Effects of confining layer and ablating layer on laser-induced shock wave characteristics during laser shock processing by PVDF gauge

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Abstract. The PVDF sensor is used to obtain the time variation curves of the shock wave pressure in the four states of the laser shock peening with or without confining layer and with or without ablating layer, the effects of confining layer and ablating layer on shock wave characteristics are analyzed. The results show that the confining layer limits the plasma expansion area, and the inverse bremsstrahlung absorption effect is enhanced, so that the peak pressure and pulse width of the shock wave are increased to 10 times and 2 times that under the condition of the without confining layer; The ablating layer significantly increases the peak pressure of the shock wave by improving the laser energy coupling efficiency. However, the influence of the ablating layer on the peak pressure tends to saturate with the increase of power density, the difference of the peak pressure is only 8.5% when the laser power density is 4.53GW/cm². In addition, the ablating layer complicates the shock wave propagation process, and the shock wave curve presents a multi-peak structure.

1. Introduction
Laser shock peening (LSP) is a technology that uses the mechanical effect of plasma shock wave induced by short-pulse and high-power density laser to strengthen the metal surface [1]. O’keefe [2] coated a light-transmitting layer on the laser-irradiated surface of the target to greatly increase the peak pressure of the shock wave induced by the laser. Anderholm [3] pasted metal foil on the target to increase the pressure amplitude. Clauer [4] adopted the processing mode of adding black coating and transparent confining layer on the metal target surface, which makes the pressure amplitude of shock wave to GPa level. It has formed the embryonic form of laser shock peening technology: laser shock structure using constraint layer and ablating layer.
However, LSP is used to process complex surface parts, such as micro-holes, corners, and large curvature surfaces, the confining layer and the ablating layer cannot be effectively applied, which directly affects the characteristics of the laser-induced shock wave.

In this paper, PVDF pressure sensor is used to measure the shock wave pressure with or without confining layer and ablating layer, the effects of constraint layer and ablating layer on the pressure characteristics of laser-induced shock wave are discussed.

2. Experimental method

The laser is a SGR-60 Q-switched Nd: YAG laser: wavelength is 1064nm, working frequency is 1Hz and energy range is 0.5~5J. Figure 1 is a schematic diagram of the PVDF test system of laser induced shock wave: the confining layer is water, the ablating layer is black tape, and the target is an aluminum plate. In laser shock peening, the generation and propagation of shock wave is ns level, so choice current mode of the PVDF sensor to measure the shock wave. The two pins of the PVDF sensor are connected to the 50Ω DC resistance and connected to the Tektronix DPO4014 oscilloscope, its bandwidth is 1GHz, the sampling rate is 5GS/s, and the record length is 10M, which meets the experimental sampling requirements. Under the PVDF sensor, adding a plexiglass, the acoustic impedance of plexiglass is similar to PVDF sensor, can transmit most of the shock wave to the plexiglass to reduce the influence of shock wave reflection on the test results.

![Figure 1 PVDF test system of laser induced shock wave](image)

When PVDF sensor receives a pressure signal $P_{PVDF}(t)$, it will be converted into a voltage signal $U(t)$. The relationship between the two is as follows [5]:

$$P_{PVDF}(t) = \frac{K}{A} \int_0^t \frac{U(t)}{R} dt \quad (1)$$

Among them, $K$ is the dynamic calibration coefficient of PVDF sensor $4.5 \times 10^8$ Pa·cm²·μc⁻¹, $A$ is the effective area of PVDF 12.6mm². Because PVDF sensor measures the pressure after the shock wave is transmitted, the relationship between the pressure $P$ generated on the laser irradiated surface and the pressure $P_{PVDF}$ measured by the PVDF sensor is as follows:

$$P = \frac{P_{PVDF}}{2} \left( 1 + \frac{Z_{Al}}{Z_{PVDF}} \right) \quad (2)$$

Acoustic impedance aluminum and PVDF, respectively $Z_{Al}=1.34 \times 10^6$g·cm⁻²·s⁻¹ and $Z_{PVDF}=0.25 \times 10^6$g·cm⁻²·s⁻¹.
3. Experimental result

3.1. Effects of confining layer on shock wave characteristics

Figure 2 shows the relative pressure curve measured under the parameters of wavelength is 1064nm and laser power density is 3.55 GW/cm²:

![Figure 2 Relative pressure curve with or without confining layer](image)

As shown in figure 2, the confining layer can effectively increase the pressure and pulse width of the shock wave. In this experiment, the pressure peak and pulse width of the shock wave with water confining layer are 10 times and 2 times that of the non-water confining layer, respectively. In the ablation mode, the plasma expands freely against the direction of the laser beam. After adding the confining layer, the plasma generated by the laser irradiation on the surface of the target material is confined between the confining layer and the target material, so that the expansion and propagation of most of the plasma is confined in the direction perpendicular to the workpiece. The plasma injection time is prolonged, which makes the density and temperature of the plasma increase, and the inverse bremsstrahlung absorption effect of the plasma is thus enhanced, and the efficiency of laser energy conversion is significantly increased. If the plasma is approximately regarded as an ideal gas, according to the ideal gas equation of state PV/T=C, in the case of a constrained layer, when the increase rate of the temperature T is much greater than the increase rate of the volume V, the peak pressure P of the shock wave will increase significantly. In addition, after the laser is extinguished, the adiabatic expansion of the plasma will be delayed, the cooling rate will slow down, and the pulse width of the shock wave will increase. Since the peak pressure and pulse width of the shock wave are significantly increased, the combined action of the two makes the impulse $G(t) = \int_0^t P(t)dt$ applied by the laser to the target material increase significantly, which improves the strengthening effect.

3.2. Effects of ablating layer on shock wave characteristics

Figure 3 shows the relative pressure curves measured by 1064nm laser under different power density parameters.
As shown in Fig. 3, the use of ablating layer increases the peak pressure of the shock wave, and also complicates the propagation process of the shock wave between the ablating layer and the target interface, resulting in multiple pressure peaks. Because the absorption coefficient of the tape for the laser is greater than aluminum, under the same laser parameters, using tape can absorb more laser energy, which improves the coupling efficiency of the laser energy. And the gasification heat of the tape is smaller than aluminum, gasification explosions can occur at a lower laser energy, and further ionize to form plasma. The formation efficiency of plasma is higher than that without the ablating layer, which can make the plasma absorb more laser energy, that is, the enhanced absorption effect of plasma is more likely to occur. Furthermore, the thermal conductivity of tape is lower than aluminum, the use of tape is more conducive to the deposition of laser energy. The use of the ablating layer also causes the shock wave to continuously reflect and transmit between the interfaces, causing the pressure curve to form several peaks.

When the laser power density is continuously increased, the pressurization effect of the ablating layer gradually becomes less obvious, the pressurization rate reaches 35% at 3.55GW/cm², but only 8.5% at 4.53GW/cm². This is mainly because the metal target surface has become high temperature plasma with close to solid density under the action of high-power and short-pulse laser, the strict boundary between the metal and plasma disappears, the optical characteristics have changed, which significantly reduces the reflectivity of the laser [6,7]. Under the irradiation of high-power density laser, the increase of electron density on the metal surface will make the plasma frequency equal to the laser frequency, so that the laser is strongly absorbed near the metal surface. Combination of these
factors, the increase of laser power density will reduce the reflectivity of aluminum to laser. Fariand [8] found that at higher power densities, the characteristics of the shock wave depend on the characteristics of the plasma, the pressurization effect of the ablating layer is weak. Therefore, at a higher power density, compared to improving the peak pressure and duration of the shock wave, the main function of the ablating layer is to protect the target from laser ablation.

4. Conclusion
This paper obtains the laser-induced shock wave pressure-time curve through PVDF sensor, discusses the influence law of the confining layer and the ablating layer on the laser-induced shock wave pressure, and analyzes the influence mechanism. The specific conclusions are as follows:
1) The use of the confining layer increases the shock wave pressure by 10 times and the pulse width by 2 times. This is because the confining layer limits the expansion of the plasma, which greatly improves the density and temperature of the plasma, thus increasing the absorption efficiency of the laser energy.
2) The use of the ablating layer significantly improves the peak pressure of the shock wave by improving the efficiency of laser energy coupling. It also complicates the shock wave propagation and forms a multi-peak structure. With the increase of the energy density, the reflectivity of the target to the laser decreases, which makes the pressurization effect of the ablating layer tend to saturate: at 4.53GW/cm², only 8.5% is pressurized.

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