Numerical simulation and experiment of TA2 sheet forming under laser shock

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The effects of laser energy and different shock spaces and shock times on the TA2 titanium sheet deformation are investigated experimentally and simulated numerically by ABAQUS software. The results indicate that the amount of TA2 sheet deformation increases with the increase of laser energy, varies with shock order and shock path, and is the greatest when the shocks are along the length of sheet and symmetrical. The numerically simulative results are consistent with the experimental data.

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In recent years, shock wave induced by the interaction of powerful laser and materials has been investigated, and great progress has been made[1,2]. The sheet deformation method by using laser impact is no other than a new sheet plastic forming technology utilizing the force effect of high amplitude shock wave induced by the laser with high energy and short pulse[3,4]. Compared with conventional punch forming technology, it has some special advantages such as without any die, manageability, good processing flexibility and so on. And because shock wave peak pressure reaches gigapascal (GPa) magnitude scale, it specially fits the plastic forming of some hardly processed materials. Because exact controllability of laser impulse parameters and shock area leads to fine technological stability and repeatability, laser shock forming has expansive applications, such as aviation and space flight, national defense industry, automobile crust parts etc.. Provided with excellent performances, for example, super high static and dynamic yield limit, good rigidity and breaking tenacity, and fine anti-stress erosion and anti-fatigue performances, titanic alloy is applied extensively[5]. Using conventional processing technology, titanium alloy sheet must be super-plastically shaped and maintain constant temperature range of 800—1000 °C for 4—5 hours for getting somewhat complicated shape, therefore, there exist two major shortcomings: the mechanical properties degrade, and the die fabricating is difficult. These flaws can be overcome by the virtue of laser impacting deformation. The simulation with ABAQUS software and the experiment of TA2 plate impacted by laser are described in this paper.

The impact experiment was investigated with the high power Nd:glass laser impact device (made associatedly by Jiangsu University with Science and Technology University of China). The device is composed of Nd:glass laser oscillatory implement ($\phi 15 \times 200$ (mm)), resonance cavity with length of 1200 mm, Nd:glass laser preamplifier ($\phi 15 \times 200$ (mm)), and Nd:glass laser main amplifier ($\phi 20 \times 520$ (mm)). Laser wavelength is 1.06 μm, pulse duration is 23 ns, and pulse repetition rate varies from 1 to 2 Hz, laser beam diameter is 8 mm, pulse energy is 35 J corresponding to laser intensity of 3.03 GW/cm^2, laser pulse is of semi-Gaussian distribution. The experimental material is TA2 with the dimension of $100 \times 60 \times 0.5$ (mm). The mechanical properties of TA2 are listed in Table 1.

The experimental setup is illustrated in Fig. 1. Sheet sample was clipped between two boards with quadrate hole of 90×50 (mm). Samples as the coating were polished, a thin layer of 10-μm high vacuum grease was spread evenly on the polished sample surface, and a thin layer of 50-μm black lacquer was spread evenly on the grease, as energy-absorption layer, then tightly pressed onto the grease. For the sake of enhancing the shock wave pressure[6,7], the sample was placed in a shallow container filled with distilled water around 3 mm above the sample. After shock processing, the coating layer and vacuum grease were manually removed. The geometry of shocked area was measured using profile meter.

For seeing about the deformation response of sheet sample impacted by laser, under the condition of invariable laser energy, four impact schemes were chosen, namely, one point and one time, one point and two times, two points and two times, and multiple points and multiple times. Two fore-and-aft spots were tangent in the

Table 1. Mechanical Properties of TA2

Property	Value
Density (kg/m^3)	4430
Poisson Ratio	0.342
Elastic Modulus (MPa)	107.9
Dynamic Yield Strength (GPa)	1.345

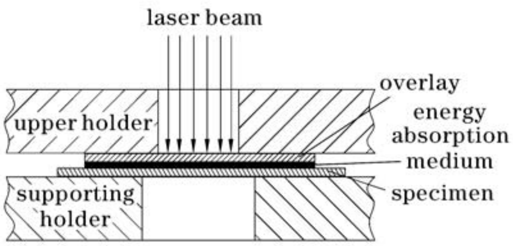

Fig. 1. Clamp sketch map of laser shock forming of sheet.

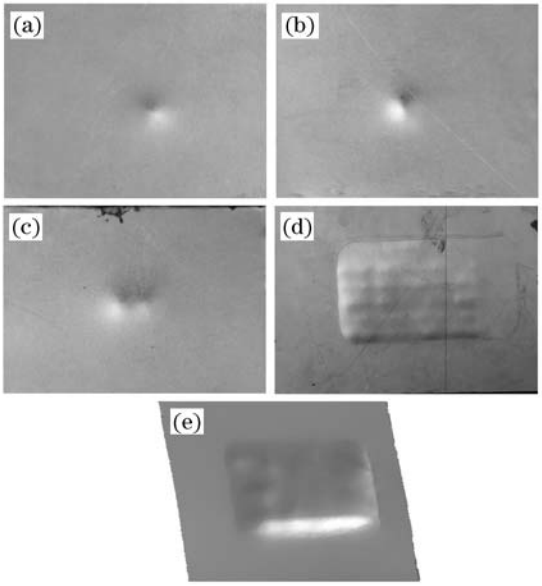

Fig. 2. Deformations of sheets impacted by laser with different impact schemes. (a) One-point impact; (b) one-point impact for two times; (c) two-points impact; (d) multi-point impact with a spot spacing of 4 mm; (e) multi-point impact with tangent laser spot.

impact experiment for the two points; two impact experiments of tangent laser spots and spots spacing for 4 mm were devised in multi-point impact.

The deformations of the impacted sheets were illustrated in Figs. 2(a)—(e), respectively. The sheet deformation for the first time was about 1.8 mm, measured by micrometer, the diameter of deformation area was about 9 mm. The accumulative deformation for two times was about 3 mm at the same position. After two-point impacts, the most deformation of two fore-and-aft impact areas were about 2.3 and 2.2 mm, respectively. It was obvious that because of the material stiffening and strain rate effect, the most deformation of the second impact area was less by 0.1 mm than that of the first area. In the course of multi-point and multi-time impact, when the adjacent two spots were tangent, the sheet deformation was even at per row and had less inequality. The most deformation was about 2.5 mm. Because some areas were not impacted between the adjacent rows, some heave areas existed therein, the most one was about 0.1 mm. In the experiment, because the work state of laser impact device was somewhat unstable, leading to the so-called “dumb cannon” phenomenon, namely some impact areas were omitted, the entire processed area was accidented, but viewing from the impacted areas, the sheet deformation was comparatively even. It was found that with the decrease of the incident laser energy, the sheet deformation decreased nonlinearly, and the impacted areas were more even; with the increase of the spaces between the adjacent spots, the impacted areas were more uneven.

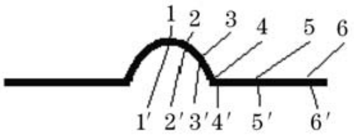

Fig. 3. Distribution sketch map of test points.

Table 2. Test Results of Residual Stress of TA2 Sample

Number of Test Point	Test Direction	Test Result σ (MPa)
Back Surface of Laser Shock		
1	0	−146.5
	90	−46.4
2	0	−55
	90	−174.6
3	0	−38.1
	90	−77.7
4	0	−64.9
	90	−128.9
5	0	−96.6
	90	−155.5
6	0	−89.4
	90	−187.3
Front Surface of Laser Shock		
1’	0	−269.3
	90	−368.7
2’	0	−275.1
	90	−305.4
3’	0	−40
	90	−182
4’	0	−63
	90	−47.1
5’	0	−87.8
	90	−10.3
6’	0	−67
	90	48.1

Residual stress affects mechanical performance, anti-erosion performance, longevity of service and so on. So, the residual stress of sample surface for one-point impact has been tested on the chance of finding out the distribution orderliness of residual stress. A new stress-tested instrument (X-350A) and a testing method of heeling fixation were used. The correlative parameters are: sway angle of 0° − 45°, diffraction angle of 162° − 150°, scan step interval of 0.1°, and time of taking count of 0.5 s. Because the residual stress of deformation curving is correspondingly difficult to test, 5—6 points on sample surface are chosen generally. Figure 3 shows the distribution of test points, and the test results of residual stress are shown in Table 2. From it, we can see that the residual stress was produced on the convex surface of the deformation area, the maximal value of which reached −187.3 MPa. The distribution of residual stress on the concave surface was not accordant, namely, residual stress was negative on the impacted point but positive on base body.

Laser shock wave acts on the sheet surface, producing a momentum pulse spreading to the interior of sample sheet, this momentum pulse brings about an outside moment acting on the impacted sheet, arousing the sheet's bending deformation, whose elastic deformation part reverts to produce residual stress. When the high-pressure shock wave spreads in the impacted sheet, because of the peak pressure being higher than the dynamic yield limit of the sheet material, the asymmetrical plastic deformation is caused, and crystal flaw, such as dense position interleaving, is produced, resulting in macroscopic representation of residual stress. Otherwise, the interactions of these mechanisms of the material stiffening, strain-rate strengthening, heat intenerate also result in residual stress. So, after laser shocks, the residual stress of the impacted sheet results from the diversified influence factors above-mentioned.

Using preprocess program of ABAQUS, geometry model is constituted and separated with finite six-node body elements. The grid schematic diagram is illustrated in Fig. 4, and four sides of sheet are fixed. In order to get the exact simulation results, firstly, appropriate model must be constituted; secondly, shock wave peak pressure must be confirmed exactly; thirdly, shockwave action time must be confirmed exactly.

In laser shock processing, the target is subjected to strong shock pressures (> 2 GPa), the interaction time is short (< 100 ns), the strain rate is high ($> 10^6$ s^{-1}). A constitutive equation for so high strain rate was given by Johnson *et al.*[8], the model for describing the work hardening and strain rate of metals is

$$\bar{\sigma} = (\sigma_0 + B\bar{\varepsilon})\left(1 + c\ln\dot{\bar{\varepsilon}}^n\right), \tag{1}$$

where $\bar{\sigma}$ is the equivalent yield stress, B, c, and n are material constants, $\bar{\varepsilon}$ is the equivalent plastic strain, and $\dot{\bar{\varepsilon}}^n$ is the equivalent plastic strain rate.

For the amplitude of shock wave, many studies have been carried out, and the estimate of peak shock pressure has been accomplished. The estimated peak pressure expression is given as[9]

$$P = 0.01\sqrt{\frac{\alpha}{\alpha+3}}\sqrt{Z}\sqrt{I_0}, \tag{2}$$

where $\alpha = 0.25$ is the fraction of the internal energy devoted to the thermal energy, $I_0 = 3.03$ GW/cm^2 is the incident laser power density, and Z is the reduced shock impedance between the target and the confining water defined by

$$\frac{2}{Z} = \frac{1}{Z_{\text{target}}} + \frac{1}{Z_{\text{water}}}, \tag{3}$$

where Z_{target} and Z_{water} are the shock impedances of the target and water, respectively. For the titanium target and water,

$$Z_{\text{target}} = \rho D = \sqrt{\rho E} = \sqrt{4430 \times 108 \times 10^9}$$

$$= 2.187 \times 10^6 \text{ g} \cdot \text{cm}^{-2} \cdot \text{s}^{-1},$$

$$Z_{\text{water}} = 0.165 \times 10^6 \text{ g} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}.$$

Substituting the values of Z_{target} and Z_{water} into Eq. (3) yields

$$Z = 0.31 \times 10^6 \text{ g} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}.$$

Substituting the values of α, I_0, and Z into Eq. (2) yields

$$P = 2.72 \text{ GPa}. \tag{4}$$

Zhang *et al.*[10] proposed that the action time of shock waves induced by laser is about 2—3 times the width of laser pulse. As simulating the laser impact deformation, we take the action time of shock waves as 3 times the width of laser pulse. Because the pulse width used in the experiment is 23 ns, the action time of shock waves is taken as 70 ns.

Through the center of the impacted areas along the length of target sheet, a path has been chosen and used as the output of simulation results and the measure tool of experimental deformation data. The deformation simulation results for impacting at one point, two points, and multiple points are illustrated in Figs. 5(a)—(d), respectively. From Figs. 5, we can see that the simulated profiles comparatively agree with the experimental results. Discrepancies are seen only at the edge of the impacted areas. This is perhaps because that the simulation model assumes that the shock wave propagates only in the vertical direction in the confining medium, while the shock wave in reality has three-dimensional (3D) propagation effects. From these simulation results, it can be seen that if choosing the less incident laser energy, or choosing to let laser spot positions overlap in part, the deformation of the impacted areas would be more even. Because simulation can avoid the impacts omitted due to "dumb cannon", it has an advantage over experiment in forecasting sheet deformation and optimizing impact paths. Figures 6 and 7 show the simulation maps of the

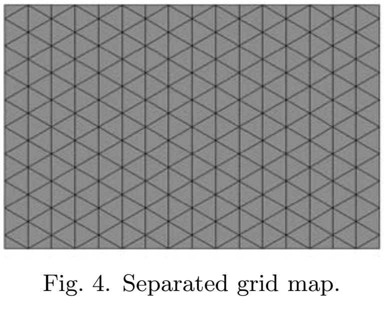

Fig. 4. Separated grid map.

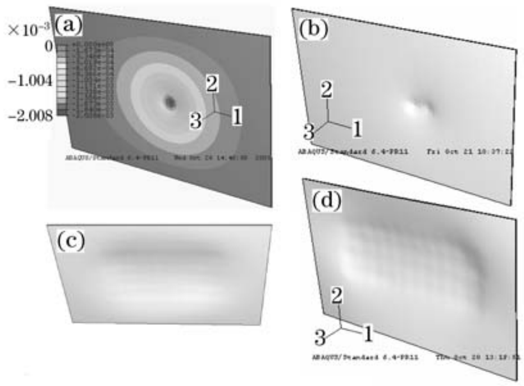

Fig. 5. Simulation results. (a) Single-point impact; (b) two-point impact; (c) multi-point impact with tangent laser spot; (d) multi-point impact with a spot spacing of 4 mm.

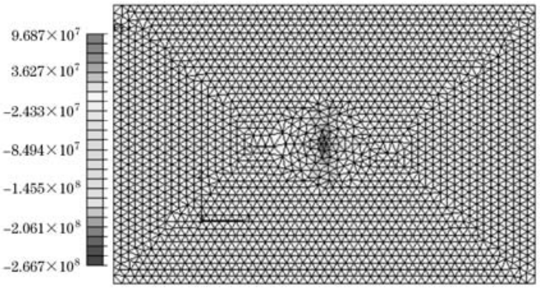

Fig. 6. Simulation map of Mises residual stress component S_{11} (one-point impact for one time).

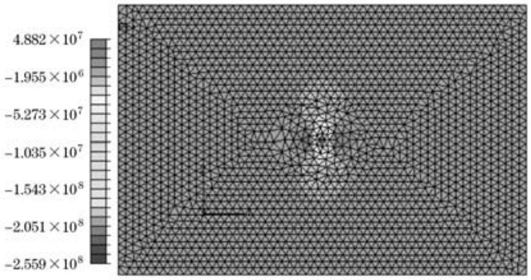

Fig. 7. Simulation map of Mises residual stress component S_{22} (one-point impact for one time).

components S_{11} and S_{22} of Mises residual stress, respectively. From them, we can see that the simulation results of residual stress are comparatively consistent with the experimental results listed in Table 2. The discrepancy of both mainly results from the somewhat unstable work state of laser impact device, the unevenly daubed coating, the man-made and instrument-brought test errors. But such a comparative consistency of both, on the one hand, indicates that the estimated shock wave peak pressure, the confirmed action time, and the chosen constitutive model are comparatively exact; on the other hand, proves that the simulation results are important on guiding experiment.

In conclusion, the sheet deformation increases nonlinearly with the increase of laser energy. When the sheet is impacted at many points, if less laser energy is used or the positions of laser spots are overlapped partially, the flatness degree of the impacted area would be greatly enhanced. The simulation results are comparatively coincident with the experimental data, the discrepancies are seen only at the edge of the dents. So, simulation is very helpful in forecasting sheet deformation and optimizing impact path.

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