Laser Cutting of Carbon Fiber Reinforced Thermo-Plastic (CFRTP) by IR Laser Irradiation

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We report on the laser cutting of carbon fiber reinforced thermo-plastic (CFRTP) with a cw IR fiber laser (average power: 1 kW). CFRTP is a composite material which contains carbon fibers and binding thermoplastic. A well-defined cutting of CFRTP which was free of debris around the groove was performed by the laser irradiation with a fast beam galvanometer scanning on a multiple-scan-pass method. The area of laser-induced damages in the samples was observed by microscopic X-ray Computed Tomography and micro- Raman spectroscopy. Laser cutting with a high speed beam scanning exhibits a clean top and an excellent sidewall quality along with a negligible heat affected zone.

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1. Introduction

Laser-induced cutting of various materials has led to the invention of numerous industrial processes that have redefined the speed of production-line manufacturing and the strength of industrial manufacturing applications. Reliable systems composed of rapid and easy operations with excellent repeatability would be able to be designed in the case of solid-state lasers. The laser cutting process achieves high-precision cuts with narrow kerfs where complex contours demand precise, fast and force-free processing [1, 2]. In particular, considerable attention has been given towards the cutting of carbon fiber reinforced plastic (CFRP) and carbon fiber reinforced thermo-plastic (CFRTP) which are generally made up by resin matrices and reinforced carbon fibers, since, in spite of the difficulty involved, CFRP and CFRTP are a high strength composite material with a lightweight, and is increasingly being used various applications in automotive and aerospace fields. The use of lasers for these composite materials can involve several approaches, such as fiber laser processing [3-16], UV laser processing [7, 11, 17-28], picosecond laser micromachining [29-33], femtosecond laser micromachining [29, 34, 35], disk laser processing [36, 37], YAG laser processing [38-49], CO_2 laser processing [9, 12, 14-16, 42, 50-58], and theoretical model/analysis [59-63].

In this paper, we report on the laser cutting of CFRTP with a cw fiber near-IR laser (λ= 1090 nm). A well-defined cutting of CFRTP which were free of debris around the grooves, were performed by the laser irradiation with a fast beam galvanometer scanning on a multiple-scan-pass method [3]. The flexibility of various shapes of the trenches is caused by the feature of laser direct cutting. The area of laser-induced damages in the samples was observed to estimate heat affected zone (HAZ), analyzing by microscopic X-ray Computed Tomography (X-CT) and micro-Raman spectroscopy.

2. Experimental

We used a cw near-IR laser (Miyachi, multi-mode fiber laser (fiber core diameter: ϕ= 50 μm, laser wavelength: λ= 1090 nm, average power: P= 1 kW)). The laser beam on the sample surface (scanning speed: 200 – 2300 mm s^{-1}) was scanned with a galvanometer scanner by multiple-scan-pass irradiation in the air (without assist gas). The beam was focused with an f-theta lens (f= 160 mm). The sample of 3 mm-thickness CFRTP prepared by compression molding was employed for the laser cutting experiments. CFRTP includes a chopped pitch-type carbon fiber (Cf= 30 wt%) and polycarbonate resin (Mitsubishi Engineering-Plastics Corp.; Iupilon, resin melting point: Tm= 220-230 degree C, resin pyrolysis in the air: 470 degree C) [64]. The CFRTP sample was mounted on a computer-controlled XYZ scanning stage. During the laser beam scanning on the CFRTP sample, the surface temperature of CFRTP at the irradiation area was monitored with a thermo-camera (FLIR; SC620, resolution: 640 x 480 pixels, frame rate: 30 fps).

The internal damages of laser-cutting samples were observed with a micro X-ray Computed Tomography system (Yamato Science Co.; TDM1000H-Sμ/TDM1600H-II, X-ray filament: LaB_6). High magnification images on the sample surface of grooves were observed with SEM (Keyence; VHX-1000).

Micro-Raman spectra of the laser-treated samples were measured with a dispersive Raman analysis system (Thermo Fisher Scientific Inc., Nicolet Almega XR, excitation laser: λ= 532 nm, P= 0.1 W). A sliced CFRTP specimen which was prepared with a microtome was used for Raman measurement. The Raman analytical laser beam was focused to the sliced specimen surface with the spot diameter of 2 μm. The analytical laser beam was surveyed at the surface layer of internal wall on the groove of CFRTP sample.

3. Results and Discussion

3.1 Laser cutting property

Figure 1 shows the cross-sectional images of 3-mm-thickness CFRTP sample measured by microscopic X-CT at two different observation angles. Fine cutting of the CFRTP sample induced by the cw fiber laser irradiation of 1 kW average power with the scanning speed of 0.8 m s^{-1} and 2.3 m s^{-1} was revealed. The complete cutting of the CFRTP sample required the multiple-scan-pass irradiation of 14 passes and 42 passes for the scanning speed of 0.8 m s^{-1} and 2.3 m s^{-1}, respectively. The kerf width of the groove on the laser beam incident surface at 0.8 m s^{-1} laser-scanning is estimated to be 1000 μm. The internal kerf of the groove in bulk region is ca. 300 μm, as shown in Fig. 1 (observation (I)). The observation (II) of Fig. 1 shows that the bottoms of the grooves are flat levels before reaching full cutting depth of the CFRTP sample.

Cutting depth of 3-mm-thickness CFRTP sample was plotted as the function of the laser pass-number (Fig. 2). Linear relation between the cutting depth and laser pass-number was obtained at four different irradiation conditions. On the three different scanning speed of the laser beam on the CFRTP surface at the laser power of 1 kW, a fast scan required a large scan-pass-number.

The total laser dose energy on CFRTP surface at the scanning speed of 0.8 m s^{-1} with 350 W corresponded to the energy at 2.3 m s^{-1} with 1 kW. The laser-pass-number for the complete cutting at 0.8 m s^{-1} with 350 W was almost same as that at 2.3 m s^{-1} with 1 kW. In addition, the incident kerf of the groove formed by the scanning at 2.3 m s^{-1} with 1 kW was narrow in comparison with at 0.8 m s^{-1} with 1 kW (Fig.1: Observation (I)). The fast scanning was effective for the reducing the incident kerf region.

These results indicate that a constant value of etching rate for the laser pass-number on CFRTP samples would be acquired on the cw fiber laser irradiation. The depth of the groove on CFRTP sample would be possible to be precisely controlled by the laser pass-number.

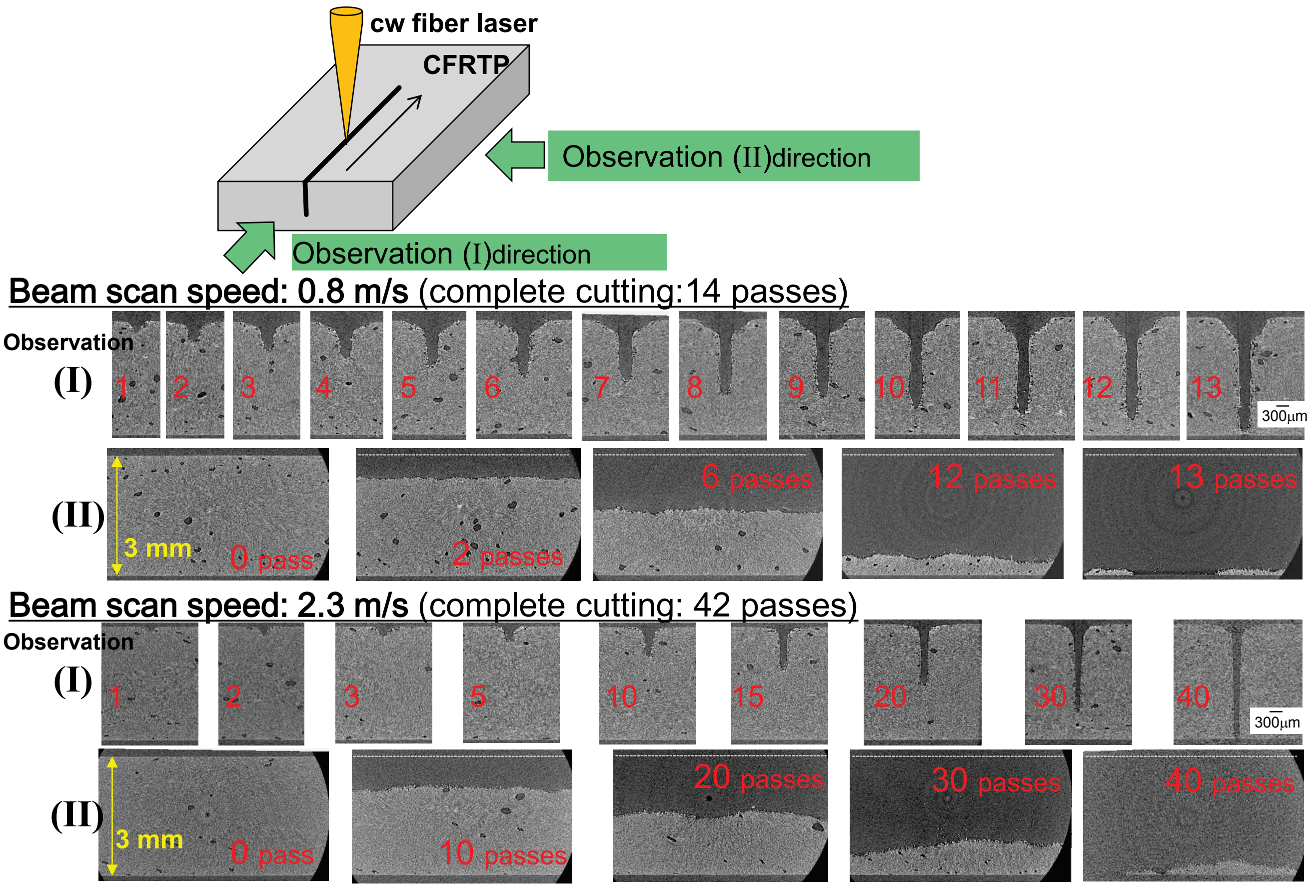

Fig. 1 Cross-sectional X-CT images of 3-mm-thickness CFRTP sample measured at two different observation directions ((I) and (II)). CFRTP sample was cut by cw fiber laser irradiation of 1 kW average power with the scanning speed of 0.8 m s^{-1} and 2.3 m s^{-1}.

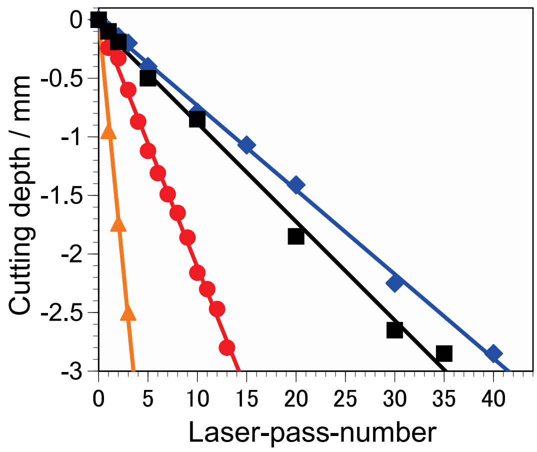

Fig. 2 Cutting depth of 3-mm-thickness CFRTP sample by cw fiber laser irradiation on a multiple-scan-pass method. Scanning speed was set at 0.2 m s^{-1} (orange colored triangle, P= 1 kW), 0.8 m s^{-1} (red colored circle, P= 1 kW), 2.3 m s^{-1} (blue colored diamond, P= 1 kW), and 0.8 m s^{-1} (black colored square, P= 350 W).

3.2 Laser-induced damages of CFRTP samples

At the laser irradiation with the scanning speed of 0.8 m s^{-1}, free of debris-deposition around the groove was observed on the laser-incident surface of CFRTP sample [3]. A high resolution X-CT image of cross-sectional CFRTP sample clearly shows the formation of micron-sized voids (dark spots in the image) in the subsurface of internal wall at the groove (Fig. 3(a)). It is worth noted that the micron-sized voids and bubbles appears within a 50 - 100 µm-thickness surface layer on the internal wall of the groove (Fig. 3(b)).

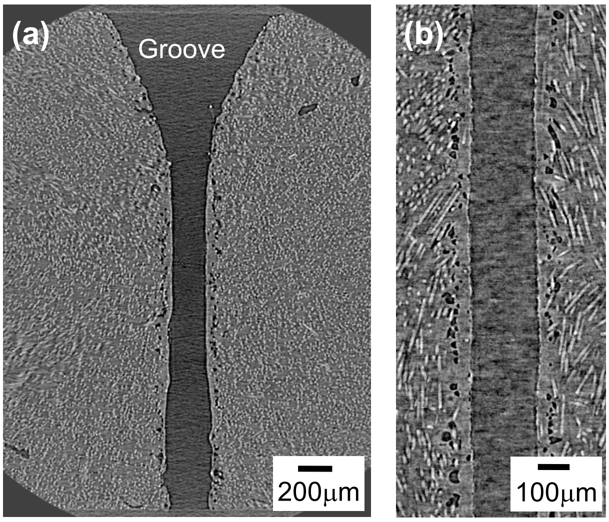

Fig. 3 Cross-sectional X-CT images of 3-mm-thickness CFRTP sample measured at high resolution measurements. CFRTP sample was cut by cw fiber laser irradiation of 1 kW average power and 14 passes with the scanning speed of 0.8 m s^{-1}.; (a) entire image, (b) magnified image.

The surface temperature observation with a thermo-camera showed that 500 degree C was detected at the area of the groove during the laser irradiation. As the resin is pyrolyzed over the temperature of 470 degree C, a small gaseous molecule produced by the laser-induced thermal decomposition of the resin would form the micron-sized voids and bubbles. These results indicated that the micron-sized voids and bubbles would be produced by thermal damage during the laser irradiation. On the surface of internal wall of the groove, micron-sized bubbles were also observed by SEM measurement in Fig. 4, suggesting that thermal damage as HAZ during the laser irradiation of CFRTP sample occurs in a nearly negligible thin surface layer of the internal wall of the groove.

At the scanning speed changed to 0.2 m s^{-1}, a large HAZ appeared on the laser-incident surface. A bump structure was observed around the groove [3]. In Fig. 5, it is clearly shown that the formation of bump was due to hundreds-micron-sized bubbles inside the sample. As the slow beam scanning would induce a higher temperature at the laser irradiation region by the accumulation of laser incident energy, resulting significant thermal decomposition of the resin to produce a large amount of gaseous by-products at the region. When CO_2 laser and fundamental YAG laser were used for the cutting of CFRP [16, 42, 51-58], a large HAZ was observed around the cutting region. Cross-sectional image of Fig. 3(a) clearly reveals that near-IR laser cutting by multiple-scan-pass with a fast laser beam scanning exhibits a minimized HAZ.

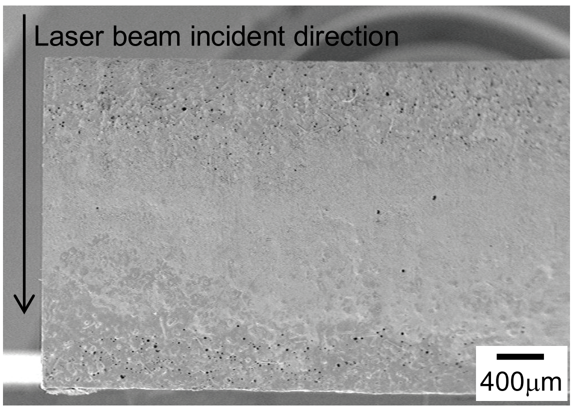

Fig. 4 SEM image of the internal wall surface on the groove of CFRTP sample. CFRTP was cut by the laser irradiation of 1 kW and 14 passes with the scanning speed of 0.8 m s^{-1}.

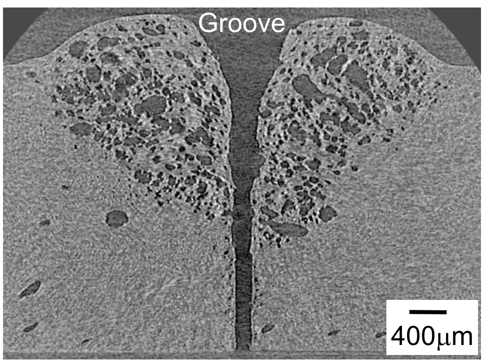

Fig. 5 Cross-sectional X-CT images of 3-mm-thickness CFRTP sample measured at high resolution measurements. CFRTP sample was cut by the laser irradiation of 1 kW and 4 passes with the scanning speed of 0.2 m s^{-1}.

Micro-Raman spectroscopy is ideally suited to characterize and spatially resolve the chemical and physical changes as HAZ that occur at the laser irradiation, particularly in a thin surface layer of the materials. Figure 6 shows micro-Raman spectra of the surface layer on internal wall of the groove of CFRTP sample which was cut by the laser irradiation f 1 kW and 14 passes with the scanning speed of 0.8 m s^{-1}. The Raman measurement was carried out at the distance of every 5 µm from 3 µm to 53 µm under the surface of internal wall.

At the distance of 3 µm to 13 µm, a strong broad signal was detected between 4000 cm^{-1} and 500 cm^{-1}, as shown in Fig. 6(a). The Raman measurements at the distance beyond 28 µm provided clear evidence of correspondence between subsurface and bulk spectrum (Fig. 6(b) and Fig. 6(c)).

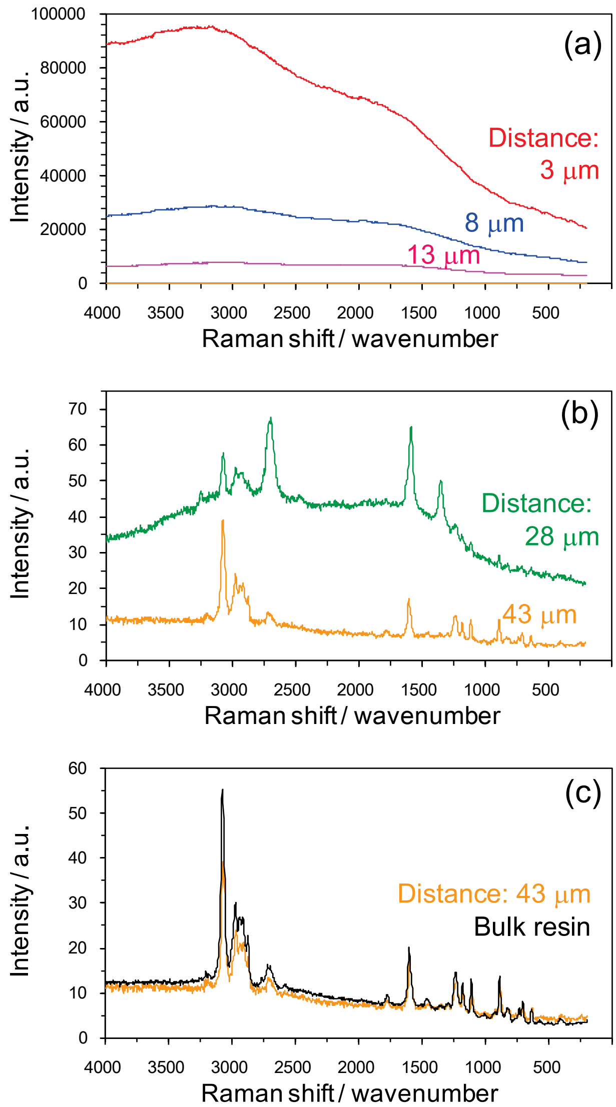

Fig. 6 Micro-Raman spectra of the surface layer at internal wall on the groove of CFRTP sample. CFRTP was cut by the laser irradiation of 1 kW and 14 passes with the scanning speed of 0.8 m s^{-1}.; (red colored line) distance from the surface of internal wall: 3 µm, (blue) 8 µm, (pink) 13 µm, (green) 28 µm, (orange) 43 µm, (black) bulk resin. The vertical axis of Figs. 6(b) and 6(c) is magnified in comparison with that of Fig. 6(a).

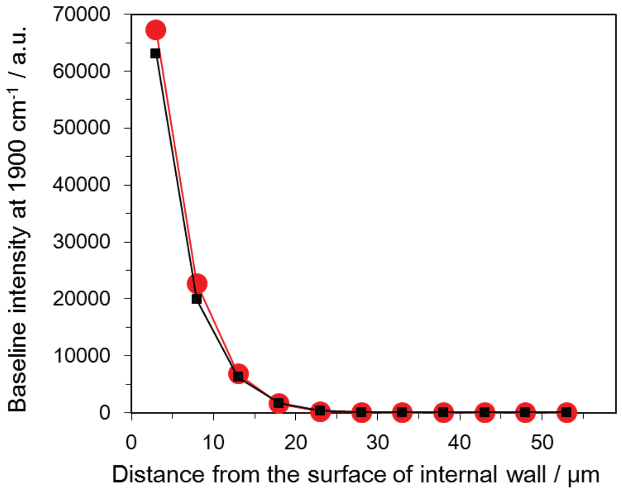

Fig. 7 Baseline intensity at the wave-number of 1900 cm^{-1} on the micro-Raman spectra was plotted by the distance from the surface layer of internal wall on the groove of CFRTP sample. CFRTP was cut by the laser irradiation of 1 kW and 14 passes with the scanning speed of 0.8 m s^{-1}.; (red colored circle) near laser-incident surface, (black colored square) near rear-surface.

The strong broad signal, which is attributed to fluorescence background, concealed the Raman signals in Fig. 6(a). The intrinsic fluorescence background would originate from contaminants that had a photo-absorption band at the wavelength of 532 nm for the excitation of Raman measurement [65 – 67]. These contaminants could be organic impurities with a π-electron-conjugated chemical structure which was produced by the laser-induced thermal reaction of the resin during the laser irradiation.

The signal intensity of Raman spectra at the wave-number of 1900 cm^{-1} was plotted as the function of the distance from the surface layer of internal wall on the groove of CFRTP sample (Fig. 7). As a significant high intensity of baseline in the spectra appears within the distance of 20 - 30 µm, thermal damaged region based on Raman analysis would be almost consistent with that based on X-CT measurement.

4. Summary

We have demonstrated that micro-cutting of CFRP was performed in ambient air upon a multiple-scan-pass irradiation with a cw near-IR laser. Laser cutting with a high speed beam scanning exhibits a clean top and an excellent sidewall quality along with a negligible heat affected zone (HAZ: < 100 µm-thickness). However, CFRP is a typical difficult-to-cut material which is generally made up by resin bond and reinforced carbon fiber.

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