Interaction between pulsed infrared Laser and carbon fiber reinforced polymer composite laminates

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Abstract: The Laser drilling processes, in particular the interaction between the pulsed infrared Laser and the target materials were investigated on the CFRP composite laminate. The incremental freezing method was designed to reveal experimentally the temporal patterns of the ablation profiles in the CFRP composite laminates subjected to pulsed Laser irradiation. The temperature characteristics of the specimens were analyzed with Finite Element Method (FEM) and the phase change history studied. The theoretical results match well with the experimental outcome.

Keywords: Laser, drilling, CFRP, FEM

1. Introduction

The carbon fiber reinforced polymer (CFRP) laminates are widely applied in the air crafts, which require accurate structure designing, reliable material processing and part manufacturing. Laser machining is promisingly attractive in the processing of the carbon fiber reinforced polymer (CFRP) composites considering its potential advantages over the mechanical techniques [1, 2, 3]. As we know, the efficiency and reliability of Laser machining is determined by the interactions between the Laser beam and the processed materials [4]. To improve the quality of Laser machining in the composites, the heat affected zone and taper angle need to be controlled by particularly designing the Laser parameters [1, 2].

Previously, the different ablation behaviors were investigated on the CFRP laminates subject to Laser of typical operation modes, i.e. continuous wave, long duration pulsed wave and short duration pulsed [4]. It was found that the continuous wave Laser made constant ablation of epoxy matrix over several layers and, the long duration pulse wave Laser made conical hole through the total laminate thickness in comparison to that the short duration pulsed wave Laser only made ablation of the

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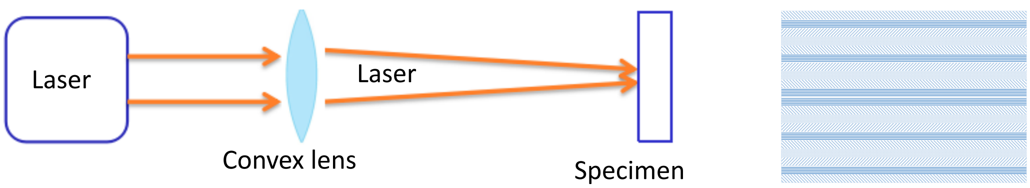
surface fabric layer without obvious change to the main body of the laminate [4].

The interaction between the long pulse Laser and the CFRP composite laminates is further investigated in the present work to reveal the drilling procedure of the specimens by the pulsed infrared wave Laser of duration about 200ns.

2. Descriptions on experiment and modeling

The autoclave cured CFRP lamina is synthesized from CCF-700 carbon fiber and BA9916-II resin matrix. The ply sequence of [45°, 0°, -45°, 90°]2s is adopted on stacking the sixteen 0.125mm thick CFRP laminas to produce the 2mm thick CFRP laminate, which is used in the Laser irradiation test as shown in Fig. 1. The effective density of the CFRP laminate is about $145g/m^3$.



(a) (b)

Fig. 1 Sketch of (a) experimental setup and (b) specimen

The infrared Laser of wavelength 1064nm, pulse duration 200ns and repetitive frequency 10Hz was used in the experiments. The Laser spot radius is 1.1mm and the output powers are about 1.1 Joule. After being irradiated by the pulsed infrared Laser, the specimen was cut along the central axial plane of the irradiated region. The cut cross sections as well as surfaces were polished and observed under microscopes.

The axial symmetry Finite Element model was set up as shown in Fig. 2 to investigate preliminarily the temperature and phase change of the CEFP specimens under long pulse Laser irradiation by solving the classic heat conduction with considering phase change of the involved materials [4], that is

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_{vh}. \quad (1)$$

The thermal boundary conditions of surface heat flux

$$q_l = q, \quad (2)$$

is applied at the Laser spot covered surface.

The thermal diffusive conditions

$$q_c = h(T - T_{en}), \quad (3)$$

and

$$q_r = \varepsilon \sigma T^4, \quad (4)$$

are used at all of the outmost surfaces.

Where,

T is temperature,

t time,

ρ density,

C_p specific heat capacity,

k thermal conductivity,

Q_{vh} the vaporization latent heat for sublimation,

q_l the surface heat flux from the incident Laser irradiation,

q_c the heat dissipated into the environment of temperature

T_{en}=293K through free air convection,

q_r the heat flux flow into the environment through surface thermal radiation,

$h=30Wm^{-2}K^{-1}$ the natural convection heat transfer coefficient,

ε=0.8 the surface emissivity and

$\sigma=5.67\times10^{-8}Wm^{-2}K^{-4}$ the Stephan Boltzmann constant.

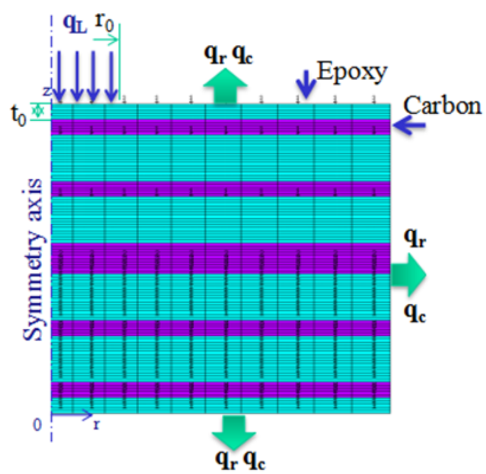


Fig.2 FEM model configuration

In Fig. 2, the thickness of every single layer is 0.125mm with the matrix and the fiber layer sequence being identical to that of the specimen used in the experiment. The basic material properties used in the Finite Element Analysis are listed in Table 1. Besides, the absorption coefficient of the specimen surface to the present Laser irradiation is set as 0.8.

Table 1 Material parameters [5, 6]

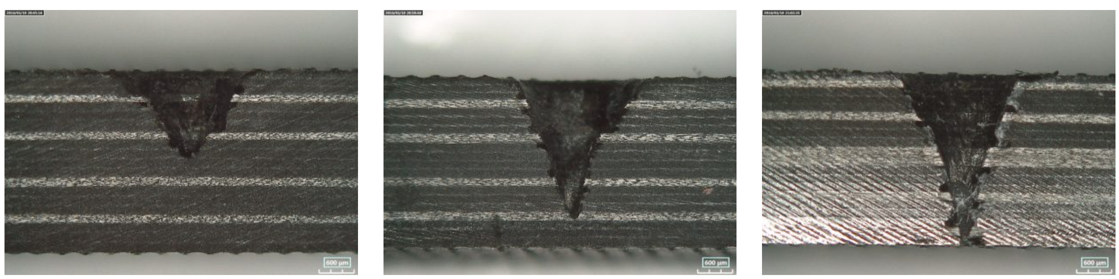
	Density (kg/m^3)	Specific heat (J/kgK)	Sublimation temperature (K)	Vaporization latent heat (kJ/kg)

Carbon	1850	710	3600	43000
Epoxy	1200	1100	700	1100

The technique of birth/ death element was used to remove the element whose temperature exceeds the sublimation temperature of the material. The Laser spot always fall onto the newly arising surface after the sublimated materials being removed based on a technique of moving interface developed by the present authors.

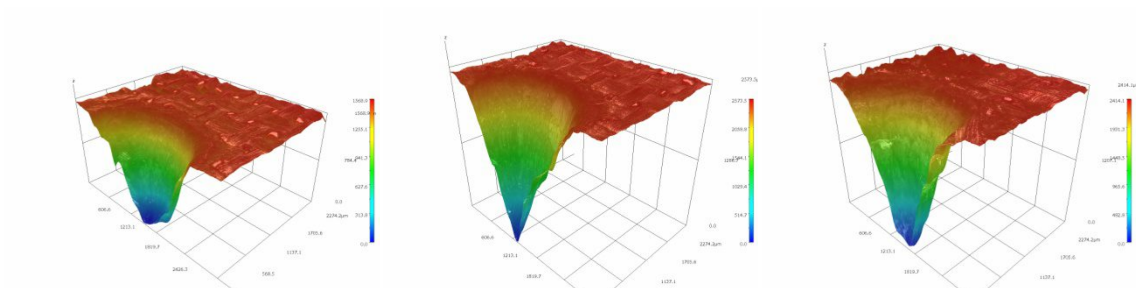
3. Results and discussion

The cross section morphologies by common optical microscope and the surface topography by 3D microscope are shown in Fig. 3 and Fig. 4, respectively. The incremental freezing profiles for the cases of typical irradiation times reveal preliminarily the drilling procedures of the CFRP laminates under long pulse irradiation. Basically, the depth of the conical hole would increase with the increasing of the irradiation time and the further irradiation would widen the hole around the back side after the hole is through the total thickness of the specimen. About 10 seconds are needed to make a through conical hole in the current CFRP laminate under the present experimental parameters.



(a) t_{ir}~6s **(b) t_{ir}~8s** **(c) t_{ir} ~10s**

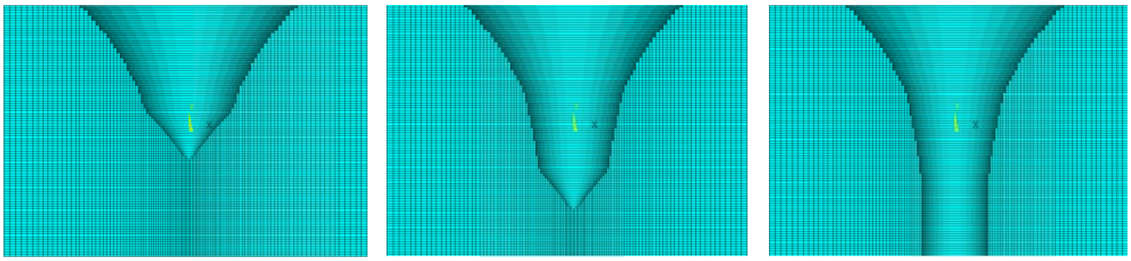
Fig.3 Cross section profiles for the cases of typical irradiation time



(a) t_{ir}~6s **(b) t_{ir}~8s** **(c) t_{ir} ~10s**

Fig.4 Surface topographies for the cases of typical irradiation time

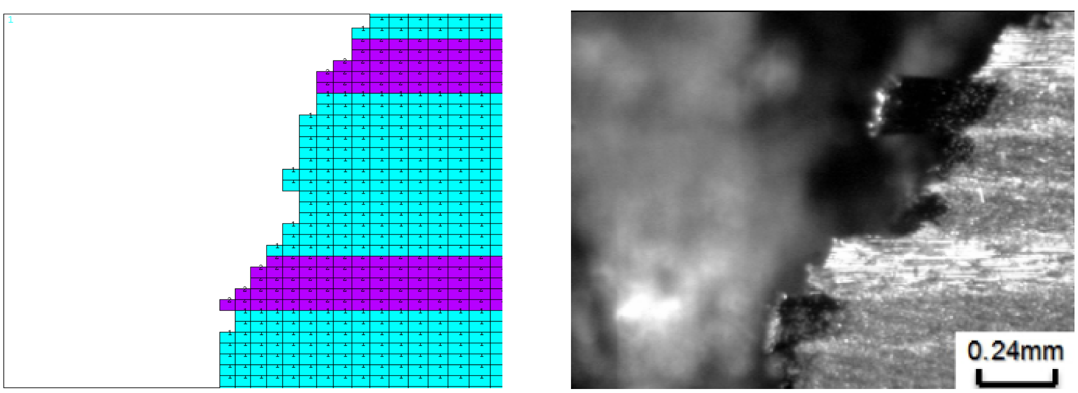
Figure 5 provides the depth profiles of the specimen at typical instants predicted by the Finite Element Simulation. The progressive procedures are approximately revealed by the numerical analysis. The theoretical simulation predicts a relatively wide hole at the directly irradiated side in comparison to the experimental results, which might be due to the deviation in the surface heat flux applied to the moving interface between the environment and the specimen.



(a) t=6s **(b) t=8s** **(c) t=10s**

Fig.5 Depth profiles at typical instants predicted by numerical simulation

More detailed cross morphology predicted by the Finite Element simulation is compared with the experimental outcome as shown in Fig.6, both of which indicate a coarse aperture wall. This could have been developed mainly by the difference in the thermal conductivity of the carbon fiber and the polymer matrix.



(a) **(b)**

Fig.6 Cross section profile by (a) theoretical and (b) experiment

4. Conclusions

The interaction between the pulsed infrared wave Laser and CFRP laminates was investigated to reveal the ablation procedures of Laser drilling of CFRP experimentally and theoretically. Experimental results reveal that a conical aperture could be made by the irradiation of Laser with appropriate parameters. The Finite Element model was validated to be accurate and useful in predicting the temperature and phase change in the drilling of CFRP by pulse wave Laser.

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