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STUDY ON 2-D SHOCK WAVE PRESSURE MODEL IN MICRO SCALE LASER SHOCK PEENING

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Abstract: Laser-induced shock pressure in micro scale laser shock peening (μLSP) is the key to numerically analyze the strengthening effect of the targets. In order to establish the model of shock wave pressure loading in μLSP process, a reasonable simplification was conducted according to the shock wave propagation theory. 2-D pressure distribution along the radial and axial direction at different time was modeled based on theory of ellipsoidal wave propagation, comprehensively considering properties of shock wave propagation in time and spatial distribution and geometric features of ellipse. Numerical simulations of μLSP with single point under 1-D and 2-D pressure loading were carried out to investigate the influence of loading in radial direction on residual stress distribution. The results showed that residual stress distribution under 2-D pressure loading was obviously different from the 1-D case, so effect of pressure in radial direction during the propagation of shock wave should not be ignored in μLSP process. 2-D shock wave pressure model lays a theoretical basis for accurate loading of shock wave pressure in the simulation of μLSP.

1. INTRODUCTION

Laser shock peening (LSP) has been the most effective and widely used method of introducing compressive residual stresses into the surface of metals to improve fatigue performance since 1960s [1-3]. The previous researches were focused on the treatment of macro-components with laser beam diameter at the order of millimeter. Laser shock wave pressure model was theoretically studied by R. Fabbro [4], in which 1-D spatial uniform wave model based on the assumption that shock wave propagates in one direction was proposed. Micro laser shock peening (μLSP with laser beam diameter at the order of micron can modify surface properties and enhance the fatigue life of micro scale components. However, the laser beam size in μLSP is the same order of the energy ablative layer thickness, propagation of shock wave induced by μLSP has great difference with LSP in many aspects. As a preliminary study, Yao et al. [5] presented an improved 1-D pressure model for μLSP process based on laser-supported combustion wave theory, and non-uniform distribution in radial direction was considered in spatial expansion effects, but the model didn't take into account the effect of pressure in radial direction and was difficult to solve. In fact, significant difference between LSP and μLSP is size effect. Since the diameter adopted in μLSP is at the order of micron equal to the thickness of energy ablative layer, shock waves propagate along both radial and axial directions, so 1-D pressure model is no more applicable, effect of pressure in axial and radial directions on micro plastic deformation must be considered in the model of μLSP.

In this paper, 2-D shock pressure distribution was investigated based on theory of ellipsoidal wave propagation. Comprehensively considering properties of shock wave propagation in time and spatial

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distribution and geometric features of ellipse, spatial pressure distribution in radial direction at different time was derived, and 2-D pressure loading was modeled. In order to investigate the influence of the loading in radial direction on residual stress distribution, simulations of μLSP with single point under 1-D and 2-D pressure loadings were conducted respectively and the results were compared.

2. 1-D PRESSURE MODEL

The spatially uniform shock pressure *P(t)* relates to the spatially non-uniform shock pressure as [5]

$$P(r,t) = P(t)\exp\left(-\frac{r^2}{2R_0^2}\right), \quad (1)$$

where r is the radial distance from the center of the laser beam, and R_0 is radius of laser beam. $P(t)$ is pressure at centre of laser beam at time t. $P(r,t)$ can be solved numerically from the above equations. The values of $P(r,t)$ are then used as dynamic load in the stress analysis.

The improved shock pressure model took into account the radius of shock wave changing with time as follows [6]

$$\begin{aligned}
&t < T_r, && P = P_{1D}, \; R = R_0, \\
&T_z \ge t \ge T_r, && P = P_{1D}\left(t/T_r\right)^{-4,5}, \; R = R_0\left(t/T_r\right)^{1/2}, \\
&t \ge T_z, && P = P_{1D}\left(t_r/T_z\right)^{4/5}\left(T_z/t\right)^{6/5}, \; R = R_0\left(T_z/T_r\right)^{1/2}\left(T_z/t\right)^{-4/5},
\end{aligned} \quad (2)$$

where P_{1D} is the plasma pressure from 1-D model described above, T_r is the time that rarefaction wave propagates into the plasma from the edge at the sound speed of the plasma, therefore $T_r = R_0/a$, where R_0 is radius of laser beam and a is the sound of speed. Axial relaxation starts after the laser pulse terminates, thus the characteristic time for axial expansion is $T_z = T_p$, where T_p is pulse duration.

3. CHARACTERISTIC OF SHOCK WAVE PROPAGATION IN WATER

Plasma shock wave induced by laser in air is created by the external expansion of plasma with high temperature and pressure and propagates as Taylor model. When the interaction between high power laser and energy ablative layer under constraint of water during μLSP process, laser induced plasma

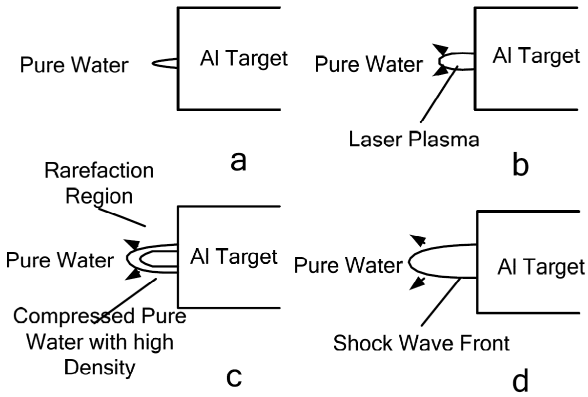


Fig. 1. Formation course of shock wave in water, courtesy of Dr. X. Chen.

shock wave is produced. Fig. 1 shows formation course of shock wave in water [7]. Self-focusing of laser is easier caused in water than air, especially impurity in focusing area makes the breakdown threshold of liquid greatly decreased, which induces elongate of plasma shock wave along the direction laser incidents at primary, with the larger energy and the shorter pulse duration the more significant trend.

For the μLSP process, ellipsoidal wave theory [7] was proposed to describe propagation of plasma shock wave in water, which assumed that propagation law of wave front along short axis submits to Formula (3), considering propagation of shock wave is in the same direction with shock wave velocity along short axis $\bar{R}$.

$$b(t) = M_0 c_0 t\left[1 - \left(1 - \frac{1}{M_0}\right)\exp\left[-\left(\frac{b_0}{c_0 t}\right)^n\right]\right] + b_0, \quad (3)$$

where b_0 is initial radius along short axis of ellipsoidal wave, M_0 is the maximum Mach number along short axis, c_o is sound speed in water.

4. 2-D SHOCK PRESSURE MODEL

According to characteristics of propagation of shock wave, ellipsoid-based model of shock wave pressure can be analyzed as follows. Any point (*x,y,z*) on the ellipsoid surface as shown in Fig. 2 can be projected onto the 2-D plane. From the geometric features of ellipse shown in Fig .3, we can get the relations (4)

$$\left.\begin{aligned}
&\frac{z^2}{a^2} + \frac{r^2}{b^2} = 1, \quad a^2 - b^2 = c^2 \\
&z' = -\frac{a^2 r}{b^2 z}
\end{aligned}\right., \quad 0 \le r \le b(t), \quad (4)$$

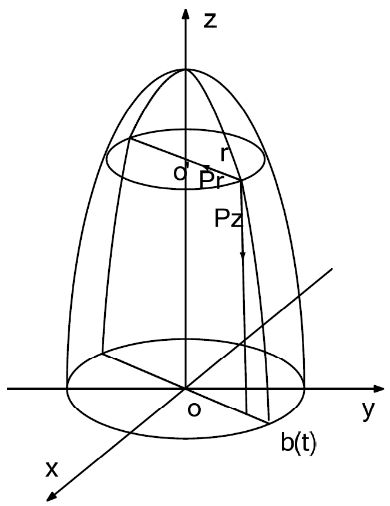


Fig. 2. Ellipsoidal wave model at time *t.*

where *a* and *b* are function of time, *b* is radius of wave front along short axis and expressed by Formula (3), *a* is radius of wave front along long axis.

For any point

$$\left(r, \frac{a\sqrt{b^2 - r^2}}{b} \right),$$

we have

$$K(t,r) = \frac{P_r}{P_z} = \frac{ar}{b\sqrt{b^2 - r^2}}, \tag{5}$$

where P_r is pressure in radial direction and P_z is pressure in axial direction, *K (t,r)* is P_r/P_z ratio of any point of wave front. According to ref. [7] when the propagation time of shock wave is 18 ns (a = 213 um, b = 81 um), *K(r)* can be derived

$$K(r) = \frac{2.63r}{\sqrt{81^2 - r^2}}. \tag{6}$$

This expression can be numerically shown as Fig. 4, it can be seen that effect of pressure in radial

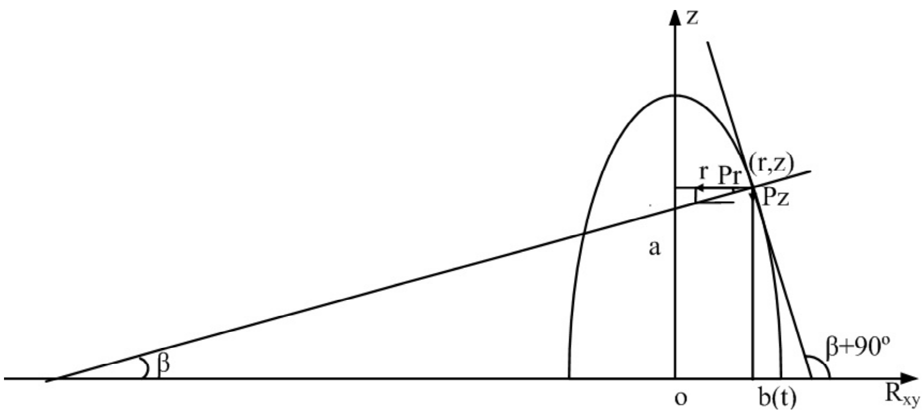


Fig. 3. Section of ellipsoidal wave across *Z* axis.

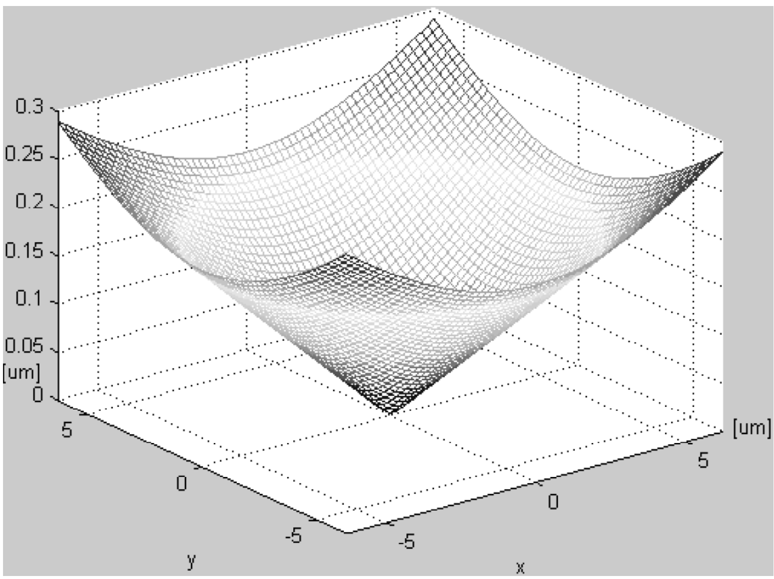


Fig. 4. Spatial distribution of *K(r)* at 18 ns.

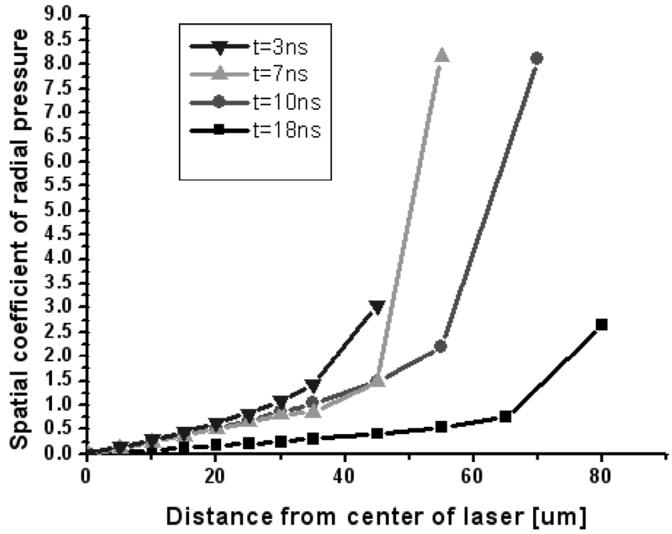


Fig. 5. Changes of *K(r)* along radial direction at different time.

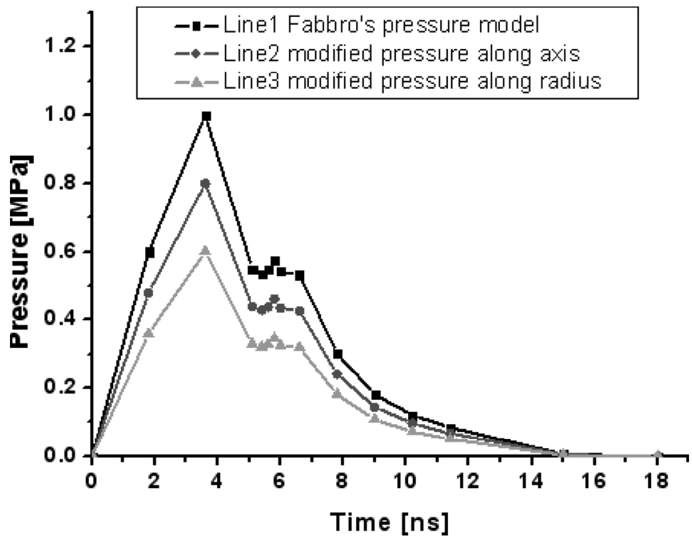


Fig. 6. Pressure loading curve of shock wave.

direction is zero at the centre of laser beam and increases with the increase of distance to the centre of laser beam. Fig. 5 shows different changes of *K(r)* along radial direction at time 3 ns, 7 ns, 10 ns, and 18 ns, respectively, it is clear that effects of pressure in radial direction increase with propagation of wave front.

Assuming that spatial pressure distribution along long axis obeys Gaussian distribution [6], then P_r can be derived

$$P_r = K(t,r)P(t)\exp\left(-\frac{r^2}{2R^2(t)}\right). \quad (7)$$

For the μLSP process, 2-D pressure model must be modified as

$$P_z' = BP_z,\ \ P_r' = AP_r, \quad (8)$$

where

$$A = \frac{ar}{\sqrt{a^2r^2 + b^2\left(b^2 - r^2\right)}},$$

$$B = \frac{b\sqrt{b^2 - r^2}}{\sqrt{a^2r^2 + b^2\left(b^2 - r^2\right)}}.$$

Fig. 6 shows pressure loading curves of shock wave, line 1 represents Fabbro's 1-D pressure model, line 2 and 3 are the modified pressure curve along axial and radial direction respectively, where A = 0.8, B = 0.6.

Spatial distribution of P_z at 18 ns was obtained (shown in Fig. 7) according to Ref. [7], it is shown that the pressure reaches maximum value at the

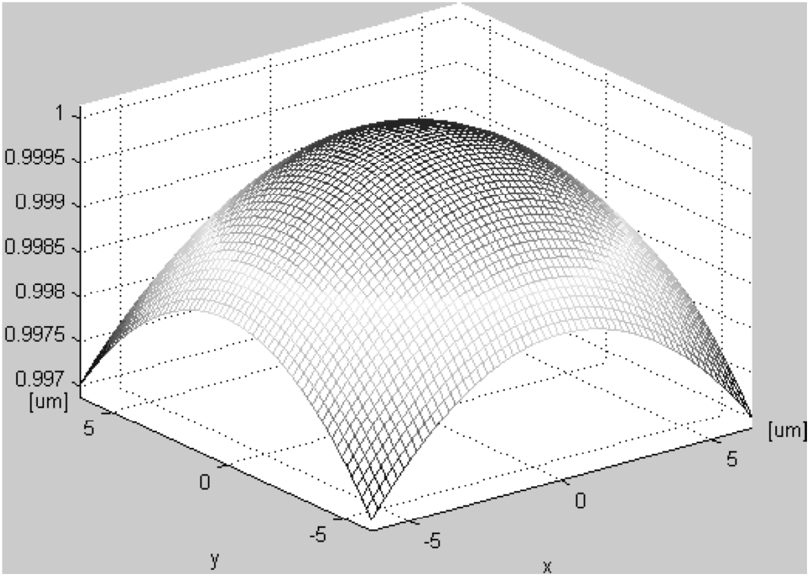


Fig. 7. Spatial distribution of shock wave along axial direction.

centre of laser beam and decreases with the increase of distance to the centre of laser beam.

Spatial distribution of P_r can be defined by the introduction of coefficient *D(t,r)*

$$D(t,r) = K(t,r)\exp\left(-\frac{r^2}{2R^2(t)}\right), \tag{9}$$

where $D(t,r)$ is function of time and radius.

Spatial distribution of P_r at 3 ns, 10 ns, and 18 ns are shown in Fig. 8 respectively, it can be seen that there is no effect of P_r at the centre of laser beam, it increases with increment of distance to the centre of laser beam and decreases with propagation of shock wave at the same action region.

According to the different spatial distribution of P_r, *D(t,r)* can be expressed as

$$D(t,r) = A(t) + B(t)\exp\big(C(t) * R(t)\big), \tag{10}$$

where *A(t)*, *B(t)* and *C(t)* are function of time shown in Table 1, respectively, *R(t)* is propagation distance of ellipsoidal wave front along radial direction at time *t*.

Table 1. Coefficient of *D (t, r)* at different time.

Time (ns)	*A*	*B*	*C*
3	-0.280	0.350	0.042
10	0.238	0.046	0.066
18	0.130	0.004	0.084

5. SIMULATION BASED ON 2-D PRESSURE MODEL

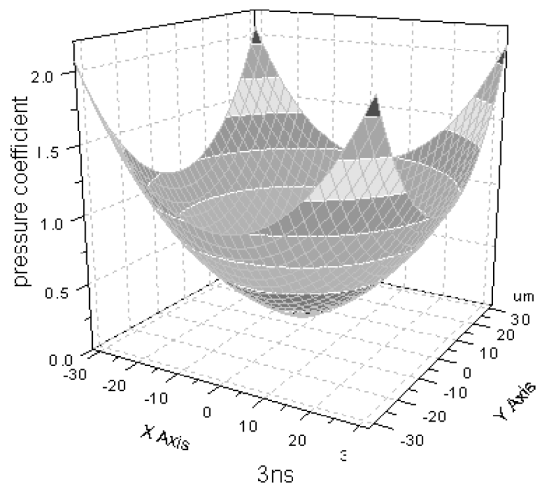
5.1. Establishment of finite element model

Pure copper sample with size 1×1×0.3 mm^3 was chosen in the simulation, laser beam diameter was 100 μm, and laser energy was 1 mJ. In the following stress analysis, strain rate and rate effect on yield strength were considered while temperature was taken as room temperature, material was assumed as isotropic and homogeneous and obeyed Von Mises' yield criterion, C3D8R element was selected for the high strain rates (10^6 s^{-1}). Shock pressure model was determined by formula (8). To compare pressure loading influence on residual stress distribution, simulations with 1-D and 2-D pressure model were conducted, respectively.

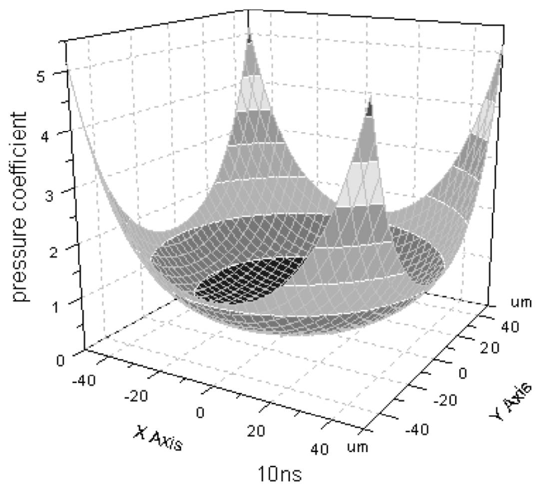
5.2. Results and discussion

Distributions of residual stress S_{11} for a single shock peening under different pressure loading are shown in Fig. 9. As seen that compressive residual stress distributes in a wide region under both loading model, the maximum residual stress is on the top surface with 2-D pressure model but sub-layer for 1-D pressure loading.

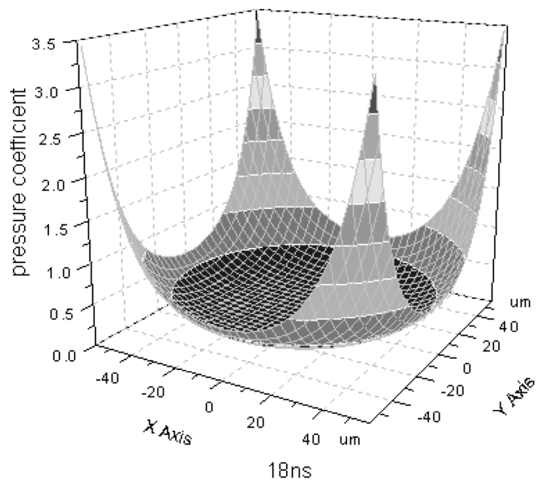
Distribution of residual stress S_{11} in radial direction is shown in Fig.10a. It can be seen that distribution of S_{11} is nearly same when the distance to centre exceeds 100 mm but greatly different within 100 mm. At surface, the magnitude of S_{11} is maximum at the centre of laser beam under 2-D pres-



(a) 3 ns

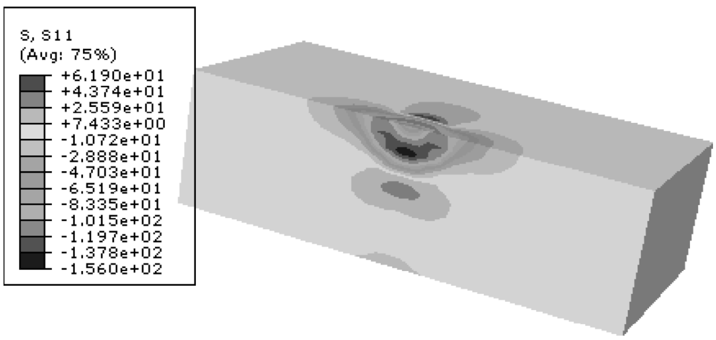


(b) 10 ns

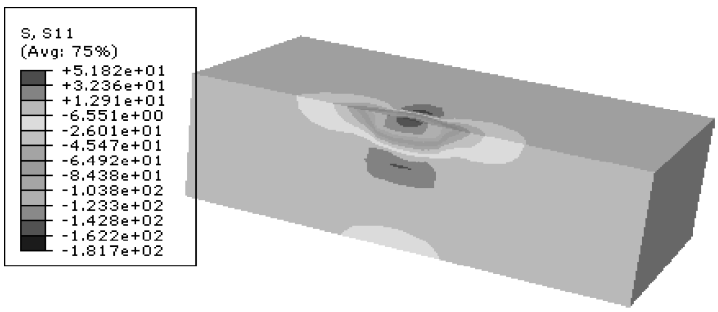


(c) 18 ns

Fig. 8. Spatial distribution of radial pressure coefficient at different times: (a) 3 ns, (b) 10 ns, (c) 18 ns.



(a) S_{11} under 1-D pressure loading



(b) S_{11} under 2-D pressure loading

Fig. 9. Stress nephogram under different load model: (a) S_{11} under 1-D pressure loading, (b) S_{11} under 2-D pressure loading.

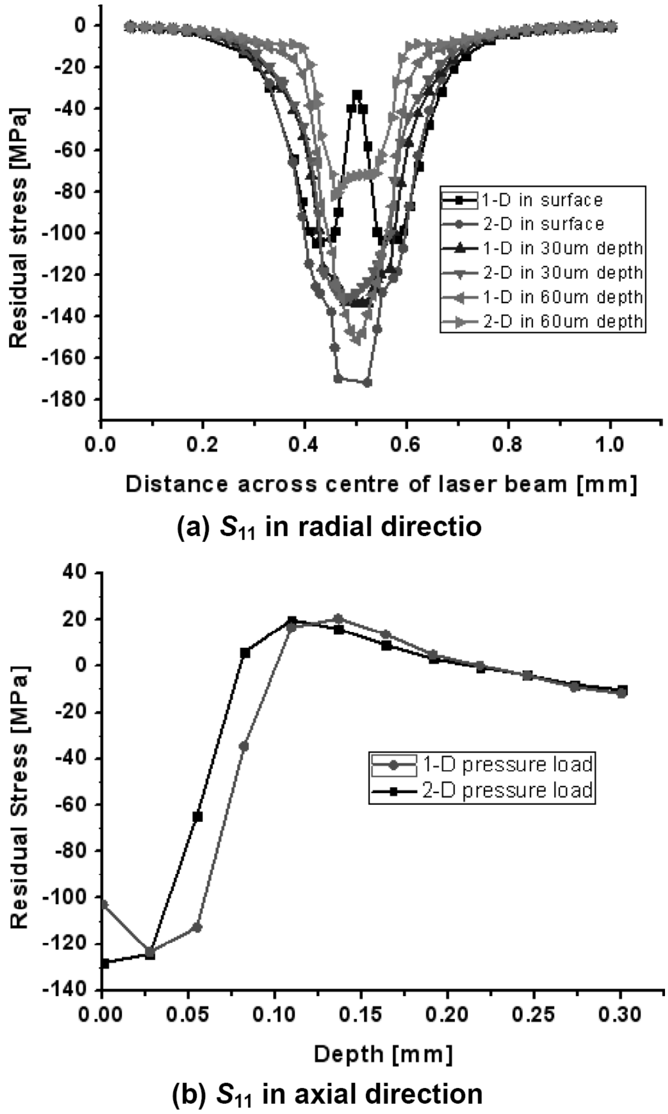


Fig. 10. Influence of distribution of residual stress under different pressure loadings: (a) S_{11} in radial direction, (b) S_{11} in axial direction.

sure loading, below the top surface about 30 μm, distribution of S_{11} are nearly same under both pressure models and below the top surface about 60 μm, magnitude of S_{11} under 1-D pressure loading is greatly larger than that under 2-D pressure loading. The results indicate that surface wave takes great effect on the distribution of surface residual stress in micro scale, the reason is the convergence of surface wave induces the increase of plastic strain in reversal direction and the decrease of stress magnitude. Under the condition of 2-D pressure loading, surface wave propagates outward along radial direction with the effect of pressure in radial direction and the maximum magnitude of S_{11} is created at the centre of laser beam. Distribution of residual stress S_{11} in axial direction is shown in Fig.10b, it is clear that influence of depth under 1-D pressure loading is much larger. The reason is that all energy was assumed to convert into pressure effect in axial direction under 1-D pressure model.

6. CONCLUSIONS

Reasonable simplified 2-D model of shock wave pressure in μLSP process was built, spatial distributions of pressure in radial and axial directions at different time were investigated respectively, and the loading mode of shock wave pressure was concluded. The numerical simulations show that pressure in axial direction plays a dominant role nearby the centre of laser beam, while pressure in radial direction is almost zero at centre of laser beam and increases with increasing of radial distance. Pressure in radial direction plays a dominant role when the distance reaches a threshold value. The results indicate that distribution of residual stress in width and depth is obviously different under two pressure models, the distribution of residual stress from 2-D pressure loading is much closer to the real situation, in order to precisely simulate and analyze the μLSP process it is necessary and important to introduce 2-D pressure loading model.

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