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Research on Formation Mechanism of Dynamic Response and Residual Stress of Sheet Metal Induced by Laser Shock Wave

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Abstract. In order to reveal the quantitative control of the residual stress on the surface of metal materials, the relevant theoretical and experimental studies were carried out to investigate the dynamic response of metal thin plates and the formation mechanism of residual stress induced by laser shock wave. In this paper, the latest research trends on the surface residual stress of laser shock processing technology were elaborated. The main progress of laser shock wave propagation mechanism and dynamic response, laser shock, and surface residual stress were discussed. It is pointed out that the multi-scale characterization of laser and material, surface residual stress and microstructure change is a new hotspot in laser shock strengthening technology.

1 Introduction

Laser shock processing (LSP) is widely used for surface modification of metallic materials owing to its characteristics like high strain rate and high pressure. The parameters of laser shock processing are closely associated with the size and distribution of surface compressive stress[1]. Presently, the multi - scale study concerning mechanism of laser shock wave propagation in the material and the deformation mechanism of the material under the high strain rate, the microstructure change, the residual stress distribution is still to be strengthened. Compared with the traditional mechanical strengthening technology such as shot blasting and sand blasting, the laser shock processing technology has the advantages of deep impact layer, controllable impact area and pressure, easy to maintain the surface roughness and dimensional accuracy and so on, which has a tremendous technical advantage in quantitative control surface residual stress. It is a research front and crucial for the current laser shock processing technology to understand the quantitative control of the residual stress on the surface of metal materials and breaking the conventional technology research of the impact of laser shock processing parameters on the material residual stress.

In this paper, the latest research trends in laser shock processing technology in regulating surface residual stress were investigated on the basis of three aspects: laser shock wave propagation mechanism and dynamic response, laser shock and surface residual stress, microstructure change[2,3]. It is pointed out that the multi-scale characterization of laser and material, surface residual stress and microstructure change is the current research hotspot.

2 Materials and Methods

The apparatus used for the of dynamic strain on surface (shown in Fig.1 (a)), consists of the black tape with 4mm×4mm×150μm closely adhered to the surface of the sample as the absorption layer, and the K9 glass with thickness of 4mm covered as the restraining layer on the black tape. PVDF piezoelectric sensor is located on the front of the sample, along with the laser spot radial direction and 2mm away from the center of the spot. Apparatus for the detection of dynamic strain consists of YAG solid state laser (Beamtech radium photonics Co.,Ltd., Canada),DL9140 digital oscilloscope (Yokogawa Group, Japan), the optical system, industrial computer, and workstations. Apparatus for the detection of dynamic strain on the back is shown in Fig.1 (b). The PVDF piezoelectric sensor is attached to the center of the laser spot at the back of the sample, and the size of the PVDF piezoelectric sensor is 30μm ×5mm×10mm.In the setting of laser shock parameters, the pulse width was 10ns, the wavelength was 1064nm, the pulse energy was 0.5J-1J, the spot diameter was 1mm, 2mm, 3mm. Under the restraining layer of K9 glass, the surface of the sample is shocked separately, and the clamping method of the constrained layer is shown in Fig.1 (c).

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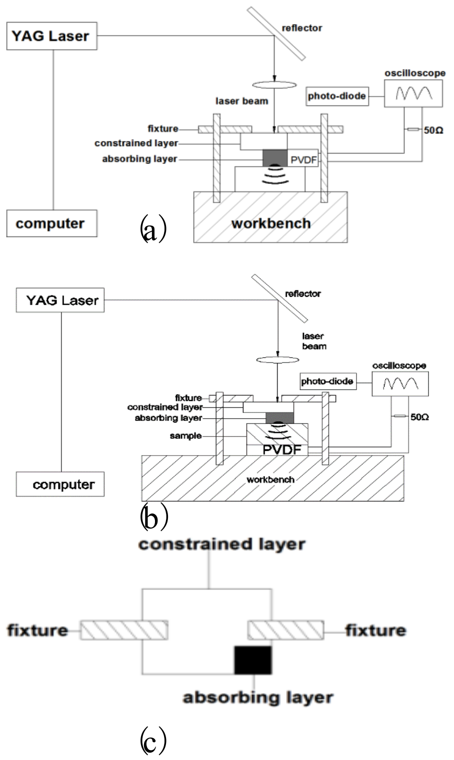

Fig. 1. Experimental apparatus of the detection of dynamic strain by laser impact the material sample. (a) surface (b)backside (c) the constraining layer was clamped by a fixture.

Based on the characteristics of dynamic strain of the thin metal plates, the correlation between laser shock processing parameters, dynamic response and distribution of surface residual stress was studied[4]. PVDF piezoelectric sensors were attached to back laser spot center and the surface of the sample along the radial, where the surface piezoelectric sensors were 3 mm away from spot center. The Gaia-R high energy pulse lamp pumped YAG laser system（France Thales Co., Ltd) was used. During the impact test, an aluminum foil of 6mm×6mm×150μm was used as an absorbent layer adhering to the surface of the 7050 aluminum alloy sheet and K9 glass as a restraining layer. The selected pulses energy were 2J、3J、3.89J、5.43J、8J, spot diameter 5mm, pulse width 10ns, wavelength 1064nm.

3 Results and Discussions

1.2 Shock wave propagation mechanism and dynamic response

The piezoelectric signal V (ε, t) was measured on the surface of the sample by means of the PVDF using fig.1 (a) device, as shown in Fig.2. V (ε, t) curve appeared the compressional wave whose waveform was the concave wave after the time point R1, and its amplitude was obviously increased to the surface Rayleigh wave. It can be inferred that when the pulse laser power density does not exceed 12.7GW / cm2, the surface Rayleigh wave and the shear wave did not produce coupling.

Using the device of Fig. 1 (b), the PVDF piezoelectric sensor measures the piezoelectric signal V (ε, t) on the back of the sample, as shown in Fig.3. The laser-induced elastic-plastic stress wave reached the back of the specimen to cause the first strain piezoelectric peak (point A1), and then reflected the elastic-plastic tensile wave propagating to the laser shock surface on the back of the sample, and caused a second strain piezoelectric peak (point B) on the back. Multiple shock waves propagating to the back of the specimen and the reverse tensile wave occurs unloading (C point), causing the back dynamic strain to fluctuate (point D, point E, point F) after the maximum peak. The stress wave decayed continuously in the reflection of the front and back surfaces of the specimen. Combined with the theory of impact dynamics, the experimental results of Zhang Yongkang, Wang Xuede and other, and the dynamic strain of the surface and the back of the sample, the "Laser Shock Wave Propagation Model 690 High-strength Steel Sheet" was established, as shown in Fig. 4. The “Propagation Model of Laser Shock Wave” describes the propagation processes of longitudinal compressional wave, reflected wave, transmitted wave, reverse stretching wave, shear wave, surface sparse wave and surface Rayleigh wave, comprehensively elaborating the propagation mechanism of laser shock wave in 690 high strength steel sheets[5]..

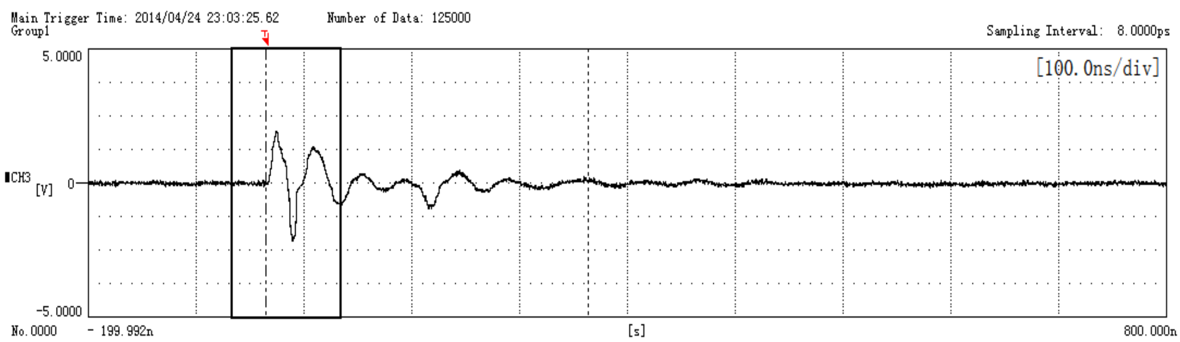

Fig.2. Dynamic strain of material at the area away from the edge of 0.5 mm when laser shock is loaded on the material surface with laser power densities of 12.7GW/cm^2

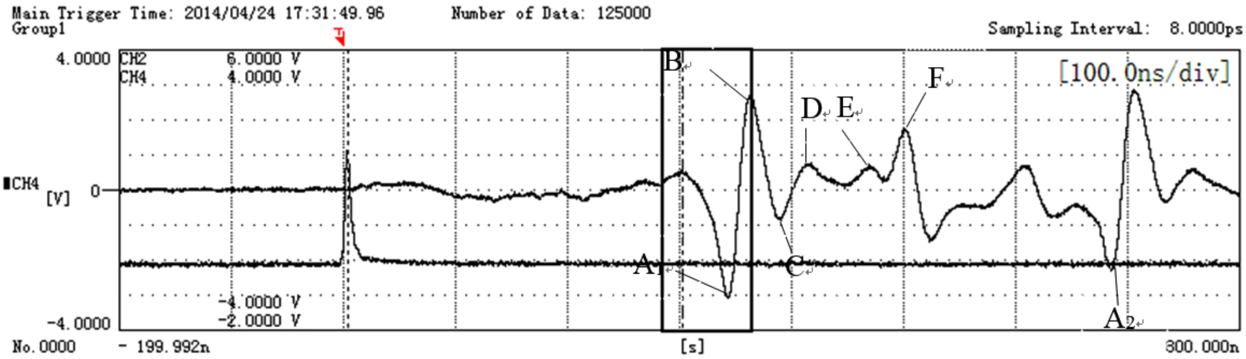

Fig.2. Piezoelectric waveform representation of the dynamic strain of sample backside when the laser shock is loaded on the thickness of 1mm material with a laser power density of 12.7GW/cm^2

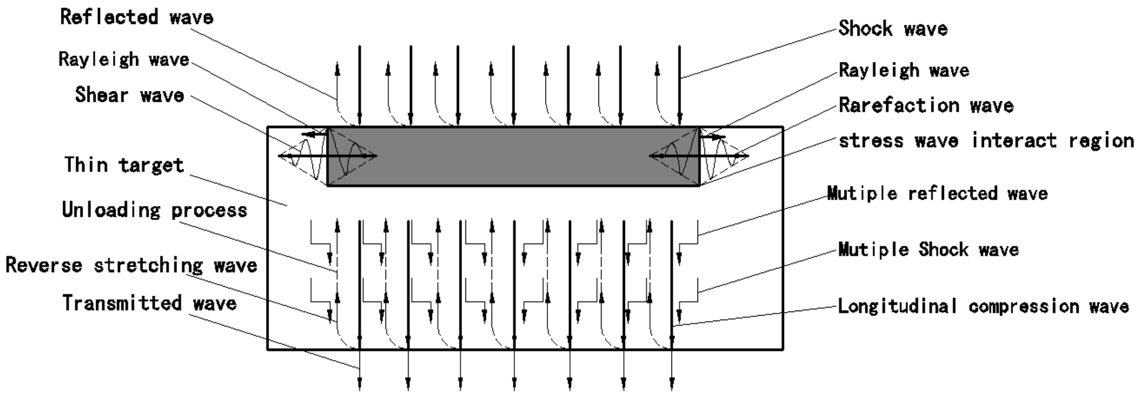

Fig.4. The laser shock wave propagation model of 690 high-strength steel sheet

3.2 Study on dynamic strain characteristics of metal sheet induced by laser shock

Based on the "Propagation Model of Laser Shock Wave", the results of numerical simulation and the boundary conditions of the surface dynamic strain test, a "Dynamic Strain Model of the Metal Sheet Surface Induced by Laser Shock" was built, and a testing method was also provided. The surface dynamic strains of 7050 aluminum alloy were measured by a PVDF piezoelectric sensor, as shown in Fig. 5 – Fig. 6. According to the attenuation law of shear wave in the 7050 aluminum alloy sheet, no coupling of shear wave and surface Rayleigh wave will be produced when the laser power density is less than or equal to 12.7GW/cm2, which is the boundary condition of surface dynamic strain model; the experimental data of 7050 aluminum alloy sheet loaded by laser shock showed that the "Dynamic Strain Model of the Surface of Metal Sheet Loaded by Laser Shock" is accurate and reliable. In the meantime, it has been also verified that the dynamic stress-strain curve of the 7050 aluminum alloy sheet under high strain rate has elasticity, yield and strengthening stages, similar to the static stress-strain curve under static tensile conditions[6]. The accuracy and reliability of the model were verified by experiments. In addition, the law of dynamic mechanical responses of metal sheets under high strain rate conditions was inventively discovered.

3.3 Residual stress formation mechanism of metal sheet surface induced by laser shock processing

Loading laser with different power densities shocks on 7050 aluminum alloy sheet, the maximum residual principal stress of the 7050 aluminum alloy sheet surface were biaxially distributed when power density was 1.53 GW/cm^2; when the power density was 1.98 GW/cm^2 and 2.77GW/cm^2, the maximum residual principal stress of the 7050 aluminum alloy sheet surface produced the "Residual Stress Hole" phenomenon; when the power density was 4.07GW/cm^2, the maximum residual principal stress of the 7050 aluminum alloy sheet was evenly distributed[3]. It can be seen from Fig. 7 (a) that when the power density was 1.53 GW / cm^2, the amplitudes of the obtained shear wave and the longitudinal wave were not large. The interaction between the surface rarefaction wave and the lateral deformation causes the maximum residual principal stress of the sample to be biaxial. As shown in Fig. 7 (b), no dynamic strain was measured by the PVDF piezoelectric sensor on the surface of the impact area after the shear wave and the Rayleigh wave was attenuated. The shock wave reflected back and forth in the thin plate sample and the rarefaction wave was propagated to the center of the spot, resulting in a large shear plastic strain in the central area of the sample, so the residual compressive stress in the central area of the laser spot were reduced, resulting in the phenomenon of "Residual Stress Hole ".With further increase of laser energy, the PVDF piezoelectric sensor pasted on the vicinity of the edge of the spot to detect the dynamic strain again, as shown in Fig.7 (c).

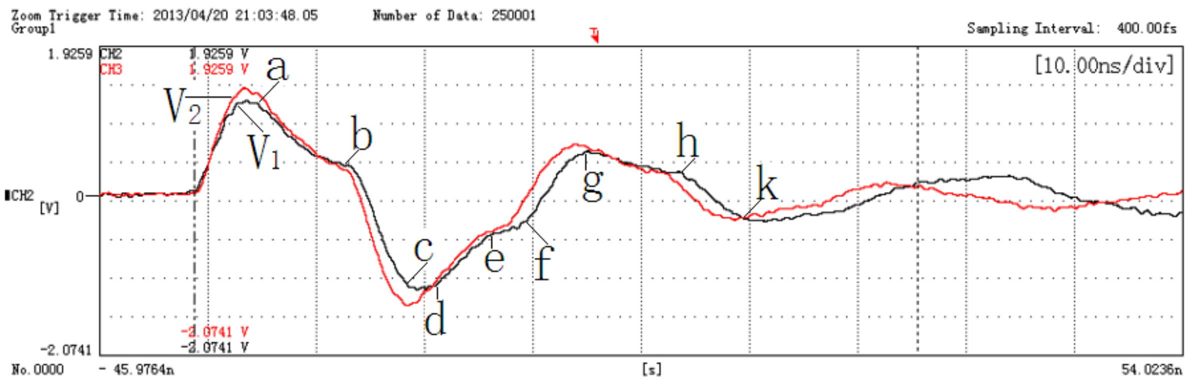

Fig.5. Piezoelectric waveforms (collected by the PVDF sensor) of the dynamic strain of the material when the laser shock is loaded with a laser power density of 12.7 GW/cm^2

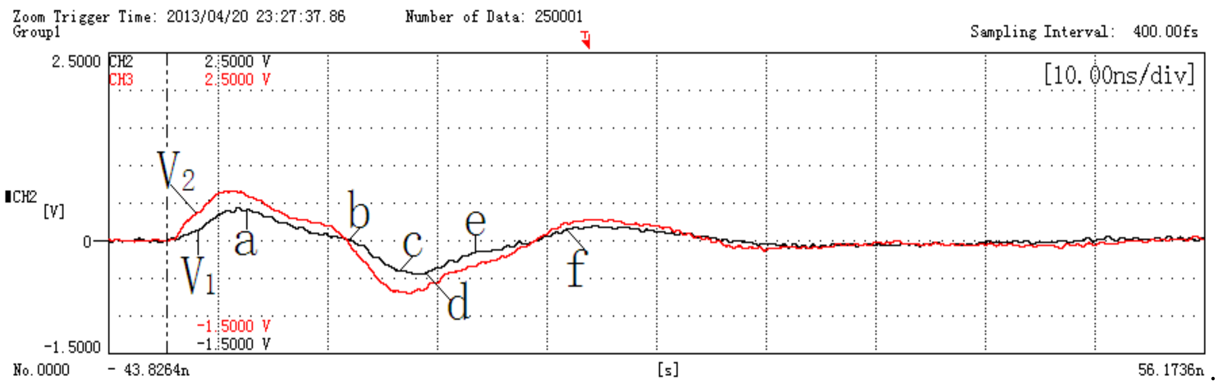

Fig.6. Piezoelectric waveform representation (collected by PVDF sensor) of dynamic strain of material when laser shock is loaded on the material surface with laser power density of 3.2 GW/cm^2.

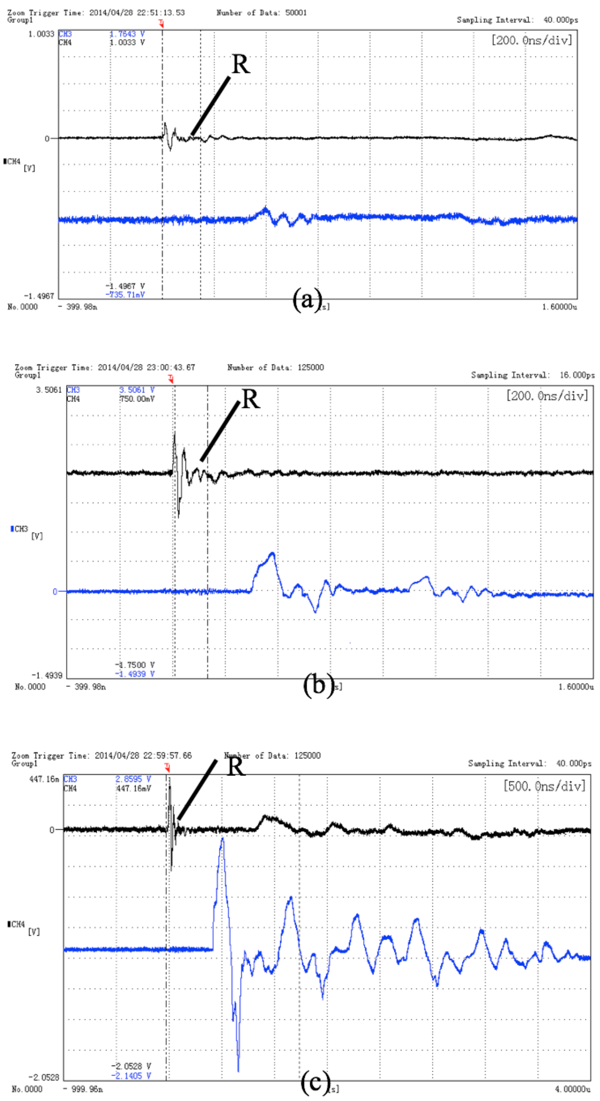

Fig. 7. Dynamic strain of material when laser shock is loaded on the material surface with laser power densities of (a)1.53 GW/cm^2; (b)2.77GW/cm^2; (c)4.07 GW/cm^2.

4 Conclusions Figures and tables

(1)The principle and method to measure laser shock wave characteristics were improved and optimized. Taking 690 high-strength steel sheet as a case, this research has, for the first time, established a "Propagation Model of Laser Shock Wave" by integrating dynamic responses on both sides of the plate. The "Propagation Model of Laser Shock Wave" described the propagation processes of longitudinal compressional wave, reflected wave, transmitted wave, reverse stretching wave, shear wave, surface sparse wave and surface Rayleigh wave, comprehensively elaborated the propagation mechanism of laser shock wave in 690 high strength steel sheets.

(2) It verified that the dynamic stress-strain curve of the 7050 aluminum alloy sheet under high strain rate has elasticity, yield and strengthening stages, similar to the static stress-strain curve under static tensile conditions.

(3) Based on the characteristics of dynamic strain of the thin metal plates, the correlation between laser shock processing parameters, dynamic response and distribution of surface residual stress was studied, and the formation mechanism of residual stress on the metal sheet surface was explored. When the power density was 1.53 GW/cm2, the interaction between surface rarefaction wave and transverse deformation resulted in equal-biaxial distribution of the maximum residual principal stress on the specimen surface of 7050 aluminum alloy thin plate; when the power density was 2.77GW / cm2, the shock wave on the back and surface of 7050 aluminum alloy sheet was reflected back and forth, and the influence of residual stress on the surface cannot be neglected, the phenomenon of "Residual Stress Hole" was caused by combined action of the shock wave reflected back and forth in the thin plate and the sparse wave converging to the center.

(4) Basic and applied research were carried out based on the multi-scale characterization of the propagation mechanism of laser shock wave in metal materials, the dynamic mechanical properties of metal materials under high strain rate, surface residual stress and microstructure change. This study provides a theoretical basis and technical support for the quantitative control of surface residual stress thin-walled induced by parts laser shock processing.

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