Study on Three-Dimensional Temperature Field Induced by Laser Irradiation with Different Intensity Distribution

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Abstract. In this paper, a three-dimensional temperature field simulation model of metal surface irradiated by laser is established to analyze the temperature field distribution of Q235 metal plate irradiated by laser beam. The difference of temperature history and temperature field between Gauss fundamental mode beam and uniform rectangular beam is compared. The results show that the rectangular beam can make the temperature field more uniform, which is more suitable for laser-assisted heat treatment and lamination process.

Introduction

As a new processing method, laser processing technology is widely used in materials, machinery and other industries, involving advanced processing technologies such as laser remanufacturing[1], cutting[2] and quenching[3]. In laser-assisted thermal processing, laser is used as a heat source to irradiate the surface of materials with extremely high power density, which makes the temperature of materials rise rapidly to meet the technological requirements. Subsequently, the material exits the irradiation zone and enters the cooling stage. The heating rate, the maximum temperature and the duration of the processing temperature are the main processing parameters. The temperature field has a great influence on the properties of materials[4]. When laser irradiates materials, the energy flow is complex. Using thermal infrared camera to measure temperature field directly is easy to be disturbed. And when using thermal resistance to measure the internal temperature of materials, the placement of thermal resistance will affect the internal structure of materials, which will also produce errors. Therefore, it will be very difficult to study the temperature field by experimental methods[5]. Most scholars use numerical or simulation methods to study the temperature field of laser irradiation. Wang G[6] established a two-dimensional temperature field model of laser irradiated materials by numerical method. Kashani[7] used Green's function to obtain the analytical solution of the transient temperature field in a rotating cylinder subjected to local laser heat source. Wang Y[8] proposed a numerical simulation method for studying the temperature field of laser quenching process. In summary, the research on temperature field of laser irradiation is mainly focused on two-dimensional simulation, ignoring the temperature field distribution in X or Y asix. And there is little research on the influence of different beam distribution on the time-dependent temperature field history.

In this paper, the three-dimensional temperature field of laser irradiation is studied by simulation model. The temperature history and temperature field distribution of the material are analyzed, and the spatio-temporal distribution differences of temperature field irradiated by Gauss fundamental mode beam and uniform rectangular heat source are discussed.

Mathematical Model of Temperature Field

When metal plate is irradiated by a vertical laser beam, most of the light energy is absorbed and converted into heat energy. As the laser beam moves, heat is continuously transmitted, as shown in Fig. 1. Therefore, according to the first law of thermodynamics, a three-dimensional heat transfer model is established. The equation of transient temperature field is as follows:

$$\rho c \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + \dot{\Phi}. \quad (1)$$

In the formula, ρ is the density of the metal plate, c is its specific heat capacity, T is the instantaneous surface temperature, τ is time, k_x, k_y, k_z is the thermal conductivity of the material in the X,Y,Z direction, $\dot{\Phi}$ is the heat provided by laser heat source to the unit volume of metal plate.

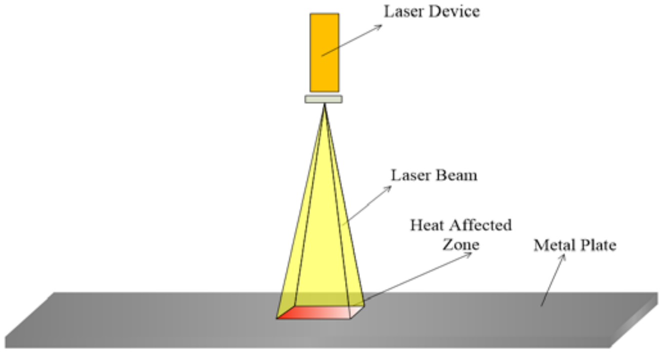


Figure 1. Schematic diagram of laser irradiation

Finite Element Analysis of Temperature Field

In the irradiation process, the material is irradiated by a moving laser beam. The light energy is absorbed and converted into heat energy. The temperature changes with time and this is an unsteady state. Abaqus software is used to analyze the transient thermal of laser irradiation process. The scanning beam is simplified to a moving heat source. The moving heat source is described by a Dflux subroutine to realize a custom distribution of the laser power density and a laser scanning process.

Material Parameters

In this paper, Q235 steel plate is used as the research object. The thermophysical properties of the material change with temperature. The thermal properties of the metal used are shown in Table 1.

Table 1. Metal sheet material parameters

Temperature [℃]	Density [kg/m^3]	Specific heat [J · (kg · K)$^{-1}$]	Conductivity [W · (m · K)$^{-1}$]
200	7 860	745	61.1
300	7 860	770	55.3
400	7 860	783	48.6
500	7 860	833	42.7

Boundary Conditions of Laser Irradiated Metal Plates

Hexahedral mesh and equidistant mesh are used in the model. The boundary condition parameters are shown in Table 2.

Table 2. Model size and boundary condition parameters

Parameters	Value
Sheet metal length [mm]	100
Sheet metal width [mm]	20
Sheet metal thickness [mm]	5
Ambient temperature [℃]	20
Scanning speed [m/s]	0.5

Laser Source Form

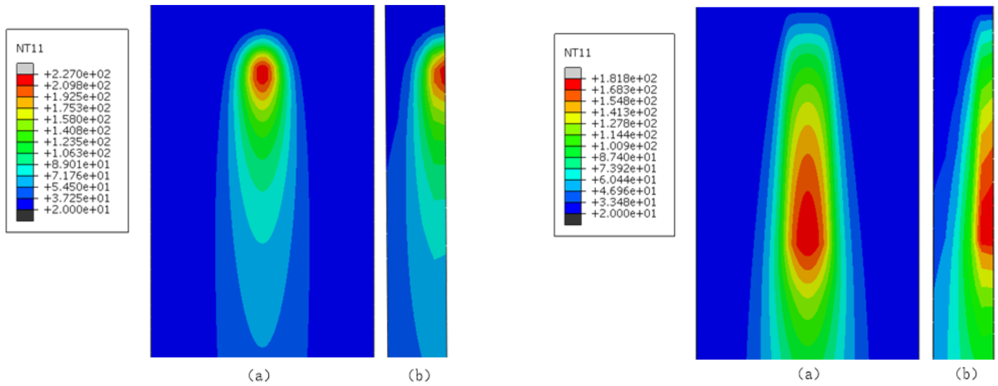
The initial beam emitted from the laser is Gauss beam, whose beam distribution is Gauss distribution. The energy intensity of Gauss beam is strongest in the focus, then gradually weakens.

In actual production, in order to meet special processing needs such as laser quenching and other processes, it is necessary to obtain a uniform temperature field. Therefore, the beam transform technology is used to transform the Gaussian beam into a flat top beam. The beam has a uniform light intensity distribution, so that the temperature tends to be uniform to improve the processing quality.

Results

Overall Analysis of the Temperature Field

The transient temperature fields of metal plates irradiated by Gauss fundamental mode beams and flat-topped rectangular beams are shown in Fig. 2. It can be seen that the heat flow is concentrated in the central area of the material.



(I) (II)

(I) Gaussian beam (II) Rectangular beam (a) X-Y plane (b) Y-Z plane

Figure 2. Transient temperature field

The first half of the Gaussian beam irradiation temperature field is similar to the beam intensity distribution, showing a Gaussian sphere. Due to the rapid movement of the beam, the heat continues to conduct in the material after leaving the laser irradiation zone. So the second half is a semi-ellipsoid distribution. The temperature gradient in the area is large. The maximum temperature exceeds 200℃, but the edge of the spot is only 120℃. The shape of the temperature field induced by rectangular beam is spindle-shaped. Since the beam is evenly distributed in a large irradiation range, the material is subjected to a lower thermal load density than the Gaussian beam, and the temperature field peak temperature is only 180℃, which is significantly lower than the temperature field of Gaussian beam. But the evenly distributed temperature field can reduce the temperature gradient, while the higher temperature heat affected area distribution range is larger.

Temperature History of Central Node

The temperature history of the central point is shown in Fig. 3. The temperature of the central point rises rapidly while being irradiated by the laser beam. The node enters the cooling stage after being separated from the laser irradiation. Its temperature descends to 50℃ at a relatively fast speed and then slowly drops to ambient temperature. In laser assisted machining, the material area remains in the process temperature range for a quite short period of time. Assuming that the suitable processing temperature of the workpiece is 100-200℃. The suitable processing temperature only lasts 207ms when irradiated by Gauss beam. While the rectangular beam lasts 454ms and the suitable processing time is greatly increased compared with that of Gauss beam. Therefore, the rectangular beam is superior to the Gauss beam in processing temperature duration.

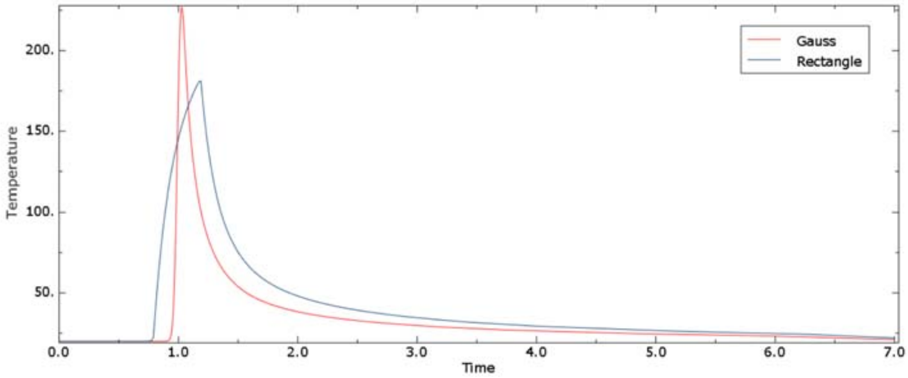


Figure 3. Node temperature history diagram

Temperature Distribution of Different Nodes along the X-axis

The temperature history of the nodes along the X-axis is shown in in Fig. 4. It can be seen from the figure that the beam intensity distribution of Gaussian source is uneven, which leads to large temperature differences. The temperature at the center is the highest. The edge temperature drops rapidly and the temperature gradient is large, and the temperature difference reaches 100℃. When irradiated by uniform rectangular beam, the nodes temperature difference is small in the range of spot. The edge temperature gradient is small, and the effective processing region temperature difference is within 60°C.

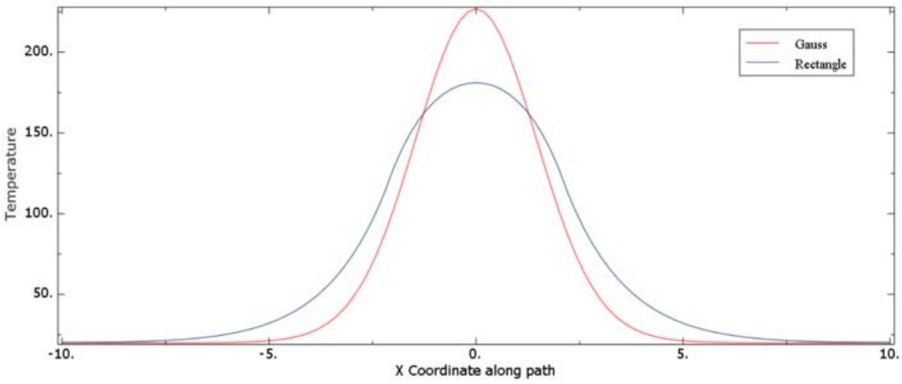


Figure 4. Node temperature distribution in the same Y-axis coordinate

Conclusion

(1) A three-dimensional finite element model of temperature field of laser irradiated metal plate is established. The temperature history of the node and the distribution of the temperature field during laser irradiation are analyzed through the model.

(2) The difference of heat flow distribution and temperature field between irradiated by Gaussian beam and uniform rectangular beam is compared. The results show that rectangular beam is more suitable for laser-assisted heat treatment and lamination process.

(3) Laser processing technology of composite materials has received extensive attention. The anisotropic properties of composite materials have an effect on the temperature field of laser irradiation. Therefore, it is necessary to establish a temperature field model of anisotropic materials.

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