Research on Laser Ablation Technology in the Material Interaction of Two-dimensional Axisymmetric Ablation Model

Yaode Wang and Changli Li*
School of Science, Changchun University of Science and Technology, Changchun 130022, China

* Corresponding author: licl@cust.edu.cn

Abstract. In order to explore the mechanism of interaction between nanosecond pulsed intense laser and material, the paper established a two-dimensional numerical model, using finite difference method to numerically simulate the temperature field of nanosecond laser pulse ablation of metal aluminium. By comparing different pulse widths, the temperature field caused by the laser under the spot and energy evolves with time. It is found that the temperature in the early stage of the pulse rises faster than in the later stage. The isotherm diagram shows that the centre temperature rises fastest, the ablation profile is similar to the shape of the laser beam, and the ablation depth reaches 1-5μm. The longer the pulse width, the narrower and deeper the ablation, the larger the spot, the wider and the shallower the ablation. The calculation results show that, compared to the uniform distribution, when the laser has a Gaussian distribution, the target aluminium centre can be obtained the higher the temperature rise, the more prone to ablation and the shorter the melting time of aluminium. The model established in this paper can be easily extended to three-dimensional situations.

Keywords. Keywords: Laser-material interaction, laser ablation technology, two-dimensional axisymmetric, ablation model, finite element simulation.

1. Introduction
The basis of laser application is the study of the interaction between laser and matter, mainly the various mechanical, physical, chemical and biological effects caused by laser irradiation of materials, structures, optical devices, photodetectors and biological bodies. At present, the heating effect of strong laser on metal aluminium has been extensively studied, mainly investigating the law of temperature rise of aluminium under the action of laser and the cooling and oxidation effects of external airflow environment. When the laser power density increases to 105~106W/cm2, aluminium will melt or vaporize; when it increases above 107W/cm2, plasma will be generated; the ablation rate is related to the laser wavelength and pulse width, and the long pulse is large Energy laser is more beneficial to increase the ablation rate of metal aluminium. Aiming at the ablation effect caused by pulsed laser irradiation of aluminium, the most direct research method is experimental measurement, which can roughly understand the ablation law of aluminium from a macro perspective. The numerical simulation method can predict the temperature field distribution of aluminium, the melting time of...
aluminium, and the geometric size of the ablation zone for different aluminium targets and different laser parameters. Through numerical simulation, the optimal laser parameters in practical applications can be theoretically guided, and the cost is low [1]. For this reason, this paper combines experimental measurement and numerical simulation to quantitatively analyse the ablation process of aluminium alloy plate under the action of pulsed laser. The numerical simulation results are in good agreement with the experimental results.

2. Laser flat ablation
According to the law of coupling between laser and material impulse, for a flat plate with area S, surface normal vector \( \vec{n} \) and surface impulse coupling coefficient \( C_n \), under the irradiation of laser with unit vector \( \vec{k} \) in the irradiation direction and energy density \( I \), the obtained impulse \( m\Delta \vec{v} \) as follows:

\[
m\Delta \vec{v} = -C_n IS |\vec{n} \cdot \vec{k}|\vec{n}
\]

When the plate starts to rotate, its surface normal vector \( \vec{n} \) changes. Specifically, in the case shown in Figure 1, the laser is irradiated in the positive X direction, namely \( \vec{k} = (1, 0) \), the plate is located in the XY plane and rotates counter clockwise around the Z axis, the angle between the plate and the X axis square is \( \theta \), and the surface normal vector \( \vec{n} = (-\sin \theta, \cos \theta) \) produces X, Y The directional impulses are:

\[
\begin{pmatrix}
m\Delta \vec{v}_{x} \\
m\Delta \vec{v}_{y}
\end{pmatrix} = -C_n IS \begin{pmatrix}
\sin^2 \theta \\
-\sin \theta \cos \theta
\end{pmatrix} = -C_n IS \begin{pmatrix}
\sin^2 (\varphi + \omega t) \\
-\sin(\varphi + \omega t)\cos(\varphi + \omega t)
\end{pmatrix}
\]

(2)

In the formula: \( t \) is the time; \( \varphi \) is the initial angle. Under the continuous action of \( n \) pulses with frequency \( f \):

\[
\begin{pmatrix}
SUMm\Delta \vec{v}_{x} \\
SUMm\Delta \vec{v}_{y}
\end{pmatrix} = -C_n IS \begin{pmatrix}
\sum_{i=1}^{n} \sin^2 (\varphi + \omega t) \\
\sum_{i=1}^{n} -\sin(\varphi + \omega t)\cos(\varphi + \omega t)
\end{pmatrix}
\]

\[
= -C_n IS \begin{pmatrix}
\sum_{i=1}^{n} \sin^2 (\varphi + i\omega / f) \\
\sum_{i=1}^{n} -\sin(\varphi + i\omega / f)\cos(\varphi + i\omega / f)
\end{pmatrix}
\]

(3)
Figure 1. Schematic diagram of laser irradiation rotating flat plate

When the laser action frequency $f=10$Hz does not change, the angle of the combined impulse deviation from the laser action direction of 60 consecutive pulses at different plate speeds is shown in Figure 2. It can be seen from the figure that when the laser frequency is constant, the faster the rotation speed of the plate, the smaller the maximum deflection angle of the combined impulse, the faster the deflection angle of the combined impulse reaches the minimum value, and the fewer pulses required, and the more pulses and the smaller the maximum value of the impulse deflection angle. When the rotation speed of the plate is greater than 50(°)/s, it can rotate more than 180° within the pulse action time, so the deflection angle periodically fluctuates between the maximum value and the minimum value, and the maximum value of the deflection angle becomes greater as it goes later. Small; when the plate rotation speed is 30(°)/s, the pulse action time is just over a 180°, the Y direction impulses cancel each other, and the final combined impulse deflection angle reaches the minimum; when the plate rotation speed is 20(°)/s, After 90° within the action time, but not reaching 180°, the Y-direction impulse starts to cancel each other out, and the deflection angle begins to decrease from the maximum value; the plate speed is 10(°)/s, and the rotation angle within the action time does not reach 90°. The Y-direction impulse continues to increase, yet it has not reached its maximum value [2]. The calculated influence law is consistent with the formula analysis result.
3. Condensation and evaporation theory

Any kind of gas has a critical temperature. When the gas temperature is higher than the critical temperature, it cannot be liquefied by isothermal compression. This gas is called permanent gas; and the gas below the critical temperature can be achieved by simply increasing the pressure. To liquefy it is called steam. The process of vapor molecules in the space returning to the liquid is called condensation \[3\]. The mass of steam condensed on a unit area per unit time is the condensation rate

\[ W = \alpha p_v \sqrt{\frac{M}{2\pi RT}} \]  \tag{4}

Where: \( \alpha \) is the condensation coefficient, \( p_v \) is the partial pressure of vapor, \( M \) is the molar mass of vapor, \( T \) is the absolute temperature, and \( R \) is the universal constant of ideal gas. According to the characteristics of gas internal pressure, \( p_v \) is actually the pressure of vapor and plasma during laser ablation, and it and absolute temperature \( T \) are both functions of time. The reverse process of condensation, that is, the phenomenon in which liquid molecules fly into space and become vapor is called evaporation. The mass evaporated per unit area of liquid surface per unit time is called the evaporation rate \( G_v \). Under the conditions of coexistence of vapor and liquid, evaporation and condensation phenomena exist at the same time. If the evaporation rate is greater than the condensation rate, the macroscopically manifests as the evaporation of liquid; if the evaporation rate is less than the condensation rate, the macroscopically manifests as the condensation of vapor; both When they are equal, they are in a saturated state \[4\]. At this time, the pressure of the space vapor is called the saturated vapor pressure at the corresponding equilibrium temperature. The saturated vapor pressure of a substance increases with the temperature. The relationship between the evaporation rate of the liquid and the saturated vapor pressure at the corresponding temperature is

\[ G_v = p_{sat} \sqrt{\frac{M}{2\pi RT}} \]  \tag{5}

Equation (5) is often used to calculate the amount of metal evaporation in the evaporation coating. \( p_{sat} \) is also a function of time during laser ablation. And from the Calderon-Clausius equation, the saturated vapor pressure \( p_{sat} \) is again a function of temperature \[5\].

Figure 2. The deflection angle of the combined impulse of the rotating plate with continuous 10Hz laser pulse
4. Calculation of Ablation Depth

The target material is LY12 aluminium alloy, and its physical parameters and geometric dimensions are shown in Table 1. The energy coupling coefficient of the target surface to the laser is 0.3, the incident laser is uniformly distributed, the spot radius is 0.05m, and the irradiation time is 3s. From the above analysis, it can be seen that the diffusion depth of heat in the target during the laser irradiation period is only 0.03m, so the radial radius of the target is 0.1m to meet the calculation requirements.

Table 1. Values of relevant parameters used in calculation

| 1/m | r_d/m | ε | α/m | k/(Wm⁻¹K⁻¹) | ρ/(kgm⁻³) | c/(Jkg⁻¹K⁻¹) | T_s−Tc/°C | L/(Jkg⁻¹) |
|-----|-------|---|-----|-------------|-----------|-------------|----------|----------|
| 0.003 | 0.1 | 0.3 | 0.05 | 193 | 2850 | 900 | 650−660 | 400000 |

Equations (4) and (5) show that the evaporation rate and condensation rate are all related to the vapor temperature, vapor pressure and saturated vapor pressure. At any temperature, condensation and evaporation co-exist. When the condensation rate is greater than the evaporation rate, the macroscopic appearance is net condensation; when the evaporation rate is greater than the condensation rate, the macroscopic appearance is net evaporation. The two formulas are the laws of thermodynamics under equilibrium conditions. The laser ablation process is a transient non-equilibrium process in general. Therefore, we must first discuss the applicability of formulas (4) and (5) to calculate the ablation depth. For metallic aluminium, surface evaporation is an important mechanism for quality erosion. The evaporated part forms a rapidly expanding metal vapor above the aluminium surface, and forms a thin layer of phase mutation near the boundary above the aluminium surface, which is called the Knudsen layer (KL). It is a critical region with highly discontinuous thermal and aerodynamic parameters, as shown in Figure 3. Assuming that the ablation process is carried out in a vacuum, the pressure and temperature balance of the aluminium surface boundary during the ablation process is analysed in the order of time.

![Figure 3](image)

Figure 3. Schematic diagram of boundary conditions and gas dynamics of laser ablation

When the laser power density reaches 10010000MW/cm², the temperature of the target surface increases with the progress of the ablation process. When the temperature reaches the boiling point, the target surface begins to vaporize, and the vapor rapidly expands to the vacuum to form vapor aluminium. Since the vapor aluminium at the initial moment expands freely to vacuum, the expansion process of vapor aluminium in the initial stage is a highly unbalanced dynamic process. Then the
vapor will absorb the laser energy through the inverse bremsstrahlung radiation of free electrons and cause the vapor molecules to ionize, forming plasma [6]. It can be seen from Figure 3 that the plasma further absorbs the laser energy and expands rapidly. The laser forming the plasma supports the absorption wave until the plasma is finally extinguished. When gasification occurs, the high-speed ejection of the gasifier substance will produce recoil pressure on the surface of the material. For a sufficiently strong incident laser, the plasma expands at supersonic speed, that is, the laser-supported absorption wave appears as a laser-supported detonation wave (LSDW), and LSDW will also generate corresponding pressure on the target material. The target surface absorbs the subsequent laser to support the evaporation process, and these two pressures inhibit the subsequent evaporation process at the target surface, so that the non-equilibrium process starting at the target surface approaches the equilibrium process.

Figure 4 is the contour map of the temperature field in the aluminium alloy plate at the end of laser irradiation or ablation under different incident power (P=25kW, P=50kW, P=75kW) (partial display). When the laser power is 25kW, the surface centre temperature at the end of the irradiation is about 391°C, which is much lower than the ablation temperature TL of aluminium alloy, and the surface will not be ablated. When the laser power is increased to 50kW, the surface centre temperature at the end of the irradiation is about 659°C, which is slightly lower than the ablation temperature TL, so the surface will not be ablated, but at this time a large area inside the target is already solid. Liquid phase change stage. When the laser power is increased to 75kW, the target melts through at 2.921s, and the radius of the perforation on the front surface is 4.075cm.

Figure 4. The temperature field distribution of the aluminium alloy plate at the end of laser irradiation or ablation (partial display)

5. Conclusion
The complete jet ablation model is used to establish a numerical model of the temperature change and ablation of the metal target under millisecond pulse laser irradiation. The results show that the established two-dimensional axisymmetric ablation model can approximate the ablation effect in the experiment. Because there are strong points distributed in the laser spot in the experiment, the light intensity distribution is not completely rotationally symmetrical. Therefore, the calculation results obtained by using the two-dimensional axisymmetric model have certain errors, which indicates that the laser beams on the metal target under the three-dimensional situation the ablation model is
necessary. It has certain reference value and significance for engineering applications in the field of high-power lasers.

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