Laser Shock Peening of aluminum and titanium using DiPOLE laser system.

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Abstract

Successful laser shock peening (LSP) of aluminum and titanium was demonstrated using the DiPOLE laser system operating at 7J, 10ns. Peak compressive stress of 220MPa and 170MPa was measured in Al7075 and Ti6Al4V with a confinement medium (water). Both peak compressive stress as well as the depth of compression increased on the application of repeat laser shocks. Aluminum foil coating as an absorptive layer showed best results when no confinement condition (No water) was used for LSP.

Introduction

Peening of materials have being practiced for decades to improve material performance and reduce fatigue failure. Conventionally, shot peening has being used for surface modification of materials [1]. Recently, laser shock peening (LSP) has being introduced as an alternative peening technique having serval advantages over conventional shot peening [2]. LSP utilises nanosecond pulses of laser light to compress the material surface and enhance their mechanical performance. High-power laser radiation impinges on the target surface, ablating and creating an energetic plasma which rapidly expands sending shockwaves deep into the material. These shockwaves compress the atoms in the material, densifying the crystal structure and strengthening it by introducing lattice defects called dislocations. The deformed region of material remains locked in a state of compression, even after the shockwave has passed through, leaving behind what is called “residual stress”. The surface becomes more resistant to damage and the material is effectively strengthened at all locations containing this compressive residual stress. Laser peening has been adopted by certain specialist sectors like aerospace and nuclear power generation where material performance is of critical concern. Example applications include aircraft engine fan blades, which are laser peened along their leading edges. Elsewhere, in the large pressure vessels of nuclear reactors, corrosion resistance is improved by laser shock peening the internal cladding material.

Blacksmiths have long exploited surface modification as an phenomenon to work metals and add strength using traditional tools like the peening hammer. With LSP, the laser becomes the tool, providing significantly deeper compression and a more intelligent process that can target precise locations such as welds and rivets for added strength. Owing to the unique advantages of DiPOLE laser, i.e control of its pulsewidth, pulseshape and energy the shockwave itself can also be tailored. In this paper, we report on the peening experiments done at the CLF using the DiPOLE laser.

Experimental setup

DiPOLE is a diode-pumped solid-state laser system (DPSSL) utilising a cryogenic gas-cooled amplifier head containing multi-slab Yb:YAG gain media producing 1030 nm wavelength output with nanosecond pulses at a maximum energy of 10 J and a maximum repetition rate of 10 Hz [3, 4, 5]. For the experiments reported in this paper, DiPOLE was operated at 7J, 10ns and 1 Hz. The target (Al or Ti) was place at a location from the lens where the spot size was 5mm by 5mm square. A protective fuse silica window (anti-reflection (AR) coated) was placed in front of the lens to protect it from water and debris ejecting from the target during the LSP process. The target was placed on an automatic XY-stage whose speed can be controlled by a home-build software. This was used to synchronise the translation of the target during LSP to control the overlapping of subsequent laser shots. (Figure 1). The flexibility offered by DiPOLE allowed full control over the laser peening variables enabling us to better understand the specific influence of changing energy, pulse duration, beam diameter, repetition rate and overlapping shocks on the residual stresses produced.

Figure 1: The laser shock peening laboratory showing target station apparatus.

Residual stress and material compression

There are a number of ways we can measure the residual stress state that exists within a sample that has been subjected to LSP. Non-destructive methods, such as X-ray diffraction can be used to probe the interatomic distances between atoms and reveal strain in the crystalline lattice but the shallow penetration depth of photons in metals make this technique only surface sensitive. In some cases it becomes necessary to physically cut open the target to relieve the internal stress whilst measuring the material relaxation using digital image correlation or strain gauges. Using this approach with help from collaborators at the University of Coventry, the residual stress state in a number of test alloys was measured after laser peening at CLF (Figures 2 & 3). Compressive stresses are produced at depths exceeding 1mm beneath the treated surface and the magnitude and depth of this compression can be increased by applying repeat shocks with higher intensity pulses.

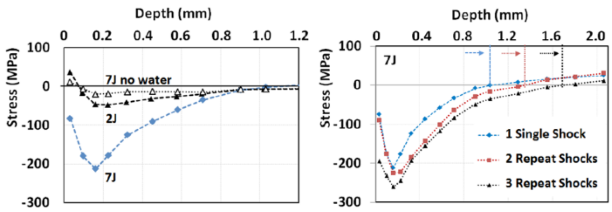

Figure 2: Residual stress data after laser shock peening of Al 7075 with different parameters,

The use of a transparent medium like water acts to trap the plasma produced during LSP, confining and directing the shockwave deep into the material. For this reason, water is routinely included in many LSP treatments, either by complete immersion of the target in a liquid bath or by flowing water over the target surface as a continuous thin layer. This latter arrangement has been used during testing at the CLF. Figure 2 contains residual stress data demonstrating the critical role played by the water confinement layer, amplifying the shockwave for an order of magnitude increase in compression at 7 Joules. Also shown is the added depth benefit of delivering multiple repeat shocks.

Figure 3 demonstrates how materials respond differently under identical laser peening conditions, with aluminium alloys displaying a greater depth of compression compared to higher strength titanium alloys at the same laser energy of 7J.

The density and acoustic impedance of these materials influences the pressure wave propagation behavior, and their thermomechanical properties dictate whether the target will plastically deform or even melt for a given intensity. Optimal conditions are achieved when the material is elastically deformed with minimal permanent deformation, as any plastic yielding could relieve the elastic compression. If surface melting occurs it is often accompanied by a detrimental tensile residual stress formed upon re-solidification and cooling, similar to that of a heat affected zone in a weld.

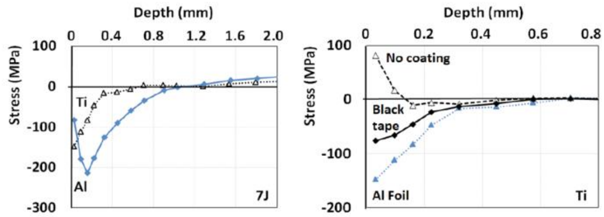

Figure 3: Residual stress data after laser shock peening for different sample materials and coatings.

Our studies have identified the optimal coatings for use during LSP that can prevent surface damage whilst still imparting the beneficial compression deep into the sample. Thin aluminum foil achieves the best results, coupling well with the metal target for good shockwave transmission, whereas black tape absorbs the IR radiation well but attenuates the shock more than foil (Figure 3). The appropriate use of sacrificial ablative coatings helps to protect the sample surface by minimising heat transfer and preventing unwanted distortion. Maintaining a high quality surface condition is often critical for engineering components in industrial environments where surface imperfections can act as stress concentrations which initiate fatigue failure or pitting corrosion cracks. To demonstrate that a high quality surface finish remains after LSP, measurement of the surface roughness before and after treatment is performed with a simple visual inspection for signs of sample discolouration or burning.

When no coatings are used it is possible to ablate the target material itself, causing vaporization at high intensities and melting of the near surface. Despite encouraging tensile stresses as described earlier, there may also be some advantages to this effect. Intentional re-melting of a shallow surface layer can smoothen out uneven topography and polish a rough surface to a uniform shine (Figure 4). This method of surface polishing shows promise and may be particularly suitable for additively manufactured components. Commonly called 3D printing, additive manufacturing (AM) of components from metal powders is an exciting new tool which is finding widespread appeal across high-value industrial sectors. One issue with AM built parts however is their surface condition is typically rough and granular, often requiring additional post-process machining. CLF is also investigating the use of LSP as a novel solution to polish 3D printed surfaces and help improve material quality in AM components.

Industrial engagement with LSP is about building confidence in the repeatability, reliability and cost efficiency of the technique. Not only must the surface treatment provide consistent performance improvements, but it should also be flexible enough to adapt to a variety of real component shapes and sizes.

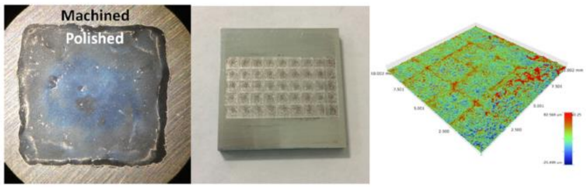

Figure 4: Surface condition after laser peening with a roughness topography map.

At CLF, a recent expansion of the LSP facility includes the addition of a second target station to deal with these concerns: the expansion integrates a six-axis robotic arm for 3D sample manipulation offering a large working envelope and the ability to peen complex sample geometries including curved surfaces found on most industrial components.

Combining high-speed, automated sample manipulation with the high repetition rate 10 Hz pulses from the DiPOLE laser system will expedite treatment of large sample surfaces and increase throughput, saving costs on energy expenditure and proving more attractive to industry. A fully synchronised robotic system, triggered directly by the DiPOLE laser is a future goal, along with docking stations for multiple sample change over.

Conclusions

In summary, successful laser shock peening was demonstrated on aluminum (Al7075) as well as titanium (Ti6Al4V) with 7J, 10ns pulses from DiPOLE laser. Peak compressive stress of 220MPa and 170MPa was measured in Al7075 and Ti6Al4V with a confinement medium (water). Both peak compressive stress as well as the depth of compression increases on the application of repeat laser shocks. Aluminum foil coating as an absorptive layer shows best results when no confinement condition (No water) was used.

Acknowledgments

The authors would like to thank Kuladeep Rajamudili and Dr. Supriyo Ganguli from Department of manufacturing, University of Cranfield. Authors would also like to thank Dr. Niall Smyth of the Faculty of engineering and computing, University of Coventry for the stress measurements.

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