiring treatment will be larger, e.g., an area on a turbine blade, crankshaft fillet, or gear. In these cases, successive spots are overlapped until the desired region is completely covered.

Properties of Laser Shock Peened Materials

A number of metals and alloys have been treated by LSP, including steels (2,3,4,5), aluminum alloys (2,6,7,8,9), titanium alloys (1), nickel-base superalloys (10), cast irons and a powder metallurgy iron alloy. In some of these cases, the investigations include both residual stresses and fatigue results in the same study, or directly compare LSP and shot peening. Because the information presented here has been extracted from a number of alloys, it clearly illustrates that the residual stress distribution and fatigue changes observed are representative of those that LSP can produce in a variety of alloys, including titanium alloys. It should be emphasized that none of the results shown here represent the optimum or maximum-benefit condition for the particular material or application.

The nature of the residual stresses will be shown first, followed by fatigue properties.

Residual Stresses

All residual stresses were measured using x-ray diffraction. The distribution of the residual stress below the material surface was determined by successively removing a thin layer from the surface by electropolishing, then making x-ray measurements on the new surface. Electropolishing does not introduce stresses into the surface as would machining or grinding. This incremental process is continued down to the maximum depth of interest, usually 0.5 to 1.2 mm deep. An analytical technique is then used to calculate the stress distribution below the surface as it existed before disturbing it by removing the layers. This analytical technique accounts for both the stress relaxation occurring as material is removed, and for the depth of penetration of the x-rays into the stress gradient.

Surface Distribution of Residual Stresses. It is important to have relatively uniform residual stresses across the treated area on a part, and LSP provides this. The surface stress distribution along the radius of a laser shock peened spot is shown in Figure 2 for an aluminum alloy (8). These observations also apply to titanium alloys. The stress distribution is essentially uniform except for a slight dip in the center of the spot. A few thousandths of an inch below the surface, the residual stress profile is the same as that at the mid-radius. There is no evidence that this dip has affected fatigue behavior.

In Figure 2, the residual stresses in both the tangential and radial directions are shown. These stresses are nominally equal in the interior of the laser treated spot, but at the spot's outside edge, they tend to differ. Immediately outside the treated spot a surface tensile residual stress forms tangentially to compensate for the compressive stresses inside the spot, whereas in the radial direction this effect is often absent. To avoid having this peripheral tensile residual stress affect the post-processed properties, the treated area must be large enough to move this stress outside the fatigue-critical area.

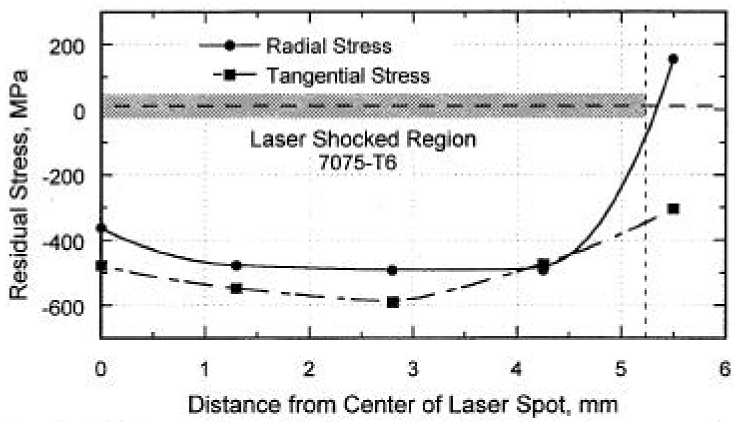


Figure 2 - Uniform surface residual stress distribution from the center to the outside of a laser shock peened spot in 7075-T6 aluminum (8).

The magnitude of the surface stress can be varied to some degree. Below a certain laser peening intensity threshold, the surface stress will increase with increasing intensity of the peening conditions. Above this threshold, the surface residual stress will remain nominally the same with increasing peening intensity, but the depth of the residual stresses increases, as shown in the next section.

<u>In-Depth Residual Stress Distribution</u>. The distribution of the residual stresses below the surface is usually much deeper for LSP than it is for shot peening. The actual depths of the LSP-induced stresses will vary depending on the type and intensity of the processing conditions chosen and the material properties, but in general the depths will range from 0.5 to 1 mm deep or more. For comparison, the depths from shot peening will generally be under 0.25 mm deep. Achieving deeper stresses with shot peening often causes a degradation of the surface caused by the severe impact conditions of the shot. Also, LSP seldom produces the “hook” in the compressive residual stress profile just below the surface that is observed after shot peening, i.e., the compressive residual stress increases with increasing depth for a short distance below the surface to a maximum, then decreases with increasing depth. After LSP, the residual stress is usually highest at the surface and decreases gradually with distance below the surface. The deep penetration of the compressive residual stresses produced by laser shock peening is

illustrated for 2024-T351 aluminum in Figure 3, where the residual stresses are still high 1 mm below the surface (6,8).

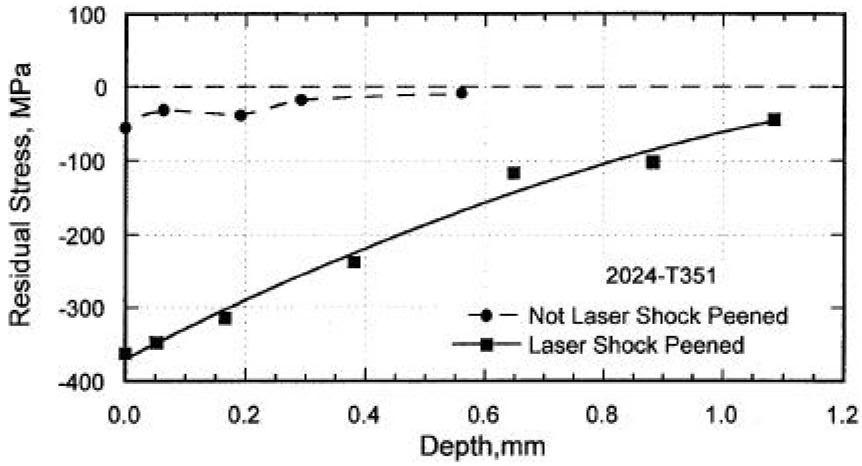


Figure 3 - In-depth residual stress profiles before and after laser shock peening (8).

The compressive residual stresses can be driven deeper below the surface by increasing the intensity of the laser peening. This is illustrated in Figure 4 for a 0.55% carbon steel (4). As the number of shots on the surface increases from one to three, the depth of the compressive residual stress increases from 0.9 mm to 1.8 mm. This same trend has been observed in other alloy systems, including titanium alloys.

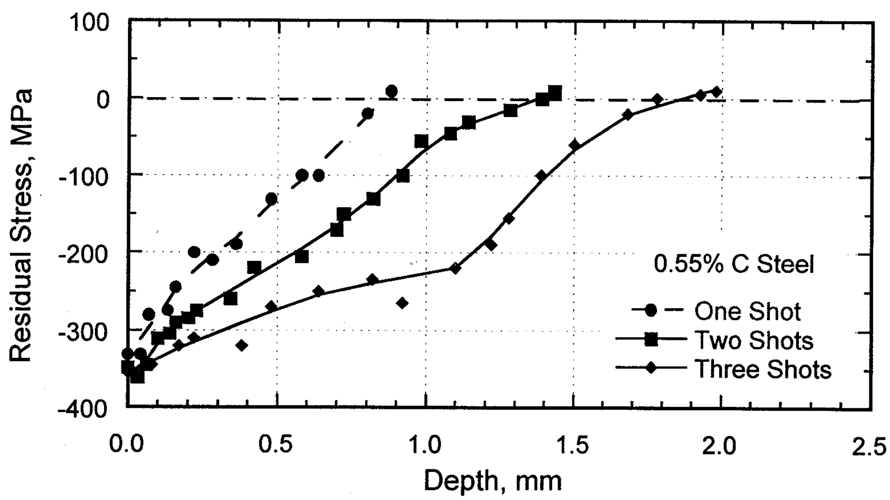


Figure 4 - The effect of increasing laser peening intensity on the in-depth residual stresses in a 0.55% carbon steel (4).

In thin sections, increasing the intensity of laser peening won't necessarily increase the depth of the compressive stresses, but it will increase the magnitude of the stresses in-depth. This is shown in Figure 5 (2). This 1.5 mm-thick 4340 steel sheet was heat treated to 54 R_C hardness before laser shock peening. It was then peened with one and five shots from both sides simultaneously, and the residual stresses measured. The depth of the compressive stress is nominally 0.5 mm for both peening conditions, but the magnitude of the compressive stresses is higher after five shots. In addition, the tensile residual stress at the mid-thickness (0.75 mm) of the sheet is higher after five shots. When doing thin sections, the processing conditions have to be carefully selected to avoid or minimize a high tensile residual stress at the mid-thickness of the section.

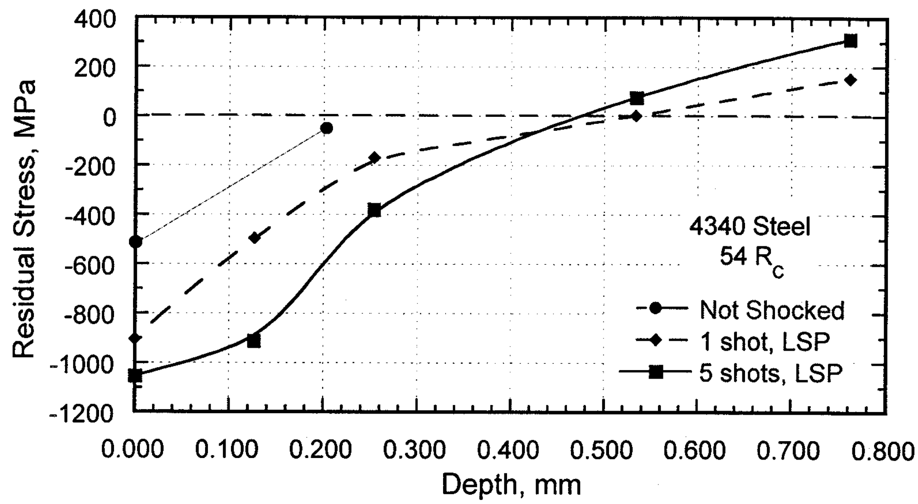


Figure 5 - Residual stress profiles in thin, 4340 steel sheet after different laser peening intensities. The mid-thickness of the sheet is at 0.75 mm (2).

Fatigue Properties

Several different aspects of laser shock processing and fatigue conditions have been investigated in aluminum alloys. One comparison made in 2024-T351 aluminum alloy plate concerned fatigue crack propagation from a fastener hole (6). The fatigue specimens were large: 6.3 mm thick, with a gauge section 102 mm wide by 254 mm long. The fatigue behavior was determined by measuring the fatigue crack length, a, vs. the number of cycles, N, for the non-shocked condition and two laser shock peened conditions. For one of the LSP conditions, the hole was in the center of a solid treated spot. In the other condition, the hole was surrounded by an annular-shaped spot whose inner diameter was larger than the diameter of the hole, enabling a crack to initiate and start to grow in a non-shocked region, then encounter the laser peened region as it grew. The specimens were tested in tension, R = 0.1, at 103 MPa maximum stress amplitude. The results are shown in Figure 6. Considering the fatigue life to be nominally the point where the crack length curves become nearly vertical, the LSP condition with the solid spot had a fatigue life about 40 times longer than the non-shocked condition, whereas the condition with the annular spot had a life about 3 times longer than the non-shocked condition.

When the areas around holes in sheet materials are laser shock peened with a solid spot around a hole, the crack tends to initiate on the hole surface at mid-thickness, and then tunnels down the mid-thickness of the sheet between the compressive surface layers before it breaks through to the surface beyond the laser shocked region. While the crack propagation rate is slowed considerably by this behavior, (Figure 6, solid spot), and fatigue life is significantly increased, the crack itself is not easily detected. This is sometimes a concern in failure-sensitive applications.

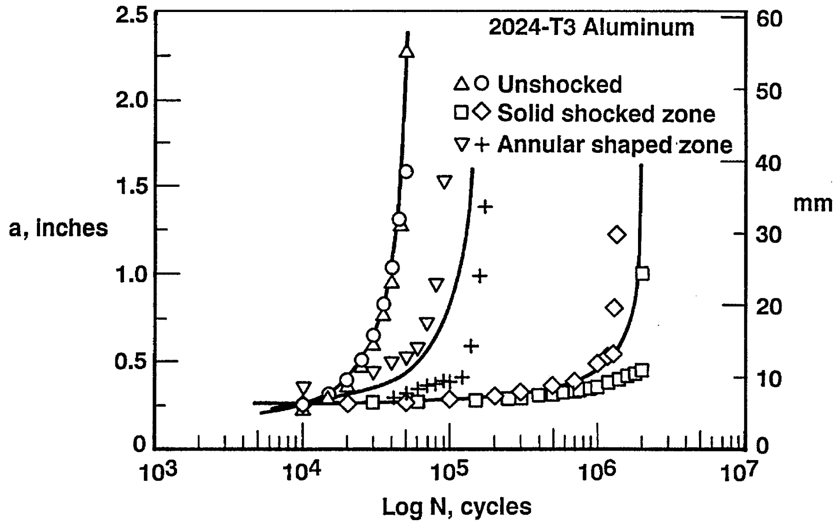


Figure 6 - Fatigue crack propagation in non-shocked and laser shock peened 2024-T351 aluminum at a stress amplitude of 103 MPa. The crack length, a, is shown vs. the number of cycles, N (6).

The annular spot was chosen to demonstrate that a crack could be initiated and detected at a fastener hole, and then be significantly slowed when it reaches the laser shocked region. This would allow ample time for the detection and monitoring of cracks originating from holes before failure.

LSP is also effective in arresting pre-existing cracks (11). Large 2024-T351 aluminum specimens similar to that described above were pre-fatigued to create cracks 0.5 mm long, coming out each side of the fastener hole. The region ahead of each crack was then laser shock peened, and the specimens re-tested in tensile fatigue, R=0. 1, at 103 MPa maximum stress amplitude. The results are shown in Figure 7. The unshocked condition had a fatigue life of about 145,000 cycles, and the laser shocked condition without a pre-crack had lives of 700,000 to 1,000,000 cycles. After pre-cracking and laser shocking, the fatigue lives were in the same range as those of the laser shocked material tested without a precrack.

The fatigue life of weldments can also be extended by LSP (11). Plates of 5456 aluminum alloy 6.3 mm thick were butt-welded together, the weld bead machined off and the weld and heat-affected-zones laser shocked with overlapping spots. Test specimens machined from this plate were then tested in tensile fatigue, R=0, in both the as-welded and laser shock peened conditions (Figure 8). At a stress amplitude of 138 MPa, the fatigue life was increased by at least an order of magnitude. More significantly, at 158 MPa the fatigue life was increased from less than 50,000 cycles to more than 3 to 6 million cycles without failure after LSP. The fatigue strength, in the non-shocked condition was about 116 MPa.

Laser shock peening is also effective against fretting fatigue (11). Dog-bone specimens and pads of 7075-T6 aluminum were laser treated around a simulated fastener hole in each piece (Figure 9a), then fastened together through the hole with a manufactured (CSK) fastener. This combination was then fatigue tested in tension at R = 0.1. The stress differential between the larger cross-section of the pad and the smaller cross-section of the dog-bone created an elongation differential between the two pieces during each cycle, leading to fretting around the fastener hole. The results are shown in Figure 9b. The tests were initially conducted at 96 MPa. When a long life was reached, the stress was raised in 10 percent increments until failure occurred within few hundred thousand cycles. Even at 113 MPa, the fretting fatigue life is increased by LSP.

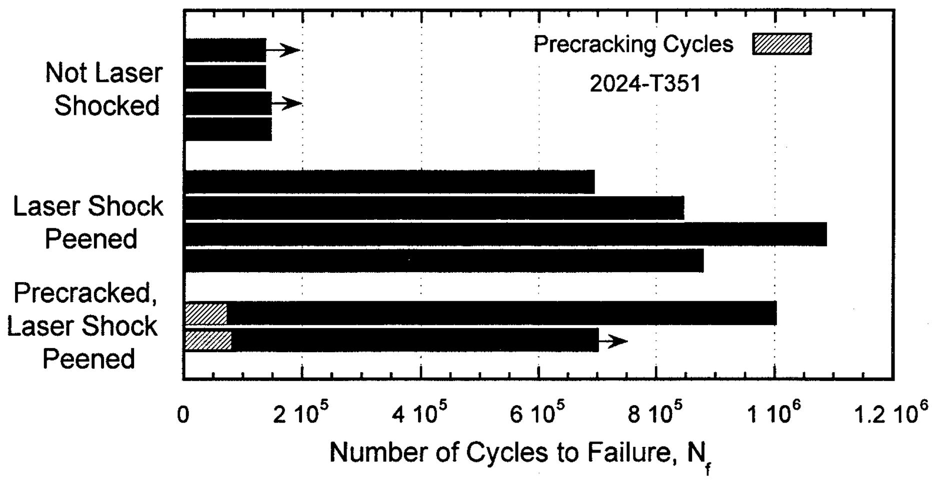


Figure 7 - The effect of laser shock peening on fatigue life of precracked specimens of 2024-T351 aluminum tested at a stress amplitude of 103 Mpa (11).

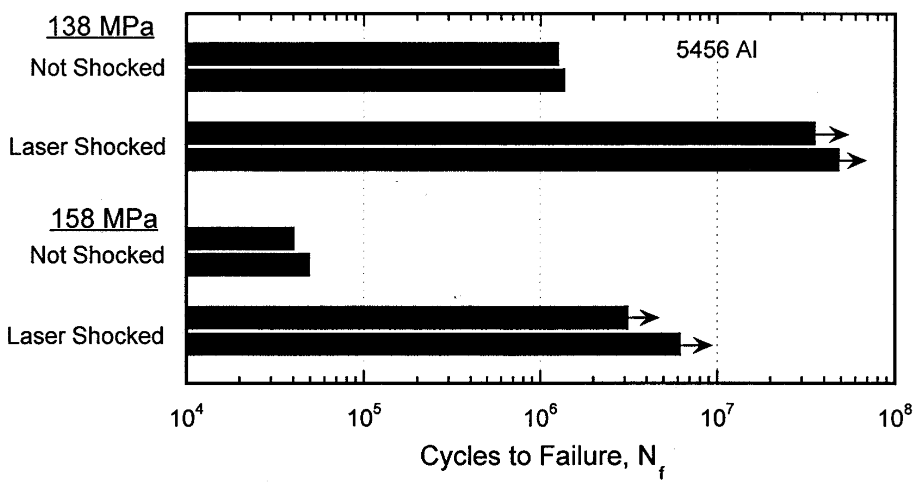
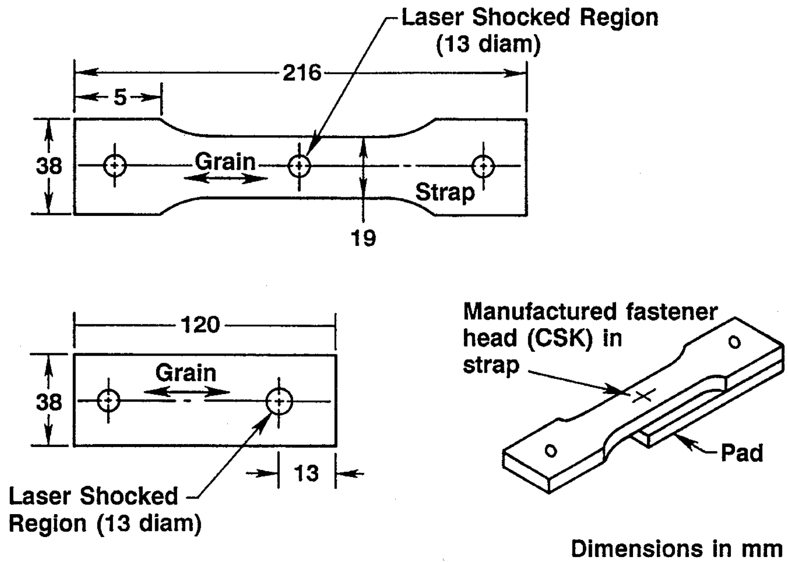
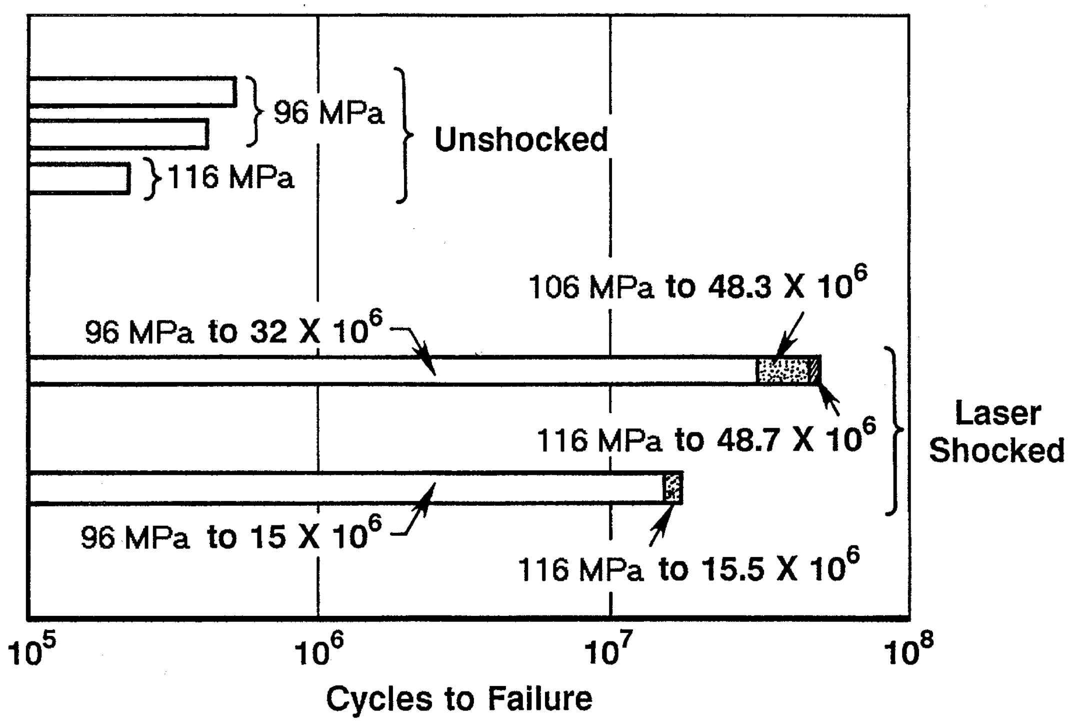


Figure 8 - Fatigue life increased in welded 5456 aluminum after laser shock peening (11).

Fatigue improvement after laser shock peening thin sections was demonstrated in steel sheet. 4340 steel sheet, 1.5 mm thick, heat treated to Rc54 hardness, was laser shock peened and tested in tensile fatigue in the specimen configuration shown in Figure 10a. The roots of both notches were laser shocked with one spot, using a split beam as shown. The fatigue tests were conducted at R = 0.1 with the results shown in Figure 10b. The run-out stress of the unshocked condition was taken from a handbook. The specimen numbers are attached to the individual data points.

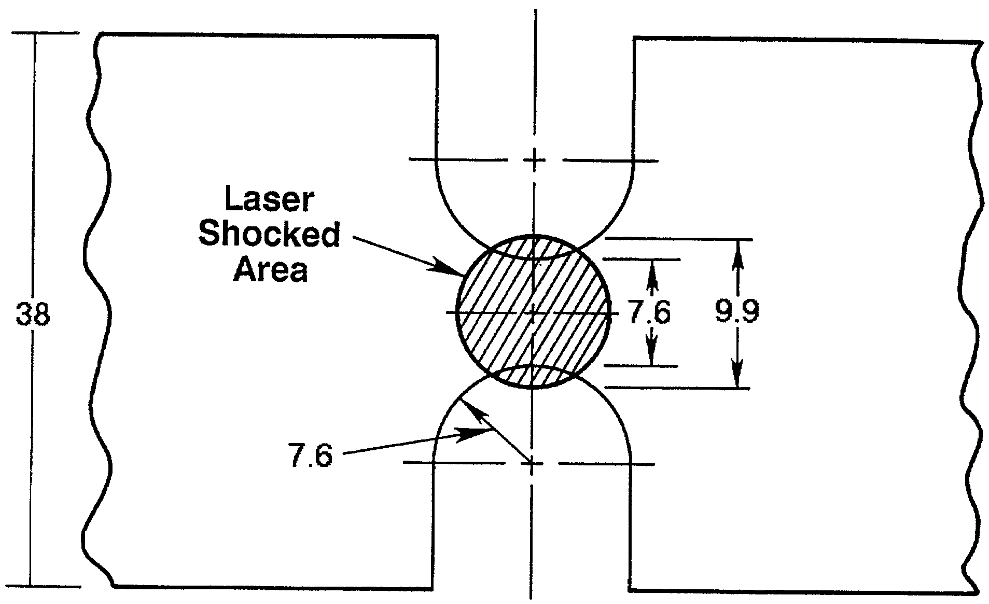


a. Fretting fatigue specimen configuration

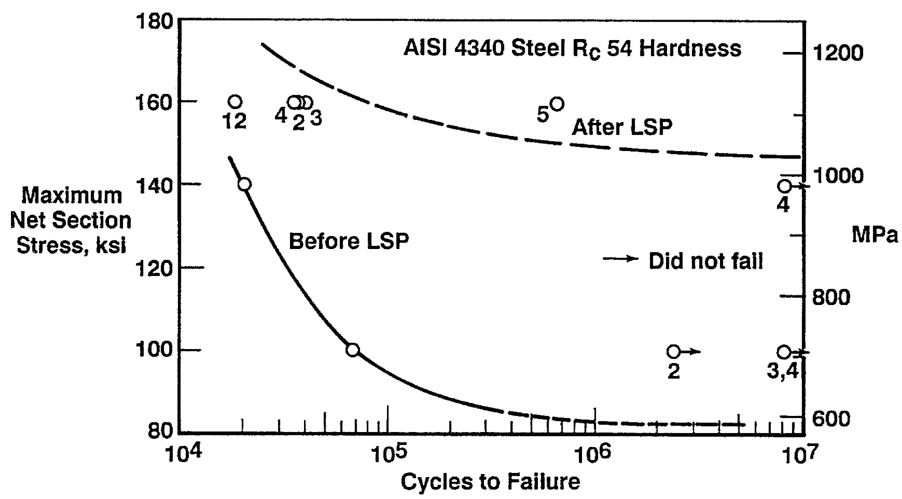


b. Fretting fatigue results

Figure 9 - Increased resistance to fretting fatigue around fastener holes after laser shock peening 7075-T6 aluminum.



a. Specimen and laser shock peening configuration. Dimensions in mm.



b. Tensile fatigue results.

Figure 10. The tensile fatigue strength of 4340 steel sheet increased significantly by laser shock peening (2).

Specimens 2, 3, and 4 were stepped up in stress after reaching well over a million cycles. Laser shock peering produced a large increase in the run-out stress, from about 586 MPa to 965 to 1034 MPa.

In thicker pieces, a notch would be treated by laser shock peening directly into the notch. To demonstrate the effectiveness of LSP in this case, a beam specimen of 4340 steel, hardened to 54 R_C, 6.3 mm thick, 19 mm deep and 203.2 mm long, had a notch having a $K_T \cong 1.7$ machined into the upper surface. The notch was shocked from one side only, directly into the notch. The beams were fatigue tested in 4-point bending with tensile loads at the notched surface. At a load of 9880 N, without LSP the specimens failed in the notch after 30,000 cycles. After LSP at intermediate and high intensities, the specimens did not fail at over 10^6 cycles. At still higher loads, 11,100 N, the beams failed under the loading pins, but not the notch (2).

A comparison of the effect on bending fatigue properties of shot peening and laser shock peering into a notch was made in 7075-T7351 aluminum (9). The specimens were tested in bending at R=0.1. The results are shown in Figure 11. Shot peening provides an 11 percent increase in the runout stress at 10^7 cycles, while laser shock peening provides a 22 percent increase.

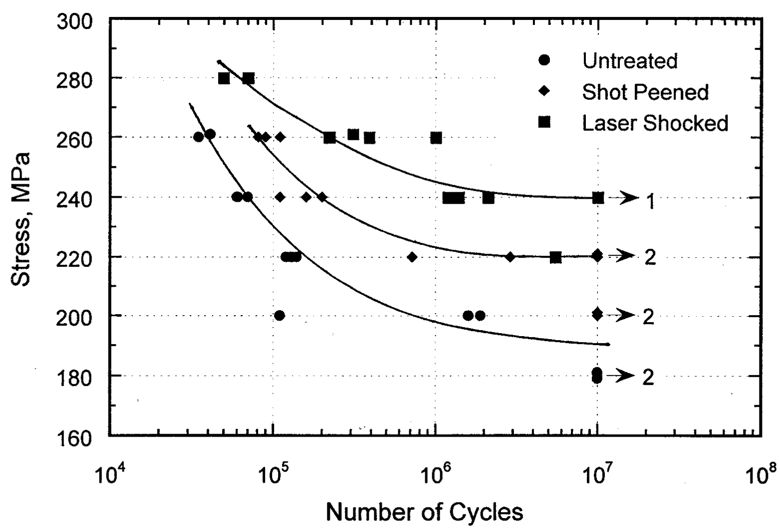


Figure 11 - Comparison of notched bending fatigue of untreated, shot peened and laser shock peened 7075-T7351 aluminum (9).

LSP significantly increases the resistance of titanium fan blades to early fatigue failure caused by foreign object damage (1). After treatment by shot peening or laser peening, and the introduction of a notch in the leading edge of the blades, the laser peened blades maintained the fatigue life of the damaged blades to equal or higher than that of undamaged blades. The shot peened blades showed some improvement over the untreated, damaged blades, but did not approach the life of the undamaged blades.

Applications of Laser Shock Processing

Many of the potential applications of laser shock processing are based on laser shock peening for increased fatigue resistance. The initial applications being implemented for LSP are representative of those anticipated at this stage of development: processing high-value-added parts for improved performance, or using LSP to replace a traditional process or material to achieve a cost advantage. Applications which fall in these categories are aircraft engine parts, aircraft structures, medical implants and prostheses, components of power generation turbines and other turbines, specialized gears and parts in valves, and other mechanism components having notches, holes and corners prone to fatigue failure.

With ongoing laser and process development, costs will continue to decrease rapidly, opening the way to an ever-broader range of applications including automotive gears, cams, rocker arms and connecting rods, tool bits, tooling and dies.

In considering applications of LSP, it should not be viewed as a competitor to shot peening, but instead, as its complement. In many cases, LSP will be used alone where shot peering is not suitable or cannot be used for various reasons. These reasons could include better properties, treatment of difficult geometries, improved quality control, smoother finished surface, or ease of processing, to name a few. In other cases LSP will be used along with shot peening, to provide additional protection in fatigue critical regions.

In addition to laser shock peening, there are potential uses in a variety of applications having nothing to do with fatigue, but instead based on the localized strain hardening or shock impact characteristics of the process. For example, localized surface plastic strain induced by shock impact could enhance diffusion bonding of small components, or similarly, a coating. The shock wave may be used to locally densify porous coatings, or to compact powders in unique situations. It may also be useful in unique metal forming operations or connector attachments.

Quality Control

Quality control issues for laser shock peening can be addressed in numerous ways. A number of the laser beam parameters can be monitored and recorded for each shot in real time. In addition, there are process parameters that can be monitored using features on the material surface, measurement of material properties, or other characteristics of the process. Periodic evaluations of the process can be made by sampling the residual stress distributions and property changes in processed parts.

Many of these process-related parameters can be measured and used to contr6l the process in real time. For these, acceptable limits of their values can be defined, and corrections made immediately if they drift outside of these limits during processing.

References

1. C. O. Lykins, "Laser Shock Peening vs. Shot Peening, A Damage Tolerance Investigation", This volume.

2. T. R. Tucker and A. H. Clauer, "Laser Processing of Materials" (MCIC Report, MCIC-83-48, Metals and Ceramics Information Center, November, 1983).

3. A. H. Clauer, B. P. Fairand, and B. A. Wilcox, "Pulsed Laser Induced Deformation in an Fe-3 WtPct Si Alloy", Metallurgical Transactions A, 8A, (1977), 119-125.

4. J. E. Masse and G. Barreau, "Surface Modification by Laser Induced Shock Waves", Surface Engineering, 11(2) (1995), 131-132.

5. P. Ballard et al., "Residual Stresses Induced by Laser-Shocks", Journal de Physique IV, Colloque C3,

supplement au Journal de Physique III, 1 (October, 1991) C3-487-C3-494.

6. Allan H. Clauer, Craig T. Walters, and Stephan C. Ford, "The Effects of Laser Shock Processing on the Fatigue Properties of 2024-T3 Aluminum", Lasers in Materials Processing, (Metals Park, OH: ASM International, 1983), 7.

7. S C. Ford et al., "Investigation of Laser Shock Processing", (Report AFWAL-TR-80-3001, Vol.2, August, 1980).

8. A. H. Clauer, "Laser Shock Processing Increases the Fatigue Life of Metal Parts", Materials & Processing Report, 6 (6) (1991), 3.

9. P. Peyre et al., "Laser Shock Processing of Materials, Physical Processes Involved and Examples of Applications", Journal of Laser Applications, 8 (1996) 135-141.

10. P. Forget, M. Jeandin, and A Lyoret, "Determination of Laser Shock Treatment Conditions for Fatigue testing of Ni-Based Superalloys", Journal de Physique IV, Colloque C7, supplement Journal de Physique III, 3 (November, 1993), 921-926.

11 Allan H. Clauer, John H. Holbrook, and Barry P. Fairand, "Effects of Laser Induced Shock Waves on Metals", Shock Waves and High-Strain-Rate Phenomena in Metals, (New York, NY: Plenum Publishing Corporation, 1981) 675-701.