Damage technology of carbon fiber composites by high-power laser

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Abstract. Based on the layer characteristics of the carbon fiber and resin composites, the damage mechanism of high power laser beam on the carbon fiber target are investigated. Analyzing the laser ablation target, the layer ablation mechanism is introduced, which is composed of an ablation layer, a pyrolysis layer and an original layer. The finite element model of the laser ablation the carbon fiber composites was established, in which a Gaussian laser beam irradiated perpendicularly on the target. Because of the advantages of finite element gridding in spatial domain and finite difference gridding in time domain, the “birth and death element” method was used to accurately simulate the temperature distribution field of the laser damage target, and those elements were sequentially stripped, i.e. "killed", exceeding the vaporization temperature “point” of the carbon fiber composites during the laser heating until the laser is shut off. Moreover, the laser damage experiment on the carbon fiber composites was carried out, the temperature distribution field of the laser irradiated target was measured, and the burn-through time of the carbon fiber target was recorded. It is found show that the birth and death element method with the sequent stripping way can be used accurately to simulate the three-dimensional temperature distribution field of the target and evaluate the laser damage efficiency to the targets.

1. Introduction

In recent years, high energy laser weapons destroy unmanned Aerial Vehicle(UAV) and other targets become a research hotspot, and the materials used for UAV are mainly composed of carbon fiber composite materials or glass fiber reinforced plastic materials. At home and abroad, the research on laser irradiation targets is mainly focused on metal shells, but the research on fiber reinforced composite materials, especially laser irradiation carbon fiber composite materials is still less. At present, a lot of research work has been done on the solution of laser irradiation target temperature field [1-6]. Wang Yizhong carried out an experiment of irradiating a carbon fiber composite material
with pulsed laser to study the thermal effect generated by laser, and established a one-dimensional thermal ablation model by programming [7]. Zhang Jialei et al. conducted laser irradiation experiments on two-dimensionally woven carbon fiber / epoxy resin composites, and obtained the temperature rise characteristics of the carbon fiber composites before and after the surface [8]. Li Gan studied the thermodynamic response of the mesostructure of fiber composites under laser irradiation and its effect on the macroscopic irradiation effect of materials [9]. Chun Lu et al. [10] analyzed the thermal stress distribution of carbon fiber epoxy resin composites by establishing the three-dimensional finite element model. The VonMises criterion was used to find the difference in thermal stress distribution and size in different regions. The main focus was on the analysis of crack distribution. Li Yazheng et al. [11] established a transient temperature field model of composite materials, and compared the calculated temperature and test results with and without ablation. At present, research on the temperature field and thermal properties of carbon fiber composites has made some progress [12-18], but the calculation methods and theories still have some limitations such as idealization, so the temperature of carbon fiber composites under laser radiation field distribution theory requires more in-depth research. Based on the characteristics of sequential stripping of carbon fiber targets under laser irradiation, the birth and death element method was used to simulate the three-dimensional temperature field generated by high-energy laser irradiation of carbon fiber composites, which is closer to the actual ablation characteristics of the target.

2. Damage Mechanism of Laser Irradiated Carbon Fiber Target
Carbon fiber composite materials are mainly composed of carbon fiber and resin matrix. Fiber is the main bearing phase of the composite material. The resin matrix and the composite interface mainly play the role of uniformly distributing and transmitting loads. Under high power density laser irradiation, the resin matrix will pyrolyze, burn, vaporize and ablate at low temperatures. Carbon fiber is an inorganic fiber, which is prone to oxidation and vaporization at high temperatures. These will be the reduction of the binding properties of the composite material, which will lead to the decrease of the elastic modulus and mechanical properties of the composite material. The mass loss caused by the pyrolysis of the resin matrix material and the thermal stress generated by the composite material due to the temperature field will cause the carbon fiber composite material and its structure to be destroyed in advance.

The absorption of laser by carbon fiber composite material belongs to surface absorption. At the initial stage of laser irradiation, the material heats up by its own heat capacity to heat up. Before reaching the resin pyrolysis temperature, the heat transfer method in the material is mainly heat conduction. When the temperature reaches the pyrolysis temperature of the resin matrix of carbon fiber composites (usually more than 300°C), the resin matrix material starts to absorb heat and pyrolyze. The resin matrix decomposes to generate volatile gases and leaves porous coke. When the temperature exceeds a certain temperature, the pyrolysis reaction of the resin matrix is basically ended, leaving only inert porous coke. Except for the coke left by pyrolysis of the resin matrix, the composition of carbon fiber has not changed at this time, but it has a certain softening effect. When the temperature reaches the vaporization temperature of the carbon fibers, the carbon fiber fibers begin to vaporize. In numerical simulation, stratification was achieved by changing the parameters of the
density, thermal conductivity, and specific heat coefficient of the carbon fiber target. The specific process can be represented by figure 1.

![Diagram of laser heating carbon fiber target](image)

**Figure 1.** A schematic view of laser heating the carbon fiber target.

### 3. Thermal effect of laser irradiation on carbon fiber targets

#### 3.1. Temperature field under laser irradiation

The basic forms of heat transfer are mainly divided into heat conduction, heat convection and heat radiation. When the sample laser beam irradiates the material, its energy is absorbed by the surface layer of the material and converted into thermal energy. This heat is diffused inside the material through heat conduction, and simultaneously radiates heat to the surrounding environment through the boundary, such as surface radiation loss, thermal convection loss, etc., thereby forming a temperature field. In rectangular coordinate system, the general form of the transient heat conduction partial differential equation is written as:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right)$$  \hspace{1cm} \text{(1)}

where $T$ is the temperature field, $\rho$ is the material density (kg/m$^3$), $c$ is the specific heat capacity (J/kg.K). The boundary conditions for laser-irradiated carbon fiber targets are:

$$T = T_0 \hspace{1cm} \text{(2)}$$

$$k_x \frac{\partial T}{\partial x} n_x + k_y \frac{\partial T}{\partial y} n_y + k_z \frac{\partial T}{\partial z} n_z = q \hspace{1cm} \text{(3)}$$

$$k_x \frac{\partial T}{\partial x} n_x + k_y \frac{\partial T}{\partial y} n_y + k_z \frac{\partial T}{\partial z} n_z = h(T_0 - T) \hspace{1cm} \text{(4)}$$

where $q$ is the laser heat flux density at the boundary, $h$ is the convection heat transfer coefficient, $k_x, k_y, k_z$ are the thermal conductivity of the material in the $x, y, z$ directions, $n_x, n_y, n_z$ are the direction cosines of the normal outside the boundary.
3.2. Finite element model of temperature field

The calculation of the temperature field of a carbon fiber target using the finite element analysis method is specifically: dividing a three-dimensional model using a finite element network in a spatial domain, discretizing a solution domain, and discretizing a three-dimensional model of continuous spatial distribution into different sizes and shapes and connected to each other. The finite-difference method is used to mesh in the time domain, and appropriate numerical differentiation is used at each time step to achieve the purpose of using the difference quotient to replace the differential quotient in the partial differential equation, thereby obtaining a numerical solution. The time difference format of the three-dimensional transient temperature field problem can be specified as:

\[ \theta^{t+\Delta t} \left( \frac{\partial T}{\partial t} \right) + (1 + \theta) \left( \frac{\partial T}{\partial t} \right) = \frac{1}{\Delta t} \left( T^{t+\Delta t} - tT \right) \]  

(5)

where \( \Delta t \) is the time step, \( \theta \) is the time integration parameter, which value range is \( 0 \leq \theta \leq 1 \). A backward difference format is used with \( \theta \) of 0.5, which is characterized by high accuracy and unconditional stability. The finite element governing equation of the temperature field can be expressed as:

\[ [K_{th}] \{ T \} + [C] \{ \dot{T} \} = \{ Q_a \} \]

(6)

where \([K_{th}]\) is the heat conduction matrix, \([T]\) is the node temperature column vector, \([C]\) is the specific heat matrix, \([\dot{T}]\) is the temperature change rate matrix, \([Q_a]\) is the column vector of applied temperature load. For time intervals \( t \rightarrow t + \Delta t \). The temperature field governing equation takes the following form:

\[
\begin{cases}
[K_{th}] \{ T \} + [C] \{ \dot{T} \} = \{Q^t\} \\
[K_{th}]^{t+\Delta t} \{ T \} + [C]^{t+\Delta t} \{ \dot{T} \} = \{Q^{t+\Delta t}\}
\end{cases}
\]

(7)

where the upper left is the time node. The temperature field \( t^{t+\Delta t} \{ T \} \) at time \( t + \Delta t \) can be obtained by formula (7) and the temperature \( t^t \{ T \} \) at a certain time. At the beginning of the solution, the initial temperature field of the model is determined, the temperature field at the next time step can be obtained. Through continuous calculation, the temperature field distribution of the entire time course can be obtained.

During the process of laser ablation the target, the thermal physical parameters such as the thermal conductivity and specific heat capacity of the material will rise with its temperature. The iterative method is used to solve the temperature control equations in equation (7) at two moments:
\[
\begin{align*}
\begin{cases}
\tau + \Delta t[K_{th}]^{(j)} + \tau + \Delta t[C]^{(j)} + \tau + \Delta t[T]^{(j)} = \\
\tau + \Delta t[Q_a]^{(j)}
\end{cases}
\end{align*}
\]

(8)

where \( i \) is the number of iterations. The initial conditions for simultaneous iteration are the thermal conductivity matrix at time \( t \), the specific heat matrix at time \( t \), and the temperature load column vector at time \( t \):

\[
\begin{align*}
\tau + \Delta t[K_{th}]^{(0)} & = \tau [K_{th}] \\
\tau + \Delta t[C]^{(0)} & = \tau [C] \\
\tau + \Delta t[Q_a]^{(0)} & = \tau [Q_a]
\end{align*}
\]

(9)

Use the corresponding thermal conductivity matrix, specific heat matrix, and temperature load column vector under the temperature distribution at the previous time point as the initial values \( \tau + \Delta t[K_{th}]^{(0)} \), \( \tau + \Delta t[C]^{(0)} \), and \( \tau + \Delta t[Q_a]^{(0)} \) at the beginning of the next time point. Substituting the initial iteration value into equation (8) can obtain the temperature correction values \( \tau + \Delta t[T]^{(1)} \) and \( \tau + \Delta t[T]^{(1)} \) for the first iteration. Then the next iteration is performed, and the values of \( [K_{th}] \), \( [C] \), and \( [Q_a] \) are updated at the same time, and a new round of temperature correction values \( \tau + \Delta t[T]^{(2)} \) and \( \tau + \Delta t[T]^{(2)} \) are obtained. The stopping condition for this iteration is be specified as:

\[
\left| \frac{\tau + \Delta t[T]^{(i+1)} - \tau + \Delta t[T]^{(i)}}{\tau + \Delta t[T]^{(i+1)}} \right| \leq \eta
\]

(10)

Among them \( \eta \) is the allowable error. When the result of the \( i \)-th iteration and the result of the \( i + 1 \)th time satisfy the conditions of Equation (10), the calculation at this time step is ended and the calculation of the next time step is entered. By calculating the temperature field of each time node in this way, the temperature field distribution of the entire time history can be obtained.

4. Temperature field simulation

The birth and death element method is to "kill" the element when its physical quantity exceeds a threshold value. The process of heating a carbon fiber material by a Gaussian laser beam can be understood as the element is killed when the temperature of the carbon fiber reaches the vaporization point. In practice, the specific implementation method is to multiply the element to be "killed" by a very small attenuation coefficient in the rigid matrix, so that the unit is no longer involved in heat transfer [7].
4.1. Finite element calculation model

Since the material exhibits complex, nonlinear, and transient thermal behavior during laser irradiation, the following basic assumptions are adopted in order to simplify the numerical model while maintaining high consistency with the actual process: (1) The spot emitted by the laser beam is loaded on the surface of the composite material plate as a surface heat source. (2) The absorption rate of the laser light on the surface of the carbon fiber target is constant. (3) Radiation heat loss from the surface, heat radiation does not account for the main part. In the process of laser irradiation, the influence of temperature on the specific heat and thermal conductivity of the target is considered, so the governing equation can be changed to Equation (6), where the specific heat, thermal conductivity, and density are all related to temperature function [8]:

$$
\rho(T)e(T) \frac{\partial T(x, y, z, t)}{\partial t} = K(T)\nabla^2 T(x, y, z, t)
$$

(11)

Initial condition is:

$$
T(x, y, z, 0) = T_e
$$

(12)

where $T_e$ is the ambient temperature. Considering the effect of thermal convection on heat loss, the boundary conditions can be expressed as:

$$
k_e \frac{\partial T}{\partial z} = A Q - h(T - T_e)
$$

(13)

where $A$ is the absorption coefficient of the target to the laser, which can generally be regarded as a constant value, $Q$ is the heat source on the laser irradiation surface, $h$ is the natural convection exchange coefficient, and the heat dissipation effect is ignored on other surfaces.

4.2. The finite element model

A carbon fiber composite material model was established by using finite element analysis software. The length and width of the model were both 1 cm and 3 mm thick. Considering the symmetry of the model and the time performance of the calculation, 1/4 of the model is taken for simulation. Figure 2 is a schematic diagram of the target mesh division. The solid unit SOLID 70 was used, which was divided into 37500 elements in total.

![Figure 2. Grid used in the simulations.](image)

The thermal physical properties of the carbon fiber reinforced composites are based on the results
in literature [6]. These parameters used in the simulations are given in table 1, where \( T, c, k, \rho \) are the temperature, the specific heat capacity, the thermal conductivity and the density. In this paper, the specific heat capacity is used to reflect the chemical reaction heat of the material, and the density change is used to explain the mass migration caused by the thermal decomposition of the substrate. The carbon fiber sublimation temperature is 3316°C, and the laser absorption coefficient of the composite material is 0.92.

**Table 1.** The material parameters used in the simulations.

| T/°C | \( c \)/\((\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1})\) | \( k/(\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1})\) | \( \rho/(\text{kg}\cdot\text{m}^{-3})\) |
|------|----------------|----------------|----------------|
| 10   | 1225.0         | 13.86          | 1596.7         |
| 330  | 2056.9         | 6.86           | 1596.7         |
| 357  | 5009.5         | 6.27           | 1596.7         |
| 496  | 4904.6         | 3.23           | 1596.7         |
| 523  | 3249.2         | 2.64           | 1596.7         |
| 524  | 1593.9         | 2.62           | 1149.7         |
| 565  | 1607.3         | 2.05           | 1149.7         |
| 815  | 1689.3         | 1.73           | 1149.7         |
| 3316 | 2509.8         | 1.73           | 1149.7         |

At the same time, we set the ambient temperature to 20°C, and the initial temperature of the target to 20°C. A two-dimensional Gaussian laser heat flux is applied to the model with a surface heat flux density \( \dot{q} = aQ_0 \exp(-\frac{2(x^2 + y^2)}{R^2}) \) on the upper surface of 3mm thickness, where \( Q_0 \) is 1528W/cm², and \( \alpha \) is 0.92 expressed a laser absorptivity, and the radius \( R \) applied to the model is 0.5cm.

4.3. **Numerical solution**

A laser surface load is applied to the surface of the unit, and the center of the circle of the light spot is located at the center of the surface of the test piece. With the progress of laser irradiation, the temperature of the composite material plate continued to increase at the laser irradiation, and the average temperature of the node of the unit represents the critical value for whether the unit was detached. When the average node temperature of some elements reaches the set unit removal temperature threshold (3316°C), the element dies, the element of death is removed, and the thermal load originally applied to the removed unit is assigned Give the next layer of elements, and then continue to calculate the laser irradiation effect on the material at this time. The entire process is repeated in this way until the set irradiation time is reached. The specific laser ablation simulation steps are shown in figure 3.
Begin
Create finite element models, mesh, and apply loads

Perform laser numerical simulation to calculate new temperature field

Update target element model, thermal load and boundary conditions

Is there a failed unit

Y
N

Y

End

Figure 3. Laser ablation simulation flow chart.

(a) Beginning of heating (b) Laser irradiation moved to the next element

Figure 4. Schematic diagram of laser irradiation boundary.

5. Experimental results and discussion
The thickness of the carbon fiber composite target is 3mm, the laser irradiation power is 1200W, and the circular spot diameter is 1cm. From this, the laser power density is 1528W/cm\(^2\), and the relevant target temperature is recorded with an infrared camera. The specific experimental device layout is shown in figure 5.

Figure 5. Experimental schematic of the carbon fiber target irradiated by laser.

Less than 1 second after laser irradiation, the carbon fiber target material produces a certain amount of dense smoke and emits dazzling light. In the time period from 1s to 2s, the carbon fiber target began to burn, accompanied by more intense dense smoke. Subsequently, the high temperature area
continued to expand, and the carbon fiber target material was burned through at about 6.8s. The left side of figure 6 shows the carbon fiber sheet burning when the laser irradiated the carbon fiber sheet, and the right side shows the ablation appearance after 3 seconds of laser irradiation. As can be seen from the figure on the right, some of the carbon fibers on the front surface of the carbon fiber target have been broken, and black coke around the circular light spot. The back surface of carbon fiber board has not been completely burned through, forming ablation layer, pyrolysis layer and original layer.

![Burning Carbon fiber target and Ablation appearance after Laser irradiation at t=3s](image)

**Figure 6.** Carbon fiber target combustion and ablation after the ending of heating 3s.

Figure 7 shows the temperature field distribution of the carbon fiber target for the time corresponding to 0.5s, 1s and 1.5s, the unit is °C. It can be seen that the temperature distribution of the carbon fiber target in the X, Y and Z directions is symmetrical. The highest temperature region extends in the Y direction, and the temperature difference between the front and back surfaces of the target is huge at 1.5s. The temperature of center point of target front surface has reached 3905.55°C, and the temperature at the center of the rear surface is less than The main reason for this phenomenon is that the carbon fiber composite target is anisotropic, and there is a large gap between the heat conduction capacity in the Y direction and the heat conduction capacity in the X and Z directions, They are almost 50 times worse in value.

![Temperature field distribution along the radial direction for different t values](image)

**Figure 7.** Temperature field distribution along the radial direction for different t values.
Figure 8 shows the temperature change from the center point of the front surface of the target from time 0s to 1.5s. From the figure, it can be seen that the slope edge of the temperature rise curve of the center point of the front surface of the target becomes 0.2s. The main reason is that in the vicinity of 0.2s, the center point of the target is undergoing a phase change and a pyrolysis reaction is underway.

![Temperature-Time Curve](image)

**Figure 8.** Time distribution of the surface temperature at the center point of the target.

Figure 9 shows the temperature distribution during the ablation process.

![Spatial Temperature Distribution](image)

**Figure 9.** A schematic view of spatial temperature distribution for the target.

From the simulation results, when the carbon fiber target is irradiated with laser for 6s, the laser just burns through the carbon fiber target, which is not much different from the 6.8s measured in this experiment. The main reason that the simulated burn-through time is shorter than the experimental burn-through time is that a large amount of dense smoke has taken away some of the heat, making the ablation speed slow.

6. **Conclusion**

Based on the ablation characteristics of carbon fiber targets, the finite element model for laser ablation of carbon fiber targets was established, and the three-dimensional temperature field during laser ablation of carbon fiber targets was simulated using the birth and death element method. The carbon fiber target ablation process was divided into an ablation layer, a pyrolysis layer and an original layer, which are reflected in the simulation process through changing thermo-physical parameters.
Temperature field is computed by using the control approach. Finally, a damage experiment of high-power laser irradiation on carbon fiber targets was carried out, and the temperature field distribution and burn-through time at the initial stage of irradiation were recorded. The experimental data with the results of numerical simulations was compared. It is found that the birth and death element method can more accurately simulate the temperature field distribution of the carbon fiber target ablated by laser heating.

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