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Investigation on residual stress distribution in thin plate subjected to two sided laser shock processing

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HIGHLIGHTS

- Stress waves propagation induced by two sided laser shot peening (TSLSP) is detailed.
- Compressive residual stresses (CRS) are induced in whole thickness of treated region.
- Tensile residual stresses (TRS) are found in surrounding region distributed with CRS.
- RS distribution in the plate is closely related to the applied parameters in TSLSP.

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ABSTRACT

Two sided laser shock processing (TSLSP) has been an innovative process to impart the favorable compressive residual stresses into thin components without producing excessively detrimental deformation. In this paper, the investigations focus on the residual stresses distribution in the 7075-T7351 alloy plate with thickness of 2 mm, whose both side surfaces are subjected to shock waves with peak pressure 2 GPa induced by laser with duration 24 ns. The dynamic propagation and attenuation process of stress waves in thickness direction of the plate is also investigated, and the critical factors on residual stresses field are further discussed. The results reveal that the whole thickness section between the irradiated areas is distributed with the compressive residual stresses, while the surrounding of the region distributed with compressive residual stresses is accompanied by the tensile residual stresses. The distribution characteristic of residual stresses in the processed plate is closely related to the exact values of the applied parameters in TSLSP treatment.

1. Introduction

Laser shock processing (LSP) can squeeze the compressive residual stresses into surface layer of metallic components by means of interaction between the laser-induced shock waves and the metallic material. It has been proposed as a promising surface modification technique to improve the fatigue durability, wear resistance, corrosion resistance and other mechanical properties of the processed components effectively [1–4]. Over the past several decades, lots of investigations have been conducted to get insight into the mechanisms of LSP, the characteristics of the induced residual stresses field and its practical application [5–8]. These investigations all illustrate that when the high pressure shock waves are applied onto the surface of thick-section components, they can give rise to the permanent shallow dent located at the impacted location, so the beneficial compressive residual stresses can be generated in the surface layer. However, if the shock waves are imposed on one-sided surface of the thin-section target, they will lead to redundantly undesirable plastic deformation, even fracture [9,10], which is on account of the unbalanced force produced by laser. In order to prevent the undesired side effects brought by one-sided LSP treatment on thin-section targets, such as the gas turbine engine compressor blade, two sided laser shock processing (TSLSP) has been proposed, which employs two same laser pulses to irradiate onto the opposing surfaces of the target simultaneously. The laser-induced stress waves pressure launched from one side of the target counteracts that from the opposite side, thus excessively unfavorable deformation in thin targets can be effectively prevented. Up to present, a few efforts have been devoted to investigate characteristics of the residual stresses field

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induced by TSLSP, which are mainly involved in establishing the finite element model to simulate the characteristics of residual stresses field [10,11]. Zhang et al. investigate the residual stresses field in metallic plates induced by TSLSP through numerical simulation and experiment [12], and the results demonstrate that the compressive residual stresses are generated on both the impacted surfaces and the mid-plane region in thin-section plates, while that only distributed in the surface layer of targets with thick section. Hu et al. employ the numerical calculation and experiment to analyze the residual stress and geometry distortion of metal foil with the alternate double-sided laser peening [13]. However, these above mentioned researches have scarcely referred to the interaction process of two head-on stress waves launched from each side surface of target respectively. The generation process of residual stresses in thickness direction is still unclear in TSLSP treatment, and the residual stresses distribution also needs to be further explored. Therefore, the residual stresses distribution of thin metal plates subjected to TSLSP is still worthy of research.

The goal of present work was to disclose the characteristic of the residual stresses distribution in thin-section components subjected to higher pressure shock waves in TSLSP, which was the extension of previous investigation conducted by Zhang et al. [12]. The test target was the 7075-T7351 aluminum alloy plate with thickness of 2 mm. The three-dimensional finite element model was established by means of the commercial code ABAQUS [14] to simulate the propagation process of two head-on stress waves and their interaction. The residual stresses field in the aluminum alloy plate after TSLSP treatment was investigated. The corresponding experiments were carried out to compare with the simulated results to verify the developed numerical model. Based on the validated model, the effects of laser pulse duration and target thickness on the residual stresses field were further discussed.

2. Mechanism of TSLSP

The pictorial representation of TSLSP is depicted in Fig. 1. A short-duration (several tens nanoseconds) and high-power (GW/cm^2 level) laser pulse is first emitted from the laser, and is then split by the beam splitter into two identical branch pulses. Each branch subsequently penetrates the transparent confining layer, and then irradiates vertically onto surface of each absorbing layer coated on each side surface of the target. The laser energy is absorbed by absorbing layer, and the material in the irradiated region is immediately vaporized into plasma with high pressure and high temperature. Then, the exceedingly rapid expansion of the high plasma brings about a pressure pulse on each target surface, and induces material particle perturbation to produce stress waves propagating into target material. If the peak value of the generated pressure pulse is high enough, the induced stress waves are elastic-plastic ones. Therefore, the material yields plastic yielding after these stress waves passing through, and the plastic strains are accompanied by the generation of compressive residual stresses. The formation of plastic strains induced by stress waves continues until its peak pressure decreases below the dynamic yield strength of target material. Subsequently, only the elastic stress waves remain, which no longer produce the plastic deformation or modify the residual stresses field within the material. In above-mentioned confined ablation model, the absorbing layer shields the target surface from laser thermal effects to help in creating a pure mechanical effect in the material, and the confining layer is used to delay the generated high pressure plasma diffusion and to extend its impact time.

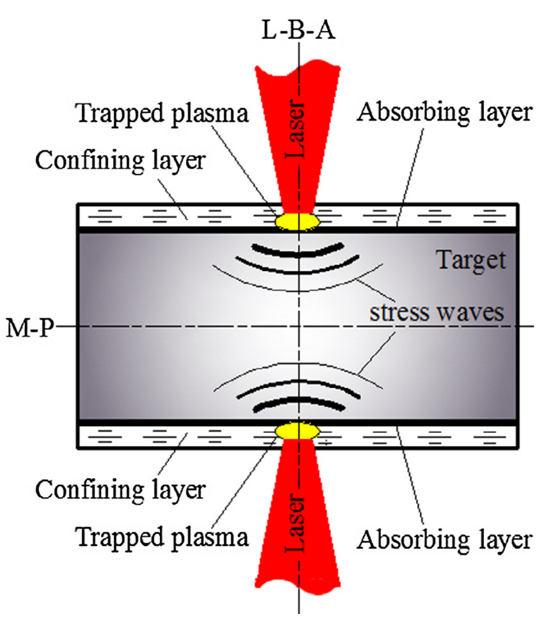

Fig. 1. Schematic of TSLSP (L-B-A represents the laser beam axis, and M-P denotes the mid-plane).

3. Numerical simulation

3.1. Finite element model

The commercial finite element software ABAQUS, consisting of explicit and standard analysis algorithms package, was applied to simulate characteristics of residual stresses field in the metallic plate impacted by TSLSP, which had been validated as an effective tool for determining the residual stress induced by LSP [2,11,15]. The entire simulation process contained two successive steps, namely dynamic analysis step and static analysis step. The dynamic analysis step was performed with the ABAQUS/Explicit code to investigate the dynamic response of material impacted by laser, and the subsequent static analysis step was accomplished with the ABAQUS/Standard code to release the stored elastic strain energy in the material generated by the high-speed dynamic deformation process and to determine the residual stresses field with state of static equilibrium. Here, the dynamic solution time and static solution time were set to 15,000 ns and 0.1 s respectively to ensure calculation accuracy during the simulation process.

Both the applied geometrical model and the uniform pressure pulse were symmetric, thus only a quarter of the model was established to conduct the simulated calculation rather than a entire one to improve the computational efficiency. The schematic illustration of the model containing boundary constraint conditions was illustrated in Fig. 2. The target size of length × width × height was 15 mm × 15 mm × 2 mm. For the sake of obtaining accurate results, it was essential to employ appropriate mesh density to acquire mechanical effects induced by laser shock. The adopted element type was C3D8R. The impacted surface on

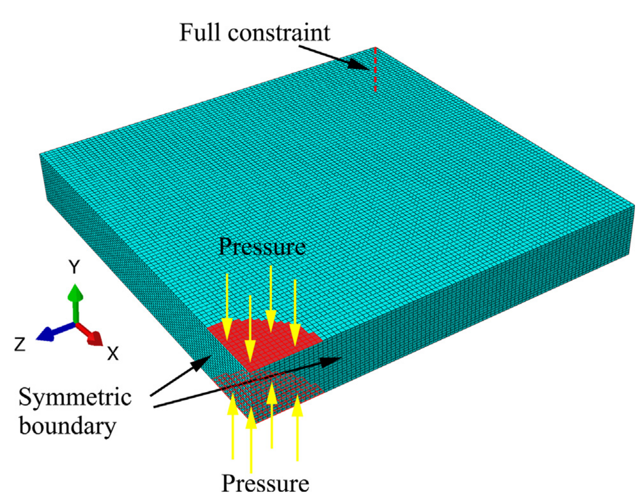

Fig. 2. Schematic of three-dimensional quarter model for TSLSP.