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Warm Laser Shock Peening: New developments and process optimization

G. Tani (3)*, L. Orazi, A. Fortunato, A. Ascari, G. Campana

DIEM - Mechanical Constructions Engineering Department, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy

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ABSTRACT

Laser Shock Peening is a well-known technology able to enhance the fatigue life of mechanical components. Surface residual stress is induced by means of the recoil pressure of an ablated coating in a confining medium interacting with a high power density laser.

Warm Laser Shock Peening is obtained by laser peening a pre-warmed workpiece surface: combining the thermal effect of the pre-heated surface and the mechanical phenomenon of the recoil shock pressure, the dynamic aging of the surface microstructure is obtained. Precipitates surrounded by dense dislocation together with residual stress considerable increase the mechanical properties of the workpiece.

1. Introduction

Laser Shock Peening (LSP) is a laser material processing technology able to generate residual stresses on metal surfaces by means of the generation of a elastic shock waves, causing the improvement of fatigue life and corrosion resistance in mechanical components. Compressive stresses, in fact, are generated by means of the recoil pressure due to the rapid expansion of the plasma plume resulting from the interaction of the first atomic layers with the laser beam. Usually, in order to avoid thermal damage of the components, laser beam irradiates an opaque coating layer, deposited on the component surface, which vaporizes during the laser interaction. The vaporization of the layer produces a plasma, whose expansion is restricted by a transparent medium which creates a confinement producing higher surface pressure with longer durations.

Typical laser equipment is based on Nd:YAG sources, characterized by short pulse durations (1–20 ns), high power densities (1 GW/cm^2), low repetition rates (a few Hz) and energy-per-pulse varying between 1 J and 20 J. According to these process parameters, the surface pressure occurring on the material during LSP easily reaches 4–5 GPa [1] causing the deformation of the workpiece material for a depth of more than 1 mm and inducing high residual stresses. This result is very interesting if compared to traditional shot peening in which the average depth of the deformed layer is 0.25 mm and the residual stresses are much lower [2].

A recent and very promising variant of LSP has been proposed in Ref. [3]. In this paper, according to previous experiences carried out in traditional shot peening by Harada and Mori [4], the authors proposed a Warm Laser Shock Peening (WLSP) where the workpiece was heated before applying the LSP process. In Ref. [5] it was observed that, if a proper temperature is chosen, the application of WLSP leads to comparable and even higher residual stress, higher surface hardness, grain refinement and, consequently, better fatigue life of the treated component. This result is consistent with the observations proposed in Ref. [4] where the comparison between warm traditional shot peening and "cold" one is analysed. WLSP gives better results due to the dynamic strain aging occurring at temperature between 150 °C and 300 °C as stated in Ref. [5].

According to the previous consideration, WLSP results depend on the pressure of the confined plasma and on the pre-heating temperature.

In Ref. [1], for the first time, a LSP model was presented. It was based on a uni-axial compressive stress generated by the shock wave along its propagation direction into the workpiece at environment temperature, but no pre-heating was considered and no plasma formation was modelled. Laser material interaction was simply resumed by means of a proportional relationship between laser power density and surface pressure.

In Ref. [2] a very detailed laser–matter interaction model was proposed. The target material, the substrate and the confining medium were considered for the plasma plume state and pressure evaluation, but no residual stress calculation was performed.

In Refs. [3,5] an extension of the model presented in Ref. [1] was proposed for WLSP introducing the Material Threshold Stress (MTS) model [6] for the flow stress evaluation in aluminium alloy 6082 WLSP but no results were presented. The surface pressure was calculated with an algebraic relationship between laser radiation and surface pressure in a steady state condition, without involving plasma plume physical phenomena.

In this paper the authors present a complete model for LSP and WLSP where the time dependant surface pressure is calculated according to the plasma formation and its expansion in the confining medium. The residual stresses are predicted according to the model proposed in Ref. [1] and the flow stress is calculated by means of the MTS model. An experimental campaign concerning

* Corresponding author.

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both LSP and WLSP trials was conducted on AISI 1042 (UNI C40) carbon steel specimens to validate the proposed model.

In order to develop a useful process for industry a transparent silicone oil was used as a confining medium instead of water or BK7 glass reported in Ref. [3] and no ablative medium was applied since the application and subsequent removal of that layer is usually a time expensive activity.

2. Modelling

The proposed WLSP model is based on the modelling of the vaporization of the target surface and on the modelling of the subsequent shock wave propagation into the bulk.

2.1. Surface pressure and plasma plume state evaluation

The proposed model for the shock surface pressure evaluation is based on the assumption that the confining medium is completely transparent with respect to the wavelength of the laser beam used in the process. According to this, the medium is only used to confine the plasma generated by the absorption of the laser beam interacting with the surface target so that the peak pressure on the surface is higher and its duration in time can be longer. No ablative layer is exploited on the surface directly irradiated by the laser and, according to this, the high pressure plasma plume is generated by means of the interaction of the laser beam with the first atomic layers of the base material, as shown in Fig. 1.

Considering the above mentioned assumptions, the pressure evaluation can be performed as proposed by the authors in Ref. [7]. Further details are reported in that work and in this paper only the topic factors are mentioned. In particular, according to the assumption that the flow of the vaporizing material follows the Hertz–Knudsen equation, the surface recession velocity of the liquid–vapour interface is calculated by means of Eq. (1) when the surface temperature T_s is known. ΔH is the heat of vaporization per atom, m is the atomic mass, k is the Boltzmann constant, T_b is the boiling temperature at the boiling pressure p_b and ρ is the target material density.

$$\left(\frac{\partial z}{\partial t}\right)_{z\approx 0} = p_b\ e^{\Delta H m/k(1/T_b - 1/T_s)}\sqrt{\frac{1}{2\pi m k T_s}}\left(\frac{m}{\rho}\right) \quad (1)$$

The knowledge of T_s implies the possibility to evaluate the amount of power density impacting the target surface during the ablation process. This quantity is the energy per unit time and per unit area interacting with the target surface without being absorbed from the plume and it depends on the physical state of the plume itself. The temperature dependant physical state of the plume is evaluated by calculating the plume temperature T_p, the plume length l and the ion density N exploiting Eqs. (2), (4) and (5) respectively and assuming the plasma being in local thermodynamic equilibrium. In this case the photoionization of the excited states and the inverse bremsstrahlung absorption are the main factors leading to the vapour breakdown:

$$\frac{d(kT_p)}{dt} Nl\gamma(Z+1)\left(\frac{M^2}{2} + \frac{1}{\gamma(\gamma-1)}\right) = I_L[1 + R_L\ e^{-(\alpha_p l/\cos\vartheta)}][1 - R_L\ e^{-(\alpha_p l/\cos\vartheta)}] - (1 - R_L)I_P \quad (2)$$

$$I_P = 4\sigma\alpha_p T_p^4 \quad (3)$$

$$\frac{dl}{dt} = \sqrt{\frac{\gamma(Z+1)kT_p}{m}} \quad (4)$$

$$\frac{d(Nl)}{dt} = p_b\ e^{\Delta H m/k(1/T_b - 1/T_s)}\sqrt{\frac{M}{2\pi m k T_s}} \quad (5)$$

γ is the specific heats ratio, Z is the charge state of the ions in the plasma plume, M is the Mach number, I_L is the laser beam power density, R_L is the reflectivity of the target material for the specific laser wavelength, I_p is the plasma plume self-emission power density, σ is the Stefan constant, α_p is the plasma absorption coefficient and θ is the angle between the normal direction to the surface and the beam radiation direction.

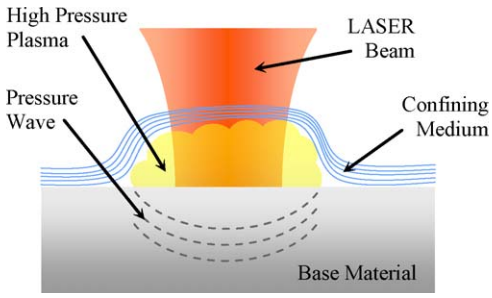

Fig. 1. An outline of the Laser Shock Peening process.

In order to apply Eqs. (2)–(5) for the prediction of the plume pressure on the surface, the authors considered that the silicone oil confines the plume expansion and that an elastic wave propagates into the oil itself at a speed characterized by a Mach number $M = 3.7$. By means of this model it is possible to calculate the surface pressure evolution in time and point by point on the treated surface, considering any type of laser beam pulse duration and pulse shape, while in earlier studies the surface pressure was simply considered to be constant or at the most triangular-shaped [8].

2.2. Flow stress model and residual stress evaluation

As pointed out before, the residual stress prediction is based on a uni-axial compressive stress evaluation generated along the direction of the shock wave propagation onto the bulk material due to recoil pressure impacting the surface after the vaporization of the superficial layer of the target material.

During the elastic and plastic waves propagation onto the workpiece material, plastic deformation occurs into the bulk when the peak pressure exceeds the metal's Hugoniot elastic limit (HEL). This value is related to the dynamic yield stress σ_y according to Eq. (6) where σ_c is a previously induced stress [1]:

$$HEL = \left(1 + \frac{\lambda}{2\mu_l}\right)(\sigma_y - \sigma_c) \quad (6)$$

Dynamic yield strength σ_y is calculated, taking into account plastic deformation, temperature and strain rate in the surface material, exploiting a three-term mechanical threshold stress strength model (MTS) [6]. MTS is a semi-empirical model and it is based on the evaluation of the material flow stress at absolute zero temperature, in absence of any thermally activated processes; it is possible to adapt this value to the actual temperature by scaling the flow stress at 0 K with Arrhenius factors which take into account thermally activated deformations.

The three-term MTS model is based on Eqs. (7)–(10):

$$\sigma_y = (\tau_a + \tau_i + \tau_e)\frac{\mu}{\mu_0} \quad (7)$$

$$\tau_i(\dot{\varepsilon}, T) = \sigma_i\left[1 - \left(\frac{kT}{g_{0i}b^3\mu}\ln\frac{\dot{\varepsilon}_{0i}}{\dot{\varepsilon}}\right)^{1/q_i}\right]^{1/p_i} \quad (8)$$

τ_a is the athermal component and it is supposed to be equal to 40 MPa [9], while τ_i is the intrinsic term depending on σ_i, which is the yield stress at 0 K or at strain rate $\dot{\varepsilon} = \dot{\varepsilon}_{0i}$. The term τ_i is known as the "intrinsic" barrier to the dislocation motion and it takes into account Peierls barriers, interactions between dislocations and vacancies, presence of atoms and solutes in the lattice and dislocation–dislocation interactions. This contribution represents a static description of the microstructure. μ and μ_0 are the shear moduli at ambient and 0 K temperature respectively, g_0 is a normalized activation energy, b is the Burgers vector, p and q are