Study on damage of polyimide target irradiated by Pulsed CO$_2$ Laser

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Abstract. In this paper, the PI damage caused by pulsed CO$_2$ laser was simulated. The theoretical model of PI damaged by pulsed CO$_2$ laser was established. The temperature and stress distribution in PI samples were numerically analyzed by finite element method. The simulation results show that under the condition of low incident laser energy, serious melting damage has occurred on the PI surface, and there exists thermal stress damage. The damage of PI by pulsed CO$_2$ laser is mainly thermal damage, and the melting phenomenon will be obvious.

1. Introduction
The use of unmanned aerial vehicles(UAVs) is becoming more and more popular. A large number of "black flights" of UAVs have caused serious security risks to air traffic safety and social security, endangering the safety of people's lives and property. Laser irradiation will become effective in controlling "black flight". By laser irradiation, the UAV is effectively physically damaged and shot down. UAV usually consist of some composite materials, which contain organic polymer material, polyimide(PI). PI is a special engineering plastics with excellent properties, which can be widely used in aerospace, machinery, electronics and other high-tech fields. Therefore, it is of theoretical and practical significance to study the damage law of PI under laser irradiation. Researches on PI by domestic and foreign scholars mostly focus on its own properties and laser etching of PI-based composite materials. So far, there is no published literature on the damage of PI by pulsed CO$_2$ laser.

In this paper, the simulation results of single pulse laser damage PI with fixed pulse width output by pulsed CO$_2$ laser were studied. The temperature and stress distribution on the damaged sample surface were simulated by using ANSYS finite element analysis software. The damage mechanism of PI under pulsed CO$_2$ laser irradiation was discussed from the point of view of thermal damage and stress damage.

2. Theoretical model
In cylindrical coordinates, the irradiation effect of pulsed CO$_2$ laser on PI was studied, as shown in Fig.1. We selected a disc PI sample with a radius of $r_s=20$mm and a thickness of $h=2$mm. Pulsed laser is incident perpendicularly on the PI surface ($z=2$mm). The Z axis is opposite to the direction of laser...
irradiation. The radius of the spot incident on the surface of the sample is $R$, and the beam center coincides with the sample center. Usually, the output laser beam of pulsed CO$_2$ laser is multi-mode flat-topped beam, which is approximately uniform distribution. So we set the uniform distribution of laser intensity to $I_0$ in the range of spot. Because the distribution of sample and incident light intensity is axisymmetrical, the two-dimensional plane physical model was selected for the system.

Considering that the pulse width of a pulsed CO$_2$ laser is generally in the order of microsecond, the interaction time with PI is very short. Air is a bad conductor of heat, so adiabatic approximation is considered, i.e. no convection heat transfer. The loss of thermal radiation energy is very small compared with the absorption of laser energy. The influence on the temperature field can be neglected, and all the laser energy absorbed by PI is converted into heat energy. So the temperature distribution on the sample irradiated by laser is also axisymmetric.

$$\rho c \frac{\partial T}{\partial t} = k \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right) + Q \quad (1)$$

In the formula, $\rho$, $c$, $k$ represent the density, specific heat capacity and thermal conductivity of the material respectively, and $Q$ represents the bulk heat source absorbed by the laser beam in depth. For the heat conduction equation (1), the initial and boundary conditions must be determined before the problem of definite solution of the equation can be discussed. Initial and general boundary conditions can be written as

$$T(r, z, 0) = T_0 \quad (2)$$

Underside: \(-k \frac{\partial T}{\partial n}\bigg|_{z=0} = 0 \quad (3)\)

Side: \(-k \frac{\partial T}{\partial n}\bigg|_{r=r_s} = 0 \quad (4)\)

In the above formulas, $T_0$ is the initial temperature, $h$ is the thickness of the sample, and $r_s$ is the radius of the sample.

3. Key Problems in ANSYS Modeling

3.1 Establishment of Finite Element Model and Mesh Generation

We selected a two-dimensional thermo-mechanical coupled axisymmetric rectangular element PLANE13, and the mesh size of the element was divided into 0.2mm. For a finite element simulation analysis, meshing is a very important problem. Reasonable meshing is the key to the success of simulation. By comparison, the mesh size of the selected element is 0.2mm, and the finite element model of PI sample was established as shown in Fig. 2.
3.2 Pulsed Laser Loading
The loading of pulsed laser is the key problem of numerical simulation. Generally, there are two types of loading for thermal effects of laser irradiation. One is to load the energy or intensity absorbed by laser irradiation on the material surface as a surface heat source, that is, there is an external heat source on the surface of the material. There is no heat source in the material, so \( Q = 0 \) in formula (1). The other initial and boundary conditions remain unchanged. The boundary conditions of the upper surface are added as follows:

\[
\text{Upper surface: } -k \frac{\partial T}{\partial n} = I_0 \quad (5)
\]

Another type of loading is to treat the absorbed laser energy or intensity as a bulk heat source, which exists on a very thin surface of the material. At present, most of the literature reports use surface heat source, which is loaded on the upper surface of the material in the form of heat flux. PI material is opaque and laser energy is almost absorbed except reflection. We chose the form of surface heat source to load pulsed laser. The working time is pulse width \( \tau \). We used the parametric design language APDL in ANSYS to compile the variation of laser heat source with the loading position.

3.3 Thermophysical parameters of materials
It is considered that the initial temperature distribution of PI sample is uniform, \( T_0 = 22^\circ C \). The mechanical boundary condition is that the horizontal displacement of all particles on the axis is 0. The thermophysical and mechanical parameters required for calculation are shown in Table 1.

| Property                           | Symbol | Value  |
|------------------------------------|--------|--------|
| Density (kg/m³)                    | \( \rho \) | 1530   |
| Specific heat (J/kg.K)             | \( c \) | 1090   |
| Thermal conductivity [W/(m.K)]     | \( k \) | 0.12   |
| Tensile strength (MPa)             | \( \sigma_b \) | 100    |
| Compressive strength (MPa)         | \( \sigma_{bc} \) | 276    |
| Melting point (°C)                 | \( T_m \) | 170    |
| Young modulus (N/m²)               | \( E_X \) | \( 4 \times 10^9 \) |
| Poisson ratio                       | \( \mu \) | 0.3    |
| Linear expansibility (K⁻¹)         | \( \beta \) | \( 2.0 \times 10^{-5} \) |

4. Calculation results and analysis

4.1 Temperature and stress field distribution
Choosing the incident energy of the laser as \( E = 1 J \), the spot radius as \( R = 5 \text{ mm} \), and the pulse width as \( \tau = 10 \text{ us} \). Temperature and stress distributions on the surface are shown in Figs. 3 and 4. \( \sigma_r, \sigma_z \) and \( \sigma_\theta \) are radial stress, axial stress and circumferential stress, respectively. Compressive stress is negative and tensile stress is positive.

As shown in Figs. 3 and 4, the surface temperature in the spot area is the same, about \( 175.4^\circ C \). The melting point temperature of PI (170°C) has been reached and melting damage will occur. Temperature drops rapidly at the spot radius, and the temperature gradient is very large near the spot radius. The \( Z \) component of thermal stress is basically 0. From the center to the edge of the sample, the radial stress \( \sigma_r \) gradually tends to 0 from the maximum compressive stress (about 17.2 MPa), which is much less than the PI compressive fracture strength (276 MPa). It reaches its maximum (about 0.1395 MPa) at the outer edge of the spot radius (about \( r = 5.8246 \text{ mm} \)), and then decreases gradually to 0. The maximum
circumferential stress (0.13596 MPa) does not exceed the PI tensile fracture strength (100 MPa), so there will be no stress damage on the surface.

\[ \text{Fig. 3 Temperature distribution on sample surface} (t=10\mu s, E=1J) \]

\[ \text{Fig. 4 Stress distribution on sample surface} (t=10\mu s, E=1J) \]

4.2 Overall morphology of laser damage
Setting the end of the pulse as a time reference point, the temperature and circumferential stress distribution of the sample at this time were calculated. Then we obtained the overall morphology of laser damage in the sample. Taking single pulse energy \( E=1J \), spot radius \( R=5\text{mm} \) and pulse width \( \tau=10\mu\text{s} \), we obtained the equivalent nephogram of temperature and circumferential stress distribution of the sample, as shown in Figs. 5 and 6.

Fig. 5 shows that PI is a material with poor thermal conductivity, and there is only a temperature change in the laser irradiated area. The maximum surface temperature here is 175.4°C, reaching the melting temperature of PI 170°C, which will cause melting damage.

Fig. 6 shows that the circumferential stress shows tensile stress in a part of the sample parallel to the spot position. The maximum tensile stress is 1.181 MPa, which is much less than the tensile strength. In addition, there are circumferential stresses in a part of the surface area adjacent to the spot area. However, once the incident laser energy increases further, the stress value in this region will also increase further, which will exceed the tensile strength and cause surface stress damage.

\[ \text{Fig. 5 Equivalent nephogram of sample temperature distribution} (E=1J, t=10\mu\text{s}) \]
5. Conclusions

Based on the heat transfer theory, a theoretical model of PI irradiated by pulsed CO\(_2\) laser was established. The establishment of model, meshing, loading of pulsed laser, setting of initial and boundary conditions, and setting of thermophysical and mechanical parameters of materials were discussed. The simulation results show that under the condition of low incident laser energy, serious melting damage has occurred on the PI surface, and there exists thermal stress damage. Therefore, the damage of PI by pulsed CO\(_2\) laser is mainly thermal damage, and the melting phenomenon will be obvious.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (Project No.61871389), Anhui Province Natural Science Foundation (Project No.1908085MF222), the Research Plan Project of the National University of Defense Technology (Project No.ZK18-01-02), the Foundation of the State Key Laboratory of Pulsed Power Laser Technology (Project No. SKL2019ZR04), Key Natural Science Research Projects in Universities of Anhui Province (Project No.KJ2019A0438), and Key Natural Science Research Projects of Anhui University of Chinese Medicine (Project No.2019zzrd12). The authors would like to express their gratitude to Prof. Jinsong Nie from the State Key Laboratory of Pulsed Power Laser Technology for his assistance in the discussion.

References

[1] Cui Yong-li, Zhang Zhong-hua, Jiang Li, et al. Applications and Characteristics of Plastics Pipes for Hot Water Installations[J]. Plastics Science and Technology, 2005(03): 50-53+64. (in Chinese)
[2] Zhou Ji, Jin Hai-lan. Research Progress of Polyimide Fiber Materials[J]. Paper and papermaking, 2017, 36(02): 14-17. (in Chinese)
[3] Zhang Xiu-ju, Chen Ming-cai, Huang Yu-hui, et al. Properties, Usages and Development of Polyimide[J]. Guangzhou Chemical Industry, 1998(03): 58-66. (in Chinese)
[4] Wang Wei, Li Cheng-xiang, Zhang Guo-bin, Sheng Liu-si. Synthesis and Studies of Polyimide[J]. Materials Reports, 2008(02): 119-120+128. (in Chinese)
[5] Liu Xiao-li, Xiong Yu-qing, Yang Jian-ping, et al. Simulation of Temperature Field for Laser Etching of Aluminum Thin Films on Polyimide Substrate[J]. Chinese Journal of Lasers, 2015, 42(07): 120-124. (in Chinese)
[6] Liu Xiao-li, Xiong Yu-qing, Zhou Li-cheng, et al. Technological Study on Laser Etching of 2\(\mu\)m Aluminum Film/PI Material System[J]. Surface Technology, 2018, 47(10): 321-327. (in Chinese)
[7] Zhang Hong-wei, Ren Ni, Xue Hong-tao, et al. Temperature Distribution for Laser Etching of Metal Thin Films on Polyimide Substrate[J]. Chinese Journal of Lasers, 2016, 43(05): 100-107. (in Chinese)