LASER SHOCK PEENING OF METALS AND ADVANCED CERAMICS

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Laser shock peening is an advanced surface treatment process that is traditionally deployed to enhance the strength of various metals and alloys. The benefits of laser shock peening have been well documented over the last two decades. The process originated in industry and made its way into academia, where greater knowledge and understanding was gained once metallurgists and engineers made in-roads into understanding the way the metallic systems responded to the process.

The process involves interaction between a high intensity laser (power density greater than 10^9 W/cm^2) and generally a metallic object, leading to the formation of rapidly expanding plasma away from the surface of the material. To achieve sufficient shock pulse pressure, the expanding plasma is normally confined to the surface of the material using a water confinement layer. For the material to plastically deform, the plasma pressure created by the laser pulse must exceed the Hugoniot Elastic Limit [1]. To obtain a significant level of compressive stress within the material, the laser process parameters must be carefully considered, so that the laser power density is sufficient enough to generate shock pulse pressure that in turn renders beneficial residual stresses. A range of parameters can be employed to undertake laser shock peening in order for the aforementioned to take effect.

Parameters and Cost

Traditionally, a laser of 1064 nm wavelength has been used for laser shock peening applications, with frequency doubling to give a wavelength of 532 nm, as the effects at this wavelength are greater due to better absorption by metals and alloys. The energies range from 1 J - 60 J, and some in excess of that for niche applications that require deeper residual stresses, larger spot sizes, faster processing speeds and in turn, throughput. With that said, there has also been much work done on laser shock peening without coating (LSPwC) that can be applied with energy levels in the range of several hundreds of mJ [2]. This leads to small spot sizes, less than a millimetre, rendering high energy density to create sufficient shock pulse pressure and generate plastic deformation within the material with increase in dislocation density. Otherwise, the spot sizes employed range from 1 mm – 10 mm depending on the maximum output energy which the laser is capable of delivering.

The pulse repetition rate ranges from 0.5 Hz to 60 Hz, and energy level from 1 J to 60 J, although much work has been published on the use of several hundred mJ to undertake laser shock peening, both with and without coating. Initially, in the early 1970s, long pulse lasers in the range of μs were deployed on metals and alloys, but with advancement in laser technology and availability of shorter pulses, it was possible to deliver high energy pulses in a ns time frame – ultimately making laser shock peening a superior process. The pulse duration is usually in the range of ns, although the use of ps and fs pulses for laser shock peening have also been reported. However, the depth of beneficial residual stress is not readily available with ultra-short pulses as yet.

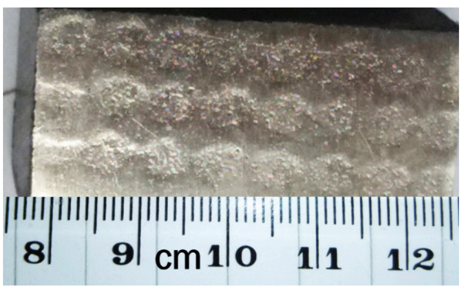
Usually, a top hat beam profile with a distributed power density is the norm, but Gaussian beams have also been reported to be effective in generating compressive residual stress in a given area over the work-piece. Overlapping is selective and is typically between 40 - 50%. It is usually correlated with the processing speed of the work-piece. The faster the pulse repetition rate, the faster the required traverse speed of the work piece to avoid excessive overlapping, unless that is desired. In addition, multiple layers have the tendency to induce greater depth of compressive stress.

The selection of the correct ablative overlay also plays an important role. Laser shock peening was traditionally conducted with black vinyl tape. However, aluminium tape overlay introduces substantially higher amounts of compressive stress in comparison. Nonetheless, it is still time consuming in production-based environments and so laser shock peening without coating is practiced, but it often leads to higher material removal, or surface melting which then has to be removed using additional processes. The use of a glass confinement layer as opposed to a water confinement layer (at the same laser energy and spot size) will result in approximately twice the amount of pulse pressure being induced within the material. However, in terms of practicality, it is more beneficial to use a water layer, due to its flowability over curved surfaces and ease of application, rather than glass. If deep compressive stresses are not required, then both can be eliminated by applying laser peening alone, but there is a high risk of losing the efficiency of the process, as the plasma is allowed to escape resulting in lesser pulse pressure, plastic deformation, and material property enhancement.

The cost of lasers has reduced over time, but there is still difficulty in deploying a full-scale laser shock peening facility for SMEs, job shops, and research labs due to a cost barrier. Depending on the laser energy available (400 mJ to 10 J), the costs range from £30 K to in excess of £300 K and beyond, for a dedicated, full-scale high energy system. If a laser source alone is purchased, additional costs such as a robotic arm and/or linear stages, appropriate beam delivery, and laser safety equipment all add up.

Laser Shock Peening at Coventry University

At Coventry University, research on peening science has been conducted since the late 1990s. More recent research has been focused on residual stress engineering by the structural integrity group, and applied laser shock peening, method development and surface engineering by the laser engineering and manufacturing group. This latter group are on their way to developing a second laser shock peening facility. The group is focused on undertaking research with both peenable and difficult-to-peen materials - titanium and nickel alloys being the former and advanced ceramics and cermet being the latter.



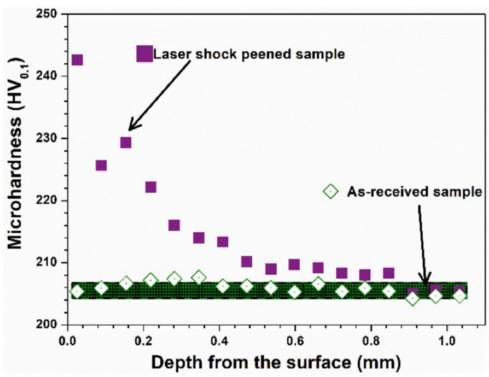


Figure 1: Laser shock peened surface of Hastelloy-X superalloy (left) and surface hardening phenomena following laser shock peening (right).

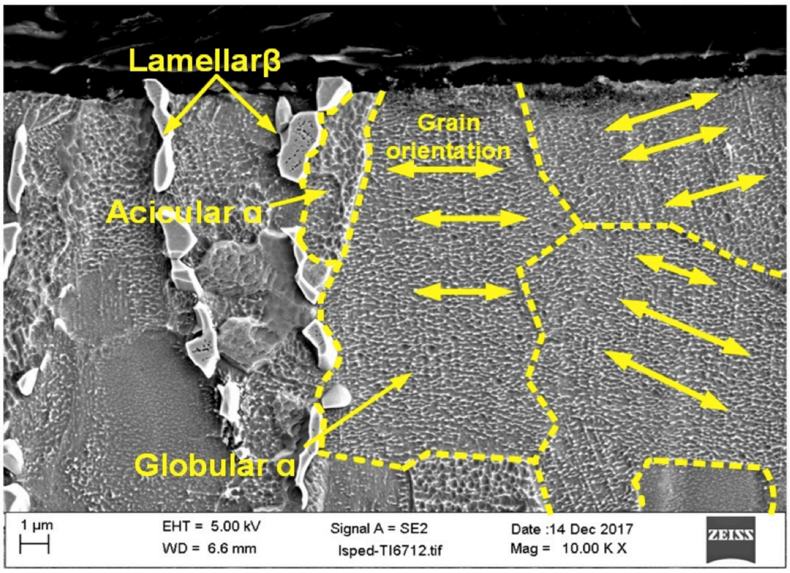


Figure 2: A micrograph of orthopaedic Ti-6Al-7Nb cross-section, post laser shock peening, showing refined grain regions.

In particular, laser shock peening of superalloys has drawn significant attention as they are being used in the harsh environment of gas turbine engines. For example, Hastelloy-X superalloys, despite having excellent oxidation resistance, formability, and high-temperature strength, fail in elevated temperature environments. Laser shock peening was able to produce compressive residual stress through to a depth of 1 mm which helped in delaying the onset of crack initiation and propagation [3]. Laser shock peening was also beneficial in increasing dislocation density in the metallic systems, which in turn increased the surface hardening behaviour as shown in Figure 1.

Laser shock peening of titanium alloys has also proved to be beneficial in strengthening titanium orthopaedic implants that are subject to wear and material loss. Worn implants often led to a second and third surgery for the end user, resulting in increased pain, cost and time [4]. The SEM image shown in Figure 2 is a cross-section micrograph of Ti-6Al-7Nb alloy after laser shock peening at 3 J, 3 mm spot size, 8 ns pulse duration, 1064 nm wavelength to strengthen the titanium alloy for biomedical applications.

The laser engineering and manufacturing group is also working on laser shock peening of advanced ceramics which is a new field of application. Much work is still to be reported in this area, but initial results have shown some good progress made with both silicon carbide and alumina ceramics. In particular, preliminary studies have shown that hardness, fracture toughness, microstructures and grain refinement are evident in these materials, as well as induction of some compressive residual stress [5]. With silicon carbide, increases in the surface roughness, changes to the surface morphology, improved hardness, and a reduction in crack lengths were found. Laser shock peening also improved the fracture toughness from an average of 2.32 MPa.m$^{1/2}$ to an average of 3.29 MPa.m$^{1/2}$.

Compressive stresses of -92 MPa were also measured with increase in laser energy. Furthermore, laser shock peening of alumina ceramics showed an increase in the surface hardness by 10%. The respective flaw sizes from the diamond indenter were also reduced by 10.5% - enhancing the K_{Ic} by 12%. These findings were a result of grain size reduction, micro-structural refinement and an induction of compressive stress layer -64 MPa [6].

The International Journal of Peening Science and Technology

The author has developed a new journal in the area of laser peening: The International Journal of Peening Science and Technology, which he also edits. The scope of the journal is broad, covering, among other things, the following areas:

- laser shock peening;
- plasma physics and dynamics;
- grit blasting;
- blast and laser cleaning;
- ultrasonic peening, water-jet/cavitation peening, oil-jet peening, shot peening, ion exchange beam peening;
- low plasticity burnishing and deep rolling;
- issues on plastic deformation and strengthening mechanisms;
- residual stress engineering;
- finite element analysis and process modelling of the peening techniques;
- topographical and micro/nano structural characteristics;
- change in mechanical, electrical and biomedical properties using peening.


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Figure 3: A cover page of Issue 1 of Volume 1 for the international journal of peening science and technology.

The journal reflects the main areas in which peening methods are used and developed for the surface engineering and for manufacturing applications.

Should anyone be interested in submitting a manuscript to this journal, further details can be found at http://www.oldcitypublishing.com/journals/ijpst-home/ and papers can be submitted to IJPST@oldcitypublishing.com.

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