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NEW LASER TECHNOLOGY MAKES LASERSHOT^{sm} PEENING COMMERCIALLY AFFORDABLE

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ABSTRACT

Lasershot^{sm} peening, a surface treatment for metals, is known to induce compressive stresses of over 0.040 in. This provides a damage tolerant component more resistant to various forms of stress related failures than more traditional forms which induce residual compressive stress. This process developed in the 1970's has now moved from a laboratory curiosity to an affordable process for industry. We have developed a unique solid state laser technology employing ND:glass slabs and phase conjugation capable of producing 100 joules at 10 hertz. We have demonstrated the ability to use this technology by employing a five axis parts handling and manipulating system enabling rapid throughput.

KEY WORDS

Laser shock peening; SBS Phase conjugation; ND:glass; Residual compressive stress.

Various forms of cold working have been used by industry for many years to induce beneficial compressive stresses in metals. These include fillet rolling, cold expansion of holes, shot peening and the newest form, laser shock peening. The significant increases in resistance to fatigue, fretting fatigue and stress corrosion due to residual compressive stresses are well known. Shot peening has been the process most widely used because of its ability to induce these stresses efficiently and inexpensively on parts of complex geometry. The depth of the compressive stress produced by shot peening is typically 0.010 in. and can reach 0.030 in. but may leave an undesirable surface finish at these high intensity levels.

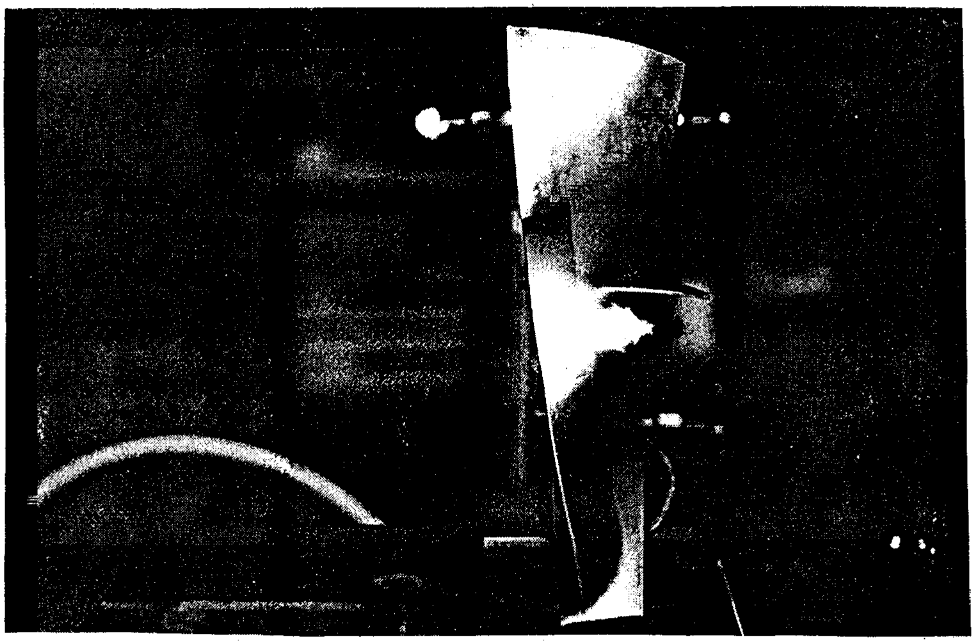

Figure 1. A jet engine fan blade being treated by a laser shock peening system whichcanextend the service life by a factor of three to five times

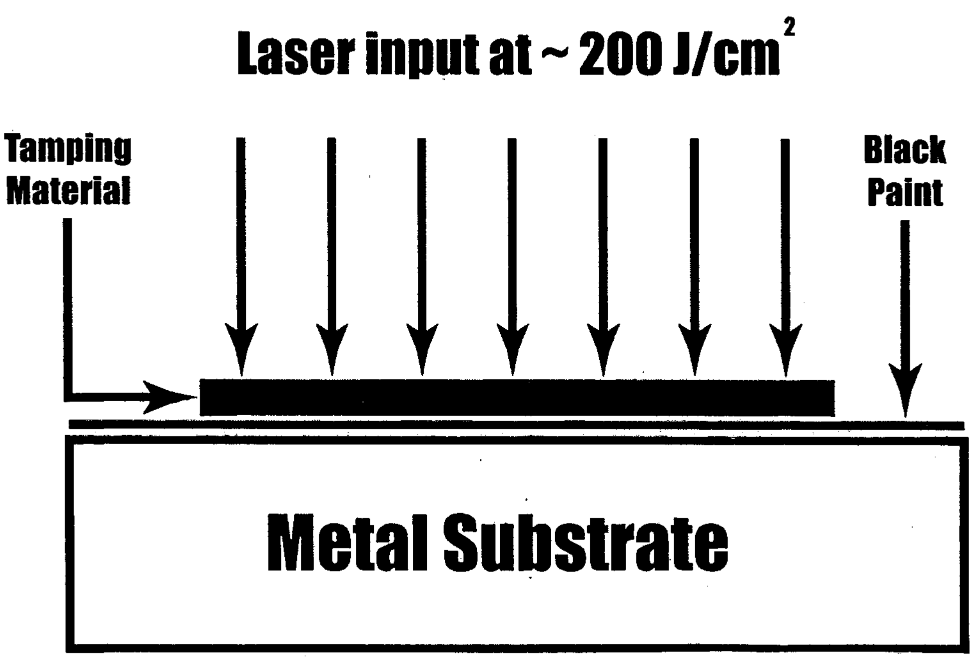

Figure 2. Typical setup for laser peening. The metal is covered with a layer of paint to provide light absorption and is covered with a thin water tamping layer which contains the shock

Laser shock peening, also a surface treatment, employs laser induced shocks to create deep compressive stresses exceeding 0.040 inch with magnitudes comparable to that produced by shot peening. Laser shock peening has proven to significantly enhance the damage tolerance of a part and has generated sufficiently impressive results to move it from a laboratory demonstration phase into a significant industrial process. Until now this evolution has been slowed because a laser system meeting the power requirements for economical processing has been lacking. Commercial lasers available now are limited to power output of 10 to 100 joules and repetition rates of around 0.25 hertz, with a new design being developed with 1 hertz capability. It is estimated that the time required to process an area 1 inch by three inches can take from one to three hours using one of these machines. We have developed a robust laser system which for the first time pushes the average power output of 100 joules at 10 hertz. It enables the processing of a 3 inch area in minutes instead of hours.

With the invention of the laser, it was rapidly recognized that the intense shocks required for peening could be achieved by means of tamped plasmas which were generated at metal surfaces by means of high energy density (~200 J/ cm^2) lasers with pulse lengths in the tens of nanoseconds range. Initial studies on laser shock processing of materials were done at the Battelle Institute (Columbus, OH) from about 1968 to 1981[1,2]. Excellent recent work has also been reported in France [3]. Figure 1 shows a typical setup for laser peening. Laser intensities of 100 J/cm^2 to 300 J/cm^2 with a pulse duration of about 30 ns can generate shock pressures of 10^4 to 10^5 atmospheres when absorbed on a metal surface. A thin layer of black paint on the surface provides an excellent absorber which produces a plasma burst which is inertially confined with a surface layer (tamp) such as water.

These shocks impart compressive stresses to depths greater than 0.040 inch. Special techniques for controlling the pulse temporal and spatial shape are used to prevent the high intensity laser from breaking down the water column or generating stimulated processes which reflect the laser energy before reaching the paint surface. With appropriate care given to the setup, impressive results can be achieved from laser shock peening.

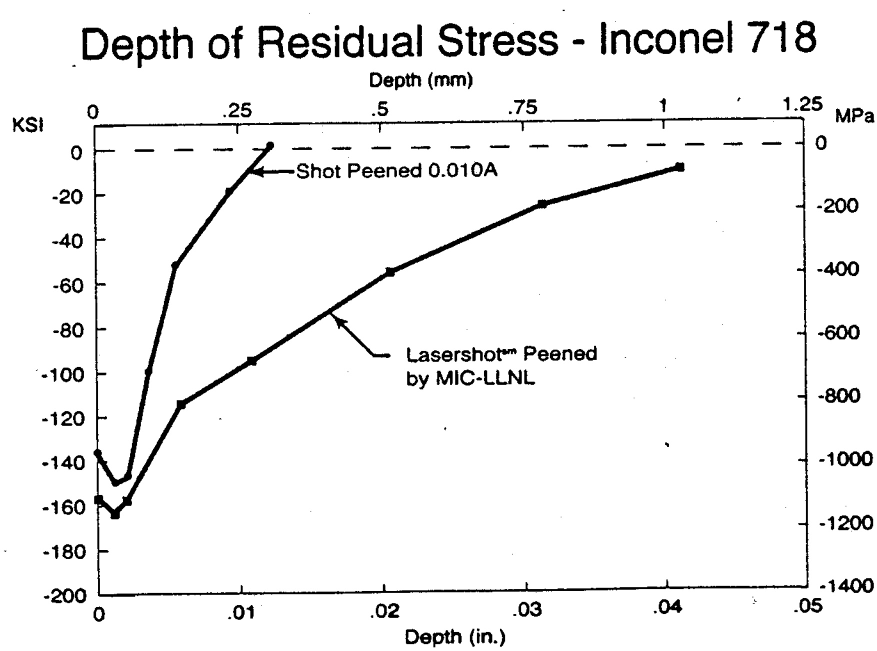

Figure 3.

In order to use the high throughput capability of the laser, it is important to have manipulation hardware to rapidly and precisely move surfaces to be treated through the rapidly pulsing laser beam. We have designed a five axis computer controlled robotics system with motion synchronized to the laser pulses.

As an example of the laser process, Figure 3 shows the residual stress induced in Inconel by laser shock peening and contrasts it with typical results achieved by shot peening. Laser generated shock can be tailored to develop deeper compressive stresses into the material with magnitudes similar to those generated by shot peening. Induced residual stress prevents treated parts from developing fatigue or corrosion related cracks. Additionally, corrosion will require longer periods of time to penetrate the compressive layer induced by laser shock peening. Deep compressive stress is important for critical areas of components, such as turbine blades, because it prevents the foreign object damage (FOD) caused by debris being sucked up into a turbine engine from becoming a crack initiation site. Most metals can be successfully laser shock peened to very deep depths of compression.

In a recently reported study by P. Prevey, D. Hombach and P. Mason of Lambda Research, a detailed study was done of thermal relaxation of the layer of compression induced by shot peening, gravity peening and laser shocking in Ti6Al4V and Inconel 718 [4] at temperatures of 230 C to 400 C. For shot and gravity peening the repeated dimpling of the surface results in a highly cold worked layer. Conventional shot peening produces from 10% to 50% cold work. Gravity peening utilizes fewer impacts with larger shot producing a less cold worked surface layer. The laser process produces remarkably little cold working of the surface (1% to 2%) because only a single or a few deformation cycles are required. The authors found that the initial thermal relaxation of highly cold worked surfaces can be far more rapid than previously realized and can result in a 50% loss of compressive stress at elevated temperatures. However, the laser process, producing minimal cold working of the surface, has exhibited striking resistance to thermal relaxation. No detectable relaxation was produced in the tests at the lower temperature and at the highest temperature, 425 C, only a small loss occurred near the surface.

In testing of operational components, such as jet engine fan blades, researchers have shown the laser treatment to be superior for strengthening new and previously damaged fan blades from fatigue failure [5]. However, the laser technology for doing these types of tests has been limited to producing pulses less than one per second thus peening areas of about 1 square centimeter per second. This rate is acceptable for laboratory demonstrations but clearly not meaningful for cost effective production. Since the cost of any high energy (100 J) laser is dominated by the hardware required to achieve the single pulse energy, it is imperative to have high repetition rate capability (~10 Hz) in order to keep the production cost per laser shot low.

The Laser Programs Directorate at Lawrence Livermore National Laboratory (LLNL) has been a world leader in developing high energy Nd:glass lasers for fusion applications for the past 25 years. The Nova laser, producing over 120 kJ per pulse, routinely fires 8 to 10 shots per day for dedicated fusion and nuclear effects studies. More recently, the Livermore Laboratory has been directed by the Department of Energy to proceed with building a newer facility, the National Ignition Facility (NIF) which will produce over 2 MJ per pulse of energy in one or several shots per day and is intended to produce more fusion energy release than laser energy input. It is clear that enormous successful investment has been made to develop high energy solid state lasers.

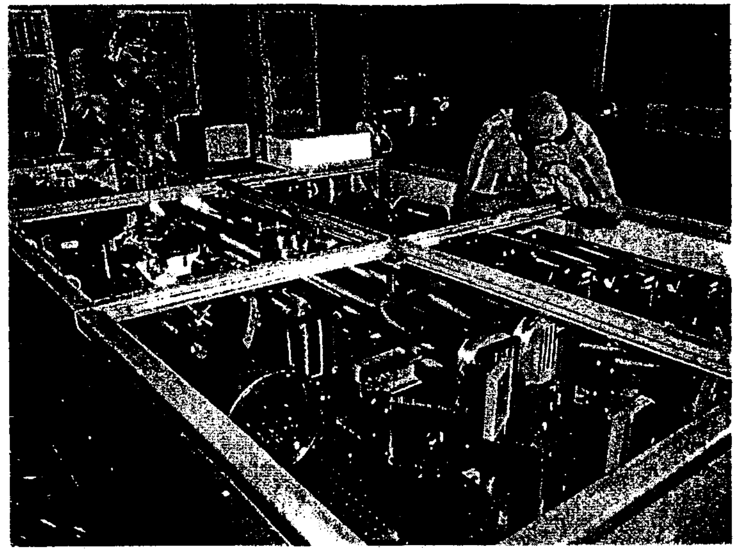

Figure 4. The laser shock peening system is a robust, reliable and fully engineered system. Internally, the laser includes advanced technologies such as zigzag slab amplifiers, passive optical switching with Faraday rotators and SBS conjugation

Generating high energy from a solid state glass laser is straightforward. However, generating high average power at high energy has been a problem. Over the past decade, LLNL has been developing higher average power systems with energies (depending on the application requirements) of 25 J to 100 J/pulse. This laser technology now demonstrates repetition rates of up to 10 Hz and average powers near 1kW. This technology development has been supported by the Advanced Research Projects Agency (ARPA) of the Department of Defense and more recently by the US Navy and the US Air Force. The ARPA funding was focused on converting the infrared light to high average power X-rays. This short wavelength has interest as a light source for proximity printing of advanced generation integrated circuits. The Navy and Air Force funding was directed toward obtaining a light source for long range and highly coherent illumination of missiles and space objects. A LLNL laser is currently in service at a Navy facility at the Kennedy Space Center, Cape Canaveral, Florida, and a second more powerful unit is being delivered to the Air Force Phillips Laboratory, Albuquerque, New Mexico. This technology has allowed development of a glass laser system with energy of 100 J/pulse, adjustable pulse length from 10 ns to 1 us, near diffraction limited beam quality and average power up to 600 W. This technology is ideal for the Laser shock peening application which by a factor of 20 to 50 exceeds the average power achievable by any other commercially available laser technology.

A system suitable for laser peening must output an energy in the range of 25 J to 100 J per pulse. The throughput of a peening system will then highly depend on the average pulse repetition rate that the laser can achieve. A laser system based on Nd doped glass gain media is the only identified technology that can realistically achieve this type of energy output with acceptable pulselength. Such a system is typically based on an oscillator and one or more rod amplifiers which are optically pumped by flashlamps. As an unavoidable consequence of providing the optical gain, the flashlamps deposit heat into the glass. This heat must be removed at a rate commensurate with the rate of deposition, that is, the pulse rate of the laser. Thus the glass must be cooled, typically by flowing water. As the glass is simultaneously heated and cooled a thermal gradient develops from the center to edge of the glass. This gradient stresses the glass, inducing wavefront deformation with significant depolarization of the beam. Thus, the thermal loading of the laser gain media is a major limitation to the available average power that can be extracted from the laser. As the repetition rate of the laser is increased, the thermal loading correspondingly increases and degenerates the laser performance often depolarizing and aberrating the laser beam to the point where the laser optics damage. In the limit, the loading will fracture the glass. The LLNL laser design alleviates this thermal problem in three ways; 1) the slab gain medium is pumped in a highly uniform manner minimizing depolarization and distortion, 2) the laser beam is propagated through the slab in a zigzag manner to average out much of the wavefront distortion and 3) SBS phase conjugation highly corrects residual wavefront distortions. The LLNL high average power Nd:glass laser technology is comprised of a single master oscillator and one or more power amplifiers. The glass is configured in a slab shape to allow one thin dimension for rapid heat removal. Unlike a more traditional amplifier where the beam is propagated through the gain medium in a straight line, our design employs a zigzag path reflecting the beam internally off the slab faces. The slab is positioned in the center of the assembly and has a water cooling channel along both sides formed by the slab face and a reflector window. Two flashlamps on each side pump the slab through the cooling channels. A diffuse reflector surrounds the flashlamps and by appropriate shaping provides uniform optical pumping. Designing a thin dimension for the gain medium creates one short path for high heat conduction from the slab center to the cooling water. The resulting high heat transfer efficiently removes the heat buildup and directly increases the repetition rate capability of the laser. Very uniform optical pumping from the reflector assembly results in uniform energy distribution from top to bottom in the slab. At high repetition rates a large thermal gradient develops in the slab from center to edge. However, the laser light is directed through the slab so that the beam propagates in a side to side zigzag manner. This zigzagging averages the side to side thermally induced pathlength differences providing a high quality horizontal wavefront.

The SBS phase conjugator allows us to generate a high power beam with nearly diffraction limited beam quality. By correcting for thermal aberrations, our design allows us to extract average powers up to the mechanical limit of the gain medium. Without the phase conjugator, the beam quality rapidly degrades as the laser average output power is increased. This degraded beam quality results in reduced focus control of the beam and less power on target. Even more important, the reduced beam quality can lead to intensity "hot spots" within the laser and consequently to self damage of the laser. The SBS phase conjugator, simply and reliably, eliminates this problem. Figure 5 illustrates the beam quality of the laser with and without the use of a phase conjugator. The SBS phase conjugator also very effectively conjugates the first order aberration of tilt. This greatly reduces the sensitivity of the system performance to small changes of optical alignment in the ring. No change in output power or pointing direction during operation are observed for large mirror misalignments in the ring. Loss in performance is limited to only those angular excursions that result in vignetting of the beams at the edges of the amplifier slab.

Finally and specifically, for the laser shock peening application, the SBS phase conjugation naturally produces a fast rising edge laser pulse. Because the SBS is a nonlinear process with a definite threshold, the phase conjugator does not respond to the initial low intensity buildup typically associated with a laser pulse. The beam returned by the conjugator has its leading edge "clipped" and thus the returned pulseshape has a sharp, subnanosecond rising edge. The fast rising pulse is critically important for laser peening because it reduces the possibility of breakdown or other nonlinear processing occurring in the tamping material and allows the full pulse energy to reach the paint area on the metal and thus contribute to building the high intensity shock.

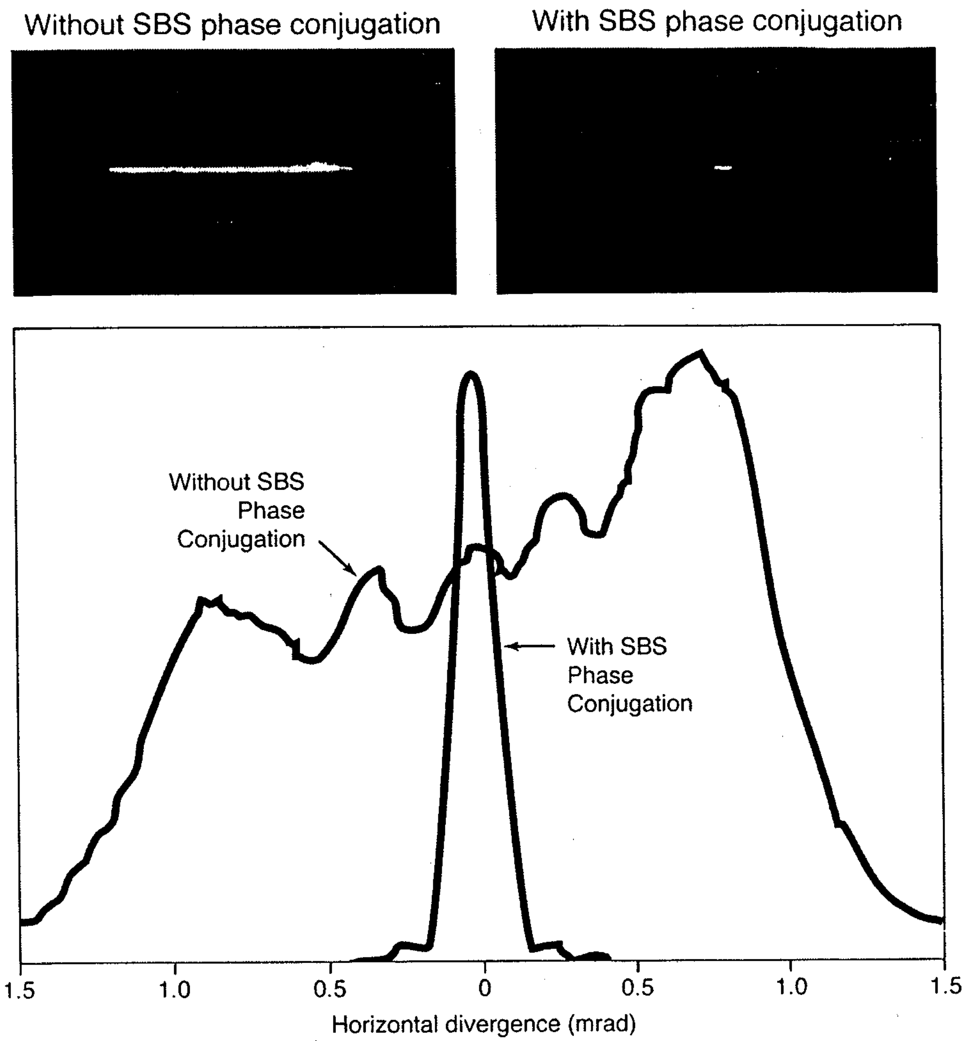

Figure 5. Comparison of laser operation using a phase conjugator or a standard mirror clearly shows the enormous improvement in beam quality

There is no commercially available laser peening system that can compare with the throughput capability, rectangular spatial profile and spatial beam control of the laser shock peening system. The high pulse repetition rate enables 10X greater system throughput and the rectangular beam profile enables more efficient coverage.

The most significant feature of our laser peening system is the high repetition rate afforded by the laser. The lack of a meaningful laser repetition rate has held back the laser peening technology from meaningful industrial introduction for many years. The breakthrough laser technology offered in our product for the first time enables acceptably high treatment area rates to generate the high throughputs required for industrial treatment of components such as jet engine fan blades and rotors. Since the cost of a laser peening system is fundamentally driven by the hardware required to produce the output energy, typically 100 J, the 10X advantage of our product's repetition rate will be translated to comparable increases in throughput per hour. With a nominally similar cost in capital investment, the higher repetition rate means a reduction in cost per part treated. Currently available lasers do not control the wavefront in an active manner as done in our system by the SBS phase conjugator technology. Wavefront distortion can directly lead to self focusing which catastrophically destroys laser rods and high value optics. The SBS phase conjugator employs a passive, inexpensive cell which automatically maintains wavefront near the physically allowable perfect limit. The conjugator allows our system to run at 10X higher average power and throughput where other systems are limited by optical damage.

Conventional lasers employing cylindrical rod designs naturally produce a round output beam spatial profile. Treatment of extended areas then requires overlapping spots in an inefficient manner. The naturally rectangular profile of our slab laser technology allows full area coverage with each spot placed directly adjacent to the next.

The high average power available from the Nd:glass slab laser system enables for the first time a high throughput laser peening system. Assuming that 200 J/cm^2 is required to generate an effective 10 kBar shock, the LLNL laser system, operating at 100 J per pulse and 6 Hz repetition rate, will have a throughput capability in excess of 10,000 cm^2 per hour for single pulse applications. Upgrading the laser with the newly developed APG2 laser glass and thus doubling its average power output, the throughputs can be increased to 20,000 cm^2 per hour.

CONCLUSION

Laser peening is a proven process that develops deep compressive stresses in a metal part. This significantly increases the fatigue strength and damage tolerance of the component. We have developed a system that provides the throughput necessary to make this very beneficial process available to industry at a reasonable cost.

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