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Ablation behaviors of carbon reinforced polymer composites by laser of different operation modes

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ABSTRACT

Laser ablation mechanism of Carbon Fiber Reinforced Polymer (CFRP) composite is of critical meaning for the laser machining process. The ablation behaviors are investigated on the CFRP laminates subject to continuous wave, long duration pulsed wave and short duration pulsed wave lasers. Distinctive ablation phenomena have been observed and the effects of laser operation modes are discussed. The typical temperature patterns resulted from laser irradiation are computed by finite element analysis and thereby the different ablation mechanisms are interpreted.

1. Introduction

Carbon Fiber Reinforced Polymer (CFRP) composites are widely used to make many high strength–weight ratio parts, especially in a great many of aero structures [1]. Even being developed with the near-net forming characteristic, the CFRP composite products always need further necessary machining, wherein the classic machining is greatly challenged for the relatively low efficiency and the probability of damaging the work pieces [2]. As an inborn flexible alternative, laser machining of CFRP materials has drawn much attention, in which laser cutting and drilling are the most typical applications [3]. In such processing, laser energy is designed to be absorbed by the target materials and dissipated into thermal energy quickly. Therefore, in order to improve the process quality as well as reduce energy consumption, it is natural to hope the thermal energy to be largely confined to a small specific region to only make the materials therein evaporate without affecting the adjacent region [4]. In physics, this actually requires high spatial and temporal concentration of the laser energy, which could be realized through focusing the laser beam and shortening the laser duration [5]. From such point of view, one can immediately understand that the laser energy would be greatly wasted as too much material is heated up beyond the objective region if the laser power density is too low or the exposure duration is too long [6,7]. While it is not so commonly recognized that too concentration of laser energy might also lead to energy waste and even failure in processing. This is because large part of the incident laser energy would be dissipated in the plasma layer near the target surface when optical breakdown is intrigued by very high power density laser [8–10]. As a matter of fact, the threshold of such optical breakdown has been theoretically predicted well for clean air and experimentally obtained for classical target materials [11–13]. However, no direct reference data in relevance to optical breakdown has been reported for CFRP composites according to our knowledge. Moreover, no comparison work has been found to describe the difference in the ablation mechanisms on the CFRP composites subjected to continuous wave laser to pulsed wave laser. It is natural to expect that distinctive ablation patterns would arise in the specimens under irradiation by differently operated lasers, which determine the spatial and temporal distribution characteristics of the light energy [7,14]. Therefore, the basic knowledge should be developed to justify the application of laser machining to CFRP composites parts. To reveal the principle thermo-physical responses of the CFRP composites to the irradiation by continuous wave laser or pulsed wave laser and, to explore the laser parameter range appropriate to the laser machining of CFRP materials, the present work designed and carried through several groups of laser irradiation tests on CFRP specimens. The typical ablation behaviors and morphologies of the CFRP specimens irradiated by the Nd:YAG continuous wave laser, long duration pulsed wave laser or short duration pulsed wave laser have been revealed and, the effects of the laser power temporal pattern on that been discussed. Temperature patterns of the CFRP laminates under irradiation by the continuous wave, long duration pulsed wave and short duration pulsed wave lasers are analyzed by finite element method.

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Thereby, the differences in laser ablation mechanisms of CFRP laminates are interpreted.

2. Experimental and model description

The laser setups used in the experiment are shown in Fig. 1 and the laser parameters are listed in Table 1. Fig. 1(a) represents the Nd:YAG continuous wave laser (denoted by CW) and Fig. 1(b) the Nd:YAG pulsed wave laser. Two modes, i.e. pulse duration of 200 ns (long pulse duration, denoted by LP) and 10 ns (short duration, denoted as SP), of the pulsed wave laser were adopted in test. The polarizations of both the continuous wave laser and pulsed wave laser are random. The total exposure times are 10 s for all of the three kinds of irradiation tests. Thereafter, the surface and cross-section morphology were examined by using a Zeiss Stemi SV11 optical microscope. Moreover, the three dimensional (3-D) sketches were drawn by the computer aided design (CAD) software to describe the ablation appearances.

Square CFRP specimens were prepared as shown in Fig. 2(a), in which plain woven carbon fiber cloth (T800) reinforced polymer (Epoxy 5228A) laminate were laid up to make CFRP laminate of dimensions 50 mm × 50 mm × 4.1 mm and an axis-symmetrical finite element model was set up as shown in Fig. 2(b) to analyze the thermo-physical responses of the specimens. In Fig. 2(b), L represents the radius of the cross-section, $t=4.1$ mm the total thickness of the specimen, $t_c=0.1$ mm the carbon fiber layer thickness and $t_e=0.4$ mm the epoxy matrix thickness in every laminate.

As a preliminary study, one could ignore the flow of the sublimation product and write the heat conduction equation as

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

within the domain with the thermal boundary conditions of

$$q_l = q \tag{2}$$

at the surface range of $z=4.1$ mm and $r<r_0$, the focus spot radius,

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

and

$$q_r = \varepsilon\sigma T^4 \tag{4}$$

at the entire outer surfaces, where T is the temperature, t is the time, ρ is the density, C_p is the specific heat capacity, k is the thermal conductivity, Q_{vh} is the vaporization latent heat during sublimation, q_l is the incident laser power density, q_c is the heat dissipated into the environment of temperature $T_{en}=293$ K through free air convection, q_r is the heat flux flow into the environment through surface thermal radiation, $h=30$ W/m^2/K the natural convection heat transfer coefficient, $\varepsilon=0.8$ the surface emissivity and $\sigma=5.67\times10^{-8}$ W/m^2/K^4 the Stephan Boltzmann constant.

The basic thermo-physical parameters of the carbon fiber and epoxy matrix are listed in Table 2, in which the subscript 's' represents the solid phase while 'g' the gas phase. The gas phases are approximately treated to be trapped in the origin locations while no pressure effects have been involved in the model. The optical absorbance in the sample should be inhomogeneous, because the absorbance characteristics are different for the epoxy matrix and the plain carbon fiber fabric layer in the sample. However, homogeneous absorbance of laser in the sample was assumed in the present numerical modeling to simplify the theoretical work. Furthermore, the laser energy is assumed to be absorbed through the most upper surface of the specimen all along. Therefore, the horizontal thermal conductivity of the gas phase ($k_{g\rightarrow}$) is set very small while its vertical thermal conductivity ($k_{g\downarrow}$) is exaggerated to be very large to simulate the downward movement of the top surface absorbing the laser energy. One can imagine that the gas phase shall continue absorb laser energy and get further temperature elevation. It is to a large extent reasonable, in particular, for the situations that only very short time spans are considered as the gas would have no enough time to escape.

3. Results and discussion

The surface morphologies are shown in Fig. 3. The cross-section profiles are provided in Fig. 4, in which Fig. 4(a-1), (b-1) and (c-1) is photographed by optical microscope and, Fig. 4(a-2), (b-2) and (c-2) is drawn by CAD software.

Figs. 3(a) and 4(a) show that the continuous wave laser irradiation has ablated through several layers of the CFRP laminate. And many voids arise in the epoxy layer remained after laser irradiation for 10 s as shown in Fig. 3(a-2), which indicates that the

Table 1
Parameters of laser beam and irradiation test.

	CW	LP	SP
Wavelength (nm)	1064	1064	1064
Focus spot radius (r_0) (mm)	3	1.5	1.5
Power or pulse energy	Power 100 W	2.0 J	2.0 J
Pulse duration (ns)	–	200	10
Repeat frequency (Hz)	–	10 Hz	10 Hz
Power density (q) (W/m^2)	3.54×10^6	1.50×10^{12}	3.00×10^{13}
Mean power density (q_{ave}) (W/m^2)	3.54×10^6	2.94×10^6	2.94×10^6
Exposure time (t) (s)	10	10	10

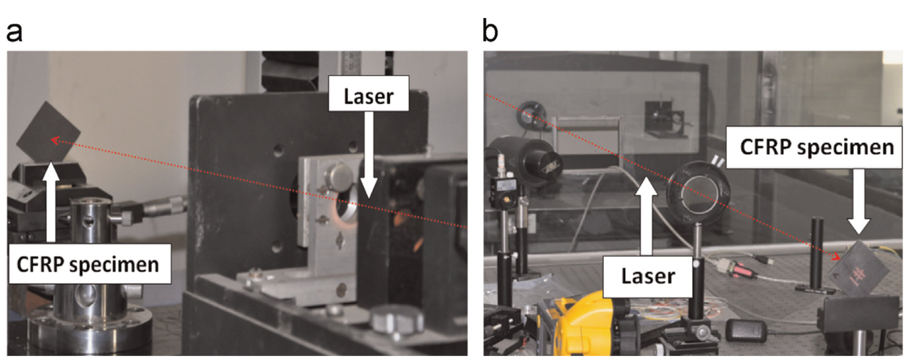

Fig. 1. (a) Continuous wave laser and (b) pulsed wave laser setups for irradiation test.