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Etching of long fiber polymeric composite materials by nanosecond laser induced water breakdown plasma

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ABSTRACT

Composite materials are widely used in industry due to their superior material properties and light weight. However, shear failure can occur at the interface between the fibers and polymer matrix when a tensile force stretches the matrix more than the fibers. Repairing the damaged composite material appears to be cost effective but still remains a challenge despite extensive research. Laser induced water breakdown plasma, which is generated by the strong interaction between nanosecond laser and water, is proposed in this work to etch the surface layer of a carbon fiber reinforced composite sample. It is found that the polymer layer can be effectively removed by the plasma while the carbon fiber remains almost intact. The dependence of the etching depth on the laser power density, laser focus position, and the number of shots are also investigated in this work. The maximum possible etching depth is around 350 μm with 50 laser shots at laser power density of 70 GW/cm^2.

1. Introduction

Carbon fiber-reinforced plastic (CFRP) is a composite material made of a polymer matrix reinforced with carbon fibers, which is widely used in aerospace, automotive, and civil industries due to their superior material properties and light weight [1]. Under excessive tensile force, however, shear failure can occur at the interface between the fibers and polymer matrix [2]. As the application of composite materials becomes more extensive, the need for repair of damaged composite parts grows.

Conventional repair of the composite structures [3] is done by grinding the damaged part manually using a diamond angle grinder and then refilling the cavity with preimpregnated ("prepreg") plies. Finally the whole system must be cured with the vacuum bag technique. This mechanical grinding process is time-consuming and highly depends on the expertise of the repair personnel. Furthermore, mechanical stresses could be introduced into the workpiece. Laser-based repair of composite materials was proposed recently [4], where direct laser ablation was utilized to remove the damaged part to obtain a cavity for further refilling. The major disadvantage the method proposed in Ref. [4] is that both the polymer matrix and the carbon fibers were completely removed by direct laser ablation under high laser fluence, which will significantly affect the material strength of the repaired patch since the fibers were broken.

One of the better alternatives to repair the damaged composite material is to etch the polymer matrix only and then refill the polymer to generate a new bond between the polymer and the carbon fibers. This method appears to be cost-effective but has never been reported in literature. Etching by laser induced water breakdown plasma, which is generated by the strong interaction between nanosecond laser and water [5–9], is therefore proposed in this work to remove the polymer matrix from a carbon fiber reinforced composite sample more effectively based on the state-of-the-art of the composite material repair.

By focusing an incident high power laser beam in water, extremely high peak power density can be generated at the focal spot. When the peak power density exceeds the ionization threshold of the water, the strong laser-water interaction will result in the generation of free electrons at the focal spot through multi-photon ionization. The cascade ionization process then becomes dominant for the fast growth of free electrons via inverse Bremsstrahlung absorption. When the free electron density exceeds the critical value of 10^{20}/cm^3, the optical breakdown of water occurs, leading to the formation of dense and optically opaque plasma at the focal spot [10].

The etching (material removal) by the laser induced water breakdown plasma starts with laser-water interaction and then becomes a thermal-kinetic process, which can be explained by the plasma-matter interaction [11]. From the thermal point of view, heat energy is transmitted from the extremely hot plasma to the

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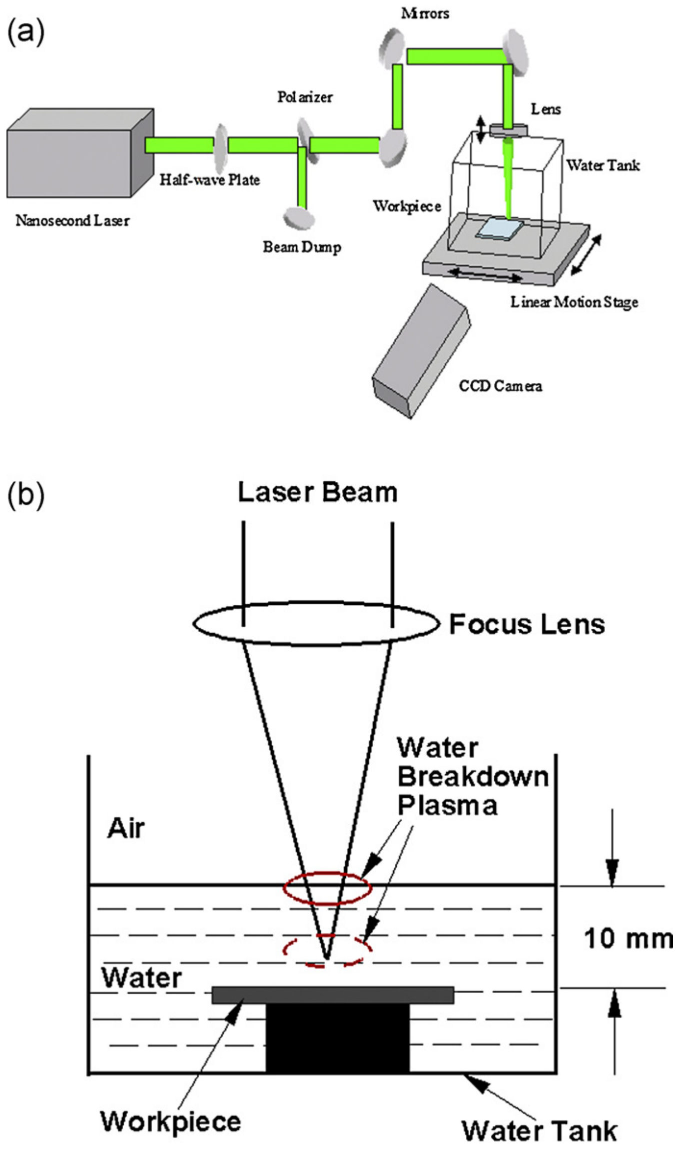

Fig. 1. (a) Experimental setup for plasma etching (b) close-up view of the air–water–workpiece system.

workpiece through conduction (if the plasma touches the workpiece surface) and/or radiation (if the plasma is away from the workpiece surface) over a relatively small area of the workpiece during the plasma-matter interaction. As a result, the local temperature of the workpiece will experience a sudden increase. When the temperature exceeds the boiling point, the high temperature region of the workpiece will be melted or even vaporized. From the kinetic point of view, the plasma also occupies the initial water region (see Fig. 1(b) for more details about the plasma position) and applies a large pressure on the workpiece surface, which holds back the molten material. As soon as the plasma collapses at the end of the laser pulse, the water flows back rapidly to fill the void. The sudden decrease in pressure due to the plasma collapse also results in an instantaneous expulsion of the molten and vaporized material from the workpiece surface, thus resulting in material etching [11]. Since the polymer matrix has a lower boiling temperature (in the order of several hundred Kelvins [12]) than the carbon fibers (in the order of several thousand Kelvins [12]), the polymer matrix will be vaporized first.

The dependence of the etching depth on the laser power density, laser focus position, and the number of shots are also investigated in this work to obtain a maximum possible etching depth.

2. Experimental procedures

The experimental setup used in this study is shown in Fig. 1(a). A frequency-doubled Nd:YAG laser (wavelength of 532 nm) is used to generate a laser beam, which passes through a half-wave plate, polarizer, three high reflecting mirrors and a focus lens, and finally irradiates on the surface of workpiece. The laser beam profile is top-hat in spatial distribution and Gaussian in temporal distribution. The focus lens has a focal length of 100 mm and a numerical aperture of 0.25. The laser beam is around 0.3 mm when in focus. The composite workpiece is placed into a water tank to produce a water-confinement regime, as shown in Fig. 1(b). The water layer depth is around 10 mm above the surface of the workpiece, which is maintained in this level during the experiment. The movement of the workpiece in *X* and *Y* directions is controlled by two linear motion stages. The distance between the focus point and the surface of the workpiece can also be changed by vertically varying the position of the focal lens. With this setup, the laser power density can be easily adjusted by fine tuning the orientation of the half-wave plate.

The laser induced water breakdown plasma image is captured by the CCD camera. It should be noted that the plasma initially forms at the laser focal spot (dashed ellipse in Fig. 1(b)) if the laser power density at the focal spot just exceeds the breakdown threshold. If the laser power density is much higher than the water breakdown threshold, the laser power density at the air–water interface may be high enough to breakdown the water at the air–water interface. Therefore, the water breakdown plasma could be observed in any region from the focal spot (dashed ellipse in Fig. 1(b)) to the air–water interface (solid ellipse in Fig. 1(b)) depending on the laser power density.

The composite sample used in this study is preimpregnated ("pre-preg") material. The polymer is epoxy resin and the carbon fiber is the intermediate modulus IM7. The sample thickness is around 3.4 mm.

A series of experiments of laser induced plasma etching were carried out to systemically investigate the etching in the presence of water breakdown plasma. According to Ref. [13–15], the water breakdown threshold for a 532 nm, 6 ns, around 300 μm laser beam is determined to be less than 30 GW/cm^2. In this work, the laser power density is chosen to be from 30 to 70 GW/cm^2. Therefore, the water breakdown will certainly occur under this condition, which will ensure the laser induced plasma etching operation. The experimental conditions are listed in Table 1.

After the nanosecond laser induced plasma etching operation, a picosecond laser is employed to cut the composite sample on the cross section. The picosecond laser cutting is chosen here because it can significantly reduce the heat affected zone compared with the traditional mechanical cutting and nanosecond laser cutting [16,17]. A groove of 200 μm (width) × 120 μm (depth) was generated by the picosecond laser cutting near the center line of the etching area.

After the laser cutting, the sample was completely cut by a conventional mechanical cutter and then polished to obtain a relatively flat surface. The sample was further sputter-coated to analyze under the SEM. Fig. 2 shows an SEM image of the center region of the cross-section of the composite sample after 50 laser shots. The carbon fibers can be clearly seen in this image. The polymer between the carbon fibers has been completely removed by the water breakdown plasma.