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Effect of laser spot size on the residual stress field of pure Al treated by laser shock processing: Simulations

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ABSTRACT

Laser shock processing (LSP) is a unique surface treatment technique. It induces high-depth compressive residual stresses for improved fatigue or stress corrosion cracking resistance. FEM simulation is an effective method to predict material behavior by LSP. A 2D quarter-infinite model was used to simulate the material behaviors of commercially pure Al by LSP. Different peak pressure with different laser spot diameter was applied to surface of pure Al. Each simulation included two steps: (i) explicit dynamics analysis for the analysis of the LSP; (ii) static equilibrium analysis for springback deformation analysis. The following conclusions could be made: (1) Plastically affected depth increased with the increase of laser spot diameter. There was an ultimate value about plastically affected depth when the laser spot diameter increased to some value, and the ultimate value was consistent with Ballard' model. When the laser spot diameter was small, there still existed tensile residual stresses on the surface layer of material although the peak pressure was below 2.5 HEL. When the diameter laser spot diameter was big enough, the tensile residual stresses on the surface layer of material were converted into compressive residual stresses although the peak pressure was higher than 2.5 HEL.

1. Introduction

Laser shock processing (LSP) or laser peening is a promising surface treatment technique. The beneficial effects of LSP on mechanical property, fatigue and stress corrosion performance of aluminum alloys, steels and magnesium alloys have been demonstrated [1–6]. The most important factor attributes to the improvement of these properties is that LSP can induce compressive residual stress in the to-be-treated materials. Compared with common treatments such as shot-peening, deeper residual stress layer and low-cold work amplitude are obtained after LSP, mostly due to the absence of contact.

The LSP process utilizes high energy laser pulses (several GW cm^{-2}) fired at the surface of a metal material covered by two layers, an absorbing layer and a water confining layer (Fig. 1). The absorbing layer vaporizes and forms plasma when a laser pulse with sufficient intensity passes through the transparent confining layer and hits the surface of the metal material. The plasma continues to strongly absorb the laser energy until the end of energy deposition. The rapidly expanding plasma is trapped between the surface of the metal material and the transparent confining layer, creating a high pressure (more than 1 GPa) [7], which propagates into the metal material as a shockwave. When the pressure of the shockwave exceeds the Hogoniu Elastic Limitation (HEL) of the metal material, plastic deformation occurs on the surface layer.

An elastic–plastic model developed by Ballard [8] is usually used to predict the surface residual stress and plastically affected depth induced by LSP. The following assumptions were used in this model: (1) the shock-induced deformation is uniaxial and planar; (2) materials obey a Von Mises plasticity criterion; (3) the pressure pulse is uniform in space. The model comes to the following conclusions: (1) the optimal peak pressure corresponds to 2–2.5 HEL (Hugoniot elastic limit); (2) the estimation of plastically affected depth *Lp* is expressed as

$$L_p = \left(\frac{C_{el}C_{pl}\tau}{C_{el} - C_{pl}}\right)\left(\frac{P - HEL}{2HEL}\right) \quad (1)$$

Where C_{el} is elastic velocity and C_{pl} is plastic velocity, τ is the pressure pulse duration, P is the peak pressure induced by LSP. According to this model, surface release waves focus and amplify from the edges of the impacts thus modifying the RS field when the peak pressure is above 2.5 HEL. However, this model does not consider the influence of laser spot size. Surface release waves also will focus and amplify from the edges of the impacts when the peak pressure is below 2.5 HEL if the size of laser spot is small enough.

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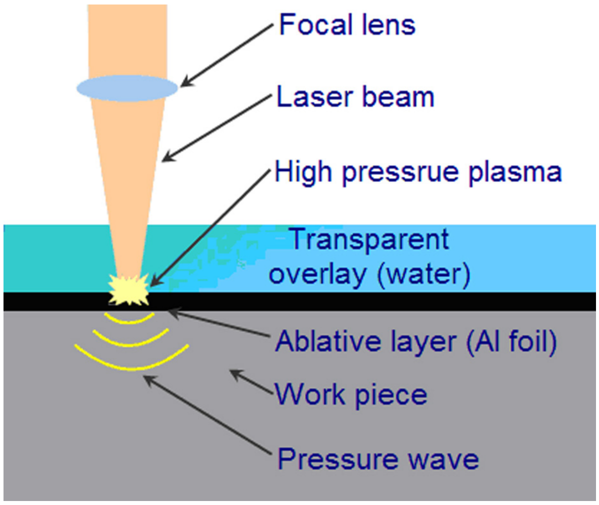

Fig. 1. Schematic of laser shock processing in confined regime.

Moreover, the scattering of shock wave induced by LSP cannot be negligible when the size of laser spot is relatively small.

Due to the severity of the pressure loading imparted in an ultra-short period of time (in the ns regime), the calculation of mechanical effects is rather complex. FEM simulation of LSP provides unique tools for evaluation of LSP in relation to materials properties, laser sources and LSP parameters [9–19]. This approach can play significant roles in design and optimization of LSP process in practical application. ABAQUS is adopted to simulate the distribution of residual stress of pure Al treated by LSP, and the simulated results are checked up by experiments. The purpose of this paper is to find the effect of laser spot size on the residual stress field of pure Al.

2. FEA simulation of LSP

2.1. Analysis technique

The FEA software ABAQUS was used to compute the metal behaviors treated by LSP in many papers [10,11,14,17]. These ABAQUS-based FE simulations provided a relatively close match with the measured residual stresses from experiments.

A 2D-axisymmetric finite element model in a semi-infinite solid was used to simulate the material behaviors of pure Al treated by LSP (Fig. 2). Each simulation was composed of two steps: (a) explicit dynamics analysis for laser shock processing analysis; (b) static equilibrium analysis for springback deformation analysis. In the first step, the shock pressure was applied on the top surface, an explicit dynamic analysis was performed using the ABAQUS/Explicit to determine the steady-state solutions and calculate the short duration shock waves until the saturation of plastic deformation occurs in the target. In the second step, the deformed body with all transient stress and strain states was imported into the ABAQUS/Standard to finally determine the residual stress field at static equilibrium. The stress and strains were allowed sufficient time to relax so that the solution could stabilize.

2.1.1. Applied spatial and temporal shock pressure

The spatial shock pressure induced by LSP was assumed to be uniform in the scope of laser spot. A useful approximation for temporal shock pressure was to assume that it followed a 6th order polynomial and the pressure pulse was assumed to be 2–3 times longer than the laser pulse [7]. In this paper, the laser used in simulation was 10 ns, and thus the shock pressure pulse was assumed to be 25 ns (Fig. 3).

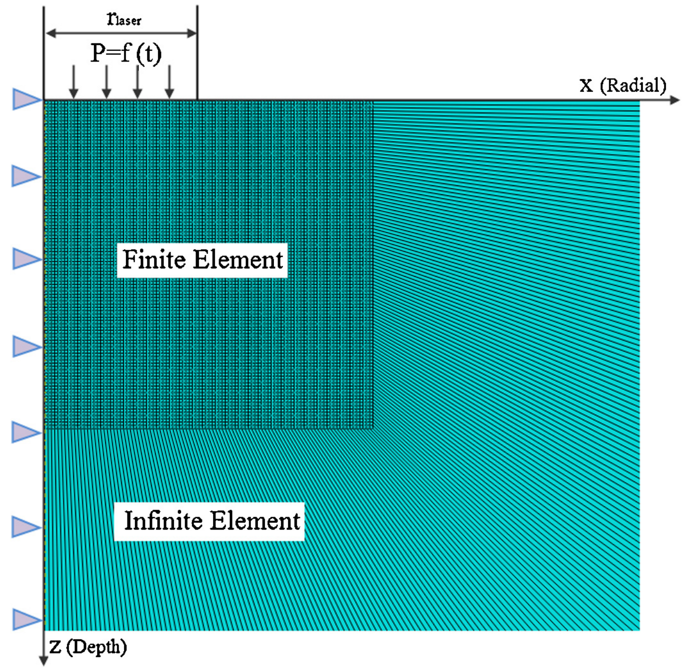

Fig. 2. Schematic of axisymmetrical models used in ABAQUS.

A commonly used estimate of the peak pressure for $P(t)$ in water confined regime is given by [7]

$$P(GPa) = 0.01\sqrt{\frac{\alpha}{2\alpha+3}}\sqrt{Z(g/cm^2s)}\sqrt{I_0(GW/cm^2)} \quad (2)$$

where P is the peak pressure, Z is combined shock impedance defined by the following Eq. (2), I_0 is the power density, and α is a correction factor for the efficiency of the interaction. The ablative material used in these experiments was Al. L. Berthe and R. Fabbro [7] reported that the experimental peak pressure of 25 ns laser pulse can be separated in two parts: Firstly, from 1 to 10 GW/cm^{2,} the pressure increased with the power density up to 5.5 GPa. Above 10 GW/cm^2, pressure values were scattered and saturated below 5 GPa. This saturation is attributed to the breakdown phenomena of water confining layer. P. Peyre and I Chaieb [12] reported that the saturated peak pressure increased with the decrease of laser pulse. In this paper, the saturated peak pressure was assumed to be 5 GPa. To investigate the effect of laser spot size on the residual stress distribution, different peak pressure with different laser spot diameter was applied on the top surface of pure Al. The peak pressure varied as 600 MPa (about 2 HEL), 1 GPa, 2 Gpa, 3 Gpa, 4

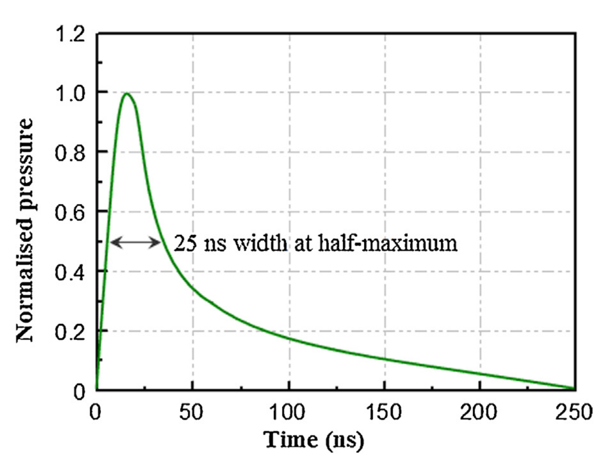

Fig. 3. Normalized pressure pulse induced by a 10 ns laser pulse used in ABAQUS.