Ultra High Speed Laser Cutting of CFRP Using a Scanner Head†

JUNG Kwang-Woon***, KAWAHITO Yousuke**, KATAYAMA Seiji*

Abstract

Laser cutting of CFRP is well known to be difficult because of the thermal damage to the CFRP material. Therefore, with the objectives of evaluating the cutting possibility for long- or short-fiber pellet CFRP sheets of 3 mm in thickness and obtaining narrower HAZ for better cut quality, ultra-high speed cutting was conducted by using a continuous-wave (cw) high-brightness disk laser with a scanner head. The increase in the laser power rendered the cutting time shorter and the kerf depth deeper for a CFRP full cut. It was revealed that CFRP cut with a narrow HAZ of less than 50 μm could be produced under the conditions of laser powers of 2 to 5 kW, a cutting speed of 5 m/s, a time interval between repeated runs of 1 second and a defocused distance of 0 mm. It was also confirmed that short fiber pellet CFRP was more easily cut and suffered less thermal damage in comparison with a long fiber one. Furthermore, it was demonstrated that the tensile strength of fully laser-cut CFRP was almost equal to that of the base CFRP specimen. This means the laser-cut surfaces of the CFRP sheet were not degraded in mechanical properties.

KEY WORDS: (Laser cutting), (CFRP), (Ultra high speed), (Heat affected zone), (tensile strength)

1. Introduction

In recent years, environmental concerns such as energy saving and CO_2 emission reduction have been spread to wider areas of industry. In particular, carbon fiber reinforced plastics (CFRP) with high strength-to-weight ratio, no corrosion and outstanding fatigue resistance in comparison with engineering metals are expected for the applications as one of attractive light-weight structural materials in various industrial fields such as automotives, aircrafts, wind energy, compressed gas storage, and so on[1-4]. However, machining including cutting or drilling for CFRP is well known to be difficult because of material properties of CFRP including different matrix properties or fiber orientation, relative volume of fiber (%) and high hardness of carbon fiber. Micro cutting- or milling-machining and abrasive water jet machining offering high cut quality have been conventionally used for cutting CFRP, but these machining methods have many problems such as high tool wear, high costs for tool and processing, delamination, limited processing time and moisture absorption[5-8].

On the other hand, laser cutting with a high power density heat source as a non-contact removal process does not involve the defects related to conventional machining methods. However, laser cutting of CFRP leads to thermal defects like wider heat affected zone (HAZ) at the specimen because of the difference in thermal properties of carbon fiber and matrix plastic.

Therefore, many researches have been performed to investigate the cutting characteristics for laser cutting of CFRP using different laser apparatuses such as CO_2 laser, Nd:YAG laser and disk laser with a continuous- or pulsed-wave in the last few decades[8-16]. Herzog, et al.[8] investigated the influence of three different laser heat sources on the cut quality of CFRP in addition to the static strength to confirm the reduction of the strength properties due to thermal damage. They indicated that the dimensions of the HAZ of CFRP cut depended on laser types and the cutting parameters, and also the static- or bending-strength produced values far above those with conventional machining, although HAZ was generated in the range of 0.6 – 1.4 mm. Moreover, CO_2 laser remote cutting results and laser ablation results of CFRP using picosecond lasers with different wavelengths from 355 to 1064 nm have been reported[17, 18]. The cut quality was good, but the processing time was too long in cutting with pulsed UV lasers.

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In laser cutting for CFRP materials, however, the development of advanced processing technology to meet the requirements of end-users for quality improvement, cost effective component and mass production is still needed. Such requirements for high productivity may be solved by ultra-high speed processing using a cw disk or fiber laser with a scanner head to accomplish ultra-high speed beam scanning.

In this research, therefore, with the objectives of obtaining better cut quality with submillimeter sized HAZ and confirming the cutting possibility for 3 mm thick CFRP sheets, ultra-high speed laser cutting was performed on two kinds of CFRP with long or short carbon fibers using high brightness cw disk laser with a scanner head. The effect of laser cutting parameters on CFRP cut qualities such as HAZ, kerf width and kerf depth was evaluated. The cutting possibility and the thermal damage of CFRP sheets with the increase in the laser power were confirmed by optical microscope and scanning electro microscope (SEM). Furthermore, the levels of strength reduction owing to the thermal damage in laser cutting were examined and assessed in the tensile test of laser-cut specimens.

2. Materials and Experimental Procedures

The materials used in laser cutting experiments are two types of CFRP sheets purchased. Material characteristics of two CFRP sheets are given in **Table 1**. Two CFRP sheets of 3 mm in thickness, 100 mm in width and 150 mm in length were manufactured by injection molding, and consisted of polyamide 6 (PA6) as a matrix plastic and two pellet types of long and short carbon fibers with the volume of 20 %.

Figure 1 represents a schematic experimental set-up for laser cutting of CFRP sheets. A high brightness cw disk laser with the maximum power of 16 kW and the wavelength of 1030 nm was utilized, and a laser beam of 8 mm·mrad BPP was delivered through an optical fiber of 0.2 mm core diameter. The laser scanner head was employed in order to accomplish an ultra-high cutting speed. The ellipse field of 180 mm × 102 mm can be processed at the maximum scanning speed of 10 m/s (600 m/min). The laser beam was focused by the lens of 292 mm focal length, and the spot size of the laser beam was about 0.3 mm at the focal point.

The length of about 130 mm from one end of a CFRP sheet was subjected to laser linear (straight-line) cutting, as schematically shown in **Fig. 2**. The cutting conditions used with a scanner head were the laser power

Table 1 Material characteristics of two CFRP sheets used.

Type	L	S
Matrix plastic	Polyamide 6	Polyamide 6
Volume of fiber (%)	20	20
Fiber orientation	Long fiber pellet	Short fiber pellet
Manufacturing process	Injection molding	Injection molding
Thickness (mm)	3	3

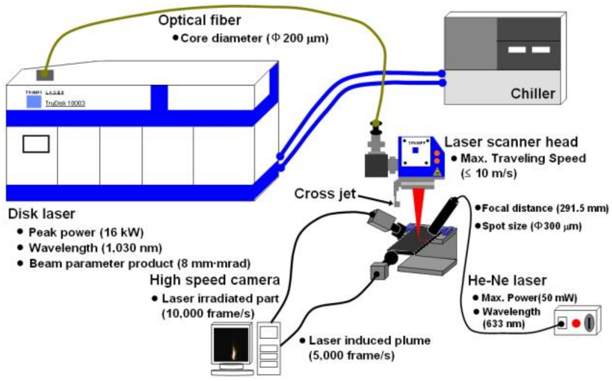

Fig. 1 Schematic experimental setup for laser cutting of CFRP sheet.

of 1 – 5 kW, the cutting speed of 0.5 – 5 m/s (30 – 300 m/min), the laser irradiated number of 1 – 80 passes, the time interval of 0 or 1 second and the defocused distance of 0 or −3 mm. In this research, in particular, extremely fast cutting speeds were used to reduce thermal damage to the cut specimen, but consequently the cut depth per one run was shallow. Thus multi-passes laser irradiation was needed to produce full cut specimens of 3 mm thick sheets. The effect of time interval was investigated because multi-passes laser irradiation was continuously repeated at an ultra-high speed within 130 mm length in this research. The subsequent laser shooting was repeated after no interval or 1 second stay in the initial position, which was expressed as 0 or 1 second time interval. The spot sizes of the laser beam at the defocused distance of 0 mm and −3 mm are about 0.3 mm and 0.36 mm on the top surface of the specimen, respectively.

Cutting phenomena and laser-induced plume behavior during laser cutting of CFRP sheets were observed by using two high speed video cameras. The effect of laser cutting parameters on cut quality for two kinds of 3 mm thick CFRP sheets was evaluated by HAZ, kerf width and kerf depth, as shown in **Fig. 2**. The surfaces and the cross sections of CFRP sheets cut at various laser powers were observed by optical microscope and SEM, HAZ and kerf width and kerf depth were measured, and the cutting possibility and the thermal damage of CFRP sheets were evaluated. Furthermore, the feasibility of strength reduction due to the thermal damage accompanying laser cutting was confirmed in the tensile test of CFRP full cut samples, as schematically shown in **Fig. 3**.

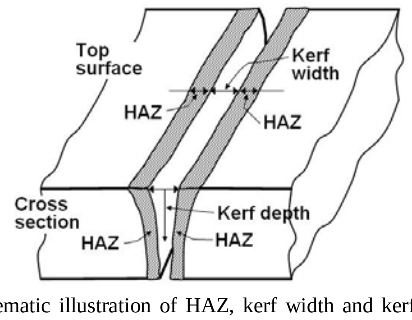

Fig. 2 Schematic illustration of HAZ, kerf width and kerf depth after laser cutting of CFRP.

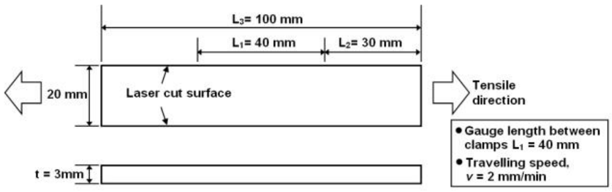

Fig. 3 Illustration of tensile test for CFRP full cut.

3. Results and Discussion

3.1 Effect of cutting speed on cut quality

In order to investigate the effect of the cutting speed on CFRP cut quality such as HAZ width and kerf depth, laser cutting was conducted by changing the cutting speed from 0.5 m/s to 5 m/s. **Figure 4** indicates the cut surfaces and cross sections of long fiber pellet CFRP sheets subjected to laser cutting, plume behavior during cutting, and cut quality results of HAZ and kerf depth at the laser power of 1 kW, various speeds, the laser irradiated number of one pass and the defocused distance of 0 mm. In the top and middle column of **Fig. 4 (a)**, the kerf and HAZ width and kerf depth became narrower and shallower with the increase in the cutting speed, respectively. Also, the thermal damage of CFRP material decreased with increasing the cutting speed. In **Fig. 4(b)**, the HAZ width of the cut surface decreased from 0.44 mm to 0.13 mm and also the kerf depth decreased from about 0.4 mm to 0.04 mm at the cutting speed of 0.5 m/s to 5 m/s, respectively. The reason for the effect of the cutting speed on the thermal damage to CFRP was interpreted by observing a laser-induced plume behavior during laser cutting of CFRP. In the lower column of **Fig. 4(a)**, it is similarly seen that the laser-induced plume was violently ejected from the laser irradiation part to the upper and rear directions at any cutting speeds. The laser-induced plume was taller in the upper direction at higher cutting speed. This behavior may affect smaller thermal damage to the CFRP cut surface. It is also considered that the radiation heat from the plume was not so high. It is therefore judged that the HAZ of CFRP sheet increased with increasing the laser heat input (P/v) because of longer interaction period between the laser and the CFRP at lower cutting speed. Here, the laser heat input is in inverse proportion to the cutting speed. In conclusion, HAZ and kerf width on the cut surface became narrower with an increase in the cutting speed, and the most excellent cut quality of small thermal damage could be obtained at the maximum cutting speed of 5 m/s used in this research.

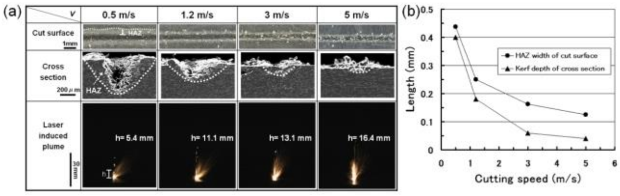

Fig. 4 Surface appearances and cross sections of type L CFRP subjected to laser cutting at different speeds, and observation results of laser induced plume during cutting (a) and cut quality results measured (b).

3.2 Effect of time interval on cut quality

As the above-mentioned conclusion, the scanning speed of 5 m/s was selected to obtain the excellent cut quality in laser cutting of CFRP, although the removal depth of CFRP achieved by one run was extremely shallow. Thus, multi-runs of laser irradiation along the same cutting line were required. The effect of the time interval between respective runs was investigated. **Figure 5** shows surface appearances and cross sections of two kinds of CFRP sheets subjected to laser runs of 20 times at the laser power of 1 kW, the cutting speed of 5 m/s and the defocused distance of 0 mm, representing cut grooves and HAZs. It is revealed that the HAZs at the cut surfaces of both CFRP sheets were wider at the time interval of 0 sec than that of 1 sec. It appears that the groove was wider on the surface and slightly deeper in Type S CFRP. It is judged that Type S CFRP is more easily evaporated and cut with a laser beam. It is also observed in the case of no time interval that the HAZ of Type L CFRP on the cross section became considerably wider than that of Type S CFRP. This reason is attributed to the length difference of fibers with high heat conductivity in CFRP and the difficulty in evaporation of long carbon fibers. In the case of the time interval of 1 second, excellent cut quality with about 50 μm narrow HAZ at the cross sections could be obtained in both CFRP sheets.

In order to further confirm the effect of the time interval on HAZ, laser irradiated parts and laser-induced plume on the cut surface were investigated by high speed video observation. **Figure 6** indicates high speed video observation results of laser irradiated parts and plume behavior during laser cutting of long fiber pellet CFRP without time interval under the conditions of the laser power of 1 kW, the cutting speed of 5 m/s, the laser irradiated number of 1st and 10th run and the defocused distance of 0 mm. These observation results of the high speed video cameras suggest the mechanism for wider HAZ in the case of no time interval. The brilliant laser-induced plume was always observed from the laser-irradiated part during cutting. The height of the plume was becoming shorter with an increase in the irradiation times.

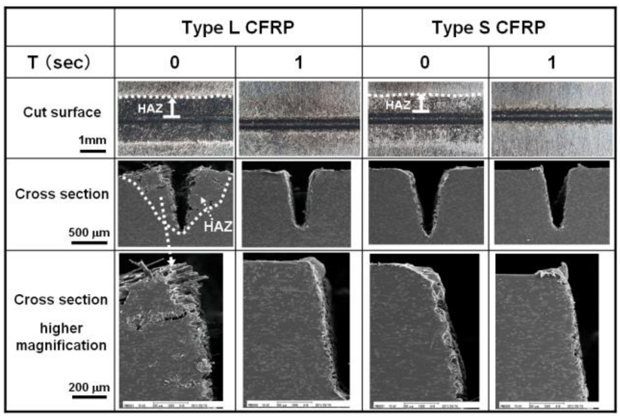

Fig. 5 Effect of time interval between passes on HAZ of cut surfaces and cross sections in laser cutting of two CFRP sheets subjected to laser irradiated number of 20 passes.

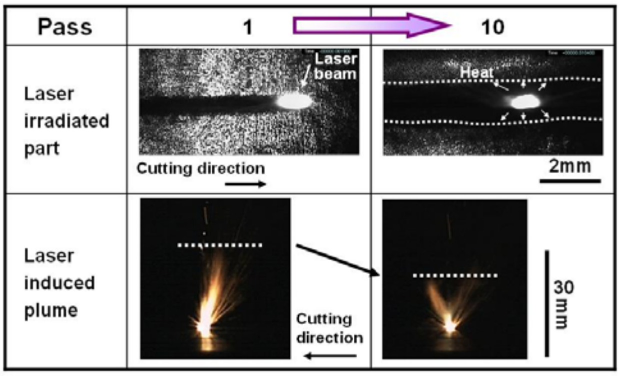

Fig. 6 High speed video observation results of laser irradiated part and plume behavior during cutting of type L CFRP without time interval.

Furthermore, a wide black zone was observed along the processed line, and the width increased with the irradiation times. It seems that the black zone gives an indication of heat accumulation and corresponds to the HAZ. These results confirm that the laser heat input remaining around the cut surface increases with the increase in the irradiation times. In other words, wider HAZ was attributed to the phenomenon that the heat inside the CFRP sheet was increasingly accumulated by continuous laser irradiation. It was consequently concluded that the time interval should be considered as an effective procedure for reducing heat accumulation in the case of multi-passes laser irradiation (within extremely short time) during ultra-high speed laser cutting of CFRP.

3.3 Effect of defocused distance on cut quality

A feasibility of improvement in the CFRP cut quality was investigated by performing several ultra-high speed laser cutting experiments at 1 kW laser power, 5 m/s cutting speed, different defocused distances and 1 sec time interval. **Figure 7** indicates surface appearances and cross sections of two kinds of CFRP sheets subjected to laser cutting as well as the values of kerf and HAZ width on cut surface and kerf depth at the defocused distances of 0 and −3 mm. The kerf width and depth for two CFRP sheets were slightly narrower and deeper at the defocused distance of 0 mm than that of −3 mm. The widths of HAZ on the cut surface in Type L and Type S CFRP were about 0.12 and 0.32 mm and 0.1 and 0.3 mm at the defocused distance of 0 and −3 mm, respectively. The HAZ could be wider by defocusing. These results are interpreted by considering a wider laser beam diameter and lower power density on the CFRP surface in the case of the defocused distance of −3 mm. In addition, it is confirmed that the kerf groove of Type S CFRP was deeper than that of Type L CFRP at both defocused distances. It is judged that CFRP sheet with short fiber pellet was rapidly melted and evaporated because of slightly easier removal tendency of shorter carbon fibers from the plastic matrix.

3.4 Cutting possibility and cut quality through laser full cutting of CFRP

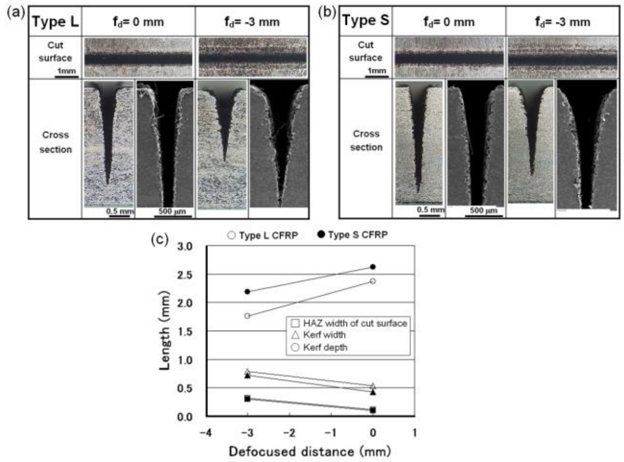

Fig. 7 Surface appearances and cross sections of type L CFRP (a) and type S CFRP (b) subjected to laser cutting at 80 passes, showing effect of defocused distance on HAZ width of cut surface, kerf width and kerf depth (c).

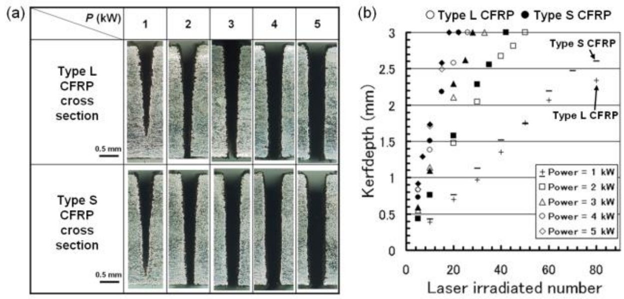

Fig. 8 Cross sections of two kinds of CFRP sheets after laser cutting of laser power of 1-5 kW (a) and kerf depths of two CFRP sheets as a function of laser irradiation times at respective laser powers (b), showing characteristics of laser cutting.

The above results demonstrated that ultra-high speed laser cutting of CFRP could produce a good quality cut with submillimeter-sized HAZ under the conditions of the cutting speed of 5 m/s, the time interval of 1 second and the defocused distance of 0 mm. These optimized parameters were then applied to full cutting experiments. In order to further evaluate the cutting possibility and the cut quality in laser full cutting of two kinds of CFRP sheets, laser cutting experiments were performed by changing the laser power and the laser irradiated times. **Figure 8** shows the cut geometry and the kerf depth or possibility of full cut in laser cutting of two kinds of CFRP sheets of 3 mm thickness at various laser powers. **Figure 8(a)** shows that full cutting of both CFRP sheets was possible within 80 passes at 2 kW to 5 kW, and that CFRP full cut was possible with a smaller number of laser irradiation at higher power. It is observed in both CFRP sheets that kerf widths of top surfaces and bottom surfaces became wider with an increase in the laser power.

In addition, it is confirmed that the kerf depth of two CFRP sheets became deeper with increasing the laser power and the laser irradiation number. The laser irradiation number required for the production of a full cut decreased from 50 to 33, 26 and 22 passes for Type L CFRP and from 42 to 28, 22 and 18 passes for Type S

CFRP with the increase in the laser power from 2 kW to 3, 4 and 5 kW, respectively. The increase in the laser power signifies the improvement of production efficiency due to the processing time reduction in laser cutting of CFRP. These results confirm that CFRP with shorter carbon fibers can be more easily cut by a cw laser.

Moreover, in order to evaluate the influence of higher laser power on the thermal damage in laser cutting, cross sections of both CFRP sheets were observed by SEM, as shown in **Fig. 9**. The cross-sectional HAZ for both CFRP sheets was within about 50 μm at 2 and 5 kW laser power. It was also confirmed that the HAZ of Type S CFRP was narrower than that of Type L CFRP.

Furthermore, the existence of cut-sectional thermal damage was observed by SEM at higher magnification. **Figure 10** shows that carbon fibers on the cut surfaces were clearly cut for both CFRP sheets. It was also observed that the matrix plastic (polyamide 6) remained around carbon fibers of the cut section in the case of short fiber pellet CFRP in comparison with long fiber pellet CFRP. Consequently, it was demonstrated that short fiber pellet CFRP sheet was more easily cut and received less thermal damage than long fiber pellet CFRP.

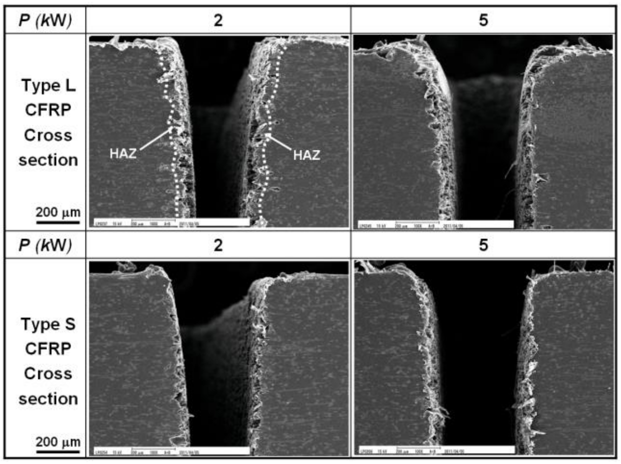

Fig. 9 Cross-sectional SEM photos of two CFRP sheets made at laser cutting, showing kerf widths and damaged zones corresponding to HAZ.

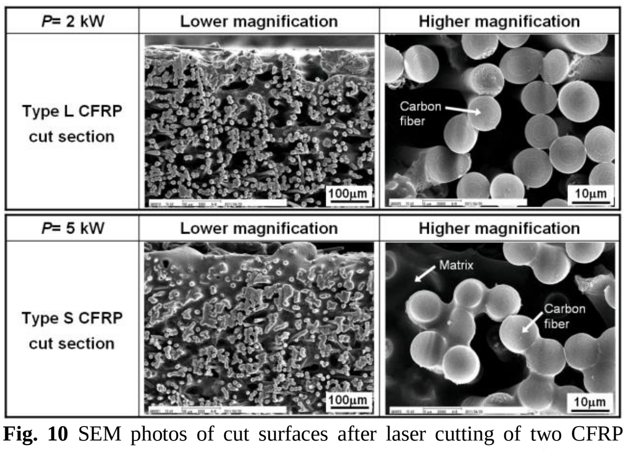

Fig. 10 SEM photos of cut surfaces after laser cutting of two CFRP sheets, showing evaporated matrix plastic and retained carbon fibers.

3.5 Cutting characteristics between long and short carbon fiber CFRP sheets

From the above results in Section 3.2 to 3.4, the cut quality and cutting characteristics between the long- and short-fiber pellet CFRP sheets subjected to ultra-high speed laser cutting are summarized and discussed. It is confirmed on the cross section that the HAZ of Type L CFRP was slightly wider than that of Type S CFRP. It is also revealed that the kerf depth of short fiber pellet CFRP was deeper and the full cutting time was shorter than that of long fiber pellet CFRP, compared under the same cutting conditions used in this research. A larger amount of matrix plastic remained around short carbon fibers on the cut surfaces, and thus it is judged that CFRP with short fibers suffered less thermal damage than that with long fibers.

The wider HAZ in Type L CFRP is attributed to extremely high melting and evaporation temperatures of carbon fibers leading to more difficult evaporation than plastic matrix, and much higher heat conductivity of carbon fibers than plastics resulting in a wider range of heat conduction caused by longer carbon fibers in CFRP. On the other hand, in the case of CFRP with short fibers the plastic matrix was extremely quickly melted and easily ejected together with short carbon fibers.

From the compared results, the effect of difference of fiber length on laser cutting results such as kerf width and depth and the HAZ of the cut can be satisfactorily interpreted from the viewpoints of easy ejection together with the matrix and heat conductivity of carbon fibers.

3.6 Tensile test results of laser-cut specimens

In order to confirm the existence of strength reduction due to the thermal damage in laser cutting, the tensile test was conducted for two kinds of CFRP sheets with long or short carbon fibers. The average tensile strengths of four base specimens for Type L and Type S CFRP sheets were about 153 MPa and 95 MPa, respectively. **Figure 11** indicates tensile strength results obtained for the specimens laser-cut at various powers. The CFRP specimens obtained at the laser power of 2 to 5 kW were all cut at the cutting speed of 5 m/s and had HAZ width with less than 50 μm on the cross section.

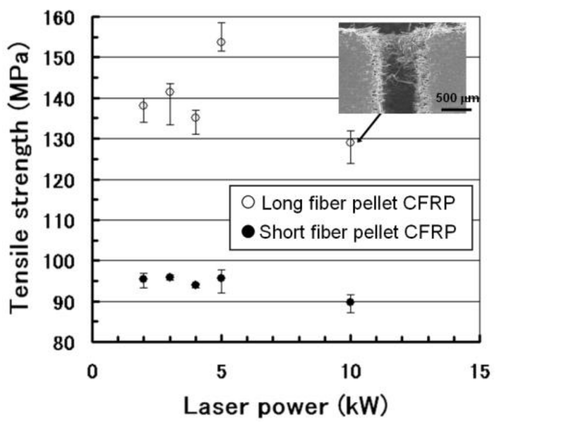

Fig. 11 Tensile test results of two CFRP specimens produced by laser cutting at various cutting conditions.

Moreover, CFRP specimens cut by only one run at the laser power of 10 kW and the cutting speed of 0.25 m/s were used as reference since they had HAZ width of about 200 μm on the cross section. In the case of the long fiber pellet CFRP, the tensile strengths were high at the laser power of 2 to 4 kW and the highest at 5 kW but the lowest at 10 kW. In the case of short fiber pellet CFRP, the tensile strengths were almost equal at the laser power of 2 to 5 kW, but were slightly lower at 10 kW. From these results, it was confirmed that the strength reduction occurred at the high laser power of 10 kW and low cutting speed of 0.25 m/s. This is attributed to the effect of wider HAZ, as seen in Fig. 11. In other words, it was revealed that CFRP full laser-cutting without strength reduction was possible if the HAZ was narrow, as achieved at the laser powers from 2 to 5 kW.

4. Conclusions

Ultra-high speed laser cutting was performed to obtain better cut quality with narrow HAZ and to evaluate the cutting possibility for two kinds of 3 mm thick CFRP sheets using a high brightness cw disk laser with a scanner head. The main conclusions are as follows.

1) The HAZ and kerf width at the cut surfaces and the cross sections became narrower and smaller with increasing the cutting speed. The cutting speed of 5 m/s was selected as the optimum cutting speed.

2) In the case of multi-passes cw laser irradiations, time interval between scanning was effective for the production of better quality cut specimens by the reduction in heat accumulation during laser cutting of CFRP. Nevertheless 3 mm thick CFRP sheets could be fully cut with a laser in an extremely shorter time compared with other cutting processes.

3) The HAZ and kerf depth of the cut groove obtained at the focal point became narrower and deeper than those at the defocused distance of -3 mm. Defocusing of a focused laser beam was not effective in ultra-fast cutting probably because of lower power density.

4) The increase of the laser power from 2 to 5 kW can reduce the processing time for full cutting, without degradation of good quality of narrow HAZ (less than 50μm).

5) Short fiber pellet CFRP was more easily cut and had less thermal damage than long fiber pellet CFRP.

6) CFRP full cut without strength reduction could be produced by ultra-high speed laser-beam scanning (at 5 m/s in this research).

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