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Process Control Techniques for Laser Peening of Metals

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1 Abstract

Laser Peening, also known as Lasershot^{SM} and Laser Shock^{TM} Peening, is a surface treatment, which can induce compressive stresses in metals at depths exceeding 1 mm. This produces a more damage tolerant component, which resists fatigue and Stress Corrosion Cracking (SCC) failures better than components treated with conventional shot peening.

A new Laser Peening facility was brought on line in early 2002 by MIC in Livermore, CA. This facility utilizes a Lawrence Livermore National Laboratory (LLNL) designed solid state laser employing Neodymium doped laser glass slabs and phase conjugation technology to enable high energy & high laser repetition rate combined with excellent beam quality. Laser Peening process parameters have been identified which will impact on the final depth of compressive stresses in a metal component. Process control techniques widely utilized in conventional shot peening have been adapted for use in Laser Peening with good success. As a result, Suppliers and Users of Laser Peening have a reliable method of monitoring the critical process parameters in a manner that will lead to consistency of production operation and repeatability of end results.

2 Introduction

Various types of surface treatments have been used by industry for many years to induce beneficial compressive stresses in metals. These include fillet rolling, cold expansion of holes and most commonly, shot peening. The significant improvements in resistance to fatigue, fretting fatigue and stress corrosion that result from imparting residual compressive stresses are well known.

Shot peening has been the most widely used process because of its ability to induce these stresses efficiently and inexpensively on components of a complex geometry. The depth of the zone of compressive stresses produced by shot peening will vary depending on the metal, but is typically around 0.010″. Although depths of 0.030″ are possible, the surface finish may be unacceptably roughened at the high shot peening intensity levels required to achieve residual compressive stresses to this depth.

3 Laser Peening Science

Laser Peening creates shock waves at the metal surface, which drive compressive stresses into the metal to depths exceeding 0.040″, and with magnitudes at the surface comparable to those produced by conventional shot peening. These deeper residual stresses have proven to significantly enhance the damage tolerance of critical components subject to fatigue or SCC. Technical studies also demonstrate that thermal relaxation of the induced residual stresses from Laser Peening is much less than that compared to Shot or Gravity Peening.

Initial studies on laser peening of materials were done at the Battelle Institute in Columbus, OH from about 1968 to 1981 [1, 2]. Figure 1 shows the basic sequence of events during laser peening. Laser energy densities (or "fluence") of 50–250 J/cm^2 are utilized with a laser spot size of 2–5 mm and the energy is delivered within a time frame of 10–30 ns. (This translates to a total power output of 4–12 GW/cm^2).

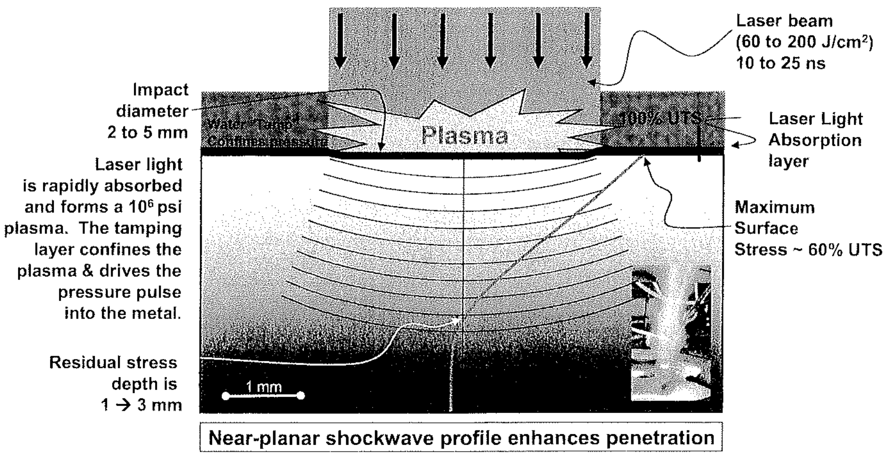

Figure 1: Laser peening mechanism

A thin layer of light absorbing material (typically paint or tape) on the metal surface absorbs the initial laser burst and produces a plasma which is inertially confined by a 1-3 mm surface layer of water (known as an inertial "tamp".) Shock pressures of up to $6.9 \cdot 10^9$ Pa are created on the metal surface; which first sends a planar shock wave into the metal and then ejects the water tamp off of the surface. The intense shock wave produces a strain rate in the metal surface that is well in excess of the spherical pressure pulse produced by shot peening. This enables the compressive stresses to be imparted deeper beneath the surface.

Depending on the material properties of each metal (Young's Modulus, Poisson's Ratio, density, strength, etc.), the laser's operating properties will be adjusted to deliver a surface pressure shock wave sufficient to cause the metal to plastically deform. Whereas a material such as 2024 T3 Aluminum might only require a laser fluence of 60 J/cm^2 to peen the surface, a high strength steel might require a fluence in excess of 200 J/cm^2 for proper laser peening.

To achieve the full benefit from laser peening, it is generally necessary to make anywhere from 2–4 separate passes with the layer, including refreshing of the ablative/absorption layer.

After the initial laser peening pass, the surface is denser & more receptive to transmitting the compressive stresses to a greater depth. The additional laser peening passes increase the depth of the imparted residual stress, but generally do not increase the residual stress levels at the surface.

As an example of the capabilities of the laser peening process, Figure 2 shows the residual stress induced in Inconel 718 by Laser Peening and contrasts it with typical results achieved by shot peening.

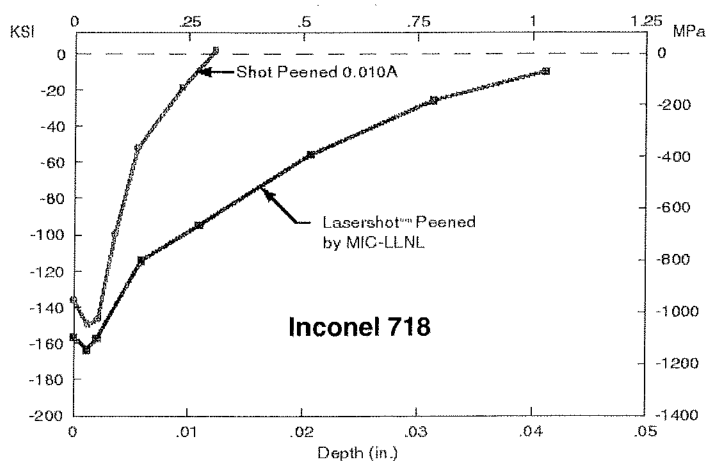

Figure 2: Comparison of depth of residual compressive stresses from Laser Peening vs. Shot Peening

P. Prevey et al of Lambda Research compared the relaxation of compressive residual stress occurring at temperatures ranging from 230 °C to 425 °C for shot peened, gravity peened and laser peened Ti-6Al-4V and Inconel 718 [3]. For shot and gravity peening the repeated dimpling of the surface resulted 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. However, the laser peening process produced remarkably little cold working of the surface (1 % to 2 %), because the shock wave accompanying laser peening more evenly distributes the cold work beneath the surface.

The authors found that the initial thermal relaxation of highly cold worked surfaces (either shot or gravity peened) can be far more rapid than previously realized and can result in a 50 % loss of the 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 Ti-6Al-4V jet engine fan blades, researchers have shown the laser treatment to be superior to other technologies for strengthening and protecting of new and previously damaged blades from fatigue failure [4].

4 The LLNL/MIC Laser

The Laser Programs Directorate at LLNL has been a world leader in developing high energy Nd-glass slab lasers for fusion applications for the past 25 years. At present LLNL is in the process of building the National Ignition Facility (NIF), which will produce over 2 million Joules of energy per pulse. It is out of this technology base that LLNL & MIC starting working together in 1997 to adapt a 1.053 nm (infrared wavelength) Nd-glass laser for use in Laser Peening. The specific LLNL/MIC laser used for laser peening is comprised of a single master oscillator and one or more sets of power amplifiers [5]. It utilizes several unique technologies relative to older technology rod lasers:

4.1 Neodymium Laser Glass Slab Technology

The laser glass is configured in a rectangular slab shape, instead of a cylindrical rod. Whereas total energy storage of a laser glass is dependent on the volume of the glass (roughly 0.5 liters of Nd doped glass volume to store 25 Joules of energy), the ability of the glass to dissipate heat will be dependent on the shortest distance to a heat sink (typically cooling water.) Assuming equivalent length of comparable slab and rod laser amplifiers, the heat is much more easily transferred out of the slab (4× faster) by the surrounding fluid. This enables more rapid laser firing rates as the internal thermal gradients (which would distort the beam) are quickly minimized.

In addition, the laser light is directed through the slab so that the beam propagates by zig-zag bouncing off the slab faces, which aids in averaging out wavefront distortions due to thermal gradients.

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 spot profile of the LLNL slab laser technology facilitates full coverage by placing each laser spot adjacent to the next.

4.2 SBS Phase Conjugation

The LLNL/MIC Laser employs a patented LLNL architecture, which includes SBS phase conjugation for correction of residual wavefront distortions. The SBS phase conjugator allows generation of a high power beam with nearly diffraction limited beam quality. By correcting for thermal aberrations, the LLNL design enables extraction of average powers up to the mechanical limit of the laser glass. Without the SBS phase conjugator, the beam quality would rapidly degrade as the laser average output power is increased leading to reduced focus control of the beam and eventually less energy on the target. Reduced beam quality can also lead to intensity "hot spots" within the laser and consequently to self-damage of the laser. The SBS phase conjugator eliminates these potential problems.

In April of 2002, MIC started up a production facility for laser peening in Livermore, CA using the LLNL laser technology & the laser peening techniques that were jointly developed by LLNL & MIC. By combining the benefits of slab laser technology and SBS Phase conjugation, the MIC Production laser was designed with capability for a 6 Hz laser firing rate per laser head and with capability for two heads that can fire in tandem or independently. If required, the firing rate can be increased to 10 Hz by the use of stronger laser glasses.

Each laser head is capable of generating up to 25 Joules of energy. The laser spot shape is square/rectangular and is selected to range in size from 2–5 mm square (depending on the fluence [J/cm^2] required by the metal being laser peened.)

The production MIC laser peening system also incorporates a 6-axis robot with repeatable dimensional accuracy to 0.005″. This enables the component surface being laser peened to be "presented" to the laser at a consistent focal length and at an angle as close as possible to perpendicular to maintain the square laser spot and maximize the pressure wave.

5 Important Laser Peening Parameters

The goal of laser peening is to impart residual compressive stresses to a metal component. From a macro viewpoint, the two primary factors which determine this are (A) the amount and quality of the energy being emitted by the laser, and (B) the amount of energy received by the component.

The major laser output parameters which in combination will determine the effectiveness of a specific laser peening pulse are Fluence (J/cm^2) & Power Density (GW/cm^2). Since it is difficult to measure these parameters directly for high power lasers, the constituent parameters are monitored instead:

- Total laser energy – (J);
- Size/area of laser "spot" – (cm^2); and
- Duration of laser pulse – (ns).

Besides these parameters defining the individual laser beam properties, two other parameters that speak to the total energy imparted to the target during laser peening are:

- Total % unpeened surface area per laser pass. This will be dependent on the laser peening spot size, shape (circle or square) and pattern. The MIC standard spot pattern strives for 0 % unpeened area per pass.
- Total number of passes. It is common to have 2 to 5 laser peening passes. As the component surface is compressed/densified, it is theorized that it is easier for subsequent laser peening passes to drive the residual stresses to a deeper level.

A recent laser peening study by J. Rankin et al [6] also highlighted the importance of the beam uniformity to achieving consistent compressive residual stresses near the surface. A 7049 T73 aluminum test coupon was laser peened twice using the LLNL/MIC laser with a 1.5 mm corner section of a 5.0 mm square beam intentionally attenuated. Each individual layer had 100 % coverage as the squares were peened adjacent to each other in a close packed tile pattern. The resulting surface residual stresses on the coupon were only 150 MPa compared to 400 MPa of a coupon which was peened exactly the same, but without the corner attenuation. This effect is reduced at depths greater than 0.3 mm beneath the surface, where the residual compressive stresses were comparable. Thus, one might conjecture that having a uniform laser beam is more important in those instances where inhibiting crack initiation is of primary importance. Other observations of this study:

- No difference in residual stress profiles was noted when all variables were held constant except for laser spot size which was varied from 3.2 to 5.0 mm square;
- A 50 % overlap between the first and second laser passes was found to yield a more consistent residual stress profile beneath the surface than that from a 10 % overlap; and
- As might be expected, laser peening at a fluence of 60 J/cm^2 produced a deeper layer of compressive residual stresses than that produced by laser peening at 45 J/cm^2.

Factors which can impact on the amount of laser energy & power which is received by the target are:

- Consistency/integrity of the absorptive layer (paint or tape). Laser peening of an area with an incomplete or damaged absorptive layer could lead to non-uniform beam energy.
- Also critical to the laser peening process is for the water tamping layer to flow over the laser target area in laminar (non turbulent) flow.

6 Control Techniques for Laser Peening Parameters

The typical component that an OEM considers for laser peening is a high value "mission critical" component, where the residual compressive stresses produced by conventional shot peening have proven insufficient. As such, preliminary development work will involve iterative testing of varying laser peening parameters; using X-Ray diffraction measurements of actual residual stress profiles, rig tests and even field evaluations to confirm the expected benefit in life extension. When the desired component life extension evaluation is satisfactory; the laser peening parameters and process are frozen & a Process Control Plan is instituted. This Process Control Plan ensures that the appropriate residual stress profiles identified during the Development program will be consistently reproduced on Production components. MIC is utilizing electronic monitoring of the laser beam properties in combination with Almen strip test coupons to monitor and control the laser peening process:

6.1 Electronic Monitoring of Laser Output

Figure 3 is a schematic of how the laser output is electronically calibrated, monitored and controlled.

The absolute calibration of the laser energy output (10–25 J) is accomplished by inserting a NIST calibration traceable calorimeter in the beam path. At the same time an additional calorimeter detector, which is sampling a small constant percentage (~0.2 %) of the beam energy, is calibrated against the total energy output. During production laser peening, this second detector readings are used as a reliable proxy for the full energy output of the laser, which is directed onto the component being laser, peened. At the same time a third detector constantly monitors the time in nanoseconds of the laser pulse. By knowing the laser energy (J) and pulse width (ns), we can compute the Power (GW).

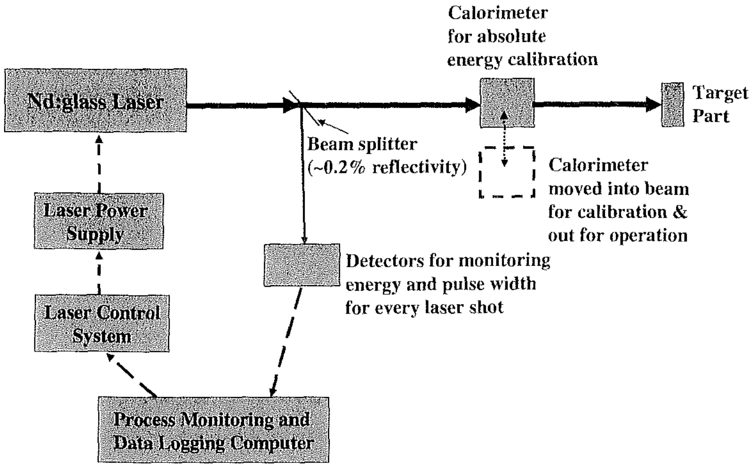

Figure 3: Calibration, monitoring and control of laser output

To compute the Fluence (J/cm^2) and Power Intensity (GW/cm^2), we need an accurate representation of the surface area of the focused laser beam. Although laser spot dimensions can be defined in theoretical terms such as Full Width Half Maximum (FWHM), a more practical method is to physically measure the dimensions of a single laser peened depression at the point where the laser is fully focused on the target. Since the optics of a laser are fixed, as long as future laser peening hits are done at the same focal length as the component is manipulated, the spot size will remain constant.

Beam uniformity is monitored by sampling of the near field output of every laser pulse using a video camera. The pixels of the camera are linear in their response, so their output represents a relative measurement of the local intensity within the beam profile. This pixel-by-pixel intensity pattern is acquired by a frame grabber that stores a matrix array of intensity vs. position within the beam. The profile is analyzed and compared to acceptable profiles.

Finally, the laser output data from each laser pulse during the processing of a component is captured and logged. At the conclusion of a run, statistics are generated on parameters such as mean output energy vs. time, standard deviation in the energy vs. time, pulse width vs. time and standard deviation in pulse duration vs. time.

6.2 Almen Strips for Process Control in Laser Peening

Almen strips have traditionally been used for the control of conventional shot peening processes, where the level of shot intensity imparting compressive residual stresses into a material is correlated with the deflected arc height in an Almen strip processed to the same parameters. During the development of the laser peening technology, many different control methods have been developed and reviewed. However, it was felt that the continued use of the Almen strip, combined with electronic monitoring, data logging and feedback control of the laser would give optimal process control.

It was demonstrated that the amount and depth of compressive residual stress imparted into a component by Laser Peening could be correlated with levels of arc height deflection of an Almen strip. Thus, Almen strips can be used as a simple and effective check on the equipment set up prior to process start up, or even during production to evaluate any levels of process parameter drift. MIC & Rolls Royce conducted trials to compare the results of using conventional 1070 spring steel Almen C strips, as well as strips manufactured out of a Titanium alloy, which was similar to the component being laser peened. It was found that the spring steel Almen C strips produced much more consistent levels of deflection at constant laser fluence and power settings than the Titanium strips. It was determined that this was primarily due to the superior methods of manufacture of the Almen C strips and the tight controls for hardness, flatness & dimension under which they were manufactured.

Almen strips can also be used to check how the laser energy and power is being received by the component being laser peened. It is a final check of laser beam integrity issues such as near field image and alignment. At the laser target area two critical items that will impact on how efficiently the energy is received and converted into residual compressive stresses in the component are the integrity of the water tamping (or "inertial confinement") layer and the receptivity/ integrity of the laser light adsorptive/ablative layer. It is well known that if either of these factors is compromised, then energy transfer to the substrate will be reduced and the desired levels of residual stress will not be produced.

In addition to measurement of the amount of deflection of the Almen strips after laser peening, it is also useful to visually assess the peened surface and the post laser peened condition of the ablative layer. An appropriately laser peened surface will be characterized by crisp indentations in the metal surface and absence of damage to the ablative layer in the region outside of the laser peened spot. Maintaining the integrity of the ablative layer during laser peening is important, as the possibility exists for the localized disruption & turbulence of the water tamping layer, which will inhibit the transfer of the full laser energy into the component.

7 Summary

Combined with electronic monitoring and data logging of the laser output, the use of Almen strips as a process control tool for laser peening can give OEM's an added measure of confidence that a laser peening process on a critical part can be reproduced and monitored in a production environment. By using the same techniques utilized for control of conventional shot peening, broad industrial acceptance of the laser peening technology should be more readily accepted. Thus, laser peening can simply be viewed as an added capability extension of conventional shot peening and surface enhancement technologies widely used in industry today.

8 References

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