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Numerical modeling of the confined laser shock peening of the OFHC copper

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A B S T R A C T

The confined laser shock peening is an innovative surface treatment technique designed to improve the structural integrity by imparting compressive residual stresses into materials. The plasma-induced shock wave pressure (∼GPa) is applied on the material surface within several tens of nanoseconds, which results in local plastic deformation at an extremely high strain rate and triggers the non-Arrhenius manner of dynamic flow stress due to strain rate sensitivity. A 3D finite element model, which incorporates a unified material model characterizing the Arrhenius and non-Arrhenius manners of flow stress and the temporal–spatial distribution of shock wave pressure, was developed to simulate the confined laser shock peening of the oxygen-free high conductivity (OFHC) copper. The modeling procedure consists of two successive explicit analysis steps: one for shock loading with a very small time increment and another for rebound analysis with a larger time increment. The performance of finite element model was examined by investigating the material model, bottom boundary conditions and analysis step time, and its effectiveness was verified by comparing the predicted dimple profile and micro hardness with the experimental data. With the validated finite element model, the interactive effects of laser power density and full width at half maximum (FWHM) of laser pulse was quantitatively investigated, which can be used to mentor the optimization of the process parameters of laser shock peening.

1. Introduction

The confined laser shock peening as an innovative surface treatment has been widely used in aerospace, mechanical and electrical industries [1]. Fig. 1 shows a typical schematic drawing of the confined laser shock peening [2], where the top surface of target is coated by an opaque absorbent film as sacrificial material and above which is a transparent overlay (usually water or glass). The laser beam passes through the transparent confining overlay and then irradiates on the bottom coating. The laser irradiation causes the opaque sacrificial material to be vaporized and ionized into the rapidly expanding high-pressure plasma which is confined by the surrounding transparent overlay. The sharp increase of pressure between the target surface and the transparent overlay induces two shock wave systems. One travels into the target and another goes into the transparent confining overlay. The intensity of shock wave traveling in the solid target is generally much larger than the dynamic yield stress of material. As a result, the local plastic deformation occurs and the expected compressive residual stresses are correspondingly attained. Compared to the direct ablation method, the confined plasma configuration allows a greater amount of impulse momentum to be transferred to the processed target [2], and is a pure mechanical treatment since the coating protects the target from thermal effects [3]. Furthermore, the confined laser shock peening can produce a deeper compressive residual stress field and a better preservation of surface roughness compared with the traditional surface treatments such as shot peening [4,5].

The plasma-induced shock wave pressure generated in the confined laser shock peening is the most fundamental external factor responsible for the impartation of compressive residual stresses into materials. The temporal distribution of shock wave pressure is relevant to the laser power density and the FWHM of laser pulse, and the spatial distribution directly relates to the laser spot size [6–8]. The laser pulse can be monitored with a fast photodiode and the resultant shock wave pressure can be measured by an x-cut quartz gauge system [3]. The measured shock wave pressure has a retarded peak relative to the laser pulse. The peak pressure increases with the laser power density if it does not exceed the threshold, otherwise a saturated peak pressure was observed [9]. The threshold of laser power density is the result of dielectric breakdown of the confining medium [6]. Moreover, the breakdown also makes the FWHM of pressure pulse decrease with the increase of laser power density [1]. The FWHM of pressure pulse is typically 2–3 times of the FWHM of laser pulse [3]. Due to

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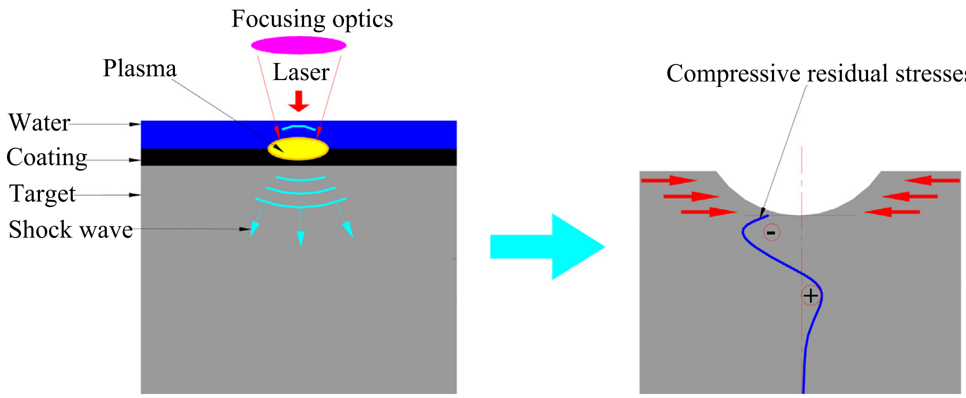

Fig. 1. Schematic drawing of the confined laser shock peening.

the adiabatic cooling of the confined plasma, the damping profile of shock wave pressure has a longer tail than laser pulse. The spatial distribution of laser power density within the laser spot depends on the laser spot size. For a smaller laser spot, its distribution approximately follows the Gaussian [10] or spherical distribution [11]. However, for a larger laser spot, the laser power density keeps a nearly constant value at the spot center and reaches to the maximum nearby the spot edge [1,6]. The heterogeneity of laser power density can be attributed to the diffraction effect of laser beam. Based on the assumption that the shock wave pressure has the same spatial distribution as the laser power density, the analytical pressure models following Gaussian [10], spherical [11] or uniform distribution [12] were developed for the numerical simulation of the confined laser shock peening. Moreover, a spherical wave front of shock pressure was observed in the case of smaller laser spots, while a plane wave front was obtained for the larger ones [13,14].

The local plastic strain rate can reach an extremely high level of $\sim 10^7\ s^{-1}$ since the plasma-induced shock wave pressure (~GPa) is applied to the shocked surface within several tens of nanoseconds. Experimental studies [14–16] indicate that the dislocation density and the microstructure within the regions affected by the laser shock peening are different from those obtained by the conventional shot peening with a strain rate of $\sim 10^3\ s^{-1}$. The special microstructure induced by the confined laser shock peening causes a much stronger strain rate hardening of flow stress. It has been found that the flow stress increases slowly in an Arrhenius manner at low strain rate but turns upward sharply beyond a certain strain rate range of $\sim 10^4 s^{-1}$ [17]. The onset of the non-Arrhenius response of flow stress with strain rate relates to the micro-mechanical mechanism such as thermo-activated dislocation glide and phonon drag. Therefore, the conventional phenomenological models, such as the elastic–perfectly plastic model with Hugoniot elastic limit [3,12,18], Johnson–Cook model [8,19,20] and Khan–Huang–Liang model [21,22], are not capable of reproducing the non-Arrhenius response of flow stress due to the absence of physical basis. Based on the theory of mobile dislocation density evolution and thermal-activation rate-control analysis, Gao and Zhang [23] proposed a unified model of flow stress to characterize both the Arrhenius and non-Arrhenius manners of flow stress. The unified model can describe the dynamic plasticity under a broad range of strain rate from very low ($\sim 10^{-4}\ s^{-1}$) to extremely high ($\sim 10^9\ s^{-1}$). It is obvious that the unified model exactly covers the strain rate induced by the confined laser shock peening.

By cooperating with the shock wave pressure models and the phenomenological material models mentioned above, a number of finite element models have been developed to simulate the confined laser shock peening. One type of these methods carries out the finite element simulation only by the explicit time integration [11,24], and another adopts the one way explicit-to-implicit co-simulation approach [25,26]. The explicit-only simulation approach has two analysis steps: the first is used for shock loading with very small time increment and the second is used for rebound analysis with larger time increment. For the explicit-to-implicit co-simulation approach, the explicit computation is carried out first and the obtained transient results are then transferred into implicit code for rebound analysis. The difference between these two types of simulation approaches lies in clearly the strategy of rebound analysis. Finite element simulation can not only obtain the resultant residual compressive stresses and dimple profiles, but also provide further insight into the propagation and attenuation of the shock wave [27–29]. The effects of laser power density, FWHM of laser pulse and spot size on the laser shock peening were studied by using different temporal–spatial shock pressure distributions [8,30–33]. Moreover, the effects of elevated temperature in laser shock induced high strain rate deformation of copper were systematically studied by finite element simulation [34]. However, it should be noted that the finite element model incorporating Arrhenius and non-Arrhenius manners of flow stress has not been developed for the simulation of laser shock peening.

This paper intends to develop a 3D finite element model for simulating the confined laser shock peening of the OFHC copper. To consider the extremely high strain rate sensitivity of dynamic flow stress, a unified material model characterizing the Arrhenius and non-Arrhenius manners of flow stress was implemented in the user material subroutine of Abaqus/Explicit. The present finite element model was then verified by comparing the predicted dimple profile and micro hardness with the experimental data. In order to mentor the optimization of the laser power density and the FWHM of laser pulse based on finite element simulation, the interactive effects of these two process parameters on residual stresses and dimple morphology were investigated in detail.

2. Modeling of the confined laser shock peening

2.1. Loading model

The typical profiles of laser pulse and plasma-induced pressure pulse [3] are given in Fig. 2. The pressure pulse has retarded peak and longer duration relative to the laser pulse. In addition, the distribution of shock wave pressure within the scope of laser spot is non-uniformed due to the uneven distribution of the laser power intensity [1,6,10]. Therefore, the analytical model of laser shock pressure should characterize reasonably both the temporal distribution in the pulse duration and the non-uniformed spatial distribution within the laser spot.