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Analysis of plasma thermal surface effects on the residual stress field induced by LSP in Al2024-t351

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In Laser Shock Processing (LSP) a high intensity pulsed laser beam is focused at the interface between a metallic target and a transparent confining material (normally water) that induces a residual stress distribution in the target material. Without a protective coating thermal effects are present near the target surface. A calculational model has been developed, able to systematically study LSP processes, starting from laser-plasma interaction and coupled thermo-mechanical target behavior. We present results obtained in LSP treatments without coating. In particular the relative influence of thermal/mechanical effects shows that: each effect has a different temporal scale and thermal effects are limited to a small region near the surface; repeated pulses increase maximum compressive residual stress and the depth of the compressive residual stress region; compressive residual stresses very close to the surface level can be induced even without any protective coating through the application of adjacent pulses.

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1. Introduction

Laser shock processing is being considered as a competitive alternative technology to classical treatments for improving fatigue, corrosion cracking and wear resistance of metallic materials [1-4].

LSP is mainly a mechanical process but in some cases it is performed without a protective coating and thermal effects are present near the surface [2,4].

In the present paper, we are presenting a calculational system SHOCKLAS that takes into account the surface heating. Numerical results of LSP treatments without coating are studied, in particular: thermal/mechanical time scales, relative influence of thermal/mechanical effects, repeated pulses and full 3D treatment with pulse overlapping.

2. Physical basis and theoretical modelling of LSP processes

Laser Shock Processing (LSP) is based on the application of a high intensity pulsed Laser beam ($I > 1$ GW/cm^2; $\tau < 50$ ns) on a metallic target forcing a sudden vaporization of its surface into a high temperature and density plasma that immediately develops inducing a shock wave propagating into the material.

During a first step (during which the laser beam is active on the piece), the laser energy is deposited at the interface between the target and a transparent confining material (normally water). The pressure generated by the plasma induces two shock waves propagating in opposite directions (inside the target and towards the confining material respectively). When the laser is switched off, the plasma continues to maintain a pressure which decreases during its expansion as a consequence of the increase of the plasma volume. Finally, for longer times, after the plasma recombination, the projectile-like expansion of the heated gas inside the interface adds further mechanical momentum to the target.

The pressure induced by the laser generated shock wave into the treated material, which is the direct responsible for the achieved material permanent deformation, has to be optimized as a function of the laser characteristics and other process parameters.

The description of the relevant laser absorption phenomena becomes hardly complicated because of the non-linear effects appearing along the interaction process and which significantly alter the shocking dynamics. Laser shock processing without coating produces a deleterious effect induced by the thermal flux generated upon laser material interaction but it is limited to a narrow layer under the target surface. This effect is very important for the mechanical behaviour of the treated piece and deserves a further detailed evaluation aiming process optimization [5].

3. Numerical modeling of LSP processes

The most popular methods reported in the literature for the analysis of the LSP phenomenology [6-8] try to induce the intensity and temporal profile of the shock wave launched into the treated solid material by means of the analysis of the impulse conservation between the external interface of such material and the frontier of the confining material without any reference to the detailed physics of the plasma formation process taking place in the outermost layers of the solid target: this plasma is assumed to be built up to certain degree as a consequence of the initial laser energy deposition, but no analysis is provided about its real dynamics.

From the point of view of the acceleration of the confining medium as a consequence of the excess pressure due to the expansion of the generated plasma, the simplified models proposed in the cited references can provide adequate results that can even be experimentally contrasted. However, from the point of view of the actual compression dynamics of the solid target (the main objective of the study and for which the contrast to experimental results is far more complicated), such simplified models are presumably not able to provide a correct estimate of the pressure/shock waves effectively launched, at least in the initial moments of the laser interaction, in which the complex physics related to plasma ionization dynamics can substantially modify the target state in view of the subsequent process development.

The modeling of LSP process requires a three level description with adequate interconnection of the data obtained in each phase in a self-consistent way.

The referred three-level description includes:

i) Analysis of the plasma dynamics, including breakdown phenomenology in dielectric media,

ii) Simulation of the hydrodynamic phenomenology arising from plasma expansion between the confinement layer and the base material

iii) Analysis of the propagation and induction of permanent material changes by shock wave evolution in bulk material

We have developed a simulation model (SHOCKLAS) that deals with the main aspects of LSP modeling in a coupled way [8-10].

3.1 Laser plasma interaction

The problem of laser-plasma interaction at very high intensities has been a subject of permanent interest from the appearance of the first lasers [11,12]. HELIOS is a 1-D radiation-hydrodynamics code that is used to simulate the dynamic evolution of laser created plasmas [13].

Fluid methods describe the dynamics of a continuous medium and are thus applicable when the mean free path of the constituent particles is small compared to the characteristic dimensions in the system. The fluid is described by its thermodynamic state and by the velocity of flow. The state variables are related by the material equation of state (E.O.S.). The Navier-Stokes equations of fluid mechanics yield five relations expressing the basic conservation laws of physics applied to the moving fluid [14].

Hydrodynamic codes for the analysis of laser matter interaction at high intensities generally use a one (common for ions and electrons) or two (differentiated for ions and electrons due to the weak energy coupling between the two populations) temperature-fluid scheme. Electrons and ions are assumed to flow as one fluid what implies no charge separation.

Material equation of state (EOS) properties are based on either SESAME tables [13] or PROPACEOS tables [14]. Opacities are based on tabulated multi-group (i.e., frequency binned) PROPACEOS data. Radiation emission and absorption terms are coupled to the electron temperature equation.

From the mathematical point of view, the equations describing the plasma fluid dynamic motion are hyperbolic and have solutions with a characteristic propagation speed, admitting, in absence of dissipative terms, discontinuous solutions than can create difficulties for finite difference schemes. The introduction of the Von Neumann artificial viscosity effectively smoothes the shock [15].

Laser energy deposition is computed using an inverse Bremsstrahlung model, with the restriction that no energy in the beam passes beyond the critical surface.

3.2 Target thermo-mechanical behavior

The study LSP processes without coating needs a coupled treatment of thermal and mechanical transient processes. The target material subject to LSP is heated due to two main mechanisms: direct laser interaction heating (input from HELIOS simulations) and heating by plastic deformation work. To study these 3D problems we have developed a model based in the FEM commercial code ABAQUS® [16]. It solves the shock propagation problem into the solid material, with specific consideration of the material response to thermal and mechanical alterations induced by the propagating wave itself (i.e. effects as elastic-plastic behavior, changes in elastic constants, phase changes, etc.). The resulting temperature rise is correspondingly computed, so that this temperature change produces, in turn, a local thermal expansion of the target material whose subsequent thermal strains have to be consistently calculated.

From the point of view of time differencing, the usual strategy of explicit differencing for the initial fast shock propagation phase followed by standard implicit differencing for the analysis of the final residual stresses equilibrium is not used, instead only explicit differencing has been used with long time evolutions in order to reach thermal and stress equilibration.

From the geometrical point of view, two kinds of configurations have been considered: an axis-symmetric one for studies of the effect of one single pulse or several pulses in the same point and a full 3D configuration for studies with geometric overlapping of pulses in which a full 3D process dependence has to be considered.

The FEM element used for the mechanical simulation is an 4-node brick reduced integration with hour glass control bilineal, namely CAX4RT, and an 8-node brick reduced integration with hourglass control trilineal, namely C3D8RT, for fully 3D simulations.

In LSP processes the material is stressed and deformed in a dynamic way, with strain rates exceeding 10^4 s^{-1}. The material behavior of Al2024 is modeled using Johnson-Cook [17].

4. Model results

4.1 Study of LSP produced plasma

HELIOS code has been applied to the simulation of plasma dynamics of an aluminium target subject to LSP conditions (λ = 1064 nm, F = 84 J/cm^2 and a Gaussian temporal profile with τ_{FWHM} = 9 ns).

In Fig. 1 plasma pressure and heating rate obtained for Water/Al plasma produced in LSP conditions are displayed. These are the boundary conditions that are applied in the surface of the target in the FEM code for the determination of the residual stress field.

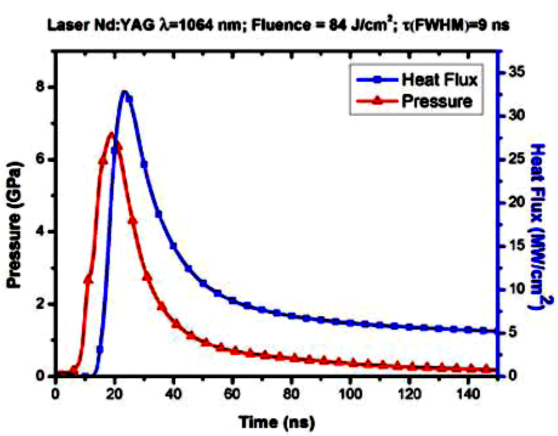


Fig. 1. Plasma pressure and heating rate for a Water/Al plasma produced in LSP without coating conditions.

4. 2 Analysis of the stress and temperature evolution: temporal scale

Mechanical and thermal effects have different temporal scales. Mechanical evolution is very fast and equilibration is reached before 1 μs (see Fig. 2). Thermal evolution is very slow in comparison with mechanical evolution and before 1 μs only the surface layer has a temperature increase and equilibration is reached after 1 ms (see Fig. 3).

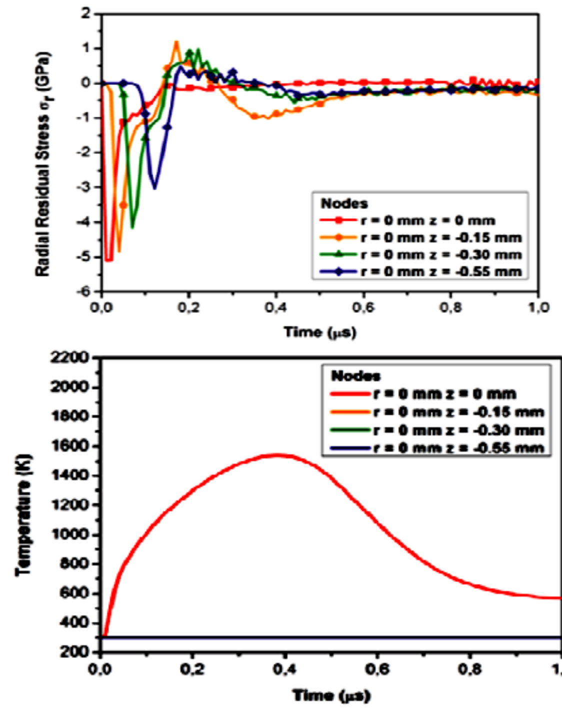


Fig. 2. Short time evolution of radial residual stress (a) and (b) temperature.

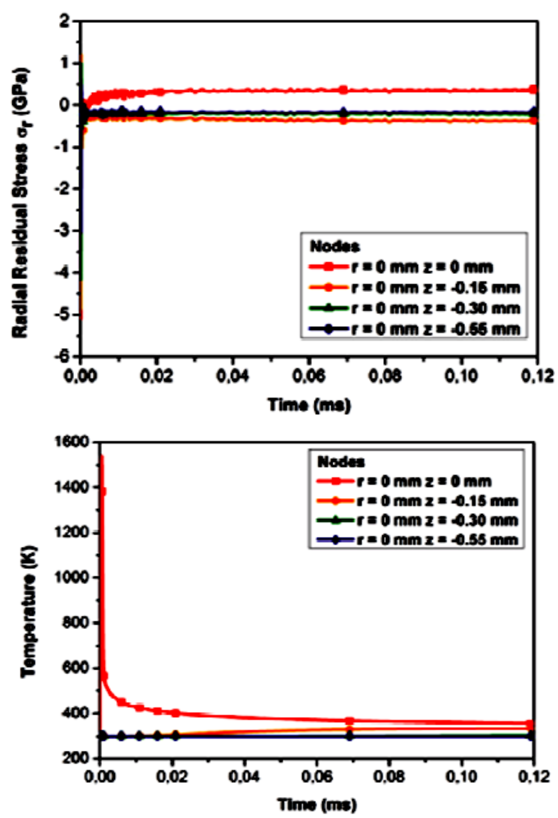


Fig. 3. Long time evolution of radial residual stress (a) and (b) temperature.

4. 3 Influence of pressure pulse and heat flux on the residual stress distribution

The analysis of the residual stresses induced by a single shot with full consideration of thermal and mechanical effects has been performed, both considering individually either mechanism and in a fully coupled way. Laser spot diameter is 1.5 mm. The corresponding residual stress distribution is represented in Fig. 4 at two different vertical axes (one coincident with the axial axis, r = 0, and the other at half the laser spot radius, r = R/2).

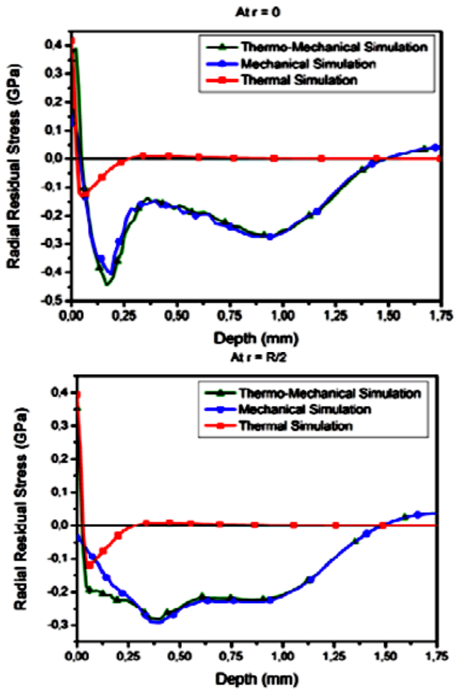


Fig. 4. Radial residual stress in a thermal, mechanical or fully coupled simulation.

In this figure, the opposite effects of the thermal wave and the mechanical shock wave on the material residual stress fields near the free surface are clearly shown: while the pure consideration of the mechanical effects induced by the shock wave launched into the material by the laser generated plasma results in an effective target compression until rather important values (for a single laser pulse) of compressive residual stresses (this profile with two negative peaks is obtained because of the interference of the compression and the rarefaction waves generated at the surface of the target), the effect of the thermal flux entering the piece as a direct consequence of contact and radiation from such plasma has clearly a deleterious effect over such residual stresses field near the surface, but the stress after this first layer is increased due to stress self equilibration.

4. 4 Analysis of the effect on the residual stress distribution of repeated laser pulses

In this case the overlapping of pulses (in the same conditions previously discussed) in the same point has been considered. The corresponding residual stress distribution is represented in Fig. 5.

Maximum residual stress and the depth of compressive residual stresses increase with the number of laser pulses. Also it is shown a saturation tendency in both parameters.

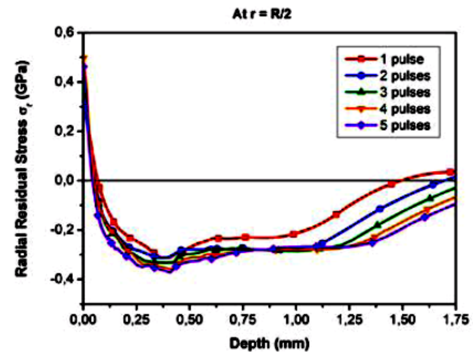
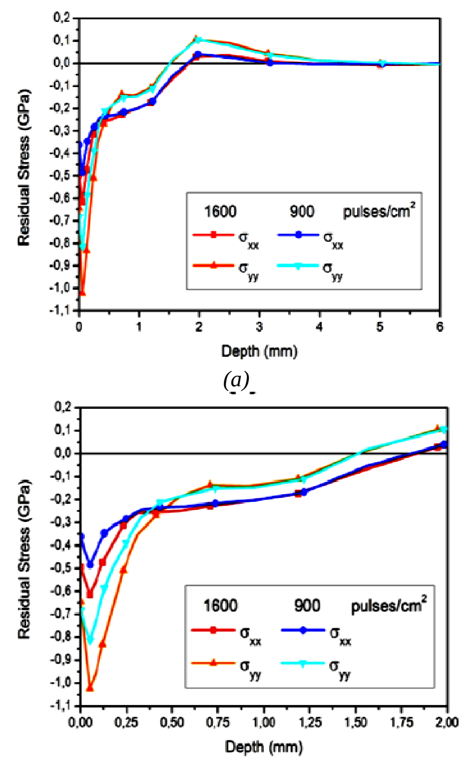


Fig. 5. Radial residual stress for different number of laser pulses.

4. 5 Evaluation of the residual stress obtained by application of adjacent pulses covering an extended surface

In this case the application of adjacent pulses covering an extended surface (in the same conditions previously discussed) has been considered for overlapping densities of 900 and 1600 pulses/cm^2. The corresponding residual stress distribution is represented in Fig. 6.



(b)

Fig. 6. Residual stress obtained with overlapping of pulses.

The effect of several pulses in the same point overcomes the tensile stress and produces compression in the surface. There is an increase in the residual stress close to the surface due to self equilibration and after that it starts to decrease until a new tensile region starts due to self equilibration.

5. Conclusions

A physically comprehensive calculational model (SHOCKLAS) has been developed able to systematically study LSP processes starting from laser-plasma interaction and coupled thermo-mechanical target behavior.

The analysis of LSP process without coating with the appropriate coupled treatment of thermal and mechanical transient processes shows:

- Existence of two temporal scales. Residual stress equilibration takes place in 1 μs while thermal equilibration takes more than 1 ms.
- Thermal effect is limited to a small region near the surface. A first layer with tensile stress is followed by a region with compressive stress due to stress equilibration.
- Several pulses increase maximum compressive residual stress and the depth of the compressive residual stress region.
- Compressive residual stresses very close to the surface level can be induced even without any protective coating through the application of adjacent pulses.

This study of coupled thermo-mechanical effects in LSP confirms the experimental results [2,4] on the feasibility of the process without coating.

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