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Numerical simulation of residual stress field induced by laser shock processing with square spot

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Abstract Laser shock processing (LSP), also known as laser peening, is a novel surface treatment technique in the past few years. Compressive residual stresses which imparted by LSP are very important for improving fatigue, corrosion and wear resistance of metals. Finite element analysis (FEA) simulation using ABAQUS software has been applied to predict residual stresses induced by LSP on Ti-6Al-4V titanium alloy with laser pulse duration 30 ns and water confined ablation mode. The residual stress field generated by different shape laser spots was studied, and the square laser spot is shown the most suitability for avoiding stress lack phenomenon and overlapping LSP. Surface residual stresses and plastically affected depth within single square spot both increased with the increase of laser intensity and laser shock times. Furthermore, compared with circle and ellipse spot, the residual stress distribution in overlapping square spots is very uniform only with small overlapping ratio. LSP with square spot can process advantageous residual stress field, and this technique will be used widely.

Keywords laser shock processing, square spot, Ti-6Al-4V, residual stress

Introduction

As a novel surface treatment technique, laser shock processing was widely applied to improve the resistance of metal surface against fatigue, wear or corrosion. The most valuable industrial application is that the treatments of fan blades sharp edges against foreign object damage. Compared with common treatments such as shot peening, deeper residual stress levels and lower cold work amplitudes are obtained after laser shock processing (LSP) treatment[1–3].

During an LSP process, a high intensity (more than 1 GW/cm^2) laser pulse vaporizes an ablative layer, and produces a high pressure caused by rapid expanding plasma. The high increasing pressure induces shock wave that can cause plastic deformation and compressive stresses at shocked zone.

Compressive residual stresses which distributed in the LSP treated area can restrain initiation and propagation of the fatigue crack. Therefore, the study of residual stress field on treated surface by LSP is significant. The residual stress field induced by the circle laser spot has been detailedly studied in the past, but few open literature investigated the residual stress field with square laser spot. Finite element analysis method was suitable to predict residual stress field in LSP accompanying highly nonlinear plastic deformation[4].

1 Finite element model and procedure

The commercial finite element analysis (FEA) software ABAQUS was used to compute the residual compressive stress distribution of the impacted metal during and after shock wave. The area that one laser pulse fired on metal surface was a square spot of 4 mm side. Two three-dimension models are considered to simulate the LSP process. To assure computational efficiency, the quarter and half of actual configuration instead of the full one for single and overlapping LSP process respectively.

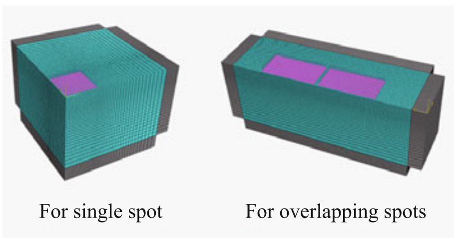

Fig.1 Three-dimensional FEM for simulation LSP

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The FEA models of LSP are shown in Fig.1. The finite element C3D8R was applied in and around the loading areas for analyzing elastic-plastic deformation. The infinite element CIN3D8 contacting with finite element was applied as non-reflecting boundaries. In this paper, all the simulation results were researched at semi-infinite bulk of materials.

Nd: glass laser system produces intensive pulse laser with wavelength 1 064 nm, duration 30 ns and near uniform energy distribution spatially. Take into account the aluminum ablative layer (1.6×10^6 g/(cm^2·s)) and water confined layer (0.165×10^6 g/(cm^2·s)), fits experimental results for a value of α=0.3 at 1 064 μm wavelength laser[5]. The shock wave pressure was estimated by the simplified Fabbro's model as follow:

$$P_{\max} = 5.47\sqrt{\frac{\alpha}{2\alpha+3}}\sqrt{I_0},$$

where I_0 is the laser intensity, α the ratio between the energy devoted to the pressure rise and the total incident energy.

In water confined mode, the pressure pulse width is approximately two times than laser pulse width[6], and Fig.2 shows temporal distributions of shock pressure with relative amplitude. Additional, the uniform distribution of shock pressure in spatially was hypothesized.

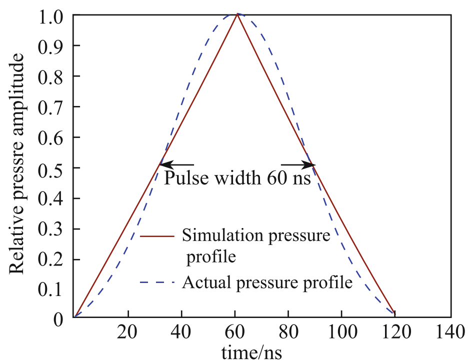

Fig.2 Temporal distribution of shock pressure

Laser-induced shock wave deforms materials at very high strain rate approaching 10^6 s^{-1}. Under such severe loading conditions, materials behave significantly their different mechanical behaviors. To accurate predict the stress-field, both dynamic yield stress and effect of strain rate are considered[7]. Therefore, the material plastic properties are defined by the Johnson-Cook model[8]. Because thermal effects in LSP process can be ignored, a simplified Johnson-Cook model is given by

$$\sigma = (A + B\bar{\varepsilon}^n)(1 + C\ln\dot{\bar{\varepsilon}}^*),$$

where $\dot{\bar{\varepsilon}}^* = \frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}$ is the dimensionless strain rate for $\dot{\bar{\varepsilon}}_0=10^{-2}$ s^{-1}; A, B, C, n and m are the parameter of material constants.

2 Simulation result of LSP

2.1 Shock wave loading

Figure 3 illustrates the elastic and plastic shock wave propagating and attenuating in depth direction at center of impacted area (with 4 GPa peak pressure). When magnitude of shock wave pressure is sufficient to exceed the hugoniot elastic limit (HEL) of the metal, the axial stresses deform the material under the spot, and this material wants to expand radially, however is constrained by the surrounding material. During material deformation step, the axial stress and radial stress follow the Von Misses criterion as below:

$$\sigma_x = \sigma_y = \sigma_z - Ys.$$

The x-y plane is the metal surface, and z direction is perpendicular to the x-y plane. The plastic loading step ended when the peak of shock wave decreases below HEL (t=270 ns). This depth is so-called affected depth in LSP. At peak pressures below the HEL (2.8 GPa), only elastic strain generates.

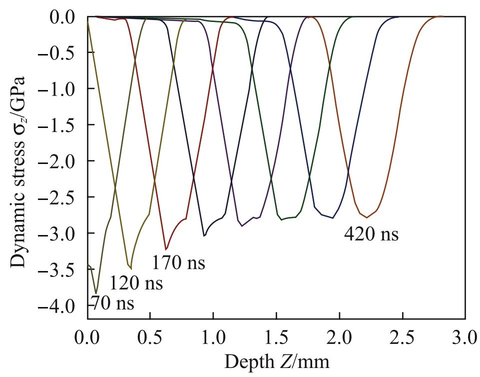

Fig.3 Shock wave attenuation in depth

2.2 Effect of laser spot shape

After shock waves have dispersed, the compressive residual stresses are remained. Figure 4 shows that the surface residual stress distribution impacted by different spot (circle, ellipse and square) along the path from spot center outward to untreated area. A large grade stress lack emerged at the center of circular impacted area. Inversely, it was normal stress distribution using elliptic and square laser spot. While it is often uniaxial strain during shock wave loading, non-uniaxial strains mainly affects the ultimate residual stress field. After shock wave loading, the surface wave generated at the edge of impacted area, as these radial waves propagate radially inward and focus simultaneously, and a large tensile pulse is generated which may eliminate the compressive residual stress near the center of spot[9]. In order to avoid this defect, the circular symmetry must be eliminated. Although, Elliptic and square spots are not sensitive to the surface wave focusing effect, do exist some degradation in the residual stress field as the laser intensity increases.

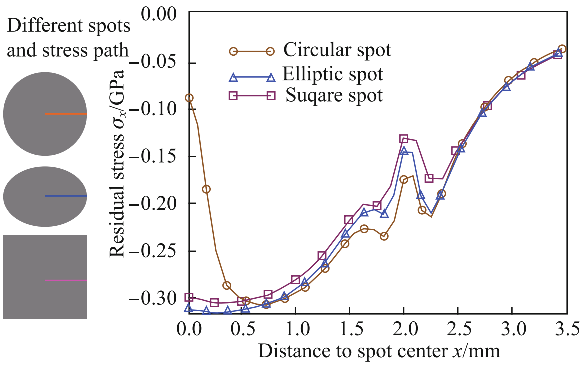

Fig.4 Surface RS distribution of three different shape laser spots

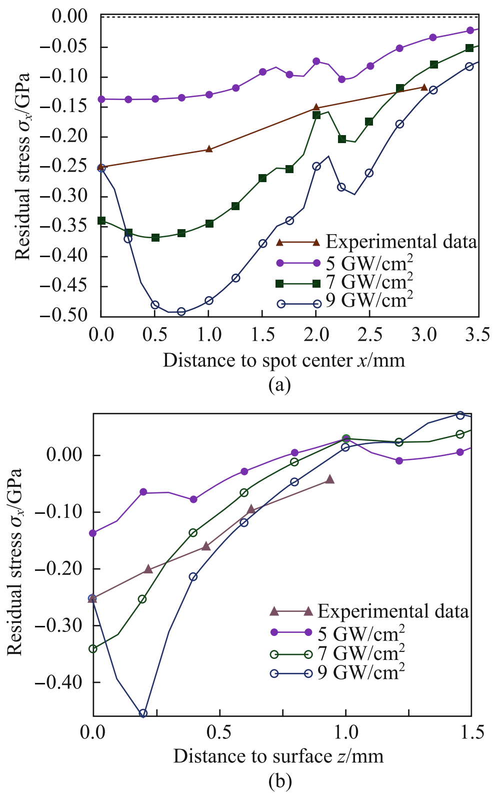

Fig.5 Residual stress distribution with different laser intensity (a) surface RS (b) RS in depth

2.3 Effect of laser intensity

In LSP process, laser intensity is obviously a very significant parameter to optimize for generating residual stress fields. Using square laser spot, the simulation results under 5 GW/cm^2, 7 GW/cm^2 and 9 GW/cm^2 respectively are shown in Fig.5. With the laser intensity increasing, the surface residual stress and affected depth both increase at the same time, and the stress lack phenomenon become badly. As the preliminary conclusion, the stress lack occurred when the shock wave pressure is up to 4 GPa. The experimental data was obtained with 4 mm square laser spot at laser intensity 6.23 GW/cm^2. The residual stress was measured by XRD method. In addition, the electro-erosion process removed material layer by layer for stress distribution in depth. The experimental and analytical data has a good coincidence with magnitude of the surface residual stress. However, the analysis tends to underestimate the residual stress in depth. The maximal residual stress is located the subsurface due to excessive laser intensity such as above 9 GW/cm^2.

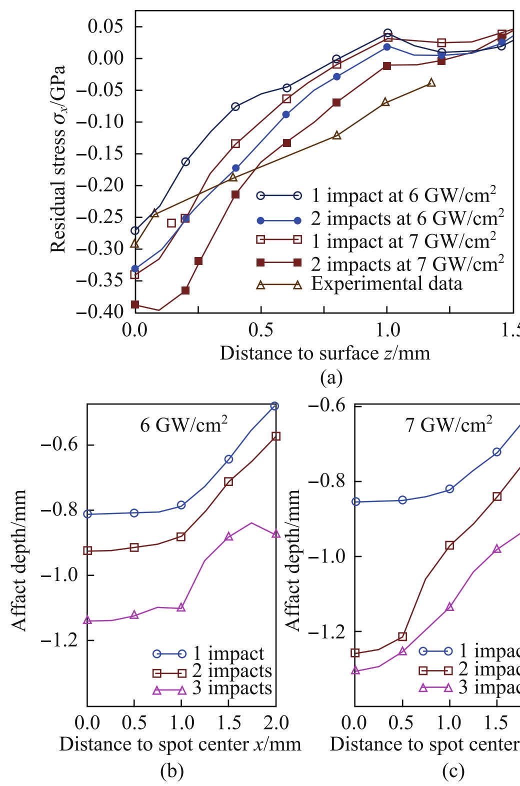

Fig.6 Effect of shock times (a) RS distribution in depth (b), (c) RS affected depth along surface

2.4 Effect of repeated shock times

Laser intensity and shock times must be very well matched each other for peening different thickness parts. Figure 6(a) shows the simulation results of different laser intensity and repeated shock times with square laser spot. As most experimental investigations published, the same trend that an increase of the shock times could increase affected depths was gained. This phenomenon may result from a purely elastic propagation of shock waves in the prestressed layers driving to a smaller attenuation depth. Maximum surface stress also increases with increasing shock times. On the side, two impacts at low laser intensity (6 GW/cm^2) can obtain similar surface residual stress level and affected depth induced by higher low laser power intensity (7 GW/cm^2) with single impact.

Repeated impacting LSP with low laser intensity is suitably applied to strengthening fans blade with thickness below 1 mm, and can effectively avoid spallation phenomenon at back surface of blade. The experimental data is obtained with two impacts at laser intensity 6.23 GW/cm^2. As is shown in Fig.6(b), residual stress affected depths also increase with the laser shock times increasing while tended to reduce with the increasing of distance to spot center. For low laser intensity (6 GW/cm^2), the second impact gets less change than the third impact, but as high laser intensity (7 GW/cm^2), the second impact got more change than the second impact.

2.5 Effect of overlapping ratio

Many laser spots overlapping one by one could generate a large strengthening area. The later impact could make redistribute stress field in prior impacted area. A suitable overlap ratio could obtain a more uniform residual compressive stress field. To avoid the untreated area distributed tensile stress, and the overlap ratio should be more than 20% with circular laser spot. Howaver square laser spot only need very small overlap ratio. The residual stress field is shown in Fig.7 with two conterminous 7 GW/cm^2 square laser spots (without overlapping). The surface residual stress near the overlapping area is steady between −350 MPa and −400 MPa. The overlapping spots enhanced the affected depth at spot edge comparing with one of single spot.

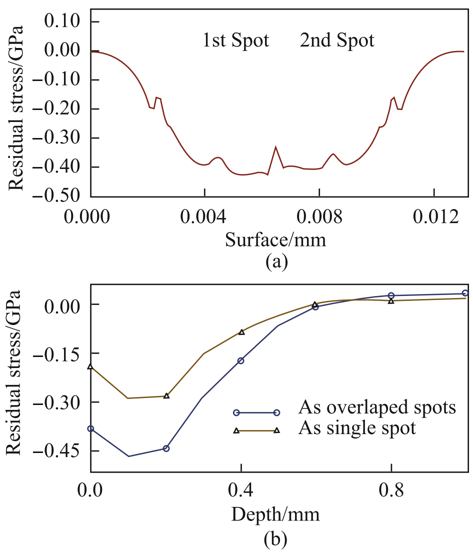

Fig.7 RS distribution in depth at overlapping area

3 Conclusions

As a result the following conclusions were reached:

Square laser spot used in LSP can get more beneficial residual stress distribution than circular laser spot.

With laser intensity or laser shock times increasing, the surface residual stress and affected depth was increased. The stress phenomenon emerged when the shock wave pressure up to 4 GPa, and became heavier after repeated impacts.

Square-spot LSP could get uniform residual compressive stresses with very small overlapping ratio below 5%. At overlapping area, the residual compressive stresses increased and were close to the magnitude of spot center.

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