

Review

Laser Shock Peening, the Path to Production

Allan H. Clauer

LSP Technologies, 6161 Shamrock Court, Dublin, OH 43016-1284, USA; ahhc1936@gmail.com;
Tel.: +1-614-718-3000

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Abstract: This article describes the path to commercialization for laser shock peening beginning with the discovery of the basic phenomenology of the process through to its implementation as a commercial process. It describes the circumstances leading to its invention, the years spent on exploring and defining characteristics of the process, and the journey to commercialization. Like many budding technologies displaying unique characteristics, but no immediately evident application, i.e., “a solution looking for a problem”, there were several instances where its development may have been delayed or ended except for an unanticipated event that enabled it to move forward. An important contributor to the success of laser peening, is that nearly 15 years after its invention, universities world-wide began extensive research into the process, dramatically broadening the knowledge base and increasing confidence in, and understanding of its potential. Finally, a critical problem in need of a solution, laser peening, appeared, culminating in its first industrial application on aircraft turbine engine fan blades.

Keywords: laser peening; fatigue; residual stress; laser shock waves; laser peening history

1. Introduction

New technologies are invented, developed and applied following many different paths. It is often difficult to accurately describe these paths in hindsight, particularly the events critical to sustaining interest and support for the technology in the early and middle stages where its proponents are few and the ultimate use not certain. Fortunately, laser peening offers the opportunity to describe such a path clearly and definitively. This is possible because its invention and early development occurred within a single organization, and relatively few people and organizations were instrumental in taking it to commercial use. The insights into the phenomena vital to the success of laser shock peening can be traced to a few basic research investigations performed in the 1960s, followed by its invention in the early 1970s. It took another 40 years to become an accepted industrial process to treat metal surfaces for increasing fatigue strength and fatigue life. Along the way several critical, key events are identified. Without these events progress would have been significantly delayed or stopped completely. If any one or more of these events had not occurred, the use of laser shocks to modify material properties would still have been recognized at some point in the future, but the path would have been much different. While under development, the technology was referred to as laser shock processing. It was lacking a defined target application until further understanding and development of the technology would bring one or more into focus. The first application became laser shock peening, or laser peening, to increase the fatigue strength and fatigue life of metal alloys. This was followed by laser peen forming. In the last two decades, investigations into laser shock processing have reached beyond laser peening, to include the use of laser-induced stress waves to evaluate adhesive bond strength in bonded structures and coatings, metal die forming, surface imprinting and other possible uses.

2. The Phenomenological Origins of Laser Processing

After the invention of the laser, the first of the key events leading to laser shock processing was provided by Askaryan and Moroz at the P.N. Lebedev Physics Institute in 1962 [1]. In an experiment to measure the pressure exerted on a metal surface by a high intensity photon beam, they discovered that the pressure was at least several orders of magnitude greater than the calculated photon pressure. They rightfully concluded that they actually measured the vaporization recoil pressure produced by vaporization of material from the target surface by the laser beam. They further speculated that it was large enough to possibly be used to steer space vehicles.

Two years later, Neuman investigated the magnitude of the momentum transfer at constant and varying beam intensities for a number of different metals, at the NASA Ames Research Center [2]. He noted that a short, 50 ns “giant” laser pulse produced a greater recoil pressure than a “normal” 1 ms laser pulse with five times the energy of the giant pulse. An observation that would later be recognized as peak pressure increasing with power density. Soon after, these findings were expanded by a number of investigators, both experimental and theoretical, pursuing studies of the creation of stress waves using lasers [3–7]. All these experiments were performed with the target residing in a vacuum chamber to avoid dielectric breakdown in the beam in air at the high power densities necessary to achieve increasing pressure. While generating high pressure laser shock waves in a vacuum was acceptable for research purposes, it would not be acceptable for industrial applications.

The path to removing this obstacle was demonstrated by the second key event, a discovery made by N.C. Anderholm at Sandia Laboratories in 1968 [8,9]. He vapor-deposited an aluminum film onto a 6 mm-thick quartz disk, irradiated this aluminum film through the 6 mm-thick quartz disk and measured the pressure profile using a piezoelectric quartz gauge pressed against the aluminum film. Irradiating the aluminum film with a 1.9 GW/cm², 12 ns laser pulse, he measured 3.4 GPa peak pressure. Although this experiment, too, was performed in a vacuum, it clearly demonstrated that with a transparent overlay, significant shock pressures could be achieved at beam power densities not causing dielectric breakdown in air. This breakthrough observation would open the door a few years later to exploring the potential for using laser-induced shock waves as a materials processing tool.

These previous investigations were focused on studying the surface effects produced by the pulsed laser irradiation. Soon, investigators began looking at the effects of the laser-induced shock waves within the metals. In 1970, Mirkin at the M.V. Lomonosov Moscow State University realized that the higher energy, short laser pulses were capable of driving a relatively high pressure shock wave into the metal surface [10]. This suggested that the known effects of explosive or plate driven shock waves on metals’ microstructure and hardness should also occur with laser-induced shock waves. He was the first to report the effects of laser-induced shocks on metal microstructure, observing twinning in steel ferrite grains located only below the laser-irradiated crater, down to a depth greater than 0.5 mm. The next year, Metz and Schmidt at the U.S. Naval Research Laboratory, investigated the effects of mild laser shocks, 0.18 GW/cm², 35 ns pulse width, on annealed, 50 μm-thick nickel and vanadium foils [11]. After again annealing the irradiated foils after laser shocking, they observed vacancy voids in the nickel foils and vacancy loops in the vanadium foils. Although this irradiation condition was relatively mild, these loops were evidence of a high density of lattice vacancies created by the shock wave.

During this same period, 1968–1972, other investigators were investigating the important issue of the effect of varying the transparent overlay on the pressure enhancement observed by Anderholm. O’Keefe and Skeen at TRW Systems Group explored the use of thin volatile coatings of RTV (Room Temperature Vulcanizing) silicone adhesive and Duco cement as transparent overlays on 76 μm-thick 1100-0 aluminum targets [7]. For a 50 ns pulse of 1.8 GW/cm², the peak pressure of the stress wave with a coating of 25 μm of the silicone adhesive was eight times higher than without the silicone coating. A 63 μm-thick coating of Duco cement increased the pressure about 15 times compared to the bare surface. With these overlays, both the plasma confinement and the vaporization of the overlay contributed to the pressure pulse. The contribution of vaporization of the overlay was deduced from the observation that increasing the curing time of the RTV, i.e., decreasing its volatility, also decreased the pressure.

3. The Transition to Laser Shock Processing

3.1. Setting the Stage

To this point, all the research was understandably dedicated to exploring the science of laser induced shock waves. There was as yet no coherent effort to define how or for what purpose they might be used. However, the third key event would both enable and foster this effort. It was the decision in 1968 by Battelle Memorial Institute in Columbus, Ohio, to purchase and install a large Compagnie Générale Electrique (CGE) VD-640 Q-switched, Nd-glass laser system imported from France for the purpose of initiating work in laser fusion. Philip Mallozzi and Barry Fairand of the Laser Physics Group were members of the team setting up and operating the laser, which became operational in 1970. The system consisted of six linearly aligned amplifying stages, each supported by a large wall cabinet containing the capacitors to operate the flash lamps energizing the Nd-glass rods as shown in Figure 1.



Figure 1. The Battelle Compagnie Générale Electrique (CGE) VD-640 Q-switched laser became operational in 1970 and was used for laser shock investigations to the mid-1990s: (a) capacitor banks; (b) laser rod amplifiers.

After the system became operational, Fairand and Mallozzi sought to expand its use within the laboratory. To pursue one possibility, Fairand approached Benjamin Wilcox in Battelle's Metals Science Group in early 1972, proposing that using laser-induced shock waves to modify metal properties might provide useful benefits. This was suggested by the known effects of flyer plate impacts on metals. Wilcox agreed and suggested laser shocking 7075 aluminum alloy tensile specimens to determine whether there was sufficient change in strength to warrant a further look. This first experiment consisted of clamping a 1 mm-thick glass slide against the gauge section of small, 1.35 mm-thick, dog bone specimens using sodium silicate as a coupling layer between the glass slide and aluminum surface. The 10 mm × 5 mm gage length of the specimens was shocked on each side consecutively with one shot at a power density of 1.2–2.2 GW/cm², 32 ns, Gaussian pulse. The specimens were backed by a 3.2 mm-thick brass plate. After laser shocking, the yield strength increased 18% for the solution treated condition, 28% for the over-aged T73 temper and a slight decrease for the peak-aged T6 temper. In this latter condition, precipitation hardening dominated the strain hardening effect of the shock wave. Transmission electron microscopy confirmed the increase in yield strength was due to the substantial increase in dislocation density in the microstructure, i.e., cold work hardening. These results were presented in the very first publication reporting an improvement in mechanical properties and the associated microstructural changes after laser shocking [12]. Based on these results, the National Science Foundation (NSF) supported a proposal to investigate the primary parameters influencing the magnitude of the in-material and property changes associated with laser shock processing of metals. The possibility that this might develop into a process that could be used for treating metals was recognized, but how and for what would play out in the years ahead.

In January, 1973, the NSF program was initiated. At that same time, Allan Clauer returned to Battelle after a year's absence at Denmark's Risø National Laboratory and Wilcox left Battelle soon after. Clauer and Fairand immediately began the journey to explore laser shock processing with this program and others to follow. In 1974 Fairand and Mallozzi were awarded the first patent for laser shock processing, "Altering Material Properties Using Confined Plasma" [13].

The NSF program had two major objectives: (1) investigate the distribution, depth, and intensity of laser shock-induced plastic strain, and (2) initiate modeling of the peak pressure and shape of the pressure pulse. The distributions of plastic strain formed by the passage of the shock wave were investigated using the etch pitting technique in specimens fabricated from Fe-3Si steel. This method had been used extensively in fracture studies at Battelle by George Hahn and coworkers to study the plastic zone size and shape at the tip of a crack [14]. A large number of disks of different diameters and thicknesses were irradiated with a range of power densities and laser spot diameters. During shocking, the back surface of the disks was a free surface except where supported on the outer rim or pressed against a quartz pressure gauge. After laser shocking, the disks were sectioned along a diameter and the sectioned surface was polished and chemically etched. Since each etch pit on the surface corresponded to a dislocation intersecting the surface, the local density of the etch pits represented the local density of dislocations and thereby the magnitude of the local plastic strain. The relative dislocation density could be easily discerned up to about 3–4% plastic strain, where the etch pits overlapped extensively. Fortunately, the plastic strains were generally below this level.

A variety of deformation patterns were observed depending on the overlay conditions, disk thickness and spot size relative to the disk diameter [15]. Generally, if the beam diameter was significantly less than the disk diameter, or the disk was 5 mm thick, the strain gradient was highest at the surface and decreased with depth as expected. By comparison, if the spot diameter was the same as or larger than the disk diameter and the thickness was about 3 mm or less, the patterns were more complex as shown in Figure 2. This was attributed to strong release waves reflected from the circumferential surface of the disk with the passage of the shock wave. These waves focused along the disk centerline and interacted with the planar shock and reflected waves traveling between the front and back surfaces. Periodically these waves constructively interfere, causing the local stress to rise above the yield strength either in tension or compression, creating various symmetrical, radial patterns like those seen in Figure 2.

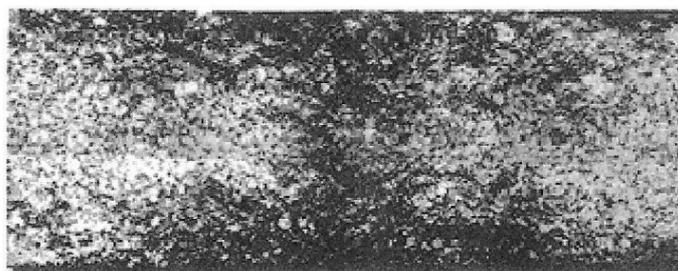


Figure 2. Etched cross-section of a laser shocked 19 mm-diameter, 3 mm-thick Fe-3Si disk showing the plastic strain distribution. 3 mm-thick quartz + 10 μm -thick lead overlays, 27 mm diameter spot, $5.64 \times 10^8 \text{ GW/cm}^2$, 30 ns pulse width. Reproduced with permission from [15], The Minerals, Metals & Materials Society and ASM International, 1977.

Shock wave pressure measurements were also made to relate the intensity of the observed deformation to the incident shock pressures. The pressure was measured on the back surface of Fe-3Si disks of different thicknesses using different overlays, i.e., bare surface, quartz and quartz plus lead. In addition, modeling of the pressure pulse on the target surface and shock wave propagation into the target was undertaken to support understanding of the experimental results [16]. The pressure profiles in Figure 3 demonstrated that the Hugoniot Elastic Limit (HEL), above which plastic yielding occurs in

the shock front, was easily visible in shock wave. In 0.2 mm-thick disks, plastic deformation occurred through the entire cross section producing an increase in hardness of nearly 25% after laser peening [15].

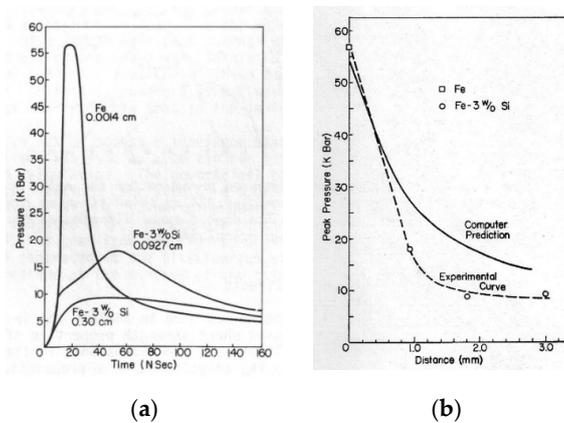


Figure 3. Pressure profiles and experimental and modeled peak pressure attenuation in Fe-3Si disks with a quartz overlay, 30 J/cm², 30 ns pulse width: (a) measured pressure profiles through different thicknesses; (b) peak pressure attenuation through iron [16].

At this early stage it was desirable to have the capability to predict the surface pressure for various overlay and target combinations of interest, and the in-material behavior of the shock wave. A one-dimensional radiation hydrodynamics code was written based on the PUFF computer program [17] to model the laser-material interaction for predicting the surface pressure, and a hydrodynamic code to predict the shock wave attenuation in the disks. This model was first applied to laser shocking the Fe-3Si disks. Figure 3b shows that the predicted surface pressure was close to the experimental pressure. The attenuation of the peak pressure appears to be largely hydrodynamic through the first 0.5–0.6 mm in depth. Beyond this, the attenuation is faster than the hydrodynamic code predicts due to microstructure-related damping effects such as plastic deformation. Lastly, beyond 2 mm the wave is elastic and only weakly attenuated. It should be noted that all pressure measurements using a thin metal foil, vapor deposited film or black paint on a quartz gauge is the pressure developed in the quartz [16].

The research up to early 1975 used only quartz as a transparent overlay. However, it was understood that while quartz was convenient in the laboratory, it was not a viable transparent overlay for a commercial process. Using a quartz overlay required firmly pressing it against a flat, smooth target surface. It could not adapt to curved surfaces without expensive custom design and fabrication of the overlay. In 1973, Fox had used water and paint overlays when investigating spallation of metal samples by laser induced shocks, and observed pressure increases with water and paint overlays [18]. Considering this, it was obvious that water as a transparent overlay had many desirable characteristics. It was transparent to the laser beam and due to the short pressure pulse durations of tens of nanoseconds, a thin, 1 mm layer effectively confined the plasma to the target surface to produce useful shock pressures. It had highly desirable properties for practical use, it was easily applied and removed, and easily accommodated curved surfaces. It was also inexpensive. In our investigation using water as an overlay, the first pressure measurements were made for three setups using a 2 mm-thick layer of still water: on 25 μ m-thick aluminum foil, with and without black paint, and on 3 μ m-thick aluminum film vapor deposited onto a quartz gauge. The tests demonstrated that water did provide the same pressure enhancement, nominally 2 GPa at 1.2 GW/cm², on both aluminum and black paint surfaces. In addition, pressure attenuation profiles similar to those in Figure 3a were also observed in 5086 aluminum using a water overlay [19]. Although these results confirmed the value of a water overlay, subsequent experiments continued to use quartz overlays when necessary to compare results to previous work.

It was also important during this early stage to understand the temporal relationship between the laser pulse and the pressure pulse. A direct comparison of a set of laser and pressure pulse profiles from the same shot is shown in Figure 4. It clearly shows that the rise time of the pressure pulse coincided with that of the laser pulse, and the pressure pulse was nominally twice the width of the laser pulse [20]. Since most of the beam energy initially goes into heating the plasma, driving the pressure, the leading portions of the laser and pressure pulses are similar. After the peak of the laser pulse, the pressure decays, but more slowly than the laser pulse, at a rate determined by the work against the confining materials by the continued expansion of the plasma and loss of thermal energy to the colder surroundings.

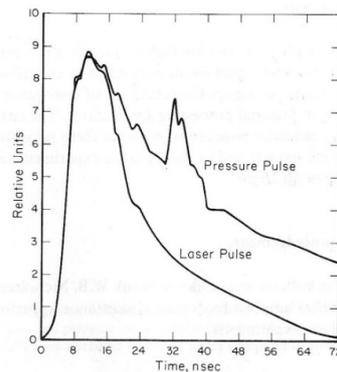


Figure 4. Comparison of laser and pressure pulse profile for the same shot measured for aluminum vapor deposited on a quartz gauge with water overlay, 1.2×10^9 W/cm² [20].

The code used for the first predictions of the shock pressures, shown in Figure 3, was of limited use. To support better understanding of the of the laser shock process going forward, the first robust model of laser induced confined plasmas was developed. A one-dimensional model named LILA, based on the method of finite differences, was written in the mid-1970s to model the laser induced pressure on a confined surface. LILA was then used for all subsequent pressure predictions.

Following development of this model, a number of pressure measurements and predictions were performed to investigate various combinations of transparent and opaque overlays, including iron with lead and quartz overlays, aluminum with water overlay, zinc with water overlay, black paint on aluminum and other combinations [21,22]. An example of water overlay on aluminum foil is shown in Figure 5 [21]. There is good agreement between the peak pressures, although the calculated rise time at the front of the shock wave is slower. The model for zinc foil with a water overlay showed similar agreement, but with the experimental trailing pressure much lower than calculated.

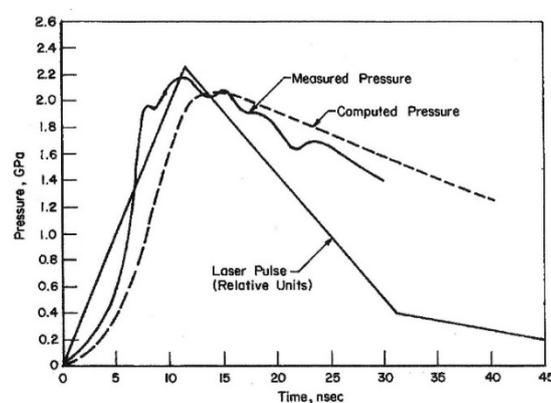


Figure 5. First modeling of pressure pulse for water overlay over a 3 μ m foil of aluminum against a quartz gauge [21].

The first investigation of the dependence of peak pressure on power density, both experimental and predicted, is shown Figure 6. The pressures were measured using quartz pressure gauges with either a 3 μm -thick metallic film vapor deposited directly onto the front electrode surface of the quartz gauges, or with 8–10 μm of ultraflat black Krylon paint sprayed onto the surface of the gauges. For transparent overlays, the films were covered with either 3 mm-thick disks of fused quartz, or 3 mm thickness of distilled water. The laser spot size was several times the gauge inner electrode diameter to ensure one-dimensional strain conditions in the gauge [21].

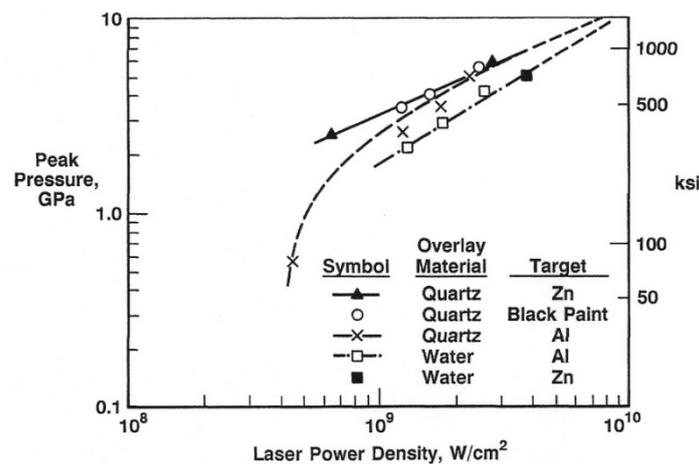


Figure 6. Comparison of predicted and measured pressures for aluminum, zinc and black paint confined by quartz and water overlays. The data points are experimental measurements. The curves are predicted by the LILA code [21].

The figure clearly shows the higher peak pressures reached using quartz overlays compared to water overlays due to the much higher acoustic impedance of quartz relative to water. The pressures created by the zinc and black paint are higher than for aluminum when using quartz overlays at the lower power densities. This was attributed to the higher thermal conductivity of aluminum conducting thermal energy from the plasma into the target. The lower thermal conductivities of zinc and black paint minimize this effect. This effect disappears at higher power densities. The agreement between the experimental and predicted pressures is very good. This series of experiments demonstrated that black paint would make an ideal opaque overlay. It could be easily applied to and removed from any surface to both protect the surface and provide a consistent surface for processing.

During this same time period, 1971–1974, others were also pursuing investigations of laser shock-induced material effects. O’Keefe et. al. investigated the laser shock-induced deformation modes in thin 6061-T6 aluminum and stainless steel targets using a Nd-glass laser and fused quartz or Plexiglass for confining the plasma [23]. They attributed the time sequence of events during bulging and puncturing the thin targets to the interplay of the dilatational and shear waves generated by the pressure pulse. Fox examined the effects of water and paint overlays on cracking and spalling of plexiglass, 6061-T6 aluminum and lead [18]. In addition, he also investigated the overlays’ effects on the peak pressure at the back surface of 1 mm-thick 6061-T6 aluminum coupons. The peak pressure increased as the surface condition was varied between bare, paint only, water only, and water plus paint. At the same time, Yang reported on an extensive study to determine the sensitivity of the peak pressure generated by a confined plasma to target composition, target thickness, and energy density [24]. He found that the peak pressure was relatively insensitive to the target material, and discussed the results in terms of various aspects of plasma generation and thermal effects.

This program helped to understand in general terms the dependence of peak pressure on power density, the pressure pulse relationship to the laser pulse, the use and selection of viable overlays and the in-material plastic strain patterns. The plastic strain distributions observed in the etch pitted Fe-3Si

demonstrated that depending on the target geometry, the interactions of the shock wave from internal surfaces could create different strain distributions.

3.2. Exploring the Effects of Laser Shocks on Material Properties

By the mid-1970s, although there remained much to learn about the characteristics of laser shocks, how to produce them, and how to adapt the means to produce them to achieve a desired result, the salient features of laser shock waves and how to apply them were beginning to take shape and define a process for application to metals. However, to maintain essential funding for developing a laser shock process it was necessary to begin identifying potential commercial uses for the process. The question was, what material properties driving commercial applications, if any, would be most affected in a positive, beneficial way by laser shocking as a process? Could it be developed into a commercially viable process? After all, flyer plate, explosive, and other similar methods had been around for years and had very limited commercial success, and then only in niche applications, such as welding. Laser shocking did have advantages over these earlier technologies. A big advantage was that it was non-contact and treatment could be limited to only the location on a part where it was needed. It appeared that with the use of black paint and water or water only, seldom would other special surface preparations be necessary. Additionally, the shock delivery system could be physically separated from the part manipulation system. The part could be manipulated to the beam by a robot or other tooling already widely used in manufacturing. The Battelle team was confident that a laser facility with sufficient power and processing speed could be reduced to a size compatible with safe processing in a manufacturing environment. It remained to convince others this was a promising, new metal treatment that had strong potential to be developed into a manufacturing process. To do this, it would have to be demonstrated that the effects of laser shock processing on commercial metal alloys would potentially increase strength and/or service life beyond the reach of existing technologies.

In the mid-1970s, one possible area of interest was the strengthening of weld joints in welded aluminum structures. Dogbone-shaped tensile specimens, 3 mm thick, of 5086-H32 and 6061-T61 aluminum alloys containing a transverse weld were laser shocked over the weld and heat affected zones simultaneously from both sides [25]. In the welded condition, both alloys have the same strength i.e., the weld was neither work hardened or precipitation strengthened. After laser shocking, the yield strength of the welded joint in 5086, a strain hardened alloy, was increased to nearly that of the parent alloy by laser shock induced work hardening. By comparison, the yield strength of the welded joint in 6061, a precipitation hardenable alloy, was increased to only midway between the welded and parent levels, at about the same strength as the shocked 5086 alloy. Figure 7 shows the sequential changes in microstructure: before welding, at the edge of the heat affected zone (HAZ) and after laser shocking. The initial microstructure of the 5086-H32 alloy has a fine-grained recrystallized microstructure. The edge of the HAZ has a coarse-grained annealed microstructure with few dislocations. The laser shocked weld zone has the dislocation clusters and tangles of a cold worked microstructure. By comparison, the initial microstructure of the 6061-T6 alloy contains fine lathe-like magnesium silicide precipitates and larger manganese-rich precipitates for strength, but few dislocations. The edge of the HAZ shows the magnesium silicide precipitates have dissolved. The laser shocked microstructure shows a somewhat higher and more tangled dislocation density than the 5086 alloy. The microstructures after shocking showed dislocation densities typical of cold working. In the 6061 alloy, the precipitates responsible for the strength in the T-6 condition had dissolved in the weld and HAZ zones and the laser-induced work hardening was unable to fully compensate for the absence of the precipitate strengthening. For both alloys the relative increases in ultimate tensile strength and hardness were smaller than the increases in the yield strength. It was also found that shocking both sides simultaneously increased the strength more than sequentially shocking both sides. This was expected from observations that simultaneous shocking significantly increased the hardness at the mid-plane of thin cross sections due to increased cold working from the superposition of the

opposing shock waves. In addition, a set of shock wave attenuation curves for different thicknesses of 5086 aluminum were very similar to those shown in Figure 3 [26].

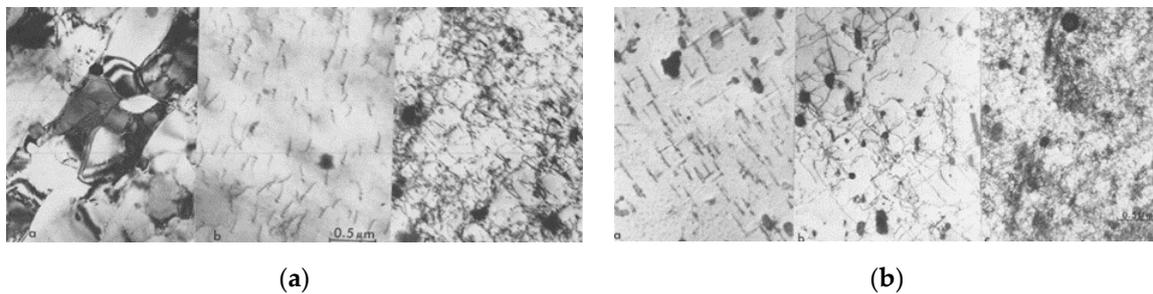


Figure 7. TEM micrographs of the microstructures of the welded and shocked aluminum alloys: (a) 5086-H32 alloy, left to right: as-received, weld heat affected zone (HAZ), laser shocked; (b) 6061-T6 alloy, left to right: as-received, weld HAZ, laser shocked. Reproduced with permission from [25], The Minerals, Metals & Materials Society and ASM International, 1977.

About this same time, the National Aeronautics and Space Administration (NASA) agreed to support an investigation on alloys and properties of interest to them. These included the effect of laser shocking on hardness and tensile strength, and stress corrosion and stress corrosion cracking resistance of 2024 and 7075 aluminum alloys [27]. The 2024 alloy was treated in the lower strength T351 temper and the higher strength, slightly overaged T851 temper. The 7075 alloy was treated in the peak aged T651 and overaged T73 tempers. There were several parts to this investigation. One was intended to compare the hardness response of 2024 to laser shocks and flyer plate shocks to determine whether there were any significant differences that may be related to the different shape of the shock waves. Concurrently laser shocking for tensile strengthening would be examined including transmission electron microscopy of the shocked microstructures. The program would also survey stress corrosion cracking behavior by polarization curves and corrosion crack initiation tests.

The hardness response in each alloy was examined over a range of peak pressure with longer pulse lengths than generally used today. With laser shocks applied with increasing shock peak pressure, the surface hardness of the 2024-T351 condition began increasing at about 1 GPa consistent with an HEL less than 1 GPa (Figure 8a). The T851 condition did not show any hardening with increasing pressure up to 5 GPa, the highest laser shock pressure (Figure 8b). For comparison, Herring and Olsen treated this same alloy in similar aged conditions with flyer plate shocks of 150 ns shock duration at increasing pressure [28]. The initial hardness of the comparable alloys is in good agreement. Despite differences in the shape of the shock wave between the two methods, the data appear to blend together well. The combined data show that the T351 condition reaches a saturation level of hardening at about 5 GPa, and the T851 condition does not show hardness increasing until about 5–6 GPa as defined by the flyer plate data. Figure 8b shows that the laser shocking and flyer plate shocking data are in good agreement at 5 GPa. Although the initial hardness of the two tempers differs by about 15 DPH (Diamond Pyramid Hardness), the saturation hardness level is the same, about 180 DPH. This suggests that the hardness of the T851 temper did not increase until the cold work hardening component exceeded the age hardening component. Then, however, with further increasing peak pressure the hardness increased at a rate similar to the T351 temper to saturation. This may also be related to the lower strain hardening rate for T851 observed in tensile tests. For comparison, a heavily hammered surface gave a hardness of 165–178 DPH [26].

To investigate effects on tensile strength, the test specimens were 1 mm thick and laser shocked either on one side only or on both sides simultaneously to increase the plastic strain at the mid-thickness where the two shock waves superpose. After laser shocking, the yield strength of 2024-T351 did increase, but the ultimate strength remained the same. The total elongation decreased, but the reduction in area increased by a factor of two or more. From limited testing, the yield and ultimate tensile strength

of 2024-T851 were relatively unchanged, the total elongation slightly reduced and the reduction in area slightly increased. These changes in yield strength with laser shocking are consistent with the observed changes in surface hardness. For 7075-T651 the changes were similar to 2024-T851. The yield and ultimate strengths increased for 7075-T73, but the total elongation and reduction in area were relatively unchanged.

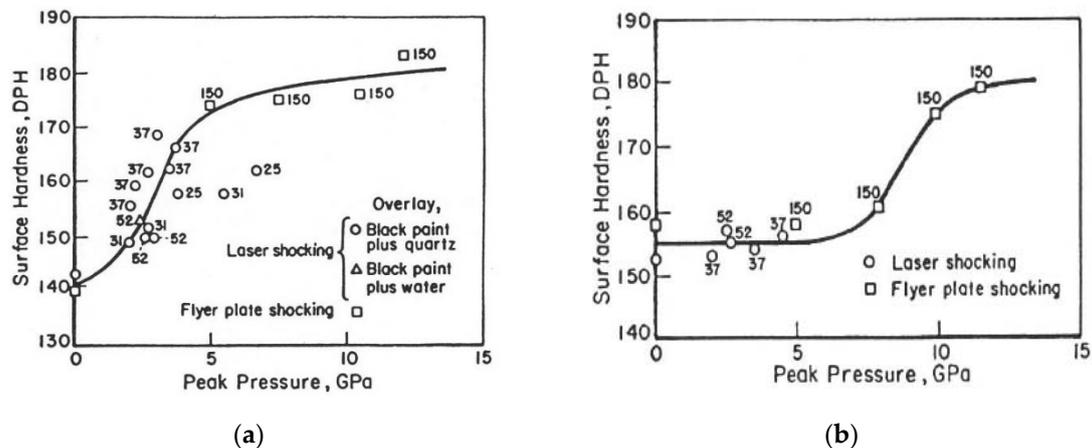


Figure 8. Shock-induced surface hardening dependence on peak pressure. The data point numbers are the pulse width for laser shocks and shock wave width for flyer plate shocks: (a) 2024-T351; (b) 2024-T851. Reproduced with permission from [26], ASM International, 2019. [27].

Transmission electron microscopy of the slightly over aged 2024-T851 and peak aged 7075-T651 coupons showed lower and more uniform dislocation densities, whereas the natural aged 2024-T351 showed dense dislocation tangles and overaged 7075-T73 showed dense dislocation bands. This is consistent with no discernable hardening in the peak aged conditions and the obvious hardening response in the non-peak aged conditions [26].

Polarization curves were measured in aerated 3.5% NaCl solution for both alloys, on sheet cut both parallel and perpendicular to the rolling direction, shocked and unshocked. The tests on 2024-T351 showed little difference between the shocked and unshocked conditions, but did suggest that the corrosion rate for the shocked condition was lower. At higher potentials where pitting originates, the results were consistent with enhanced pitting resistance after laser shocking. The tests on 7075-T651 showed much less effect of shocking. There was an indication that there was an increase in pitting resistance, but not on pit propagation behavior after shocking. Overall, the results indicated that the effect of shocking on stress corrosion cracking resistance should be greater in 2024-T351 than in 7075-T651 [27].

Crack initiation tests were conducted with specimens fixed in a four-point bend jig with outer fiber stress of 60% of the yield, alternately immersed with a cycle of 10 min immersed and 50 min air dry in 3.5% NaCl over a 21-day period. Both shocked and unshocked specimens showed many secondary intergranular cracks, but shocking did have some effect in making the surface more resistant to corrosive attack. However, this was more pronounced in the 7075-T651 than in the 2024-T351, contrary to the polarization results. Concerning time to initiation of stress corrosion cracks, shocking provided no benefit to 2024-T351, cracks appeared about nine days earlier in shocked than in unshocked specimens. However, 7075-T351 did show some benefit. Cracks appeared in two unshocked specimens after 13 days, whereas it took five more days to initiate cracks in shocked specimens. Unfortunately, the crack propagation studies were inconclusive due to limited specimens and experimental difficulties. Overall, the electrochemical and crack initiation experiments did not indicate which alloy was aided more by laser shocking [27].

This program supported the earlier results that the surface of precipitation hardened aluminum alloys in the peak-aged condition did not increase in hardness with laser shocking at the lower power densities usually applied to them. In any case, laser shock strengthening is only effective for thin sections, but can be enhanced by simultaneous, split beam shocking. The very limited corrosion investigation suggested that laser shocking could benefit the 2024 alloy, while the corrosion cracking investigation indicated it could benefit 7075.

Late in the 1970s a research program supported by the Army Research Office investigated the possibility of developing pressure-induced ω phase in titanium-vanadium alloys using laser induced shock waves [21]. To increase the chance for success, it was necessary to increase the laser induced shock pressure on the Ti-V disk specimens. Two approaches were evaluated, one using a high acoustic impedance tungsten backup to a 2.5 mm-thick Ti-V disk to reflect a magnified compressive wave from the back surface of the target, and the other to simultaneously laser shock the front and back surfaces of the Ti-V disk, superimposing the compressive waves at the mid-plane of the disk. Modeling these two scenarios with a quartz overlay at a laser power density of 3 GW/cm² predicted peak pressures of 10.2 GPa with the tungsten disk backup compared to 12.5 GPa with simultaneous laser shocks. Unfortunately, no ω phase was detected by either X-ray or microstructural analysis, perhaps because the pressure pulse was too short.

Beginning in 1977, Battelle, sensing commercial potential in laser shock processing, began to fund exploratory research to demonstrate benefits for commercial applications. This required identifying applications where laser shocking could enhance properties of commercial alloys to increase their commercial value. It was suggested by Steve Ford that Battelle consider fretting fatigue around fastener holes in aircraft structures, a concern in the late 1970s. The test specimen is shown in Figure 9a [29]. This specimen paired a tensile specimen and rectangular pad of 7075-T6 aluminum fastened together with a steel aerospace quality aircraft fastener through a hole in the pad and the gauge length of the tensile specimen. The difference in the cross-sectional areas of the pad and tensile specimen caused a 30% load transfer, creating a cyclic fretting strain differential between the two pieces at the fastener hole. Laser shocking was simultaneously applied to both sides of the fastener hole of the fatigue specimen with a 13 mm-diameter spot centered on the hole. The tensile fretting fatigue results are shown in Figure 9b. These very encouraging and welcome results pointed toward a focus on fatigue related properties as a promising path to commercial use for laser shock processing [26].

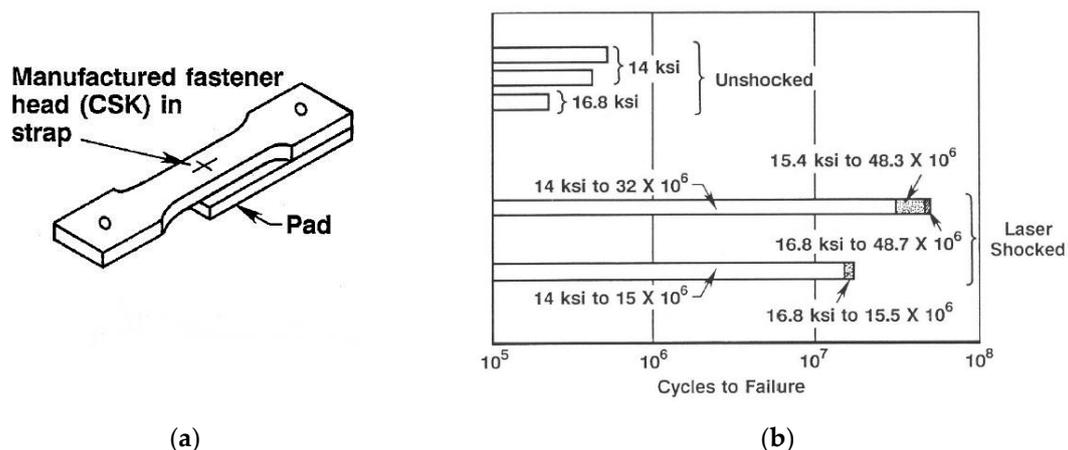


Figure 9. Fretting fatigue of 7075-T6 laser shocked and unshocked in tension with 30% load transfer, $R = 0.1$. (14 ksi = 96.5 MPa, 15.4 ksi = 106 MPa, 16.8 ksi = 115.7 MPa): (a) the test specimen; (b) test results. The stresses indicate steps in the applied stress [29].

Post-test examination showed the fretting surface contained short fretting cracks, but no differences due to laser shocking. At the time, the reason for the life improvement was not clear. It was speculated that the fatigue life improvement may have been due to compressive residual stress, but an earlier

measurement of residual stress in 7075 showed only about 10 ksi (68.9 MPa) surface compressive stress. This earlier measurement was the first measurement of residual stress in a laser shocked surface and there was no other data to compare it to. This low surface stress can now be attributed to a low power density shot. It was also puzzling that the fretting test was duplicated with a shot peened surface and there was no life increase, although it was expected that the surface compressive residual stress would be much higher than 10 ksi (68.9 MPa). It was only after residual stress measurements were made later, that the cause of the extended fatigue life in the laser shocked specimens was understood to be the deeper compressive stress inhibiting the growth of the short surface fretting cracks deeper into the surface.

It was then decided to do a quick test to determine whether crack propagation could be slowed by laser shocking as would be expected if residual stresses were induced. A 0.5 mm deep notch was machined into each side of the hole in the dog-bone tensile fatigue specimen used for the fretting fatigue tests and laser shocked as in the fretting test. The specimens were tested at 82.7 MPa, somewhat lower than the fretting fatigue tests. After the test, the unshocked specimen had a single crack emanating from the root of each notch, one across the width and the other nearly across the width, failing at 4.3×10^5 cycles. By comparison, the laser shocked specimen did not fail from the notches, instead, repeated failure of the grips necessitated terminating the test at 2.3×10^6 cycles. After the test, several small cracks were observed at the root of each notch with the maximum crack growth being 0.8 mm [26]. This dramatic demonstration of crack growth retardation after laser shocking confirmed significant potential for laser shock processing to enhance fatigue properties; another encouraging early result.

This led to the first study of the effect of laser shocking on fatigue strength. Some interest had been expressed concerning increasing the fatigue strength of welds in aluminum, so welded 5456-H116 aluminum alloy tensile fatigue specimens were tested after laser shocking the weld and heat affected zone. The results of these first fatigue tests on laser shocked specimens are shown in Figure 10. At 25 ksi (172.3 MPa), laser shocked specimens ran out at 5×10^6 cycles, compared to typical runouts below 17 ksi. The fatigue life was improved by more than an order of magnitude [30].

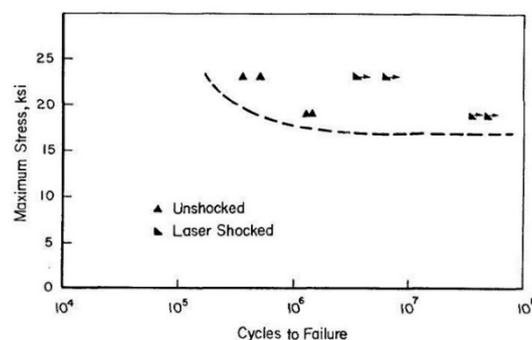


Figure 10. Effect of laser shocking on the fatigue life of welded 5456 aluminum, tension, $R = 0$. The dashed line represents the typical, unshocked tensile fatigue curve for this condition (10 ksi = 68.9 MPa) Reproduced with permission from [30], Springer US, 2019.

Other exploratory tests funded by Battelle included laser shocking ceramics and stainless steel. Laser shocking silicon nitride showed a small hardness increase after laser shocking, indicating it might be possible to develop a compressive surface stress in this ceramic. Additionally, an attempt was made to create a compressive residual stress near the back surface of yttrium stabilized zirconium coupons by driving the tetragonal to monoclinic phase transformation with the reflected tensile wave. This transformation is accompanied by a volume increase and can be activated by a localized tensile stress. It was considered that the toughness of this ceramic could be complimented by a compressive residual stress created by the volume expansion. However, for the limited conditions tried, laser shocking caused only cracking and fracture of the zirconia. Further, to take advantage of the high work hardening behavior of 304 stainless steel, the surface was shock hardened with multiple shots on

the same spot. The surface hardness increased steadily with the number of shots, increasing nearly 70% in hardness after 10 shots [30]. Wear and galling tests after laser shocking showed no discernable improvement in wear, but did appear to reduce galling.

Throughout the 1970s, laser shocked microstructures were examined by transmission electron microscopy in aluminum alloys, including weldments, 304 stainless steel, and Ti-V alloys. The dislocation microstructures were those typically observed in shock hardened alloys. They consisted of greatly increased dislocation density, dense dislocation tangles, some evidence of bands of high dislocation density indicating localized high shear strain in 7075. Some twinning was observed in 304 stainless steel. The first transmission electron microscopy micrographs of high pressure laser shocked structures were made by Wilcox [12].

Based on the fretting fatigue results and the non-propagation of cracks from a notch in the fastener hole of the fretting fatigue specimen described above, in 1978 the US Air Force funded a program to investigate laser peening fastener holes in 2024-T3 and 7075-T651 alloys to mitigate crack initiation and propagation from these holes in aircraft structures [31]. The investigations included fatigue tests for large laser spots centered on 3 mm diameter holes in 3 and 6 mm thick sheet, crack initiation and growth with laser spots slightly overlapping each side of the hole, fretting fatigue, and a limited comparison between constant stress amplitude cycling and a flight-by-flight spectrum (variable stress cycling) for fatigue testing. Quartz and black paint overlays were used throughout the program except for limited tests with water and transparent plastic tape overlays on black paint. In retrospect, it is not clear why quartz overlays continued to be used. It was probably because it was desirable to maximize the pressures for the power densities used at the time. The fatigue specimens were large, 457 mm long with a 250 mm × 102 mm gauge section. Two 3.2 mm diameter holes were drilled along the central axis of each gauge section 102 mm apart. Each hole had side notches having a radius of 0.75 mm to facilitate crack initiation. An 11 mm-diameter laser spot was centered on the predrilled hole, providing 3 mm of laser shocked surface surrounding the notches. The crack initiation and propagation specimens had only one hole with an 11 mm spot overlapping the notches on each side of the hole to provide a longer laser shocked path in front of the cracks.

Residual stress measurements on laser shocked specimens were made to confirm the expectation that laser shock induced compressive stresses were the source of the fatigue life improvements previously observed. These surface stress profiles were measured using X-ray diffraction with measurements spaced across the diameter of the laser spot as shown in Figure 11. The measurements were made to determine whether the magnitude of the surface stress depended on drilling the hole before or after laser shocking. The profile before hole drilling shows the maximum compressive stress at mid-radius as confirmed later by others, but the residual stress outside the hole is the same whether the hole is drilled before or after laser shocking. Based on these results, the holes were predrilled during fabrication of the test specimens and the laser spots were centered on the hole. A few tests were made using water and plastic adhesive tape overlays at higher power densities with mixed results.

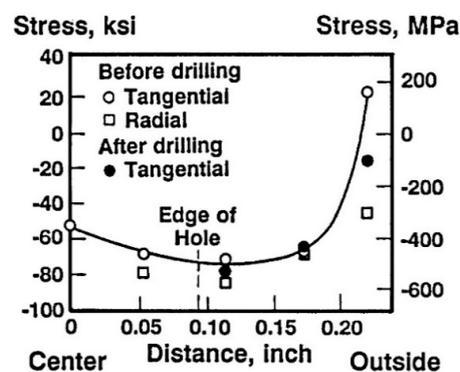


Figure 11. The first residual stress measurements on laser shocked 7075-T651, 5 GW/cm², 3 mm quartz and black paint overlays, 11 mm spot diameter, 6 mm-thick specimens (0.1 inches = 2.5 mm) [29].

The fatigue life of 2024-T3 was extended up to an order of magnitude for both the 3 and 6 mm thicknesses after laser shocking around the holes. However, laser shocked 7075-T651 showed an increase in fatigue life only for the 3 mm thickness specimens. In fatigue testing using a flight-by-flight stress spectrum (a cyclic stress profile having varying stress amplitudes that simulates stress variations during service), 7075 showed improvement by laser shocking at the 40 ksi (275.6 MPa) maximum stress, but little or no benefit at 15 ksi (103.4 MPa) or 17 ksi (117.1 MPa) constant stress amplitude tests. This was attributed to the lower average stress level for the flight-by-flight tests.

The crack propagation results for 2024-T351 are shown in Figure 12. For comparison, the top two sets of bars represent fatigue lives of non-precracked specimens shocked with a 13 mm diameter spot centered on the 6 mm hole. The crack propagation specimens were pre-fatigued to grow a 0.5 mm crack from the notches on each side of the hole, then laser shocked with 11 mm spots as shown in Figure 12a. The effect of laser shocking ahead of the pre-existing crack on fatigue life is shown in the lower set of bars in Figure 12b. Laser peening over an existing crack significantly slowed the crack growth rate and produced a fatigue life approaching that of the non-precracked condition.

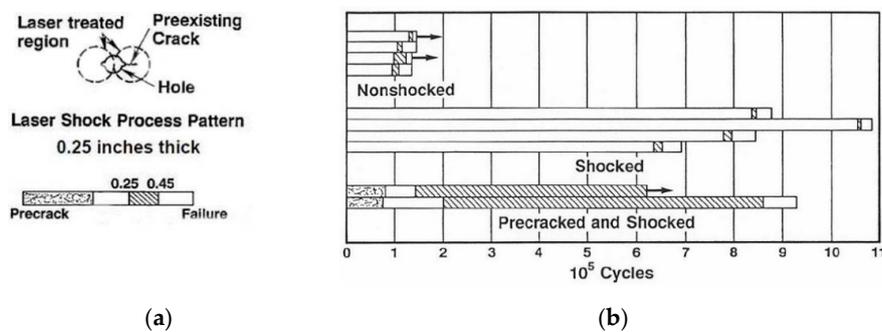


Figure 12. The effect of laser shocking around holes to mitigate crack initiation and propagation in 2024-T351 6 mm thick plate: (a) the laser shock pattern around the hole; (b) test results. The cross-hatched portions are the cycles for the longest crack to increase from 6 to 11 mm long from the center of the hole (0.25 inches = 6 mm) [29].

Fatigue tests using a flight-by-flight spectrum on precracked specimens of 7075-T651 showed a significant reduction in crack propagation rate by half to a third, probably due to the number of low load levels in the flight spectrum. Low-load-transfer fastener joint fretting tests for 7075-T651 showed a factor of 2–3 improvement in life for lower maximum load flight-by-flight tests, but none for higher maximum load tests. In light of other work on 7075 aluminum before and after this program, it is clear that the higher strength 7075-T651 specimens were not laser shocked with sufficient intensity to achieve better fatigue results [30,31].

At the completion of the program, although some benefits were demonstrated, they were not sufficient to continue the program. Looking back, this outcome can be attributed in a large part to having used lower power densities than are now applied, not applying multiple impacts and not shocking material a larger distance from the edge of the hole. Additionally, in retrospect, over 30 years later, Ivetic et al. demonstrated that drilling the hole after laser peening may well have led to longer fatigue lives in this program by reducing or eliminating the mid-thickness tensile residual stress on the hole surface [32]. In this case, even though it may have extended the fatigue life significantly, it would probably have been difficult to implement in the manufacturing process. At the U.S. Air Force's request, one part of the program developed a design for a pre-prototype laser looking forward to eventual commercialization of laser shock processing. Later, this design provided the starting point for designing and building an industrial pre-prototype demonstration laser at Battelle in the mid-1980s.

Although the results of the program were disappointing, the team gained a great deal of valuable experience. The laser peened area around the holes should extend further from the hole. Multiple shots and higher power densities should be applied to achieve deeper residual stresses and/or cold work.

In addition, applying multiple shots on the inside surface of the hole to inhibit in-hole crack initiation would have given better results. These lessons would be applied in the future.

After the U.S. Air Force program ended in 1979, Battelle funded a program to extend the investigation of laser shocking and fatigue phenomena in an aircraft structural alloy, 2024-T3 aluminum [33]. The work focused on issues associated with fastener holes noted in the preceding Air Force program. There was still no emphasis on using water as the transparent overlay for process development work at this point, so this program relied primarily on quartz overlays to enhance the shock pressures. Acrylic transparent overlays were also used for residual stress comparisons. The acrylic overlay produced residual stress levels and depths comparable to the quartz overlay, but showed scatter that indicated more testing would be necessary to use it with confidence.

The fastener holes were 4.7 mm in diameter. The laser spots were either 11 or 16 mm in diameter and placed concentric to the holes after the holes were drilled. A few tests were made using spring loaded momentum traps placed on the rear surface of a hole to explore processing changes to address instances where there was laser beam access from only one side of a thin section and it was necessary to minimize distortion.

In the Air Force program, it was observed that during fatigue of the laser shocked holes, the crack initiated on the surface of the hole at mid-thickness where the compensating tensile residual stress resided. A comparison of the crack initiation and propagation behavior for unshocked and split beam shocked holes is shown in Figure 13 as maps of the progression of the crack front. In the unshocked condition, the crack opens along the entire height of the hole before propagating away from the hole with a straight front. In the shocked condition the crack initiates on the hole surface at mid-thickness of the sheet, followed by tunneling between the compressive surface stresses until it is beyond the laser shocked area. While tunneling it is not visible on the surface and when the ends of the crack do break through to the surface, the compressive stress clamps it closed, making it very difficult to detect. By the time the crack is detected outside the laser shocked spot, it is already many millimeters long, and rapidly propagates to failure. Not being able to see a propagating crack concerned the Air Force.

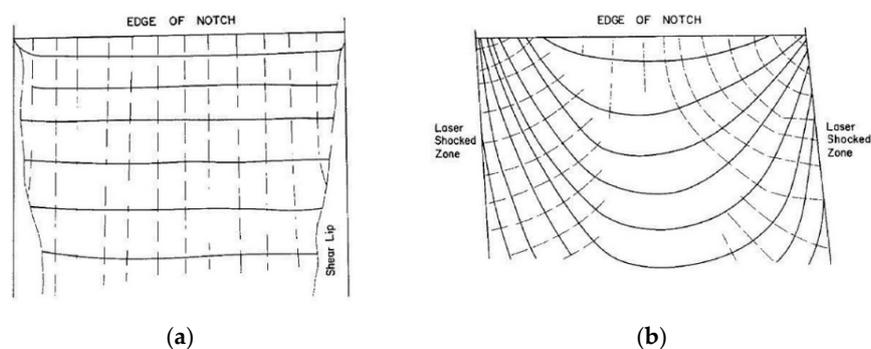


Figure 13. Maps of the crack front progression from the tip of the notch in the side of a hole in 2024-T3: (a) not shocked; (b) shocked both sides simultaneously with a split beam [33].

To address this problem, the shape of the beam was changed from a solid spot to an annular shape as shown in Figure 14a. This would enable a crack emerging from the hole to be observed at the surface shortly after initiation, but slow its growth when it encountered the compressive stresses from the annular beam. The annular beam was applied concentric to the hole with about 2 mm between the edge of the hole and the inside edge of the annular spot. It turned out that this configuration also created a lower surface compressive stress inside the annulus, in the unshocked region to the edge of the hole. This laser shocking configuration was effective in slowing crack propagation outward from the fastener hole, but not as effective as a full circular spot, as shown in Figure 14b. However, the annular beam would provide some factor of safety for inspection or delaying a repair, by, in this case, about a factor of two.

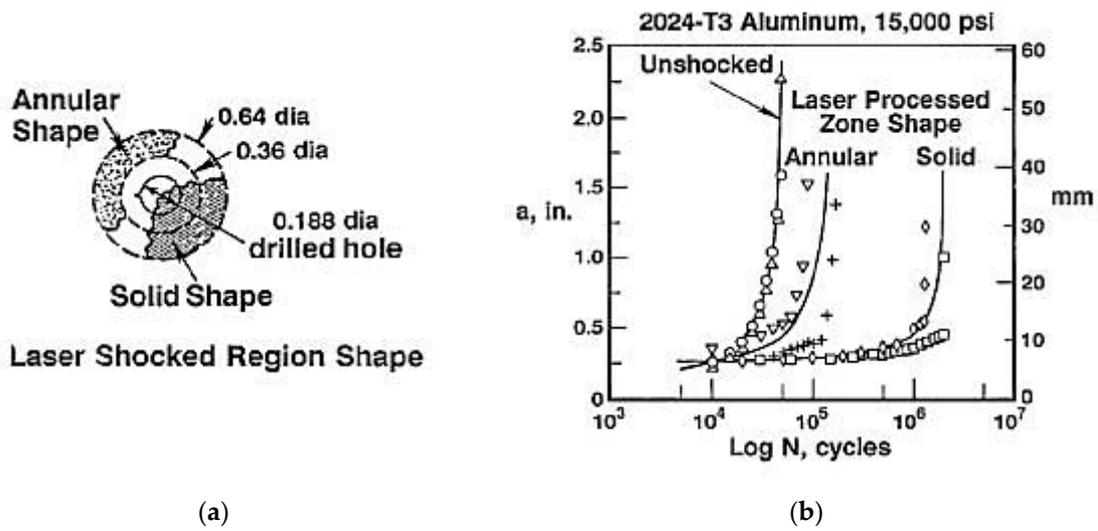


Figure 14. Crack propagation comparison for solid spot and annular spot laser shocking. The hole is 4.8 mm diameter. The annular beam has 9.1 mm ID and 16.3 mm OD; (a) annular spot application configuration; (b) crack growth comparison for shocked annular ring (15,000 psi = 103 MPa) [29].

Despite their commercial importance, up to this time no laser shock processing had been tried on steels. In 1980, Battelle funded a small exploratory task on 4340 steel having hardness levels of 42 Rc and 54 Rc. 4340 steel is often used in cyclic fatigue environments. The first fatigue tests used dog-bone shaped sheet specimens 1.5 mm thick and 38 mm wide having side notches 15.2 mm deep with a root radius of 7.6 mm giving a stress concentration of $K_T = 1.3$ at the bottom of the notches. The 7.6 mm of steel bridging the roots between the opposing notches was laser shocked on opposite sides simultaneously with a 10 mm-diameter spot, applying either one or five shots at 8.5 GW/cm^2 , 15 ns, using quartz and black paint overlays. The surface compressive stress reached about half the tensile strength of the steel after five shots for each hardness. The depth of the compressive stress was limited by the sheet thickness to about 0.45 mm for both one and five shots.

The fatigue results for the 54 Rc hardness specimens after five shots are shown in Figure 15. The unshocked curve beyond 10^5 cycles is handbook data. Specimens 2, 3, and 4 were step loaded. The fatigue results were very encouraging with the fatigue strength increasing over 70% after laser shocking. These tests demonstrated that a significant increase in fatigue life could be achieved by laser shocking both sides of a thin cross section in the vicinity of a stress riser. This would later be the case for laser shocking the leading edge of airfoils.

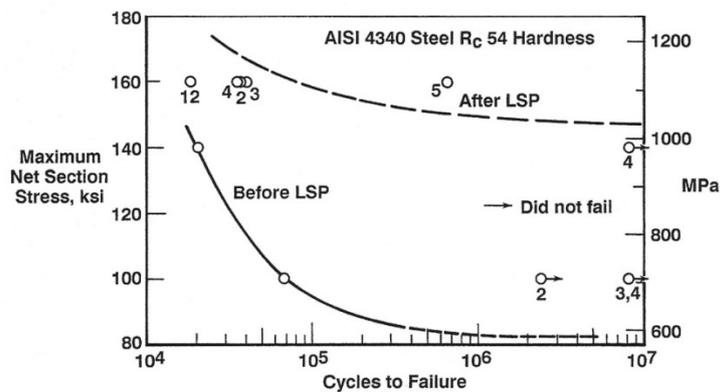


Figure 15. First fatigue life tests on laser shocked steel, 4340 steel at 54 Rc hardness, $R = 0.1$ [29].

Another set of tests using 4340 steel at 54 Rc involved laser shocking directly into the notch of beam specimens loaded in four-point bending. The specimens were 7.5 mm wide by 19 mm high by 204 mm long. The notch in the tensile surface of the beam had a root radius of 4.5 mm and a depth of 1.5 mm. It was laser shocked with multiple shots using a 9 mm diameter spot centered on the notch. The increase in fatigue strength was at least 30% over the notched, unshocked condition. At that load level the beam deformed under the loading rods, preventing testing at higher loads.

These tests demonstrated that a significant increase in fatigue life could also be achieved by laser shocking directly into a stress riser such as a notch or fillet in a thick section, e.g., a change in diameter of a shaft or the fillet at the base of an airfoil.

By 1980, after seven years of research, a basic understanding of the process had been achieved and its potential for increasing the hardness, strength and fatigue properties of metals had been demonstrated, along with some understanding of the effects of part shape and size. However, funding for further investigations of laser shock processing became difficult to obtain. The response for further funding from supporters of the technology was “It is time to go out and find someone interested in developing it commercially for specific applications.” You have a “solution looking for a problem”. The search for funding was hindered by the current large size of the laser, the slow repetition rate, and probable high costs of building a viable production prototype laser with no identifiable critical need. It was difficult for potential users to look past the current circumstances and envision a viable commercial process.

Finishing up the funded programs in 1981 and 1982, Clauer presented a paper at the Conference on Lasers in Materials Processing in Los Angeles in 1983 [33]. He believed this was the beginning of a long interruption in the development of laser shock processing until another group and organization in a more favorable situation continued the effort. Fortunately, this was not the case.

4. Path to Commercialization

The key event that enabled the development to continue, closely followed Clauer’s presentation at the conference. Within a week after returning from the conference, he received a call from the plant manager of Wagner Casting Company, a cast iron foundry for automotive parts in Decatur, Illinois. The plant manager had attended the talk, and upon returning to Decatur, immediately discussed the possibilities of the process with the company management. The discussion concerned the potential of using laser shock processing to upgrade the fatigue properties of iron castings to make them competitive with wrought steel parts at a lower cost. Following a visit to Battelle by Wagner management it was decided Battelle would laser peen and fatigue test several different types of cast iron specimens. A few showed an increase in tensile fatigue strength of 10–15% encouraging further interest.

Wagner Castings was also considering buying a powder metallurgy plant and developed an interest in evaluating the potential of laser shock processing to improve the fatigue properties of ferrous powder metallurgy parts for automotive use. To investigate this possibility, automotive iron-nickel powder was pressed and sintered to 89% density directly into net shape tensile fatigue specimens. The specimens were 100 × 25 × 6 mm having side notches 6 mm deep with a 6 mm radius. These were then laser shocked directly into the notches with an 11 mm diameter spot using water and black paint overlays over a range of pulse energies and 30 ns pulse length. The results are shown in Figure 16. Figure 16a shows the surface residual stress versus cumulative energy on a spot, because different combinations of pulse energy and number of shots were applied. The surface residual stress was unchanged after multiple shots of 30 J and single shots up to 70 J. For single shots of 100 J and multiple shots of 50 J and above there was a steady increase in the compressive stress with increasing cumulative energy. Figure 16b shows the fatigue life versus cumulative energy. It was somewhat unexpected to see that the fatigue life increased steadily with increasing cumulative energy, considering the porous nature of the sintered specimens. The fatigue life increased from 5×10^4 cycles to runouts at nearly 6×10^6 cycles using multiple 70 and 100 J pulses. All future laser peening from this point was performed with black paint and water overlays.

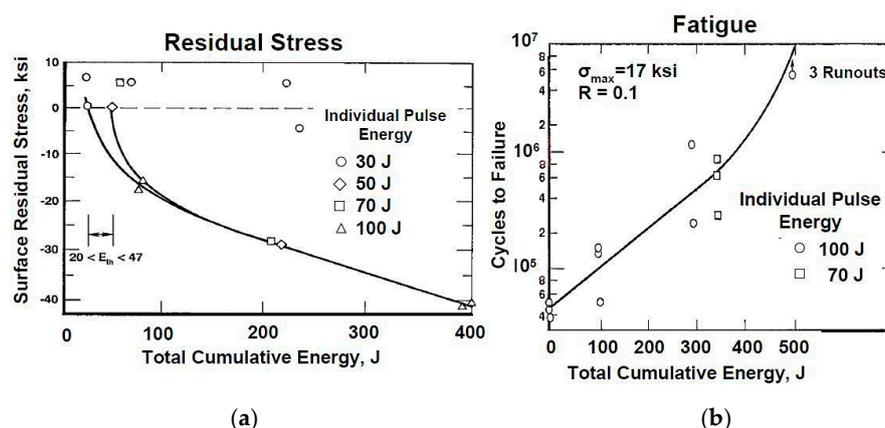


Figure 16. Surface stress and fatigue life of laser shocked, pressed and sintered Fe-2Ni-0.5C powder: (a) surface residual stress; (b) cyclic fatigue life.

Wagner's interests, along with the two larger programs on laser shock processing for enhancing fatigue properties of aluminum alloys described earlier, were now defining the primary focus of laser shock processing as laser shock peening (LSP). Based on the promise shown by LSP to deliver deep compressive stresses and improve fatigue properties of metals beyond that attainable by shot peening, along with other considerations, Wagner Castings purchased the exclusive worldwide license for LSP from Battelle.

To successfully commercialize LSP, it was necessary to design and build a high energy pulsed laser system that would demonstrate that LSP was capable of operating in a manufacturing environment. The system had to have a reasonably small foot print, a pulse frequency and energy demonstrating a capability to produce a reasonable throughput of product and meet environmental and safety requirements: all at a reasonable cost per shot. In 1984, Wagner Castings funded the design and construction of a first-generation prototype laser to demonstrate commercial viability and to process candidate commercial parts for potential users. Harold Epstein designed the laser and Jeff Dulaney oversaw the fabrication and testing of the prototype. In addition, also instrumental in the success of the prototype system were Battelle colleagues Mark O'Loughlin and Steven Toller. The prototype laser, shown in Figure 17, became operational in 1986, producing two beams of 50 J each, 20 ns at 0.5 Hz. In the Figure a He-Ne laser beam defines the beam path of the Nd-glass laser beam. The two cabinets behind the operator contained the electronic control system and capacitors. This was a major step away from the large system shown in Figure 1.

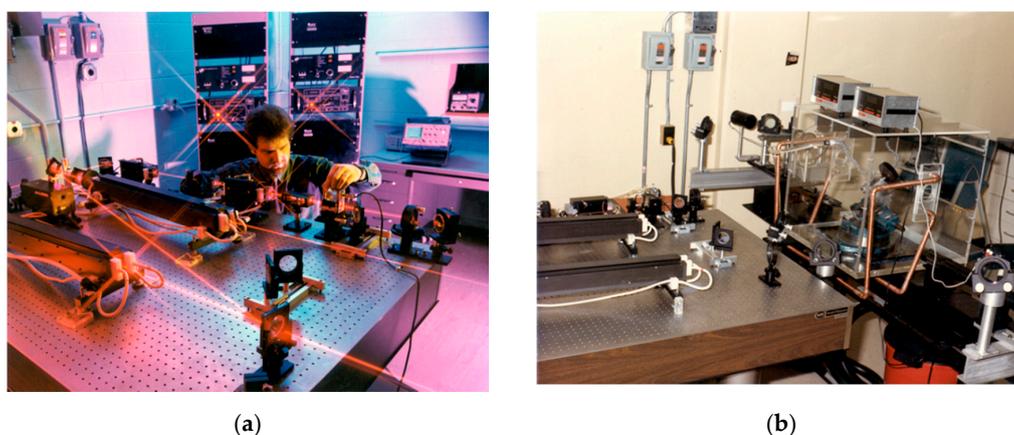


Figure 17. Laser designed and built at Battelle to demonstrate the ability to build the small, high energy pulsed lasers necessary to commercialize laser shock peening; (a) laser; (b) work cell.

After the new laser became operational, it was used for all subsequent laser shock peening using a Plexiglas box containing a three-axis stage and flowing water as the peening cell. During break-in testing of the equipment, it was found that the residual stress profiles from the prototype laser were unacceptable compared to the profiles generated by the CGE laser. The CGE laser used an aluminum blow-off foil to provide isolation between the oscillator and the amplifier chain, but this element was left out of the new prototype laser. In comparing the laser pulse temporal profiles generated by the two lasers, it was obvious that the aluminum blow-off foil of the CGE laser produced a sharp rise time on the leading edge of the pulse. The CGE laser pulse shown in Figure 4 clearly has a rise time of less than 5 ns. Now recognizing that a laser pulse having a steep rise time was a key element for better results, especially at higher power densities, a laser pulse rise-time modifying device was incorporated into the prototype laser. Rise-time modifying devices (e.g., Pockels cells, SBS cells, etc.) are now used in all production laser peening systems that do not naturally produce a rise time less than 5 ns.

In 1984, a marketing effort for laser peening was begun. The market was the equipment and parts producers, but very few, if any, people in industry had ever heard of laser peening. John Koucky, Vice President of Engineering for Wagner Castings, led this effort assisted by Clauer. Over the next nine years, they made many calls and presentations to companies throughout the aerospace, automotive, medical and other industries. With time, awareness and interest in laser peening slowly began to build. A major selling point of laser peening compared to other existing and developing surface treatment technologies such as shot peening and its variations and water jet peening, was that the residual compressive stress extends much deeper below the surface. The compressive stress introduced by the latter technologies is nominally 0.1–0.5 mm deep. By comparison, laser peening extends from nominally 1–1.5 mm in most applications. From this effort, there was a steady flow of parts and laboratory specimens to laser peen for fatigue testing and residual stress analysis, many of which had a problem of premature failure or a need to extend life and reliability without redesign. Although there was much interest in view of the fatigue and compressive residual stress benefits, there was a reluctance to implement the process commercially. The most significant obstacle was the absence of an immediate capability to provide laser peening services or production-ready systems. Another was that without an exceptionally dramatic improvement in properties or a compelling need to avert a crisis in product performance, the inertia stemming from the need to perform qualification testing, modify specifications, change product flow and possibly introduce a new process onto the factory floor was too great to overcome. The comment was made that it is much easier to introduce a new alloy into a part than a new process, even though the end result in product improvement might be greater. Fortunately, the crisis needed to pull LSP into an industrial process was coming.

In October and December of 1990, in-flight engine shut downs occurred during two B-1B bomber flights due to severe engine damage resulting from a fan blade being ingested into the engine [34]. These two incidents led to grounding for more than 50 days of all B-1B bombers not on nuclear flight status. The cause was traced to foreign object damage (FOD) on the first stage fan blades in the F101 engines. During flight, fatigue cracks initiating from the FOD propagated across the airfoil, causing it to separate from the blade and pass through the engine. To avoid these events, preflight checks of the leading edge of all the first stage fan blades were required, since a very small dent in the leading edge of only 0.25 mm could be a problem. Before each flight a thread or thumbnail would be passed along the leading edge of each first stage fan blade. If a defect snagged the thread or fingernail, the blade would be replaced before the next flight. These measures dramatically increased the maintenance costs to keep the planes flying and an element of risk was still present.

Serendipitously, early in 1991, Koucky and Clauer made a presentation at the Air Force Aeronautical Research Laboratories (ARL) within Wright-Patterson Air Force Base. Immediately after the meeting, William Cowey of ARL set up a meeting with the manufacturer of the engines, General Electric Aircraft Engines (GEAE) in Evendale, Ohio. Out of this meeting began the relationship between LSP Technologies and GEAE that became the genesis for solving the FOD problem with the F101 engine

and the first commercial application of LSP. The action item from this first meeting was to laser peen a GEAE test coupon. The laser peened coupon demonstrated to GEAE the potential effectiveness of LSP.

Battelle/Wagner was then asked to laser peen four first stage F-101 engine fan blades for GEAE to test and evaluate. Battelle was asked to laser peen the leading edge using just one peening condition. When the laser peened blades were returned to GEAE, they gave them a rigorous fatigue test. Instead of placing a small damage site equivalent to the ones requiring a blade to be replaced in an engine, a 6 mm-deep notch was hacksawed into the leading edge in the fatigue sensitive location. When tested, the blades displayed the fatigue life of an undamaged blade, much to the disbelief of everyone concerned. After a few more test sequences, in 1995 the Air Force performed their own independent evaluation of the laser shocked blades [35]. They compared the fatigue properties of blades given several different surface treatments on the leading edge and types of simulated damage. The treated conditions included undamaged blades, blades shot peened to the manufacturing specification, high intensity shot peening to achieve greater compressive stress depth, and LSP. After laser peening, simulated foreign object damage was introduced into the leading edge of the surface treated blades, either a 6 mm-deep v-notch pressed into the edge by a chisel, or a 3 mm-deep electrical discharge machined notch. The former had a highly deformed, work hardened surface, whereas the latter had a recast surface layer which probably contained a fine network of shrinkage cracks. The fatigue test results are shown in Figure 18 [34]. The testing consisted of vibrating the airfoils at high frequency using a high velocity air jet, beginning at a maximum stress amplitude of 138 MPa, testing for 10^6 cycles, then raising the stress amplitude by 69 MPa and again testing to 10^6 cycles. This sequence was repeated until the airfoil failed. The results validated the original test results. As shown in Figure 18, damage with no pretreatment caused a large degradation in fatigue strength. Both shot peening treatments improved the fatigue strength somewhat compared to the untreated condition. The laser peened blades amazingly retained the fatigue strength of the undamaged blades. This wholly unexpected result occurred because the compressive residual stress extended through the thickness of the thin leading edge of the blade. The compensating tensile residual stress was positioned behind the laser peened strip, not at mid-thickness up to the leading edge.

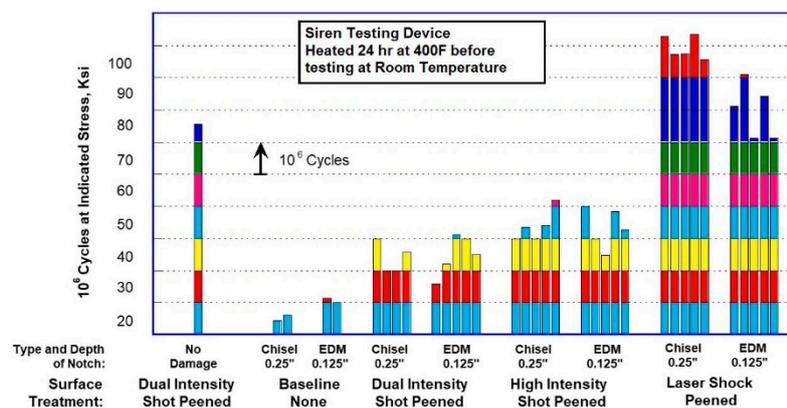


Figure 18. Fatigue strength of F101 fan blades comparing the influence of various surface treatments for protecting against the loss of fatigue strength from foreign object damage.

While the necessary further processing and testing of the laser peened fan blades was underway, by 1994, Wagner Casting had become a subsidiary of another company with a different business focus and they returned the license to Battelle. Dulaney, who had been leading the laser physics team, took advantage of this opportunity. He left Battelle in late 1994 to start up LSP Technologies (LSPT). His goal was to take LSP to the market. In 1995, he acquired an exclusive worldwide license from Battelle. Clauer retired from Battelle and joined LSP Technologies in 1995 to continue his quest to help commercialize LSP. Meanwhile, after a thorough testing program, GEAE and the US Air Force decided that laser peening had to be applied to the F101 1st stage fan blades to remove their vulnerability to FOD.

The most immediate need was to obtain a laser system capable of production laser peening. There were no commercial lasers available and all laser manufacturers were deemed to be high-risk suppliers of a high-energy, high-reliability laser system that met GEAE's specifications. With no existing commercial alternative, GEAE contracted with LSP Technologies to design and fabricate three production-capable lasers, under the strict guidance and control of GE's Corporate Research and Development center in Schenectady, New York. Todd Rockstroh and Seetharamaiah Mannava were the technical contacts within GEAE. These systems were delivered to GEAE in Evendale, Ohio throughout the late-1990s and were the first commercial lasers sold specifically for laser shock peening. With this equipment GEAE began production laser peening F101 1st stage fan blades in 1997 and became the first industrial user of LSP. After laser peening was applied to in-service blades reinstalled in the engines, they were no longer vulnerable to normal FOD and the preflight fan blade inspections were terminated.

In 1996, following LSP Technologies' delivery of the first production laser to GEAE, LSPT began a program funded by the US Air Force, to design, fabricate, and demonstrate a second-generation production laser for in-house use. This laser was completed and successfully demonstrated the following year and served many years as a production laser. In 1999, the Air Force awarded LSPT a multi-million dollar joint program with GEAE and Pratt and Whitney to design and build a production laser peening system as a manufacturing system prototype, expand the use of laser peening within gas turbine engines and develop non-aerospace commercial laser peening opportunities. In 1999, LSPT began working with Pratt and Whitney to apply laser peening to the airfoils of an integrally bladed rotor (IBR) for the F119 engine used on the F-22 fighter aircraft. LSPT began production laser peening on the IBRs in March 2003, becoming the first commercial provider of laser peening services. LSPT has grown and expanded production to other turbine airfoils and non-turbine components since then.

Through the late 1990s and early 2000s the financial support of the U.S. Air Force Aeronautical Research Laboratory at Wright-Patterson Air Force Base was critical to developing laser shock peening as an industrial process. In addition to the financial support, the technical support and advocacy of the Air Force Man Tech project engineers played a crucial role.

In the late-1990s, a third company became interested in laser peening technology. The Metal Improvement Company (MIC) began working with the Lawrence Livermore National Laboratory to design and build a slab laser for laser peening. They began production laser peening of fan blades for the Rolls Royce Trent 800 commercial gas turbine engines in 2003, and have expanded production to other blades and components since then. They have made significant innovations in laser peening systems and have extended laser peening to a production laser peen forming process forming wing skins for the Boeing 747-8 aircraft. With their entry into the field as an independent supplier of laser peening services, laser peening overcame a significant barrier for growth. Without the backup of an alternative provider of laser peening services, manufacturers have some reluctance to commit to using laser peening only to find that at some point they may be losing the only service provider.

5. Global Expansion of Laser Shock Peening

While process and business developments were being vigorously pursued in the United States, strong, productive research programs were being pursued elsewhere. In the mid-1980s, interest in laser shock peening took hold in France, an extension of their years of previous work with high-energy pulsed lasers. A short time before 1986, Jean Fournier began the first investigation into laser shock processing in France as his doctoral dissertation under Professor Remy Fabbro at the Ecole Polytechnique in Paris. In 1986, Fournier and Fabbro visited Battelle for a mutually beneficial extended discussion of laser peening with Clauer. Their first paper on laser shock waves using a confined plasma concerned determining the impulse imparted to copper specimens [36]. This was followed by a publication describing a model for pressure pulse generated by a confined plasma in 1990 [37]. In the years since then, Fabbro, Patrice Peyre and colleagues conducted an extensive, broadly-based program in laser peening centered around their high energy pulsed laser facilities. Their

investigations have covered many aspects of laser peening, including material property effects such as fatigue, stress corrosion, wear, laser beam interactions with water overlays and target materials, pressure measurements for a variety of laser pulse widths, wavelengths and power densities, and the pressure spatial distribution within the laser spot. In addition, a significant amount of modeling of the pressure pulse and in-material shock wave behavior was pursued. This effort has supported a large number of doctoral dissertations and research programs, particularly in the late 1990s and has been sustained for over 30 years in their universities and laboratories. The French programs have made an important and significant contribution to advancing the understanding of laser shock processing to where it stands today.

In China, interest in laser induced shocks using a confined plasma first appeared in 1996 from the University of Science and Technology in Hefei, where Zhiyong Li and colleagues studied the attenuation of laser-induced shock waves in copper using an acrylic transparent overlay [38]. At that same time, Yongkang Zhang initiated a laser shock processing program in Nanjing University [39]. Later, Yongkang Zhang and Jianzhong Zhou directed laser shock processing programs at Jiangsu University in fatigue, modeling and laser shock metal forming [40]. Recently Zhang moved to Guangdong University of Technology to set up another laser shock laboratory. In addition to these university programs there are several other laboratories doing research in laser processing in China.

There are a number of other productive university and national laboratory programs in laser shock processing other countries, but unfortunately, there is not enough space to acknowledge their efforts.

The globalization of laser peening is also evident in the growth of the number of patents related to laser shock processing, most of them about laser peening. Due to the possibility that laser shock processing could become a commercial process, early on there was an awareness that it was necessary to patent important aspects of the process and equipment developments being discovered. The resulting growth in the number of patents related to laser shock processing is shown in Figure 19. The growth rate accelerated dramatically with the beginning of production at GEAE and the startup of LSP Technologies in the mid-90s. Later, around 2000, the numbers of World, European and Asian patents accelerated. In 2012 the total patents reached 380, representing 15 countries, with the major regions being the United States, Europe, Japan, and China. The number of technical papers related to laser peening follows a similar trajectory, growing slowly until the mid-90s, then rapidly accelerating. At this time the number of technical papers concerning laser shock processing is approaching 800–1000, representing the research of tens of laboratories.

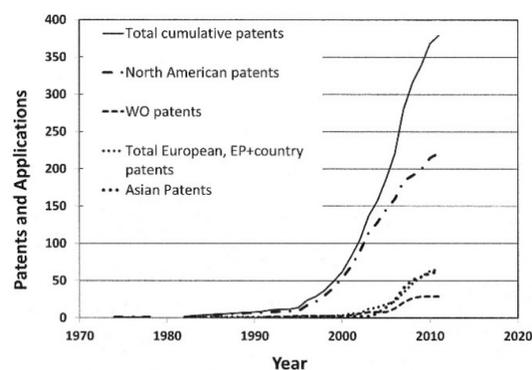


Figure 19. Growth of the number of patents associated with laser shock peening (LSP).

A Modified Laser Peening Process is Developed

In 1993, Yuji Sano at Toshiba in Japan, unaware of the laser peening work elsewhere, independently began developing a laser peening system entirely different from the high energy pulsed lasers being used in the USA and Europe at the time [41]. His system was specifically developed to treat structural features inside water-filled boiling water reactors (BWR) and pressurized water reactors (PWR) to mitigate stress corrosion cracking problems. The prevailing laser peening approach taken by the United

States and France at that time used Nd-glass lasers with 1054 nm wavelength, pulse energies of 10–40 J, pulse widths of 10–30 ns, and spot diameters ≥ 2 mm, with five or more spots per cm^2 applied at 1–5 Hz on surfaces covered with a protective opaque overlay of tape or paint. The modified approach developed by Sano at Toshiba used Nd-YAG lasers frequency doubled to produce a beam of 532 nm wavelength, pulse energies of ≤ 0.1 J, pulse widths of ≤ 10 ns, spots diameters ≤ 1 mm, with thousands of spots per cm^2 applied under water with no protective overlay. The 532 nm wavelength decreases the absorption of the beam while passing through the water. This process is referred to Laser Peening without Coating (LPwC). Although the bare surface being peened initially experiences tensile stress on the surface due to melting and lesser thermal effects, as the density of spots applied increases, the subsurface compressive stress increases and “bleeds” through to the surface, reversing the initial tensile stress. Although the small spot size precludes achieving compressive stress much deeper than 1 mm, the magnitude and depth of the compressive stresses are comparable to those achieved by the historical peening conditions using higher energy, larger spots.

In 1994, Sano achieved the first demonstration of compressive surface stress for LPwC and in 1999 was able to make the first application to a BWR shroud. This was followed by the first application using fiber-delivery of the laser beam in 2001 and by the first application to nozzles in a PWR in 2002. In 2006 the development of an ultra-compact portable system was completed and first used in applications in 2012. Through the early 2000s Sano decreased the size of the laser, increased the repetition rate and developed a portable laser peening system, paving the way for this process to be used in air outside reactor vessels. LPwC began to be applied to nuclear steam turbine blades in 2010. Recently, a hand-held laser has been developed.

In the late 1990s, Professor José Ocaña and colleagues at the Universidad Politécnica de Madrid, began developing a comprehensive model for laser shock processing [42]. In the early 2000s they initiated an experimental program using an approach similar to Sano’s, but with a slightly larger spot size of 1.5 mm diameter and higher pulse energy of 2 J applied at 10 Hz. Ocaña and his colleagues have contributed significantly to the understanding of laser processing technology over the last 20 years. Their investigations have been wide ranging, including theory, overlay effects on residual stresses and surface roughness with and without black paint overlay, fatigue [43], hardness, and wear on a number of metal alloys. They have also demonstrated the potential of laser shock processing for micro-metal forming for Micro-Electro-Mechanical Systems (MEMS) applications [44]. In addition, his laboratory’s laser has been available for others to use to pursue their research.

6. Present Status of Laser Shock Processing

Laser shock peening is now firmly entrenched as a mature commercial process to mitigate fatigue problems and for highly controlled bending or forming of aluminum plate into complex contours. Publicly available industrial specifications exist for laser peening (AMS2546) and the commercial providers are AS9100 certified. There are currently two laser peening companies, LSP Technologies located in Dublin, Ohio and the Metal Improvement Company (MIC) located in Livermore, California, giving customers the opportunity to choose the best fit for their needs. These peening companies have expanded their customer base worldwide; LSP Technologies from the United States into Germany and China, and MIC from the United States into Great Britain. GEAE does laser shock peening in-house for its own parts only, and is not a commercial supplier of laser peening. Business partnerships and alliances have begun to develop around this technology. In 2010, LSP Technologies and General Electric entered into an intellectual property cross-licensing agreement, allowing each access to the other’s patents and intellectual property. In August 2012, the cross-license was expanded to allow sub-licensing of each other’s patents.

Growth has been slow, but steady, as with most new industrial processes. The years following laser peening’s entry into the market have provided potential users the opportunity to evaluate its commercial viability and reliability, its adaptability to new applications and manufacturing environments, its decreasing cost trajectory and its versatility. As this scenario has been unfolding,

unanticipated opportunities for applying the technology, each with their own challenges, are appearing. Meeting these challenges to implement laser peening in new ways makes this an exciting time in the growth of the technology and the marketplace.

Fortunately, the two laser peening providers have taken a different approach to the market place, giving customers a choice. LSP Technologies provides both laser peening systems and laser peening services in-house. It has recently developed the Procudo Laser Peening System, the first commercially available laser developed specifically for laser peening, shown in Figure 20. The Procudo Laser Peening Systems requested by customers include the Procudo Laser and custom peening systems designed and engineered for the user's particular needs. The Procudo Laser produces pulses up to 10 J at 1–20 Hz. Considering the range of pulse frequencies available for laser peening, it is desirable that the effect on the target is independent of frequency for the same spot size. Figure 21 shows the consistency in the residual stresses produced from 1 to 20 Hz on Ti-6Al-4V. The processing conditions were water and black tape overlays, 2.5 mm diameter spots, 9 GW/cm², five layers with same spot pattern. The residual stress was determined by the slitting technique.



Figure 20. The next generation laser peening laser, the Procudo Laser Peening System by LSP Technologies, Inc.

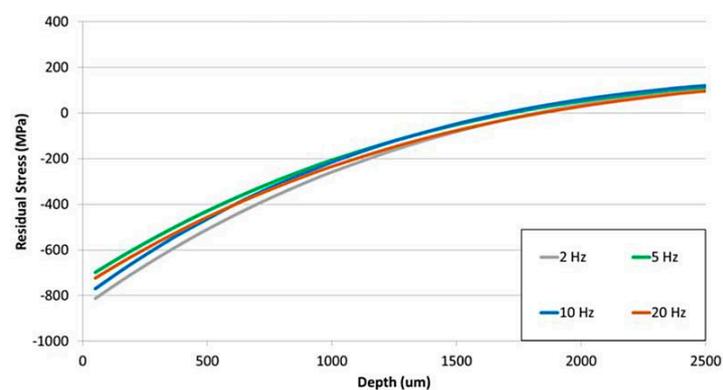


Figure 21. Residual stress profiles in 19 mm-thick Ti-6Al-4V coupons produced by the Procudo Laser Peening System applied at 1, 5, 10, and 20 Hz.

MIC provides laser peening services both on-site and off-site. It appears that off-site laser peening is either done in the customer's facility through a business agreement, or uses MIC's truck-transported lasers and processing systems set up in the customer's facility. MIC uses their own custom designed lasers.

The second industrial application of laser peening, controlled bending or curvature of metal wing skins for aircraft has been implemented for contoured wing skins by MIC on Boeing aircraft in Boeing's

facility. This process has also been demonstrated by LSP Technologies on large aluminum plates in collaboration with Navy projects, forming desired contours with great accuracy.

A recent third application is now mitigation of stress corrosion cracking of stainless steel casks for holding spent nuclear fuel in storage by MIC [45].

One of the important tools now available to decrease the cost and time to move a part benefitting from laser peening into production is finite element modeling. In the 1990s, it was realized that getting a part approved for production entailed extensive exploratory processing and testing to ascertain the best processing conditions for maximum benefit to the peened part, followed by further processing and testing to qualify the process and the part for production. The substantial expense and time involved in this endeavor was a significant negative factor when considering new applications. It was clear that to minimize the informed, empirical approach to selecting the initial processing conditions, a modeling approach to preselect the most promising exploratory processing conditions was needed. The first 1D codes developed at Battelle in the 1970s discussed earlier, were limited to predicting surface pressures and included only hydrodynamic attenuation of the shock wave in the material. In 1990, Fabro et al. published their extended 1D model to elucidate the various physical processes occurring in confined, laser induced plasmas, providing an incentive for laser peening modeling efforts ever since [37]. Subsequently the French teams modeled the in-material shockwave behavior extensively with their SHYLAC code [46]. To initiate modeling development for laser peening in the United States, the Air Force supported a joint LSP Technologies-Ohio State University (OSU) program as a dissertation study in 1998 [47]. Abaqus finite element software was used to model in 2D and limited 3D with explicit and implicit steps to predict the magnitude and gradient of the compressive residual stress. The intent was to eliminate modeling the laser-material interaction step and instead to apply just the pressure pulse to the surface of the model over the area of a laser spot. The peak pressure of the pulse for a selected power density was taken from peak pressure vs. power density plots as shown in Figure 6. Models of different thickness, single and split beam applications, the Johnson-Cook constitutive equation, various yield criteria, and wave damping methods were among the aspects investigated. The predicted results were compared to experimental residual stress measurements for Ti-6Al-4V as shown in Figure 22. Very good agreement was obtained for single shots at two power densities, one of which was predicted before making the measurements. For multiple shots, the model predicted higher compressive stresses, but was not checked experimentally. The results for the split beam application was not even close. This was attributed to not having the ability to handle the extensive reversed plasticity occurring in this case. Unfortunately, an extensive publication of this work did not occur. The only publication of this work was by Clauer et al. [48,49]. Braisted and Brockman's model was similar to the OSU model [50]. In 2003, Peyre et al. in France [51,52], and in 2004, O'caña et al. in Spain [42,53], also used finite element models for 2D and 3D modeling of shock waves and residual stresses. In 2012, Brockman, et al. did an extensive modeling analysis of the non-uniformities in the residual stress field in a laser peened volume, demonstrating that care must be taken to ensure that these uniformities do not jeopardize the reliability of the processing [54]. Fortunately, the process is robust enough that these concerns can be alleviated to a degree by spot overlap in practice. These and many other modeling efforts have greatly increased the understanding of the process. However, expanding this modelling approach to larger areas containing many spots, multiple layers and nonplanar geometries typical of most laser peened parts, required substantial computer time, model tweaking and further development.

Fortunately, in the early 2000s a much different modeling approach to representing residual stresses in laser peened parts appeared. This approach could be applied to a finite element model of any desired size or shape and did not require simulating the passage of a shock wave to develop the stress field. Instead, a residual stress gradient is created in a finite element model by inserting an appropriate eigenstrain distribution into it [55–57]. The eigenstrains are derived from actual residual stress magnitudes and gradients measured on coupons of an alloy of interest after laser peening with different conditions. The eigenstrains are inserted into a finite element model of the part geometry under the anticipated laser peened area by either inserting a distribution of different thermal expansion

coefficients at element nodes and raising the temperature one degree, or by maintaining a constant thermal expansion coefficient in the model and imposing a temperature on the surface to develop a thermal gradient into the model. This eigenstrain approach makes it relatively easy to explore how the residual stress field over the laser peened area adapts to different geometries. By this means, the extent and shape of the area to be processed and the appropriate range of processing intensities can now be determined relatively quickly before processing the first test parts. This approach now reduces the time and expense for developing new applications and increasing the odds of a successful implementation of the process.

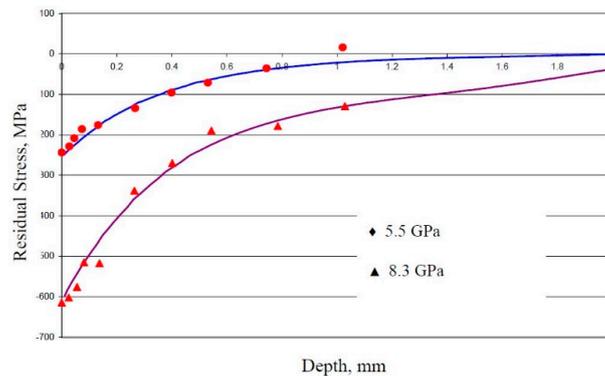


Figure 22. Comparison of experimental and predicted residual stress gradients in Ti-6Al-4V [48,49].

Over the last 25 years, it has been established that laser peening is a robust and versatile process. Deep compressive stresses can be obtained with a broad range of laser capabilities and laser peening conditions. One way of illustrating this is to categorize laser shock processing systems into roughly three categories according to the energy range of the pulses generated. The original lasers were high energy pulsed lasers having Nd-glass rods producing a beam with a wavelength of 1054 nm. These lasers output pulses of 10–40 J, 10–30 ns long, operating at 1–5 Hz. The working spot sizes are 3 mm–10 mm in diameter. Larger spot sizes have the advantage producing deeper compressive stresses in thicker sections. In the mid-1990s, it was demonstrated that acceptable results could also be obtained with what we may describe as intermediate energy and low energy lasers. The intermediate energy lasers have Nd-YAG rods producing a beam with a wavelength of 1064 nm. These lasers output pulses of 1–10 J, nominally 10 ns long, operating at 1–20 Hz. The working spot size is 1–2 mm diameter. The low energy pulsed lasers also have Nd-YAG rods. These lasers output pulses of ≤ 1 J, ≤ 10 ns long, operating at 40–100+ Hz. The working spot sizes are ≤ 1 mm in diameter. In general, decreasing the laser's energy per pulse is a trade-off enabling pulsing the laser at higher frequencies. The laser footprint of these lasers is nominally in the range of 1–6 m² with the low energy lasers at the small end. This range of options enable the size of laser peening systems to be scaled in size, cost and capability to fit the needs of the manufacturer and product. The trend now appears to favor the intermediate energy pulsed lasers. Higher beam repetition rates favor the use of a tape opaque overlay or processing the bare metal surface.

While the forgoing described the present state of laser peening, some of the activities pursuing the use of laser-induced shock waves in a broader context are nearing commercialization to meet specific industry needs. For example, the Laser Bond Inspection (LBI) system developed by LSP Technologies, Inc. to evaluate the strength of adhesive bonds in composite bonded structures is used to evaluate the strength at the bond interface between composite layers. The major aircraft manufacturers are working towards implementing this technology as a method to evaluate the bond strength integrity during the manufacture of adhesively bonded structures [58,59].

Another example is the LASer Adhesion Test (LASAT) developed by the French National Center for Research. This is a method of measuring and testing the adhesion of thin films to metal and ceramic

substrates. There are variations of this test for different situations, and tests may be performed with a confined plasma in air or unconfined in a vacuum.

7. The Future

Predicting what lies ahead is always risky, but a few comments will be ventured. More laser peening facilities will be equipped with the intermediate size lasers due to their small footprint and lower operating costs. These lasers will be located in, and operated by, the companies and incorporated within the normal flow of their production lines.

The low energy, high frequency laser systems will find their niche, perhaps first as their small size and portability will enable laser peening of critical locations in large structures to benefit from laser peening.

Eventually, applications will be found for other aspects of laser shock processing. Several have been explored in laboratories and have shown promise technically. However, they have to address a real need to justify the costs of further development. Some of these are metal forming of small objects such as MEMs components, welding of dissimilar metals for small assemblies, surface imprinting of shape memory alloys, laser peening additively manufactured parts and using thermomechanical processing, i.e., laser peening at elevated temperatures, where it contributes to higher compressive residual stress and strength.

One last comment: it has been a wonderful gift to have had the opportunity to be part of the birth and maturation of laser shock peening over the past 46 years.

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