Study on laser irradiation temperature field of carbon fiber reinforced plastic composites

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Abstract

Based on Abaqus software, the temperature profiles during laser heating CFRP materials in different fiber directions was investigated in this research. The 3D temperature distribution and temperature history of laminates with different ply directions were analyzed and compared through the homogenous model. It is found that the focusing characteristics of laser causes a large temperature gradient. Meanwhile, the temperature field of CFRP laminate extends toward the direction of fibers because of the large axial thermal conductivity of carbon fibers. The thermal conduction in the thickness direction is poor, so the lower layer will not reach the melting temperature. In order to verify the validity of the model, a real-time temperature field measurement device consisting of thermal imager and thermocouples was built. The results show that the model can effectively simulate the temperature field of composite materials irradiated by laser.

Nomenclature

CFRP Carbon fiber reinforced composites
CF/PPS Carbon Fiber/Polyphenylene Sulfide
c Equivalent specific heat coefficient
c_c Specific heat capacity of carbon fiber
c_p Specific heat capacity of the matrix
\( \rho \) Equivalent density
\( \rho_c \) Density of carbon fiber
\( \rho_p \) Density of the matrix
\( V_c \) Volume fraction of carbon fiber
\( V_p \) Volume fraction of the matrix.
\( k_c \) Thermal conductivity of carbon fiber
\( k_p \) Thermal conductivity of resin matrix

1. Introduction

The establishment of temperature field model of laser irradiation is of great importance for the study of interaction mechanism between laser and material, which is the main direction of laser-assisted processing technology research [1]. Carbon fiber reinforced plastic composites (CFRP) are composed of carbon fibers and resin matrix. Their thermal properties are different, which makes the temperature field of laser irradiation more complex. Therefore, it is of great significance to study the temperature field of carbon fiber reinforced plastic composites under laser irradiation.
In the process of laser thermal-assisted composite material forming, laser beam scanning the surface of laminate at uniform velocity. The laminate absorbs light energy and converts it into heat energy, then the resin matrix reaches melting temperature. In this process, the distribution of temperature field will affect the properties of forming materials, which is an important parameter of the process. If the temperature is too high, the matrix will degrade [2]. If the temperature is too low, the melting will be incomplete. The thermal conductivity of carbon fibers differs greatly from that of resin matrix, and the anisotropy of carbon fibers leads to the non-uniformity of temperature conduction [3]. The conduction of temperature field will vary with the direction of fibers. In order to explore the mechanism between laser and composite laminates, it is necessary to study the temperature field of composite materials irradiated by laser.

The anisotropy of composite materials has a significant impact on the distribution of temperature field. Zhang Yingcong [4] calculated the transient temperature field of anisotropic materials by means of integral transformation, and found that the anisotropy of materials leads to asymmetric temperature rise. Ohkubo [5] conducted a three-dimensional numerical simulation of the laser processing of CFRP materials, and studied the difference between the melt removal rates of carbon fibers and resins. Yan Hui [6] analyzed the temperature field of the composite under laser irradiation from the perspective of microstructure. The results show that the properties of the matrix have a significant effect on the temperature field. Nanya Lia [7] studied the effect of fiber orientation and layer thickness on temperature distribution and found that laminate thickness is an important factor affecting the temperature field. Therefore, in order to study the temperature field of composite materials, it is first necessary to establish a composite material model. Li Jun [8] established a one-dimensional transient heat transfer model for the curing process of composite laminates. Wang Zhiping and others [9] used Abaqus software to establish a homogenous and fiber-matrix model of CFRP laminates. In addition to the finite element model, Bahad-ori [10] proposed a new three-dimensional transient heat conduction solution for meshless multilayer composites based on Monte Carlo method.

In this paper, the temperature field model of the composite material irradiated by laser was established by Abaqus software, and the distribution of temperature field was analyzed from three dimensions. The fiber-matrix model is simplified as a homogeneous model, and the material parameters of the homogeneous model are calculated. Three samples with different fiber placement methods are used to study the difference of temperature field during laser scanning, so as to explore the influence of fiber direction on temperature field. From the model, the distribution image of temperature field in each layer and the thermal history of characteristic points are obtained, and the peak temperature and temperature curve of temperature field in different layers are compared. In order to verify the accuracy of the model, a real-time temperature field measurement system is established. Through the combination of K-type thermocouple and thermal imager, the surface and internal temperature data of laser scanning composite materials are collected and compared with the temperature history of simulation model.

2. Temperature field model of composite material

In order to study the interaction mechanism between laser and composites, a three-dimensional finite element model of carbon fiber reinforced composites was established. We analyze the influence of anisotropic material properties by simulating the temperature field of samples with different fiber laying angles. In order to simplify the calculation, the fiber-matrix model of carbon fiber reinforced composites is equivalent to the homogeneous model.

2.1. Calculation of equivalent homogeneous model parameters

The material used in this study is carbon fiber reinforced polyphenylene sulfide laminate. The laminate consists of five single layers, whose thickness is 0.3 mm. The material parameters of the laminate are obtained by equivalent calculation. The fibers are laid in 0°, 90° and orthogonal stacking. The sketch of orthogonal ply laminates is shown in the figure 1.

(1) Equivalent specific heat coefficient $c$:

\[ c = \frac{c_r p_f V_c + c_p p_m V_p}{\rho} \]  

Where $c_r$ is the specific heat capacity of carbon fiber, $c_p$ is the specific heat capacity of the matrix, $p_f$ is the density of carbon fiber, $p_m$ is the density of the matrix, $V_c$ is the volume fraction of carbon fiber, and $V_p$ is the volume fraction of the matrix.

(2) Equivalent heat transfer coefficient:
Taking a 0° single-layer board as an example, the thermal conductivity $k_x$ of the laminate along the fiber direction is:

$$k_x = k_c \left( \frac{k_c}{k_p} - 1 \right) V_c + 1$$

(2)

The thermal conductivity $k_y$ perpendicular to the fiber direction:

$$k_y = \frac{k_p}{\left( \frac{k_p}{k_y} - 1 \right) V_c + 1}$$

(3)

Where $k_c$ is the thermal conductivity of carbon fiber, $k_p$ is the thermal conductivity of resin matrix, and $Z$ direction is the same as $y$ direction.

The laser moves uniformly along the X direction of the laminate. The laminate absorbs light energy and converts it into heat energy. Heat is transferred from the surface to the lower layer. According to the first law of thermodynamics, a three-dimensional heat transfer model of pavement is established. The heat transfer equation is as follows:

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

(4)

Where $\rho$ is the density of the composite, $c$ is its specific heat capacity, $T$ is the instantaneous temperature, $\tau$ is the time. $k_x$, $k_y$, $k_z$ are the corresponding thermal conductivities along the corresponding coordinate axis. $\Phi$ is the heat provided by laser heat source for unit volume of laminate.

3. Finite element simulation of laser heating based on abaqus

In the process of laser irradiation, the laser moves uniformly along the X-axis. The irradiated area of the laminate is constantly changing. The temperature field is in a dynamic process. Therefore, the irradiation process is a non-steady heat transfer process. In this paper, laser irradiation process on composite laminates is simulated by Abaqus. The transient temperature field of each layer and the temperature history of the joint are analyzed.

3.1. Finite element analysis of temperature field

In the finite element software, the governing equation of heat conduction for transient thermal analysis is as follows:

$$[C][\dot{T}] + [K][T] + [R][T^4] + P = 0$$

(5)

where $[C]$ is the specific heat capacity matrix, $[\dot{T}]$ is the derivative matrix of nodes’ temperature to time, $[K]$ is the heat conduction matrix, $[T]$ is the nodes’ temperature matrix, $[P]$ is the heat load matrix. After entering material parameters and boundary conditions, the software can calculate the node temperature according to the equation. In this paper, in order to study the three-dimensional temperature field of laminates irradiated by laser, three-dimensional solid DC3D8 element is selected. DC3D8 element is 8-node element. In Abaqus, this element has only one degree of temperature freedom. The three-dimensional solid element can clearly present the temperature field in three directions, which is convenient for its analysis.
3.2. Material parameters and boundary conditions

The thermal properties of the resin-based composite such as density, specific heat capacity, and thermal conductivity vary with temperature. Meanwhile, the change of material properties is non-linear. In this paper, carbon fiber reinforced polyphenylene sulfide matrix composites are used as the research object. After calculation, the equivalent material properties of the laminates are shown in the table 1.

3.3. Finite element simulation model of composite materials

In order to simplify the calculation, a three-dimensional flat plate model is used in this simulation. Equidistant meshing is used in the model. Laminate is given material properties layer by layer. The specific model size and boundary condition parameters are shown in the table 2.

4. Finite element simulation analysis

4.1. Temperature field of unidirectional fiber reinforced composite

The transient temperature field is shown in figure 2, when the Gaussian beam scans the sample, whose fibers are laid at 0 degrees. The front part of the laminate surface is directly irradiated by laser. Laser irradiation is the most important factor in this area. Therefore, the shape distribution of the temperature field in the first half is a semi-circle with Gauss distribution, which is similar to the beam energy distribution. The axial thermal conductivity of the carbon fiber reaches 10 times in the radial direction, which makes the heat conduct faster on the X-axis, and the latter half of the temperature field is narrow and long. The CF/PPS material reached the melting requirement at 300 °C and began to degrade at 450 °C. Therefore, the target temperature is assumed to be 300 °C–450 °C in this study. The maximum width of the region on the top layer, which is above 300 °C is 4 mm. The temperature distribution of the second layer is similar to the shape of the surface temperature field. The maximum temperature is 92.1 °C, which is lower than the surface temperature. Meanwhile, the high temperature region shrinks to 3 mm. While the region, whose temperature is between 200 °C and 300 °C is basically the same as the surface.

The temperature field of the sample whose fibers are laid at 90° is shown in figure 3. This temperature field is significantly different from the 0° sample, and the maximum temperature is 13.3 °C lower than the 0° sample. Due to the change of the fiber direction, the heat transfer coefficient on the Y-axis is higher. Therefore, the temperature field slightly extends to the Y-axis, the width of the high-temperature region is increased by 1 mm. But the distribution in the X-axis direction is shortened, so the temperature duration will be reduce. The temperature field of the second layer also shows a trend toward the Y-axis. The length of the high temperature region is shorter. The peak temperature is 90.5 °C lower than the first layer, and the temperature difference is slightly smaller than the 0° sample.

The temperature histories of the central joints of each layer of 0°, 90° fiber reinforced composite board are shown in figures 4 and 5. Taking a 0° sample as an example, the surface is in a natural convection state before

| Temperature/°C | Density/(kg m⁻³) | Special heat/(J kg⁻¹ °C) | Axial conductivity/(W/(m °C)) | Transverse conductivity/(W/(m °C)) |
|----------------|------------------|--------------------------|-------------------------------|-----------------------------------|
| 0              | 1660             | 890                      | 3.2                           | 0.38                              |
| 100            | 1641             | 1138                     | 4.2                           | 0.49                              |
| 200            | 1613             | 1452                     | 6.2                           | 0.59                              |
| 300            | 1584             | 1705                     | 6.7                           | 0.65                              |
| 400            | 1551             | 1800                     | 7.0                           | 0.69                              |

Table 2. Model Size and Boundary Conditions.

| Parameter                              | Value |
|----------------------------------------|-------|
| Laminate length/m                      | 0.1   |
| Laminate width/m                       | 0.02  |
| Single Layer Thickness/mm              | 0.3   |
| Ambient temperature/°C                 | 25    |
| Beam scanning speed/m s⁻¹               | 0.05  |
| Laser power/W                          | 100   |
being irradiated by laser. When the surface node is subjected to laser scanning, the heat source makes its temperature rise rapidly. The heating rate reaches $1501.5 \, ^\circ\text{C} \, \text{s}^{-1}$. The node is separated from the laser irradiation area at 0.2 s. At this time, the temperature reaches a peak value of $442.9 \, ^\circ\text{C}$. Then, the temperature begins to decrease at a rate of $419.5 \, ^\circ\text{C} \, \text{s}^{-1}$, and the rate of temperature drop is continuously decreasing. During this process, the node temperature, which is in the processable range lasts for 0.56 s. Heat is transmitted downward
from the first layer, which is directly irradiated by laser and has a higher temperature. Because of the heat conduction between layers, the lower nodes will still rise to a certain temperature after leaving the illumination area. So the peak temperature will appear later than the surface nodes. The peak temperature of each layer is quite different. The peak temperature of second layer is 92.1 °C lower than that of the first layer, and the duration of reaching the melting temperature is 0.37 s. The peak temperature of third layer is 135.9 °C lower than that of the second layer and does not reach 300 °C. At the same time, the lower layer temperature is lower, and can’t reach the melting temperature. This indicates that the rest layers that have already been laid will not be affected during processing. When the peak temperature is reached, the cooling rate of each layer is continuously reduced. The whole laminate begins to slowly cool to room temperature, when the temperature of each layer is reduced to substantially the same. The temperature history of the 90° sample is basically the same, the highest surface heating rate is 1448.6 °Cs⁻¹, the peak temperature is 429.8 °C, the highest temperature drop rate is 529.6 °Cs⁻¹, and the melting temperature duration is 0.37 s. Compared with the 0° sample, the heating rate is slightly lower, while the cooling rate is higher, so the temperature duration is greatly shortened. The peak temperature difference of the first and second layers is 90.5 °C. The melting temperature of the second layer lasts for 0.20 s. Meanwhile, the temperature difference of the second and third layers reaches 147.75 °C. It can be seen that when the fiber direction is perpendicular to the laser scanning path, because of the higher thermal conduction in the width direction, the temperature field is slightly diffused, which makes the heat dissipate to sides. The lower layer, which is dominated by interlayer thermal conduction, will produce a larger temperature gradient.

In conclusion, the temperature field conduction direction of the unidirectional composite laminates is mainly determined by the beam scanning path and material parameters. Due to the higher thermal conductivity along the fiber axis direction, the fiber laying direction has a greater influence on the temperature field. The temperature field distribution will extend along the fiber axial direction, while the radial conduction range is smaller, thereby affecting the processable area and the operable time. When the fiber direction is consistent with the scanning direction, the heat concentration, the heating rate of the irradiation center is the highest, and the temperature difference of the lower layer is small. When the fiber direction is perpendicular to the scanning direction, the temperature field will extend slightly to the width direction, the peak temperature will decrease, and the temperature duration will be shortened, resulting in shorter processing operation duration and wider processing area.

4.2. Temperature field of orthogonal fiber composites

The temperature field is shown in figure 6, when the laser scans the laminate sample which is stacked orthogonally at 0°/90°. The top layer is laid at 0°, resulting in a peak temperature of 441.9 °C, which is consistent with the distribution of 0° unidirectional layer samples. The maximum temperature of the second layer is 346.3 °C. The width of the high temperature zone is slightly increased, while the length is much shorter. It can be seen that the orthogonal placement of the fibers has less influence on the top layer, which is directly irradiated by the laser. However, the inconsistency of fiber directions between different layers has a great influence on the heat conduction between the layers.

The temperature history of the center node of the orthogonal sample is shown in the figure 7. After being irradiated by laser, the temperature of the surface center node rises to 441.9 °C at a rate of up to 1500.6 °Cs⁻¹. The cooling trend is basically the same as that of the unidirectional laminates. The rate is 439.6 °Cs⁻¹, and the melting temperature lasts for 0.50 s. The temperature difference between the first and second layers is 95.5°C,
and the third layer is 145.0 °C. The melting temperature of the second layer lasts for 0.28 s, which is greatly shortened.

In summary, the single-layer temperature field of the orthogonal sample is similar to that of the unidirectional plate sample. Since the laser irradiation is the main factor affecting the surface temperature field, the uppermost temperature field is basically the same as the 0° sample. The orthogonal placement of the fibers results in a large difference in material properties between the two layers, which is not conducive to the heat conduction between the layers, so that the temperature difference of the lower layer is increased and the duration of the melting temperature is reduced.

5. Laser irradiation temperature field experiment

In order to verify the composite temperature field simulation model, a laser irradiation temperature field measuring device was built to measure the surface temperature field and the interlayer temperature history of the laser irradiated carbon fiber reinforced composite laminate.

5.1. Real-time temperature field acquisition device

The complete set of laser equipment is provided by GW Company, including laser head, laser water cooler, laser controller and other equipment. The laser is SMAT 3c-500mc fiber laser. It can provide 500 W CW single-mode output light and the output band between 900 nm and 1100 nm. The laser head and material are fixed on a three-dimensional moving guide rail controlled by a stepping motor controller, and the model is Suruga Seiki D120. The moving accuracy of guide rail is 0.01 mm. Surface temperature field is captured by a Fluke Ti45FT thermal infrared camera, which provides direct access to the temperature field distribution image. Thermal imager accuracy reaches 0.08 °C and maximum measurable temperature reaches 1200 °C. Since the ordinary infrared

![Figure 6. Temperature field of orthogonal ply laminates.](image)

![Figure 7. Temperature history of the center point between orthogonal sample layers.](image)
thermometer cannot measure the temperature inside the material, the K-type thermocouple is used to measure the temperature inside the laminate in this experiment. In order to measure the internal temperature field, four thermocouples are fixed at the center points and the points which are 5 mm away from the central points between the first, second and third layers as shown in the figure 8. The temperature history of the center point and its surrounding area is measured. The voltage signal is processed by the acquisition circuit and transmitted to the Labview software by the NI USB-6009 data collector, and then converted into temperature data. Placement of thermocouples can cause variations in the thickness of the composite layer. In order to reduce the thickness variation and the voids caused by the thermocouple placement, the thermocouples are staggered. Since the temperature field is symmetrically distributed, the thermocouple is placed only on one side of the center point.

5.2. Analysis of results
5.2.1. Thermal infrared camera image
Figure 9 shows the thermal infrared image taken by the Ti45FT thermal infrared camera when the 100 w laser scans the laminate at a speed of 5 cm s⁻¹. It can be seen from the figure that the temperature field of the experimental laser irradiation region is basically the same as the simulation model. The peak temperature is 442.4 °C, appearing in the center of the irradiation zone, the high temperature zone is elliptical as is in the simulation model. Due to the thickness variation of the laminate caused by the thermocouple mounting, the laser scanning path is uneven, and the temperature field in the middle section is notched, matching the true situation.

5.2.2. Temperature history of nodes
Figure 10 is a comparison of temperature signals collected by thermocouples through data acquisition devices and simulation temperature history. The full line is the temperature history of four test points measured by temperature measurement circuit, and the dotted line is the simulation temperature history. From the image, it can be seen that in actual measurement, because of the heat transfer process between the measuring head and the material, the actual temperature is obtained after the temperature is transmitted to the thermocouple. As a result, the temperature signal is 0.05 s later than the simulation process. The peak temperature of point B is 346 °C, which is 4 °C lower than the simulation temperature. The thickness of interlayer increases slightly due to the laying of thermocouples, and the gap between layers contacts with air, which makes the test temperature
slightly lower than the simulation temperature. However, the trend of the whole temperature history is basically consistent with the simulation results.

In summary, the three-dimensional temperature field measuring device consisting of a thermal imager and thermocouples can accurately measure the laser irradiation temperature field. Because of the placement of thermocouples, the thickness of laminates changes slightly. This resulted in gaps that caused the inter-layer temperature to be lower than the model. The experimental results are basically consistent with the simulation results, which shows that the simulation model is effective.

6. Conclusion

(1) Based on Abaqus software, the finite element model of temperature field of laser irradiated carbon fiber reinforced plastic composite laminate was established. The temperature field distribution and temperature history of each layer in different fiber direction samples were studied. And the influence of carbon fiber direction on the temperature field of composites was analyzed. The results show that since the thermal conductivity coefficient of carbon fiber in the axial direction is much larger than the radial direction, the temperature field conduction will extend along the fiber placement direction. When the fiber direction is the same as the laser scanning direction, the temperature field presents a narrow and long shape, which leads to the highest heating rate, and the temperature difference of lower plies is small. When the fiber direction is perpendicular to the laser scanning direction, the temperature field will extend to the width direction, making the processable width larger, but the peak temperature is lower, and the high temperature duration is shortened. It can be seen that the fiber direction will be an important parameter in actual processing. Meanwhile, it can be found that the heat conduction between the composite layers is poor, and the peak temperature of the third and lower layers is lower than 200 °C, which indicates that the laser can process the upper material without affecting the lower layer too much.

(2) A temperature field real-time measuring device was built. The surface temperature field and internal temperature history of the laser-irradiated carbon fiber reinforced plastic composite laminate were measured by the combination of thermal imager and K-type thermocouple. Although the temperature field is affected by the gap between layers caused by the laying of thermocouples, the experimental results are consistent with the simulation model, and the error is small. It is verified that the finite element model established in this paper can accurately model the temperature field produced by laser scanning composite materials.

(3) The study of the temperature field during laser scanning of composite materials in this paper reveals the influence of fiber orientation and the number of composite layers, which has guiding significance for laser composite processing technology. The huge advantages of laser-assisted layup processes make it an important new technology for the preparation of composite materials. In the following work, a dynamic model of laser-assisted composite layup will be established on the basis of this model. The change of the temperature field during the laser-assisted composite lamination process in which the material gradually adhered to the substrate was studied. To make the model more accurate, parameters such as the laser angle, frequency and other parameters, which can also influence the temperature field will be to the model.
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