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Deep-Trench Structure of Carbon-Fiber-Reinforced Thermoplastics (CFRTP) by Laser Cutting with a Single-Mode IR Fiber Laser

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We report deep-trench microstructures fabricated on carbon-fiber-reinforced thermoplastic (CFRTP; a CFRP containing thermoplastic resin). Well-defined laser cutting free of debris around the trench was achieved for various types of CFRTP plates by single-mode laser irradiation with a fast beam galvanometer scanner using a multiple-scan-pass method. The microfabrication of a CFRTP containing pitch-type carbon fibers and a polycarbonate resin, performed by 600-scan-pass irradiation with a cw kilowatt single-mode IR fiber laser (average power: 1 kW), yielded a trench microstructure with a depth of 18.2 mm and an opening width of 0.32 mm. The laser-induced damage in the samples was analyzed by microscopic X-ray computed tomography. Laser cutting by high-speed beam scanning resulted in a clean top and excellent sidewall quality, along with a negligible heat-affected zone.

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1. Introduction

Laser cutting of carbon-fiber-reinforced plastics (CFRPs) with a high-power laser enables well-defined microfabrication without debris around grooves [1]. This cutting process yields high-precision cuts with narrow kerfs where complex contours demand precise, fast and force-free processing [2, 3]. To explore the possibility of 3D laser processing, a CFRP was cut into a three-dimensional molded sample using a five-axis laser cutting machine [4]. Single-mode fiber lasers are expected to provide narrow cutting kerfs with high aspect ratios for CFRPs [5], as their beams can be tightly focused with a longer depth-of-focus (DOF) than multi-mode lasers.

In this paper, we report deep-trench microstructures fabricated by laser cutting of carbon-fiber-reinforced thermoplastics (CFRTPs), which are composite materials of thermoplastic resin matrices and carbon fibers, using a cw single-mode fiber laser ($\lambda = 1084$ nm). Well-defined cutting with a high aspect ratio was achieved for CFRTPs by irradiation with a single-mode laser with a fast beam galvanometer scanner using a multiple-scan-pass method [1, 4]. The deep-trench microstructure in the samples was characterized by X-ray computed tomography (X-CT) to determine the heat-affected zone (HAZ).

2. Experimental

The output of a near-IR cw laser (Furukawa Electric, Yb-doped fiber laser, $\lambda = 1084$ nm, single-mode ($M^2 < 1.1$, BPP: 0.345 mm mrad, fiber core diameter: 12 μm), 1 kW average power) [6] was scanned on the sample surface by single-line irradiation of the multiple-scan-pass method with a galvanometer scanner in ambient air (scanning speed: 3.6 and 2.3 m s^{-1}, without assist gas) [1, 4]. The beam was incident normal to the sample surface and focused with an f-theta lens (Showa Optronics Co., Ltd., FT300/5-1080F, non-telecentric lens, f = 306 mm, calculated focal diameter of laser beam on sample surface: 120 μm). The time interval (breaking time) between the scan-pass irradiations was set to 5 s to avoid an increase in temperature due to heat accumulation on the sample.

To determine the laser beam profile in the vertical direction, laser engraving of the CFRTP plate was performed with a single sweep at a cw laser power of 130 W. The sample plate was irradiated at an incident angle of 45°. The sweep length of the laser beam for this verification was around 50 mm on the sample surface.

3-mm-thick and 30-mm-thick CFRTP samples, prepared by compression molding, were employed for the laser cutting experiments. CFRTP-PC consists of a chopped pitch-type carbon fiber (Cf = 30 wt%) and polycarbonate resin (Mitsubishi Engineering-Plastics Corp.; Iupilon, resin melting point: Tm = 220–230°C, resin pyrolysis in air: 470°C) [7, 8]. In addition, two other types of CFRTP plate samples were employed for the laser cutting. Both prepared by injection molding, these samples were a chopped PAN-type carbon fiber (Cf = 30 wt%) in ABS resin (ABS; copolymer of acrylonitrile-butadiene-styrene, Toray Industries Inc.) and in PA6 resin (polyamide 6 (nylon 6), Toray Industries Inc.).

High-resolution images of the sample surface with a large field-of-view obtained by the image stitching method were captured with an optical microscope (Keyence, VHX-1000). The deep-trench microstructure in the samples was determined with a microscopic X-CT system (Yamato Science Co.; TDM1000H-Sμ/TDM1600H-II, X-ray filament: LaB_6, X-ray spot diameter: 0.8 μm).

3. Results and Discussion

3.1 Deep-trench structure formation of CFRTP-PC material by laser cutting

Figure 1 shows cross-sectional images of the trench structure on a CFRTP-PC sample obtained after cw fiber laser irradiation with an average power of 1 kW using the multiple-scan-pass method. A deep trench with a depth of 18,200 μm was obtained by 600-multiple-scan-pass irradiation (Fig. 1(a)). The kerf width of the trench at the laser incident surface was 320 μm. The internal kerf in the middle region of the trench was around 150 μm, as shown in Fig. 1(b). The focal position of the laser beam during the laser irradiation was fixed at 10 mm beneath the laser incident surface.

Figure 1(c) shows a trench with a depth of 14,800 μm obtained after 300-pass irradiation. The kerf width of the trench at the laser incident surface was around 300 μm, while that of the internal kerf in the bottom region of the trench was around 100 μm. In addition, the HAZ, as analyzed by X-CT measurement, was 30–50 μm at the internal wall of the groove, as shown in Fig. 1(d). These results indicate that irradiation with a single-mode laser by the multiple-scan-pass method is effective for fabricating a deep-trench microstructure on the CFRTP-PC material.

3.2 Laser engraving of the CFRTP plate by single-mode laser irradiation with an incident angle of 45°

The kerf width of the trench on the sample surface was monitored by laser engraving of the CFRTP plate with an incident angle of 45°. Figure 2 shows the optical micrograph of a large field-of-view on the CFRTP-PC plate surface after a single sweep of the laser beam (average power: 130 W). The laser beam was swept across the sample surface at a speed of 5.1 m s^{-1} (5.1 m $s^{-1} \approx$ 3.6 m $s^{-1} \times \sqrt{2}$). A track on the CFRTP-PC surface by the laser engraving in Fig. 2 reflects the laser beam profile in the vertical direction. At the focal point, the CFRTP-PC plate was etched by a track width of 0.20 mm. An etched width of 0.4 mm was observed at a distance of 14 mm from the focal position. This indicates that laser cutting with a narrow kerf and high aspect ratio took place within a vertical depth of ±10 mm from the focal position ($\pm 10 \approx \pm 14/\sqrt{2}$). The above results are also consistent with the long depth-of-focus of the single-mode beam, which is an essential property for microfabrication.

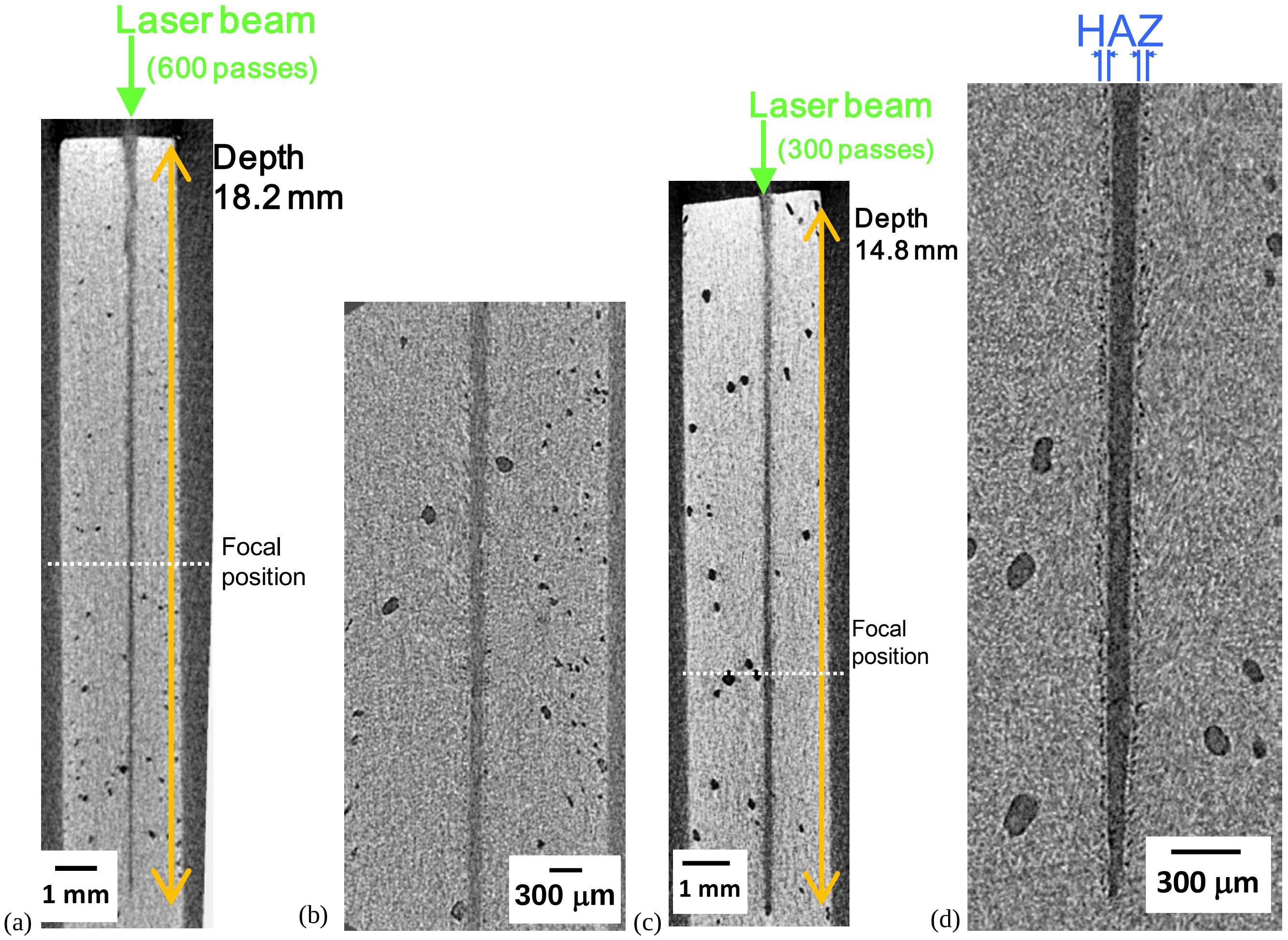

Fig. 1 X-CT image of the 30-mm-thick CFRTP-PC plate cut by cw 1-kW single-mode fiber laser irradiation using the multiple-scan-pass method. Laser scanning speed was set at 3.6 m s^{-1}. (a) Cross-section of the trench fabricated by 600-multiple-scan-pass irradiation (the deepest area), (b) close-up near the middle of the trench by 600 passes, (c) cross-section of the trench by 300 passes (the deepest area), and (d) close-up of the lower part of the trench by 300 passes.

3.3 Laser cutting properties of CFRTP-PC

3.3.1 Laser cutting properties of 3-mm-thick sample

The cross-sectional images of the CFRTP-PC sample taken after cw laser irradiation at normal incidence by the multiple-scan-pass method are shown in Fig. 3. The laser scanning speed was set at 2.3 m s^{-1} or 3.6 m s^{-1}. In addition, observation normal to the grooves (observation II) verified that the groove depth remained uniform until the plate was cut completely. The kerf width of the groove at the laser incident surface was estimated to be 200 μm, and that of the groove in the bulk region was also around 200 μm. The HAZ at the internal wall of the groove was estimated to be 30 μm based on a X-CT measurement.

The depth of the cut grooves increased in proportion to the number of passes of cw 1-kW laser radiation (Fig. 4). Compared to irradiation with a multi-mode fiber laser (fiber core diameter: 50 μm; 42 passes at a scanning speed of 2.3 m s^{-1}) [9], the cutting speed by single-mode laser irradiation was 2.3 times higher.

These results indicate that the etching rate of the CFRTP-PC samples by repeated irradiation with the cw fiber laser is constant throughout the cutting process of the 3-mm-thick plate and that the depth of grooves in CFRTP-PC samples can be precisely controlled by varying the scan speed and the number of passes.

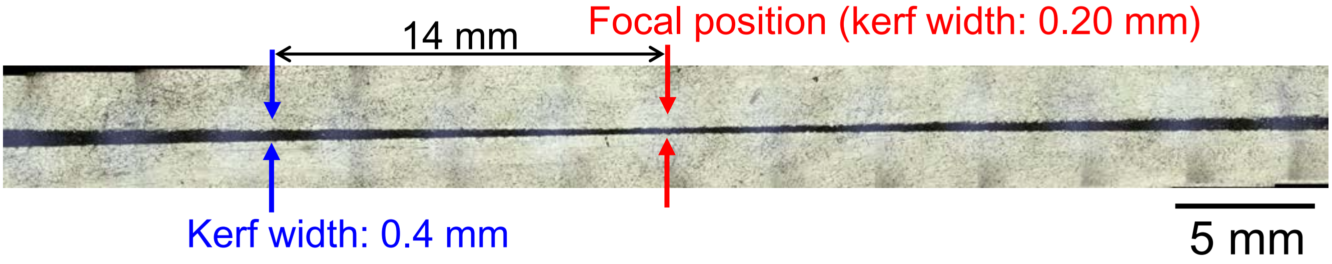

Fig. 2 Optical micrograph with a large field-of-view on the CFRTP-PC plate surface. The CFRTP-PC plate was tilted by 45° with respect to the incident direction of the single-mode laser (scanning: single sweep with a speed of 5.1 m s^{-1}, cw laser power: 130 W). The focal position on the plate surface was on the center axis of the scanner.

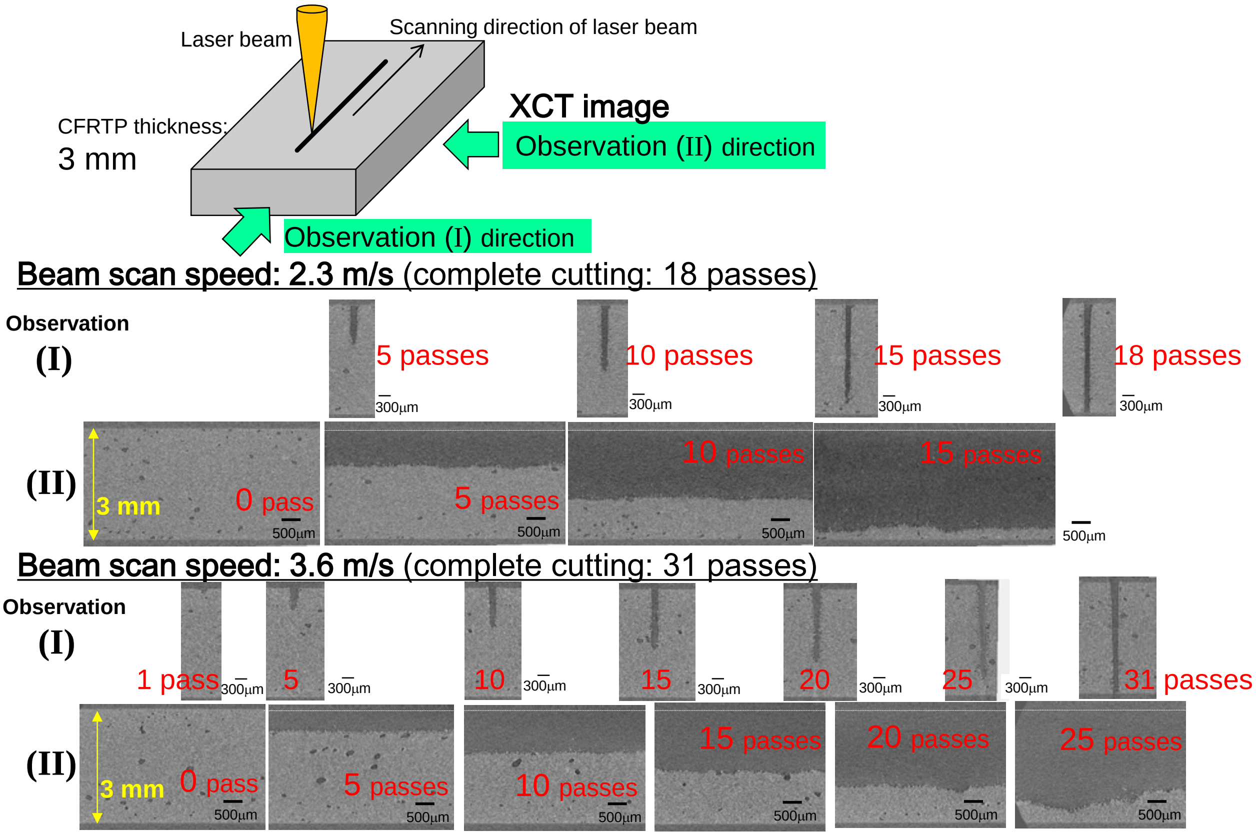

Fig. 3 Cross-sectional X-CT images of the 3-mm-thick CFRTP-PC samples measured from two different observation directions ((I) and (II)). The CFRTP-PC samples were cut by cw single-mode fiber laser irradiation at an average power of 1 kW and scanning speeds of 2.3 and 3.6 m s^{-1}.

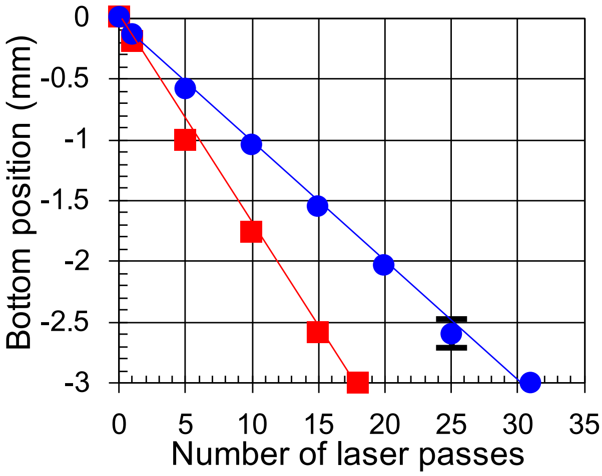

Fig. 4 Bottom position of the trench on 3-mm-thick CFRTP-PC plates fabricated by fiber laser cutting with the multiple-scan-pass method (cw laser power: 1 kW); blue circles: laser scanning speed of 3.6 m s^{-1} (error bar at 25 passes represents the relief of the bottom level); red squares: 2.3 m s^{-1}.

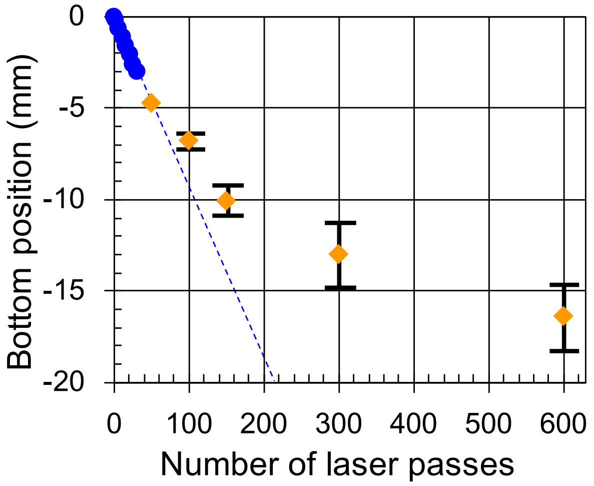

Fig. 5 Bottom position of the trench on CFRTP-PC plates fabricated by fiber laser cutting with the multiple-scan-pass method (cw laser power: 1 kW, scan speed: 3.6 m s^{-1}); blue circles: 3-mm-thick CFRTP-PC plate (blue broken line is a linear extrapolation of the 3-mm-thick CFRTP-PC depths.); orange diamonds: 30-mm-thick CFRTP-PC plate (error bars represent the relief of the bottom level).

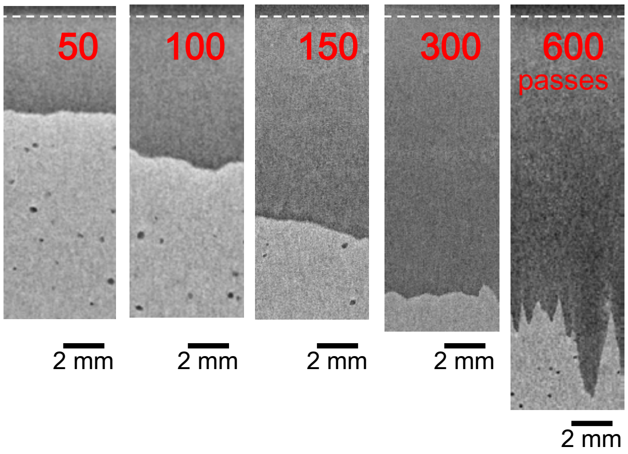

Fig. 6 Cross-sectional X-CT images of the 30-mm-thick CFRTP-PC samples (observation II). The samples were irradiated for 50, 100, 150, 300, and 600 passes (cw laser power: 1 kW, scan speed: 3.6 m s^{-1}).

3.3.2 Laser cutting properties of 30-mm-thick sample

Figure 5 shows the bottom position of the trench on the 30-mm- and 3-mm-thick CFRTP-PC plates obtained by cw fiber laser irradiation using the multiple-scan-pass method at a laser scanning speed of 3.6 m s^{-1}. The cutting rate of the 30-mm-thick CFRTP-PC plate was fast and constant for the first 50 passes. When the number of passes exceeded 100, the cutting depths of the CFRTP sample deviated from a linear extrapolation based on the 3-mm-thick CFRTP-PC depths. In addition, the cutting depths obtained by laser irradiation with over 150 passes were poorly reproducible for all CFRTP-PC specimens.

Figure 6 shows significant disturbance at the bottom of the trench after 600 passes of laser irradiation. The error bars in Fig. 5 represent the relief arising from the disturbance of the bottom level. Similar behavior, i.e., formation of narrow kerf and bottom disturbance, was reported by single-line laser cutting on CFRP prepreg laminates consisting of a thermoset epoxy resin with PAN-based continuous carbon fibers (cross-ply 0/90°) [1, 4].

3.4 Deep trench formation of CFRTP materials

Table 1 shows the laser cutting properties of three types of 30-mm-thick CFRTP plates subjected to single-mode fiber laser irradiation with an average cw power of 1 kW. The cutting depths of the deep trench structure of CFRTP-ABS, CFRTP-PA, and CFRTP-PC exceeded 10 mm after 300-600 passes. The bottom positions (depths) of the trench were measured for several specimens.

The top surface kerf width of the three CFRTP samples ranged between 0.60 and 0.32 mm (see Table 1), which indicates that single-mode laser irradiation is effective for deep trench formation in CFRTP materials with a high aspect ratio. Figure 7 also shows the disturbance of the bottom level of the drove for CFRTP-ABS and CFRTP-PA after 300–600 passes. This may be because the kerf width of the trench is too small. A sufficient kerf width of around 0.45 mm of CFRP materials [1], achievable by double scanning the laser along two lines with a gap of 0.1 mm, would enhance the cutting rate of CFRP materials. In other words, the combination of double-line scanning and multiple-scan-pass irradiation would enable the fast fabrication of a fine deep trench on CFRTP plates.

Table 1 Laser cutting properties of 30-mm-thick CFRTP plates by single-mode fiber laser irradiation[*].

Polymer matrix of CFRTP	Number of passes	Bottom position[**] and surface kerf of the trench (mm)	Number of specimens[***]
Polycarbonate (CFRTP-PC)	600	18.2–14.5 and 0.32	5
ABS resin (CFRTP-ABS)	300	10.8–7.0 and 0.40	2
Polyamide (CFRTP-PA)	600	16.7–6.1 and 0.60	3

[*] Average power: 1 kW (cw), beam scanning speed: 3.6 m s^{-1}.

[**] Bottom position of the trench by laser cutting represents the range of the relief of the bottom level.

[***] The number of specimens is the number of laser-irradiated samples.

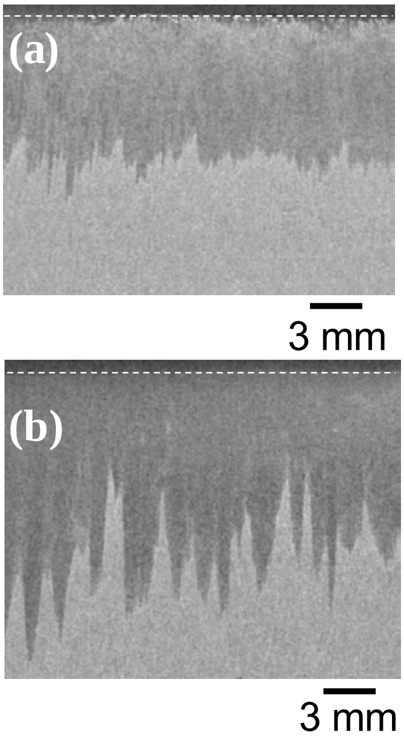

Fig. 7 Cross-sectional X-CT images of the 30-mm-thick CFRTP samples after laser irradiation (1 kW (cw), 3.6 m s^{-1}); (a) CFRTP-ABS after 300 passes, (b) CFRTP-PA after 600 passes.

4. Summary

We have performed micro-cutting of CFRTP in ambient air by multiple-scan-pass irradiation with a cw near-IR laser. The beam properties of the single-mode laser have a significant effect on the depth of the microtrench on the CFRTP plate. Single-mode laser irradiation with a large DOF of the focused beam afforded a trench structure with a depth of more than 10 mm and a submillimeter narrow kerf. Laser cutting by high-speed beam scanning with a galvanometer exhibits a clean top and excellent sidewall quality along with a thickness of tens of microns for the HAZ region in the trench.

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