Simulation Study on Laser Damage of Iron Plate

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Abstract. Studying laser damage effects are of great significance in the field of industrial production. In order to evaluate the damage effect of laser on iron, the process of pulsed laser and continuous laser irradiate an iron plate was simulated by using COMSOL. The relationship between temperature and surface energy absorptivity of iron plate was discussed. The initial simulation parameters were set as follows: the pulsed laser wavelength is 1064nm, the pulse width is 10ns, the pulse energy is changed from 2mJ to 8mJ, and the average power of continuous laser is 225mW. The simulation results show that pulsed laser can rise the surface temperature of iron plate very quickly, and improve surface energy absorptivity of the plate. Thus using pulsed laser to radiate an iron plate before using continuous laser can improve damage efficiency of continuous laser on an iron plate.

1. Introduction
Laser damage is a very important part in instrument design, precision measurement and other industrial production activities. Therefore, it is significant to know laser damage mechanism of materials.

During the past few years, many research has been put into effect, most of which, however, focused on only one type of laser to irradiate materials\textsuperscript{[1-7]}. Other studies, which concentrate on using combination laser to irradiate targets, were carried out too\textsuperscript{[8-9]}. Among these cases, high power pulsed laser were used to damage target materials, and continuous laser play the part of keeping temperature of targets. We didn't find anyone of them using continuous laser to damage materials while using pulsed laser to rise the surface temperature of targets. In this paper, damage effect of the special combination type has been identified.

Meanwhile, metallic materials are widely used in our daily life and industrial production. Besides all the metallic materials, iron is one of the most important one. In this paper, we establish a model of an iron plate to simulate the process of laser heating.

2. Model Established
Theoretical Model. The effect of laser damage includes heat effect and mechanical effect. The iron plate absorbs heat from laser. For lasers are non-uniform spatial distribution, heat absorbing is non-uniform spatial distribution too. Then the energy passes inner the plate, leading to thermal stress between different parts of it. When the volume of the plate is small, mechanical effect is not
significant. In order to simplify the operation, mechanical effect is ignored, while heat effect is mainly discussed in this paper.

For metal materials have lower electronic-lattice power and skin tropism, there is a huge number of free electronics on the surface of them. Two-temperature equations are used to describe the radiate process\(^\text{[10]}\). The equations divest the whole heat transfer process into two steps. First of all, the free electronics on the surface absorb energy from laser. Then the energy is passed from electronics which are heated to cold lattices. Eq. 1, the classical one-dimensional two-temperature equations, are shown below.

\[
\begin{align*}
C_e \frac{\partial T_e}{\partial t} &= \partial \left( K_e \frac{\partial T_e}{\partial x} \right) - G(T_e - T_l) + s(x, t) \\
C_l \frac{\partial T_l}{\partial t} &= G(T_e - T_l)
\end{align*}
\]  

Eq. 1

In the equations, "\(C_e\)" stands for heat capacity of electronics, and "\(C_l\)" stands for that of lattices. "\(G\)" is the energy exchange function between electronics and lattices. "\(s\)" is used to describe the heat absorbed from laser.

In practical research, if the power of laser is not too large or pulse width is not too short, heat passing between electronics and lattices can be ignored. During the reaction time of middle power and low power nanosecond laser, electronics and lattices can reach heat balance.

Surface absorptivity of iron is one of the most important parameters which influence the surface temperature of the plate under irradiated by the same laser. Ignoring other effects, energy that the plate absorb only depends on the power of laser and the reflex rate of the plate. In ideal vacuum environment, iron's one wavelength reflex rate can be calculated by Hagen-Rubens equation\(^\text{[11]}\):

\[
0 \lesssim \frac{cR \lambda_0}{\sigma^2} \lesssim 1
\]

Eq. 2

Substituting Ep. 1 into Ep. 2, surface absorptivity of iron can be described by Eq. 4\(^\text{[11]}\).

\[
R = 1 - \frac{c}{\sqrt{\frac{\sigma^2}{\lambda_0^2}}}
\]

Eq. 3

Basic Parameters. Some basic parameters of iron are shown in Table 1.

| Material | Density[kg/m\(^3\)] | Specific heat capacity[J/(kg K)] | Melting point[K] | Latent heat of fusion[J/kg] | Heat conduction[W/(m K)] |
|----------|----------------------|----------------------------------|-----------------|--------------------------|------------------------|
| Fe       | 7860                 | 460                              | 1812            | 269550                   | 82                     |

The plate is put in ideal vacuum environment. The ambient temperature is 298K, the pressure is 1atm, and the initial surface energy absorptivity of the plate is 0.0951. Thermal convection effect is ignored in the simulation. The radius of light plot on the surface of the plate is 0.5mm.

Fig. 1 is the model of iron has been established.
Lasers Model. In the ideal case, laser pumped from a Q-switch Nd:YAG laser is fundamental mode Gaussian beam. Both time and space distribution of power is in gauss distribution. Power distribution of pulsed laser in time after normalization is shown in Fig. 2.

3. Simulation Result

Pulsed Laser Ablate the Iron Plate. Pulsed laser, which energy of one pulse is 2mJ, 5mJ and 8mJ, irradiate the iron plate. Using one pulse to heat the plate, 3D temperature patterns of the three situations are shown from Fig. 3 to Fig. 5.
Fig. 3 A 2mJ Pulse Heats the Plate

Fig. 4 A 5mJ Pulse Heats the Plate
The surface temperature of the plot area arises quickly in all three situations, and nearly the same area has been heated. The higher energy of a pulse, the higher surface temperature of the heated area is.

When the energy of pulse is 2mJ, the highest temperature of the plate is 460K, the surface energy absorptivity of the plate rises to 0.1467. When the energy of pulse is 5mJ, the highest temperature of the plate is 1434.3K, the surface energy absorptivity of the plate rises to 0.3476. When the energy of pulse is 8mJ, the temperature of the plot area is more than 1812K. In other words, damage has taken place during the burning time. However, when the energy of pulse is 8mJ, the power density of the laser is $6.35 \times 10^{11} W/m^2$, lower than $3 \times 10^{11} W/cm^2$, no plasma would be produced.

As it is shown in Eq. 4 that the surface energy absorptivity of the plate doesn't change when the surface temperature is over 1100K. It is unable to rise surface energy absorptivity of the plate by rising the energy of laser under the condition, so it's unnecessary to use pulsed laser with too high energy. Thus the pulse with the energy of 5mJ is chosen to use as part of combination laser.

**Continuous Laser Ablate the Iron Plate.** Different with pulsed laser, the reaction time of continuous laser is long. When volume of the iron plate isn't too big, all the plate would be heated during several seconds. As is shown in Fig. 5, while using a pulse whose energy is 5mJ to heat the plate, the temperature of the spot area can reach 1434.3K. In other words, the temperature rises by 1136.3K. Ignoring heat exchange effect, we can use Eq. 5 to calculate how much energy continuous laser need if the temperature rises to the same level with the pulsed laser.

$$ P = \frac{c \rho v \Delta T}{At} $$

"c" is heat capacity of iron. "ρ" is iron's density. "V" stands for volume of the model plate.

Substituting values, when the reaction time is 20s, $P=258.3mW$. Continuous laser which average power is 225mW is chosen to irradiate the plate. The result is shown by Fig. 6. The highest temperature of the plate reaches 1496.7K.
Pulsed laser with energy of 5mJ and continuous laser with average power is 225mW are chosen to irradiate the plate. The burning effect of the combination laser is shown in Fig. 6.

Fig.6 225mW Continuous Laser Heat the Plate

Combination Laser Ablate the Iron Plate. Pulsed laser with energy of 5mJ and continuous laser with average power is 225mW are chosen to irradiate the plate. The burning effect of the combination laser is shown in Fig. 6.

As is shown in Fig. 6, the average temperature achieves 1563.2K. It is higher than both that of only using the continuous laser to irradiate the plate and that of only using the pulsed laser. What's more,
damage has happened at the center point after 20s burning. So using pulsed laser before burning can improve the ablation efficiency of the iron plate.

4. Summary
When the surface temperature of the iron plate is under 1100K, the higher surface temperature the plate is, the higher surface energy absorptivity of it. However, if the surface temperature of the plate is over 1100K, the surface energy absorptivity of it doesn't change with temperature. The surface energy absorptivity of the plate rises to 0.0976 from 0.0951 by using pulsed laser with energy of 5mJ and the pulse width of 10ns. If the energy of the pulse rises to5mJ, the surface energy absorptivity of the plate rises to 0.3476. However, if the energy of the pulse becomes 8mJ, the surface energy absorptivity of it doesn't go up anymore.

The highest temperature of the iron plate achieves 1496.7K by using continuous laser with average power is 225mW. The maximum temperature difference of the plate within 1K after burning.

The combination laser consists of the pulsed laser with the energy of 5mJ at the front and the continuous laser with the average power of 225mW follows the pulsed laser. The average temperature reaches 1563.2K, and damage has happened at the center point while burning.

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