Processing of CFRP by Using 3-kW Single-mode Fiber Laser

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A high-speed continuous processing of carbon fiber reinforced plastic (CFRP) has been demonstrated using a 3-kW single-mode fiber laser and galvanometer scanner. The 3.1-mm-thick thermoset CFRP has successfully been cut with 100 scans at a scanning speed of 13 m/s. The effective cutting speed was 7.8 m/min. The laser was scanned continuously at a time interval of less than 20 ms. The surface was in good condition with a heat-affected zone (HAZ) of 97 µm on average. The test results indicate the high power continuous wave (CW) single-mode fiber laser can be used for high-speed CFRP processing.

1. Introduction

Recently, weight saving of vehicles is promoted in the automotive industry due to significant growth in demand for reduction of greenhouse gases, and CFRP is drawing attention as a lightweight replacement for car body parts materials. A general method for cutting CFRP uses machine tools. However, tools used for cutting are easily damaged due to the high strength of CFRPs. Since worn tools lead to the degradation of cutting quality, they need to be replaced frequently. Laser processing is a promising candidate for a wear-free method for cutting CFRP.

A major challenge in laser cutting of CFRP is the reduction of HAZs. Since the evaporation temperature of plastic is much lower than that of carbon fiber, plastic is easily damaged by the spread of heat and a HAZ is generated. Therefore, laser cutting is inferior to processing with machine tools in the surface quality. Using a pulsed laser or ultrashort pulsed laser is an effective way of minimizing HAZs [1)]. The processing by an ultrashort pulsed laser is called laser ablation, which can reduce the width of HAZ by its extremely short radiation time and high peak power. However, the low average power of those lasers lead to relatively long processing time. In the automotive industry, an effective cutting speed of several meters per second is required for sufficient productivity. One way to improve the processing speed is to use high power CW lasers. Although CFRP cutting at over 10 m/min using high power lasers have been reported [2) 3)], the widths of HAZs in those reports are relatively large. Processing with a single-mode fiber laser and a galvanometer scanner is a promising solution to achieve a short processing time and small HAZ simultaneously. As a single-mode fiber laser can achieve a high power density and small spot diameter, energy needed for processing is effectively provided. In addition, high speed scanning by a galvanometer scanner will reduce the widths of HAZ.

We have reported processing tests carried out using our in-house single-mode fiber laser [4) 5)]. This report describes the high speed cutting of CFRP using a 3-kW single-mode fiber laser. A 3.1-mm-thick CFRP plate has successfully been cut with 100 scans at a scanning speed of 13 m/s. The effective cutting speed was 7.8 m/min. The laser was scanned by a multi-pass method with a time interval of 20 ms, which is extremely shorter than a general value. The width of HAZ was reduced to 97 µm on average and less than 200 µm even at the largest point. The results show the potential of the high power CW single-mode fiber laser for high-speed high-quality cutting of the CFRP.

2. Processing Conditions

Figure 1 shows the processing test setup. The Fujikura 3-kW single-mode fiber laser was connected to the galvanometer scanner via the laser delivery cable. The M-squared value, which indicates the beam quality of a laser, was 1.3. The optical magnification of the galvanometer scanner was 3 and the corresponding spot diameter was about 100 µm. The CFRP plate consists of 13 layers made of unidirectional fabric layers, with fiber orientations of 0 degrees and 90 degrees. The size of the plate was 150 mm × 30 mm. To remove the carbon fiber deposition and cool the workpiece, nitrogen gas was blown from the upper side.

Figure 2 shows the scanning condition of the laser. The multi-pass method, in which a laser is scanned on

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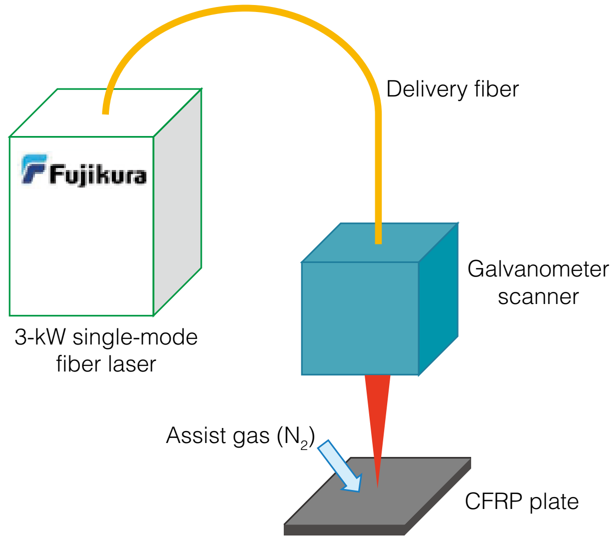

Fig. 1. CFRP processing setup.

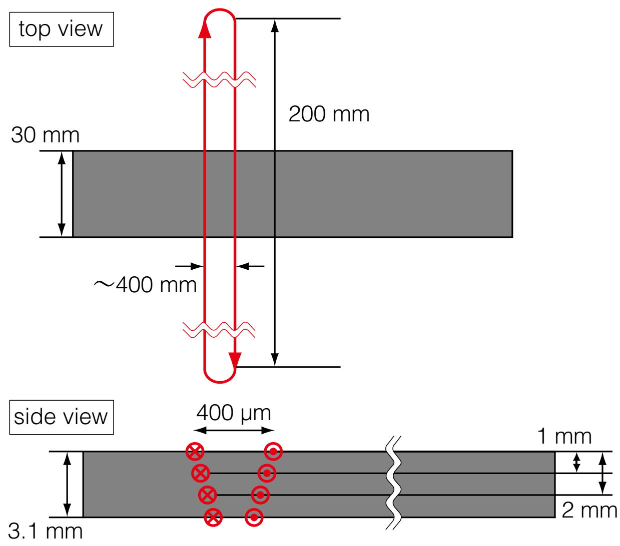

Fig. 2. Scanning condition.

the same position at high speed, is known to be an effective way of reducing the width of HAZ. The scanning distance was 200 mm, and the continuous round-trip scanning was carried out to achieve a faster effective cutting speed. In the multi-pass method, the time interval is generally set between each scan. As the time interval set under this condition was 20 ms, which was much shorter than a general value, the scanning was almost continuous. To process with a sufficient kerf width and remove the carbon fiber deposition efficiently, a gap of 400 μm was set between the forward and the backward scanning paths. The focal point was shifted into the CFRP plate by 1 mm after a certain number of scans. At the same time, the distance between the forward and the backward scanning paths was narrowed.

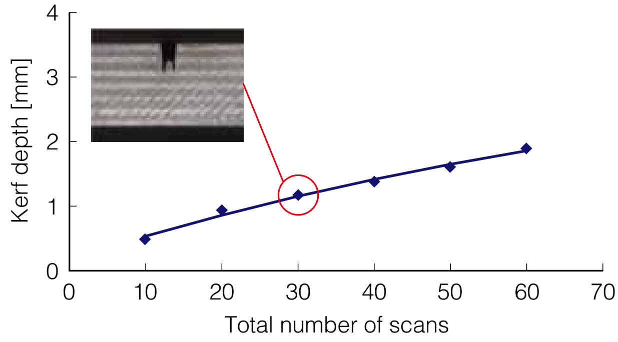

Fig. 3. Kerf depths versus the number of scans. Focal position is the surface of the CFRP plate.

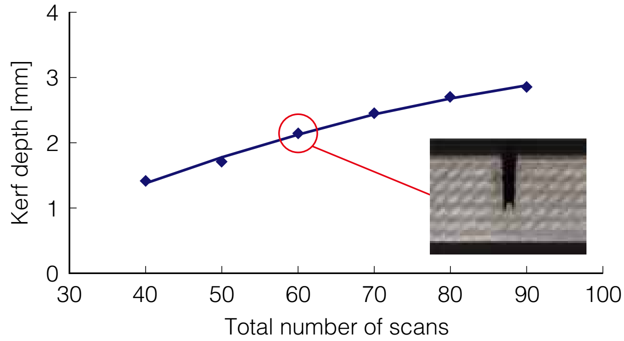

Fig. 4. Kerf depths versus the total number of scans. Focal position is shifted to 1-mm below the surface of the CFRP plate after 30 scans on the surface.

3. Optimization of Processing Condition

To improve the effective processing speed, the number of scans should be reduced. We determined the kerf depth at each number of scans and optimized the processing condition. Figure 3 shows the kerf depth versus the number of scans when the focal point was set to the surface of the CFRP plate. The processing efficiency gradually decreased as the number of scans increased. The cross-sectional image after 30 scans is shown in the figure. While the CFRP remained in the center of the kerf, the kerf depth reached 1 mm.

Next, the focal point was shifted to 1 mm below the surface of the CFRP plate after 30 scans at the surface of the plate. The distance between forward and backward scanning paths was narrowed from 400 μm to 350 μm with the shift of the focal point. By narrowing the distance of the scanning paths, the reflection of the laser light on the kerf walls will be reduced and the laser light will reach the area being worked on more efficiently [2]. Figure 4 shows the kerf depth versus the number of scans under the condition and the cross-sectional image after 60 scans. In comparison with the kerf depth at 60 scans shown in Fig. 3, the deeper kerf was obtained under this condition.

In a similar way, the focal point was shifted to 2 mm below the CFRP plate surface after 30 scans on the surface and 30 scans on 1 mm below the plate. The distance of the forward and backward scanning paths was changed from 350 μm to 300 μm. Figure 5 shows the kerf depth versus the number of scans and the cross-sectional image after 100 scans under the described condition. The 3.1-mm-thick CFRP was cut completely with 110 scans. By shifting the focal point at an earlier time and scanning the bottom of the plate, the number of scans should be further reduced.

4. Processing Test Results

Based on the experimental results described above, the processing condition was set as shown in Table 1. The focal point was shifted by 1 mm deeper in the plate after each 25 scans, and the distance between the forward and the backward scanning paths was changed by 50 μm at the same time of the focal point shift. The total number of scans was 100, which corresponds to 50 round trips.

The 3.1-mm-thick CFRP plate was successfully cut under the described condition. Figure 6 shows the side view and the cross-sectional view of the processed CFRP plate. The kerf angle was below 3 degrees and the good surface conditions were achieved. Since the scanning speed was set to 13 m/s, the effective cutting speed was 7.8 m/min. Figure 7 shows the top views of the processed CFRP plate. These images were obtained using an optical microscope and scanning electron microscope (SEM), respectively. The widths of HAZ were limited to 97 μm on average and less than 200 μm even at the maximum point. Due to the fast scanning speed and cooling by the assist gas, the spread of the heat was successfully limited.

We further investigated the influence of the assist gas on the widths of HAZ and cutting results. The pressure of nitrogen gas was changed from 0.1 MPa to 1.3 MPa. Figure 8 shows the width of HAZ versus the assist gas pressure. The bars shown in each point indicate the standard deviation in each condition. The high-velocity gas flow by the higher pressure led to the relatively small spread of HAZ. However, the widths of HAZ were reduced to about 120 μm even at a low velocity of flow. These results indicate that a fast

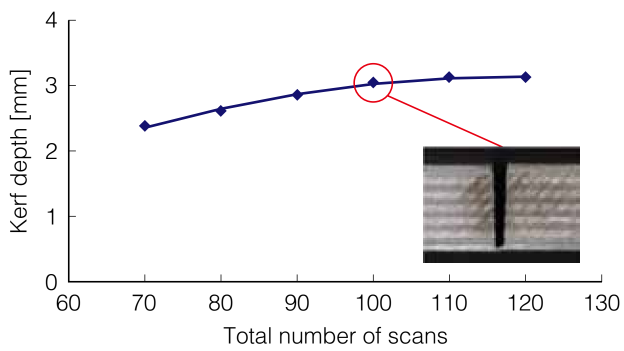

Fig. 5. Kerf depths versus the total number of scans. Focal position is shifted to 2-mm below the surface of the CFRP plate after 30 scans on the surface and 30 scans on 1-mm below the surface.

Table 1. Scanning condition in cutting experiment.

Focal position (mm)	Gap of scanning position (μm)	Number of scans
0 (surface)	400	25
1	350	25
2	300	25
3	250	25

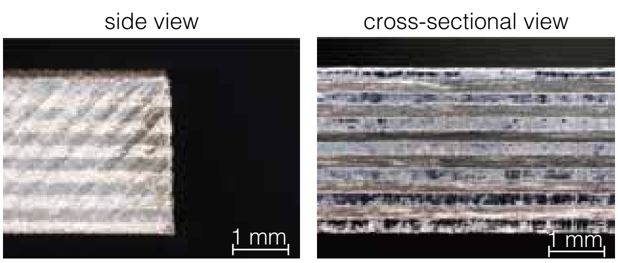

Fig. 6. Side and cross-sectional views of the processed CFRP plate.

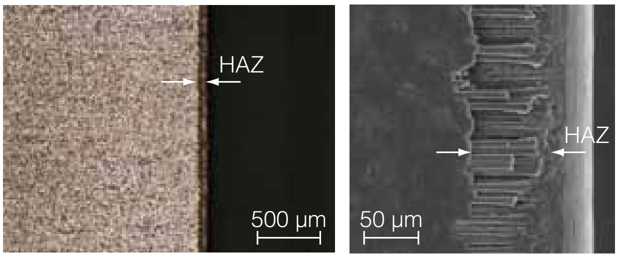

Fig. 7. Microscopic and SEM images of the top views of the processed CFRP plate.

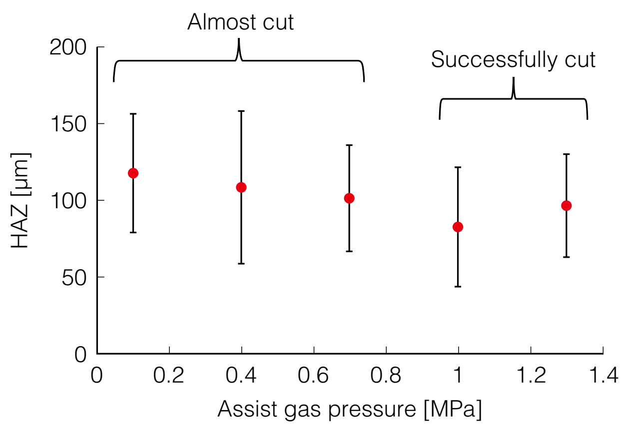

Fig. 8. Width of the HAZ versus the pressure of the assist gas.

scanning speed of the galvanometer scanner and a high power density of the single-mode fiber laser are significant in reducing the widths of HAZ. However, CFRP plates were not cut at a pressure of less than 0.7 MPa due to the decrease in cutting efficiency caused by remained deposition of the carbon fibers. Since the influence of the assist gas is not limited to the flow velocity, further investigation including the distance and angle of the nozzle is needed.

5. Conclusion

The 3.1-mm-thick CFRP plate was successfully cut with the Fujikura-made 3-kW single-mode fiber laser and the galvanometer scanner. The number of scans for the cutting was 100 at a scanning speed of 13 m/s, which corresponds to an effective processing speed of 7.8 m/min. The time interval between each scan was less than 20 ms, and therefore the laser was scanned almost without a time interval. The widths of HAZ were limited to 97 μm on average and less than 200 μm even at the largest point. The high scanning speed and high power density led to the fast effective processing speed with the small HAZ. The results show the potential of the high power CW single-mode fiber laser for high-speed high-quality processing of the CFRP.

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