Optics and Lasers in Engineering 88 (2017) 91–101

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Interlaminar damage of carbon fiber reinforced polymer composite laminate under continuous wave laser irradiation

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ARTICLE INFO

Article history:
Received 18 February 2016
Received in revised form
8 July 2016
Accepted 5 August 2016

Keywords:
Laminates
Damage
Continuous wave laser
Finite element analysis (FEA)

ABSTRACT

The interlaminar damages were investigated on the carbon fiber reinforced polymer (CFRP) composite laminate under laser irradiation. Firstly, the laminated T700/BA9916 composites were exposed to continuous wave laser irradiation. Then, the interface cracking patterns of such composite laminates were examined by optical microscopy and scanning electron microscopy. Finally, the Finite Element Analysis (FEA) was performed to compute the interface stress of the laminates under laser irradiation. And the effects of the laser parameters on the interlaminar damage were discussed.

1. Introduction

The widely application of the carbon fiber reinforced polymer (CFRP) laminates in the aircrafts requires accurate structure designing and reliable part manufacturing [1–5]. The laser beam is a promising machining tool for CFRP composite processing as it is always accompanied with better quality and higher productivity. It can also be utilized in processing the small and complex parts due to the fact the beam spot could be very accurately refined and heating affect zones be largely constrained. Besides, the laser machining is of lower cost in comparison to other techniques such as milling shape cutting and water jet-cutting [6,7].

However, laser machining might also has some noticeable size effects as it develops a local temperature elevation in the CFRP laminates [8]. As we know, the composite gradients are always combustible and the CFRP laminates are susceptible to deterioration in mechanical properties when exposed to the high temperature atmosphere [9,10]. Therefore, the present laser machining of the CFRP composites, which is based on the physical and chemical actions such as pyrolysis and ablation, would induce thermal damage in the CFRP laminate beyond the objective regions [11,12]. Among all of the probable thermal damages, the interlaminar damage is of most important effects as the large scale interlaminar cracking would lead to catastrophic results in the CFRP laminate structures. That's also why much research have been focused on the interlaminar damage during various thermo-mechanical process of CFRP parts.

Theoretically speaking, the interlaminar separation in the CFRP laminates is dominated by the evolution of the interlaminar damages, in particular the propagation of the interlaminar cracks. It was revealed that the fiber lay angle influences greatly the propagation of the interlaminar cracks [13]. And the relative weak fiber-matrix interface would contribute greatly to the multi-interlaminar shear failure mode [14]. Moreover, some fracture mechanics experimental work were carried out on the CFRP laminates under different temperature environment and it has been revealed that the apparent interlaminar strength would be reduced with the temperature elevation [15–20]. Recently, a few methods have been developed to enhance the interlaminar strength and improve the overall interlaminar performance of the CFRP laminates [21–23]. While, to describe correctly the interlaminar behaviors of the CFRP laminates under laser irradiation should be the important prerequisite for any possible optimization in designing or manufacturing of the CFRP composite materials as far as the processing performances are taken into account.

In the present work, firstly, the interlaminar damage morphology of the CFRP laminate specimens under continuous laser irradiation was observed by optical microscopy as well as scanning electron microscopy. Then, the interlaminar damage pattern was analyzed and its space distribution characteristic was discussed. Finally, a finite element model was set up to calculate the temperature, deformation and stress arising in the CFRP laminates

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http://dx.doi.org/10.1016/j.optlaseng.2016.08.001

during laser irradiation.

2. Experimental description and results

The sixteen 0.125 mm thick CFRP laminae are stacked via the ply sequence of $[45°, 0°, -45°, 90°]_{2\,s}$ to produce the 2 mm thick CFRP laminate used in the laser irradiation test as shown in Fig. 1. The size of the specimen is 50 mmx50 mmx2 mm. The autoclave cured CFRP lamina is composed of ccf700 carbon fiber and BA9916-II resin matrix. The effective density of the CFRP laminate is 145 ± 5 g/m^3.

The specimen is placed in a cabinet full of Nitrogen with a transparent window, through which the Laser beam enters and impinged at the specimen vertically. Geometrically, the axial plane of the laminate specimen is parallel to the laser beam direction. The continuous wave laser of wavelength 1070 nm was used in the experiments. The laser beam is focused on the front most surface of the specimen and the initial spot radius is about 5 mm. Of course, the spot radius will slightly change with the removal of the surface material as the static irradiation is adopted in the present experiment. The irradiation holds for 3 s under different output laser powers, which are typically 500 W, 800 W and 1000 W.

After being irradiated by the Laser, the specimens were split along the axial plane of the irradiation spot to reveal the cross section. The cut sections of the laminates were polished and the specimens were ultrasonic cleaned to show the cracks clearly. The optical microscope and scanning electron microscope were used to observe the section morphology, in particular the interface damages.

The typical cross section morphologies by optical microscope are shown in Fig. 2. It is revealed that the obvious pyrolysis happed in the irradiated region of the specimens, and the interlaminar cracks could be found close to the backward surface other than the irradiated forward surface.

Fig. 2 also reveals fiber fracturing in the surface layer directly irradiated and the pyrolysis could be observed in up to eight

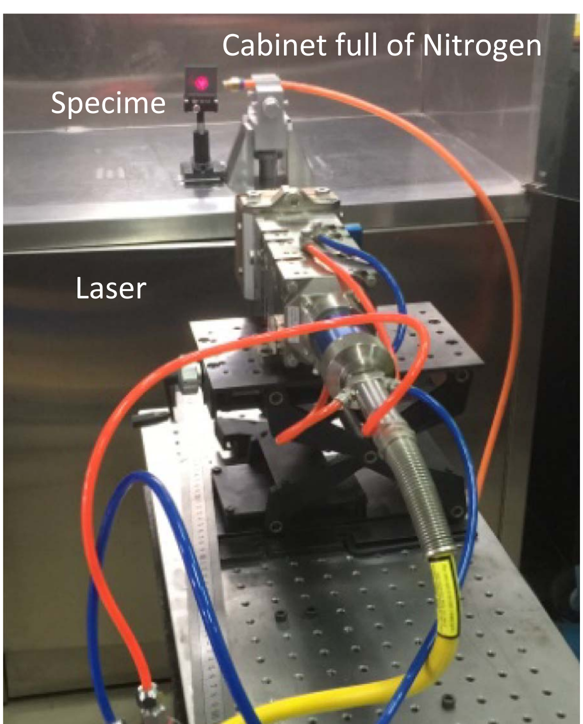

Fig. 1. The experimental setup.

Fig. 2. Cross section for the cases of laser power (a) 500 W, (b) 800 W and (c) 1000 W.

laminae counted from the forward surface layer. Moreover, it is shown that several layers of carbon fiber remained even after the matrix removed by the laser irradiation. To reveal further characteristics of the interface damages in the specimen, the cross section morphology observed by scanning electron microscope are shown in Fig. 3 and 4. The interface cracks, indicated by black lines and the pyrolysis front edge, indicated by red lines are further sketched in Fig. 5 to reveal clearly their locations and geometrical characteristics. The distinctive line widths are intentionally chosen in the sketch to approximately represent the opening displacement of the interlaminar cracks. The crack of maximum opening displacement, which always appears at the center of the penny-shaped cracks, than the half thickness of a single lamina is simply named as coarse crack in the manuscript, otherwise as fine crack. According to the experimental observation, the location of the most coarse crack and the pyrolysis front edge would move to the backward surface were the laser power increased, which is also sketched in Fig. 5. Of course, the crack opening displacement should be intrinsically related to the thermal strain and thermal stress developed in the specimen. The out-of-plane deformation of the laminate contributes largely to the opening displacement of the interlaminar cracks, which is directly resulted from the asymmetric thermal expansion of the laminates.

It is indicated in Fig. 3(a), Figs. 4(a) and 5(a) that the primary interface crack arises at the middle depth location of the laminate, i.e. between the fourth laminae and the fifth laminae counted from the backward surface for the case of laser power 500 W. The primary crack locates at the second interface for the case of laser power 800 W as shown in Figs. 3(b), 4(b) and 5(b) and the first interface for the case of Laser power 1000 W as shown in Figs. 3(c), 4(c) and 5(c). It looks like that the location of the primary cracks approaches to the backward surface were the laser power increased. This is also the case for the pyrolysis front edge as demonstrated in Fig. 5. Moreover, it is indicated that the interlaminar cracks would be widened and lengthened by increasing the output laser power, which is similar to the phenomenon observed in carbon/carbon composite subjected to elevated temperature [24]. It is also noteworthy that there are always short cracks arising close to the backward surface for almost all of the specimens irradiated by different laser powers, while as the irradiation by higher output laser power might have been more capable in changing the small cracks into primary coarse cracks.

The numerical analysis was conducted based on Finite Element Method (FEM) to preliminarily demonstrate the thermo-mechanical responses of the CFRP laminates under the irradiation of continuous wave laser. In particular, the interface stresses between adjacent laminae responsible for the interlaminar damages are investigated.