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Investigation on fiber laser cutting of polyacrylonitrile-based carbon fiber tow

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ABSTRACT

Carbon fibers (CFs) are often chopped through conventional metal cutting tools. The wear of cutting tool is unavoidable, resulting in low productivity and unsteady product quality. In this work, cutting CFs by fiber laser was studied. The laser absorptivities of three types of CFs and sizing amounts were measured to evaluate their photothermal conversion properties. The cutting-off mechanism of CF was clarified by its kerf cross-sectional morphology and multiphysics simulations. The morphology, chemical composition and mechanical properties around the CF kerf were analyzed to investigate the characteristics of laser cutting method. In addition, the effect of laser parameters and sizing amounts on CF tow cutting were investigated. Results show that laser-cutting CF in the heat affected zone has poor mechanical properties compared to mechanical cutting CF, but composite nonwoven fabrics made by either of them have substantially equal tensile strength. The critical cutting-off speed of the three CFs has a linear relationship with the laser power. Compared to mechanical cutting, laser cutting of CF tows can reduce about 50% energy consumption. And the laser cutting speed can be adjusted within a large range, whereas the mechanical cutting speed is only determined within a relatively narrow range. This low-energy consumption and speed-adjustable cutting method shows great potential to produce chopped CF-based high-quality composites.

1. Introduction

Chopped carbon fibers (CFs) have shown great promise to enable their use as structural and functional materials, such as composites (Song et al., 2016), electrode materials (Razaq et al., 2012), and electromagnetic interference shielding materials (Lu et al., 2017b). In comparison with the common metals, a variety of advantages have emerged to meet the demand of industry, such as light weight, high mechanical strength, excellent corrosion/thermal resistance properties (Donnet and Bansal, 1998). Chopped CFs are made from continuous CF tows. However, the processing of chopped CFs faces many challenges owing to its anisotropy and machining tools abrasion (Karpat et al., 2012; Madhavan et al., 2015). Wear patterns and wear mechanisms of cutting tool were investigated by previous research (Shen et al., 2015). The wear of the metal machining tools is unavoidable, which leads to low productivity and unsteady product quality.

Great interests have been plunged into the research on laser cutting technology because of its excellent reliability for industrial production. Laser cutting is a non-contact operation process, which does not have machine tools abrasion (Ghany and Newishy, 2005). What is more, laser cutting has advantages over other known thermal processes, such as narrow kerf width, low material waste, high quality cutting surface, and etc. For these reasons, laser cutting behavior of different materials has been reported by many researchers. Ghany and Newishy (2005) evaluated the optimum laser cutting parameters for stainless steel sheets, and pointed out the laser cutting quality, kerf width and surface roughness were closely related to the cutting parameters. Choudhury and Shirley (2010) investigated the effect of laser cutting parameters on cutting quality of three types of polymers, and established model equations relating the parameters with heat affected zone, surface roughness and dimensional accuracy. To obtain better cut quality, Jung et al. (2012) performed ultra-high speed laser cutting on two types of CF reinforced plastics (CFRP) with long or short CF using CW disk laser and studied the effect of laser cutting parameters on CFRP cut qualities. Among these studies on laser cutting associated with CF, laser cutting of CF reinforced composite materials are the main focus of current research, such as CF/plastics (Herzog et al., 2015; Riveiro et al., 2012), CF/polymers (Dold et al., 2012; Fuchs et al., 2013), CF/

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polyetheretherketone (Hocheng and Pan, 1993), plain-weave carbon/CF (Al-Sulaiman et al., 2006) and so on. However, the laser cutting-off mechanism and cutting behavior of CF tow have not been investigated so far.

In this work, we propose to manufacture chopped CFs by fiber laser cutting method. To investigate characteristics of the fiber laser cutting method, the kerf morphology, chemical composition and mechanical properties around the kerf were analyzed using scanning electron microscopy (SEM), energy dispersive spectrometer (EDS)/X-ray diffraction (XRD) and designed cutting device, respectively. The effects of laser parameters (laser power and cutting speed) and sizing amounts on CF tow kerfs were examined. Comprehensive comparison of laser cutting and mechanical cutting methods was performed. In addition, the CFs cutting-off mechanism was explained with the temperature simulations of CF monofilament irradiated by moving laser beams. This non-contact laser cutting method showed a great potential to produce chopped CF-based high-quality composites with low-energy consumption and speed-adjustable.

2. Experimental materials and methods

2.1. Materials and experimental setup

Three types of polyacrylonitrile (PAN) CFs were employed as workpiece materials. Each bundle of the CFs has 12,000 filaments with an average diameter of 7 μm. Other mechanical properties of the CFs are listed in Table 1. To study the effect of sizing amount on CF tow width and kerf, an aqueous sizing agent with 5 wt% Polyurethane (PU) (Shanghai Institute of Organic Chemistry, China) was used. In addition, different types of weights (100, 200,…, 600 g) connected with the CF tow by a 20 g clip were used to provide different tow tensile force.

Cutting CFs was conducted using a Q-Switch pulsed fiber laser marking machine (QSFL-20 A, Shenzhen super laser technology Co., Ltd, China) with 1064 nm central wavelength. The nominal average output power of the laser was 20 W. The laser beam was focused onto samples with a set of focusing lens (Carman Hass SL-1064-110-160). The focused mean diameter of the laser spot was ~20 μm with a repeat accuracy of ± 2 μm. Other specification parameters of the laser system are listed in Table 2. All samples were cut at one time under room temperature (25 °C) and ambient air. In addition, a power meter (VEGA ROHS/10 kW-BB, OPHIR, Israel) was used to measure the actual output power of the laser.

2.2. CF tows cutting process

Fig. 1(a) shows a photograph of a laser cutting device which mainly consists of fiber laser, scanning galvanometer, lifting device, focusing lens, computer-controlled systems (including computer, controller, and monitor), workbench and clamping device. The partial magnification of working area for CFs cutting is shown in Fig. 1(b). As shown, a bundle of CF was fixed by a clamp, and its end was pressed with a weight of 100 g to provide preload. Before cutting, the focus of the laser was moved on the surface of CF by the sliding of lifting device, and a red line laser spot was formed on the CF for preview. To reduce the experimental error, six tests were repeated for each parameter. The three CFs were shot to observe their surface features for comparison, presented in Fig. 1(c). It can be seen that T700SC and SYT49S have smooth surfaces and similar surface features, whereas KFT35 is rougher on the surface and narrower in width.

Table 2
Specifications of characteristic parameters of the laser system.

Characteristics	Parameter range	Process conditions	Unit
Central wavelength	1059–1070	1064	nm
Nominal average output power	19–22	20	W
Pulse width	80–120	100	ns
Focused diameter	10–12	11	μm
Beam quality (M^2)	1.2–1.6	1.4	/
Output beam diameter	7–9	8	mm
Max. single pulse energy	0.7–0.8	0.8	mJ
Repetition frequency: f	20–60	20	kHz
Laser power: P	0–20	2, 4, 6, 8, 10, 12, 14, 16, 18, 20	W
Cutting speed: v	0–2000	10, 20, 30, 40, 50, 60, 70	mm/s

To control the laser irradiation temperature, the laser fluence F was applied by individually adjusting the laser power, laser cutting speed and focused spot size (Fischer et al., 2010):

$$F = \frac{P}{vd_i} \tag{1}$$

where P is the laser power; v is the laser cutting speed; and d_i ($i = 1,\ldots$) is the focused spot diameter, which is estimated from the lens equation in terms of a Gaussian laser beam (Darvishi et al., 2012):

$$d_i = \frac{4M^2 f_L \lambda}{\pi d} = 2\omega_0 \tag{2}$$

where M^2 is the beam quality with $M^2 = 1.4$; f_L is the lens focal length; λ is the laser wavelength; d is the output beam diameter without passing through the focusing lens; and ω_0 is the focused spot radius, which is defined as the point where the laser fluence decays to $1/e^2$ of the maximum fluence $F_{\max}$ occurring at beam centreline (Khosrofian and Garetz, 1983). As for the laser fluence distribution of a Gaussian laser beam, it can be expressed as (Darvishi et al., 2012; Liu, 1982):

$$F_G(r) = F_{\max}\exp(-2r^2/\omega_0^2) \tag{3}$$

where r is the radial distance from the beam centerline.

2.3. Characterization

The top and cross-sectional views of CF kerf morphology were characterized using field emission SEM (LEO 1530 V P, 5 kV, Germany) and three-dimensional super depth optical microscope (VH-Z100R, Keyence Corp., Japan). To minimize experimental errors, the CF tow kerf width was measured by magnifying the optical microscope 600 times and eight areas for each sample were selected. To characterize the depth of cut of CF tow, a CCD camera of the optical microscope was mounted over a sample. Three-dimensional images of the sample surface profile were obtained by multiple shots of the camera from bottom to top and three-dimensional image synthesis function of the microscope. The compositions of the laser-cutting CF were characterized by EDS (Oxford instruments, UK) and XRD (Xpert powder, Bruker,

Table 1
Mechanical property of three types of CFs (manufacturer's data).

Manufacturer	Type	Filaments	Tensile strength (GPa)	Elongation (%)	Tensile modulus (GPa)	Linear density (g/km)	Density (g/cm^3)
Toray, Japan	T700SC	12000	4.90	2.00	230	800	1.80
Zhongfu Shenying, China	SYT49S	12000	4.90	2.10	240	800	1.78
Kingfa Sci. & Tech., China	KFT35	12000	3.87	2.19	256	777	1.77