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Review of Laser Shock Processing of Aluminium Alloy

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ABSTRACT

Laser peening or laser shock peening (LSP) is the process of hardening or peening metal using a powerful laser. Laser peening can impart a layer of residual compressive stress on a surface that is four times deeper than that attainable from conventional shot peening treatments. A coating, usually black tape or paint, is applied to absorb the energy. Short energy pulses are then focused to explode the ablative coating, producing a shock wave .The beam is then repositioned and the process is repeated, creating an array of slight indents of compression and depth with about 5-7% cold work. A translucent layer, usually consisting of water, is required over the coating and acts as a tamp, directing the shock wave into the treated material. This computer-controlled process is then repeated, often as many as three times, until the desired compression level is reached, producing a compressive layer as deep as 1-2 mm average.

1. INTRODUCTION

As we know, all manufacturing processes introduce residual stress into mechanical parts, which influences its fatigue behavior and breaking strength and even its corrosion resistance. Few metal working methods exist which do not produce new stresses. The role of residual stress is therefore very important when designing mechanical parts. Over the last few years, an increasing number of studies have been carried out to understand the effects of residual stress on mechanical performance. This article attempts to present a global approach to including residual stress in expected fatigue life calculations, and the possibility of introducing it into mechanical engineering design offices.

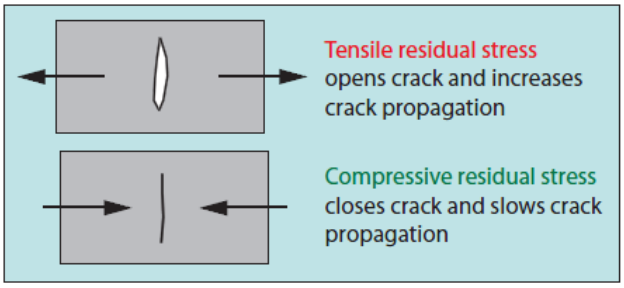


Figure.1 Total Stress in a Component

The total stress experienced by the material at a given location within a component is equal to the residual stress plus the applied stress.

TOTAL STRESS = RESIDUAL STRESS + APPLIED STRESS

If a material with a residual stress of a -400 MPa is subjected to an applied load of +500 MPa. The total stress experienced by the material is the summation of the two stresses, or +100 MPa. Therefore, knowledge of the residual stress state is important to determine the actual loads experienced by a component. In general, compressive residual stress in the surface of a component is beneficial. It tends to increase fatigue strength and fatigue life, slow crack propagation, and increase resistance to environmentally assisted cracking such as stress corrosion cracking and hydrogen induced cracking. Tensile residual stress in the surface of the component is generally undesirable as it decreases fatigue strength and fatigue life, increases crack propagation and lowers resistance to environmentally assisted cracking.

Laser peening or laser shock peening (LSP) is the process of hardening or peening metal using a powerful laser. Laser peening can impart a layer of residual compressive stress on a surface that is four times deeper than that attainable from conventional shot peening treatments. A coating, usually black tape or paint, is applied to absorb the energy. Short energy pulses are then focused to explode the ablative coating, producing a shock wave .The beam is then repositioned and the process is repeated, creating an array of slight indents of compression and depth with about 5-7% cold work. A translucent layer, usually consisting of water, is required over the coating and acts as a tamp, directing the shock wave into the treated material. This computer-controlled process is then repeated, often as many as three times, until the desired compression level is reached, producing a compressive layer as deep as 1-2 mm average.

Laser peening is often used to improve the fatigue resistance of highly stressed critical turbine engine components, and the laser (or component) is typically manipulated by an industrial robot.

Prototype laser peening machines were developed in the 1970s, but they and subsequent versions over the past two decades were not cost effective because the lasers lacked the high repetition rate required for treating parts rapidly.

2. LASER SHOCK PROCESSING (LSP)

Author Lin Ye et. al. had studied Laser shock processing and its effects on microstructure and properties of metal alloys. [1]

Laser shock processing (LSP) has been proposed as a competitive alternative technology to classical treatments for improving fatigue and wear resistance of metals. [2]

For the past six decades, shot peening has been the most effective and widely used method of introducing compressive residual stresses into the surface of metals to improve fatigue performance. Shot peening is relatively inexpensive, uses robust process equipment, and can be used on large or small areas as required. However, the shot peening process has its limitations. In determining the compressive stresses produced, the process was semi-quantitative and depended upon a metal strip or gage called an Almen type gage to provide an indication of shot peening intensity. This gage did not guarantee that the shot peening intensity would be uniform across the component being peened. Secondly, the compressive residual stresses were limited in depth, usually not exceeding 0.25 mm in soft metals such as aluminum alloys and less in harder metals. Thirdly, the peeing process resulted in a roughened surface, especially in soft metals like aluminum. This roughness needs tobe removed before use in wear applications and typical processes used removed the majority of the compressive layer. An alternative novel surface processing technology, namely laser shock processing (also known as laser peening), can induce greater depths of residual stress into metal surfaces using high-power, Q-switched laser pulses. The ability of a pulsed laser beam to generate shock waves was first recognized and explored in the early 1960s. [1]

2.1 Experimental Arrangement Of Laser Shock Processing [2]

The principle of laser shock processing is shown in Fig.2. The sample surface is completely immersed in water, when the laser beam is directed onto the surface to be treated, it passes through the transparent overlay and strikes the sample. A short laser pulse is focused onto the sample. Immediately a thin surface layer is vaporized. The energy absorption at the water/plasma interface leads to the formation of a shock wave which strikes the sample with an intensity of several GPa.

High pressure against the surface of the sample causes a shock wave to propagate into the material. The plastic deformation caused by the shock wave produces the compressive residual stresses at the sample surface.[2]

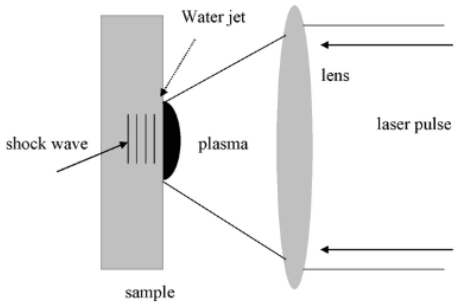


Figure .2 Principal of Laser shock processing [2]

The experimental arrangement is shown in Fig 3. The laser source is a Q-switched Quanta-Ray Nd:YAG pulsed laser operating at 10 Hz. The FWHM of the generated pulses is 8 ns, the maximum pulse energy is 1.2 J/cm2 with a wavelength of 1064 nm. A flat mirror and convergent lens are used to deliver the pulse produced by the Laser. Both optical components are AR-coated for 1064 nm, which guarantees a high transmittance efficiency. In this irradiation setup, we are using purified water as confining medium. Control of water purity is important in order to avoid the formation of water bubbles or the concentration of impurities coming from the material ablation due to laser treatment. The appearance of suspended elements can affect the LSP process by their interaction with the high energy laser beam. Water in continuous circulation may be a good solution to avoid these disturbing elements. Therefore a special device to produce a controlled water jet has been implemented to form a thin water layer on the sample to be treated. In this way, it is possible to assure water in continuous circulation.

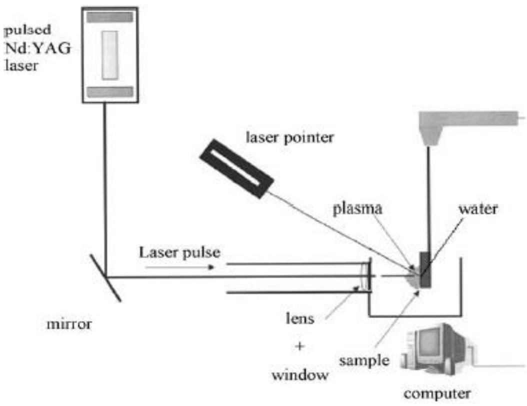


Figure. 3 Experimental arrangement of laser shock processing. [2]

2.2 Use of transparent overlay and absorbent sacrificial coatings

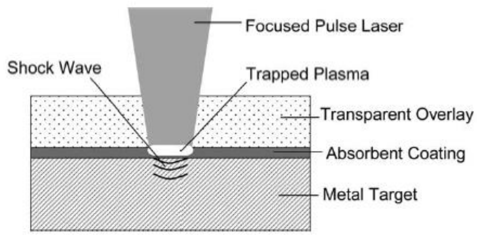


Figure. 4 Schematic representation of the laser peening

The use of coatings transparent to the laser energy as shown in Fig.3. has been found that to increase the shock wave intensity propagating into the metal increases up to two orders of magnitude, as compared to plasma generated in a vacuum.

The increase in shock wave intensity is achieved because the transparent coating prevents the laser generated plasma from expanding rapidly away from the surface. This results in more of the laser energy being delivered into the material as a shock wave.

The use of laser absorbent sacrificial coatings has also been found to increase the shock wave intensity in addition to the protection of the metal's surface from laser ablation and melting. Among the absorbent coatings, commercially available flat black paint has been found to be the most practical and effective, as compared to other coating systems. [1]

3. PRODUCTION OF COMPRESSIVE RESIDUAL STRESSES

Author G. Gomez-Rosas et. al. [2] had examined examine the effect of LSP to induce very highcompressive residual stress in aluminum alloy specimens and the capability to penetrate deeper in the sample.

In a typical laser shock processing operation with an absorbent coating and confining medium, a uni-axial compressive stress is generated along the direction of the shock wave. As the shock wave propagates into the metallic target, plastic deformation occurs to a depth at which the peak pressure no longer exceeds the metal's Hugoniot elastic limit (HEL). A metal's HEL is related to the dynamic yield strength according to Johnson and Rhode. [1]

$$HEL = \frac{1-\gamma}{1-2\gamma}\,\sigma_y^{dyn}$$

Where,

γ is Poisson's ratio and,

σydyn is the dynamic yield strength at high strain rates. [1]

The residual stress measurements are usually performed using either of two methods.

Non-destructive method.

Incremental hole strain gauge rosette method.

Author G. Gomez-Rosas had performed the laser shock processing on 2024 Al and 6061-T6 Al alloy and presented a configuration and result for metal surface treatment in under water irradiation at 1064 nm. A convergent lens is used to deliver 1.2 J/cm2 in a 8 ns laser FWHM pulse produced by 10 Hz Q-switched Nd:YAG, two laser spot diameters were used: 0.8 mm (for 2024 Al) and 1.5 mm. (for 6061-T6 Al). He used the different pulse densities 2500 pulses/cm2 for 6061 –T6 Al sample and 5000 pulses/cm2 for 2024 Al sample.

The sample is a 50 mm × 50 mm plate with thickness of 5 mm, and it is mounted on a motor controlled x–y stage with 1 mm of resolution and maximum speed of 20 mm/s. Controlling the speed of the system, the desired pulse density was obtained. The treated area was 15 mm×15 mm as shown in Fig.4 [2]

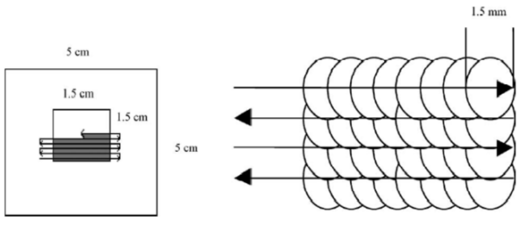
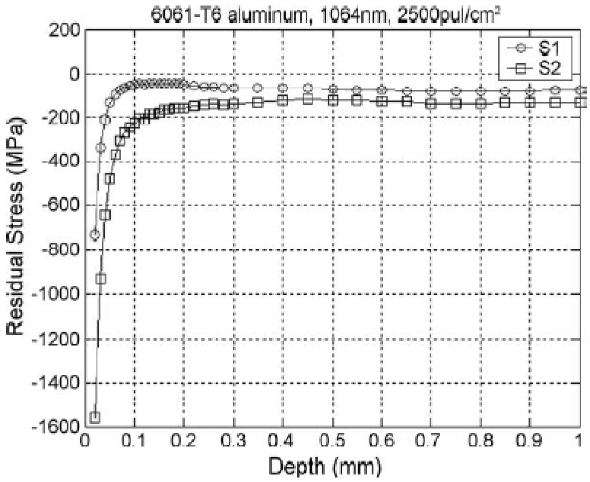


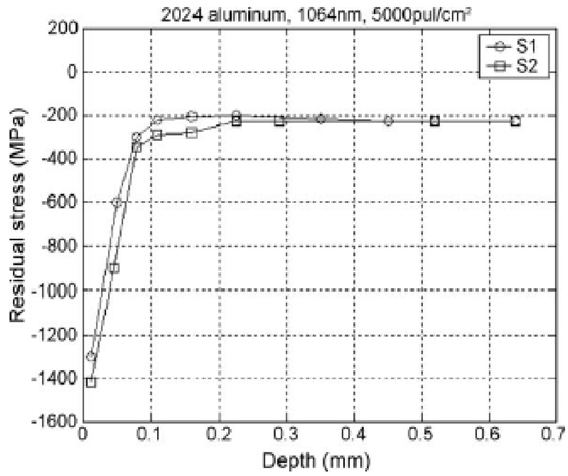
Figure. 5 Sample and processing area

The maximum principal compressive residual stresses are measured at the center of the irradiated area by the hole drilling method.

Principal residual stresses as a function of depth for the 6061-T6 aluminum sample, treated with 2500 pulses/cm2 are shown in Fig.5, where S1 and S2 mean principal stresses. Note that high compressive residual stress is observed (1600 MPa in compression). The corresponding in-depth residual stress profiles for 2024 Al sample, treated with 5000 pulses/cm2 are shown in Fig. 5 (b). Again, a high level compressive residual stress, around 1400 MPa, is observed near the surface. From Figs 5 (a) and (b) it is worth noting that the highest compressive residual stresses are localized near to the surface, at depths less than 100 mm. After that depth, the residual stresses reach a plateau between -100 and -200 MPa. This behavior is similar for 6061-T6 and 2024 aluminum alloys. [2]



a)



b)

Figure. 6 In-depth residual stress profile of a sample processed with

(a) 5000 pulses/cm^2 in 6061-T6 aluminum alloy

(b) 2500 pulses/cm^2 in 2024 aluminum alloy

Conclusion

Laser shock processing, also known as laser peening, can produce a compressive residual stress layer more than 1 mm deep in commercially available aluminum alloys, and has been shown to significantly improve fatigue performances. Moreover, laser peening has been shown to harden the surface and improve the mechanical properties of some structural metal components such as commercially available carbon steels, stainless steels, cast irons, aluminum alloys, titanium alloys, and nickel based super-alloys.It has been shown that surface residual stress level is much higher than that achieved by conventional shot peening and with deeper penetration.

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