ENVIRONMENTAL EFFECTS ON MECHANICAL BEHAVIOR OF CFRP USING LASER CUTTING PROCESS

Y. Harada[1,2*], T. Ito[1,3], T. Suzuki[1,2], M. Nishino[2,4], H. Niino[1,2], T. Teramoto[1,3]

[1]*National Institute of Advanced Industrial Science and Technology (AIST), 1-2-1 Namiki, Tsukuba, Ibaraki 305-8564, Japan*
[2]*Advanced Laser and Process Technology Research Association (ALPROT), 1-17-1 Toranomon 5, Minato-ku, Tokyo 105-0001, Japan*
[3]*Graduate School of Systems and Information Engineering, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8573, Japan*
[4]*Mitsubishi Chemical Corporation, 14-1 Shiba 4, Minato-ku, Tokyo 108-0014, Japan*
**harada.y@aist.go.jp*

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Abstract

Carbon fiber-reinforced plastics (CFRP), which is expected to reduce the weight of transportation vehicle, was cut by laser irradiation with an CO_2 gas laser and CW single-mode fiber lasers, and conventional machining with a diamond sawing. The effect of cut process on the cutting quality, tensile and fatigue properties under temperature and moisture environments was investigated for cross-ply [0/90] CFRP. The laser-cut specimens identified a thermal damage with micro-cracking on the cutting surface. The tensile and fatigue strength decreased with introducing the temperature of 110 ºC and the humidity of 50 %.

1 Introduction

Carbon fiber-reinforced plastics (CFRP) composite is most attractive materials to reduce the weight of transportation vehicle such as automotive, airplane or train [1-3]. However, it is difficult to produce components made of CFRP in a mass production rate. Therefore, an automated, a highly productive, precise and cost-efficient technologies are needed. One process that is necessary during CFRP component is trimming and cutting. In general, the cutting technology of CFRP is machining with a tool and water-jet [4,5]. The machining with a sawing, milling or grinding occur high tool wear which depends on a machining speed and a cutting quality. The water-jet cutting is less wear, but an abrasive solid material in the water is needed for CFRP cutting. In addition, the cutting speed by both processes is limited to less than 1 m/min. Although laser cutting meets these requirements, it is not used for trimming and cutting tool because of insufficient knowledge about the effect of thermal damage on the material behavior [6,7]. In addition, in such applications, a considerable amount of temperature and moisture can be encountered in the service environment. It is considerable for synergistic interactions between cutting process and environmental effects.

In the present study, several cutting CFRP specimens were prepared and the static tensile strength and the fatigue strength were evaluated under moisture environments. The material was cut using lasers: a CW single-mode fiber laser and a CO_2 gas laser, and a conventional machining with a diamond sawing. The mechanical tests were conducted using our constructing of a materials testing system that simulates severe environments such as high temperature up to 200 ºC and humidity. Full details of the effect of moisture on the mechanical properties were identified.

2 Experimental procedures

2.1 Specimen

The CFRP investigated in this study was prepreg laminates consisting of an epoxy resin and a continuous carbon fiber with PITCH-based. The stacking sequences were [0, 90, 0] cross-ply. The volume fraction of carbon fiber was approximately 60 % and the thickness was approximately 2 mm.

For the laser processing in CFRP cutting, a pulsed-CO_2 laser and a CW single-mode fiber laser were used. The TRUMPF TFL5000 system was used as the pulsed-CO_2 laser. The cutting conditions were the mean power of 800 W, the pulse-width of 8 μs, the pulse frequency of 20 kHz, the beam quality of M^2=1.82 and wavelength of 10.6 μm. The cutting was operated at the rate of 1 m/min and the spot size of 134 μm. For single-mode fiber lasers, the IPG YLR-300-SM and IPG YLR-2000-SM Yb single-mode fiber laser were used. The cutting parameter of 300 W system was the continuous wave (CW) power of 300 W, $M^2 <$ 1.05 and wavelength of 1.07 μm. The cutting rate was 1 m/min and the spot size was approximately 20 μm. The cutting parameter of 2 kW system was $M^2 < 1.05$ and wavelength of 1.07 μm. The cutting rate was 7 m/min and the spot size was approximately 20 μm.

As compared with laser-cut CFRP specimens, the machining with a diamond sawing of 1 mm width was used. The cutting speed was operated under 0.12 m/min. By increasing the rate up to 0.5 m/min, the generation of burr and chipping in the cut edge was occurred.

2.2 Mechanical tests

Specimens for static tensile test and fatigue test were made using the machining-cut, CO_2 gas laser cutting and CW single-mode fiber laser cutting. The specimen was shaped with the length of 200 mm and the width of 15 mm. The used bonded tab material was Aluminum alloy, A2017, in length of 50 mm and width of 15 mm.

Figure 1. Materials testing system simulating a severe environment. System consists of a materials-testing machine, pressure vessel, environmental simulator and PC controller.

The static tensile and fatigue tests were conducted in moisture environment using a material testing system developed for simulating severe environments shown in figure 1. This apparatus was configured with severe environmental simulator generating a temperature up to 200 ºC, high-pressure range up to 0.5 MPa and humidity up to 90 % (depends on temperature) using a slow strain/load rate testing machine as a basic unit. The testing machine controlled with the crosshead speed range of 0.0001-1 mm/min and maximum load up to 20 kN using a

closed loop servomotor. Test temperature was measured by K-type thermocouples located near the specimen gage length. The temperature and humidity were maintained within ±1 ºC and ±2 % of the set point throughout each test after a 5 h soak at the test temperature and humidity.
The static tensile tests carried out at a constant displacement rate of 0.5 mm/min. For fatigue tests, the specimens were subjected to tensile cyclic loads having a triangle wave at a frequency of 0.01 Hz and stress ratio of 0.1. The test condition was set at temperature of 110 ºC, humidity of 50 % and pressure of 0.002 MPa.

3 Results and discussion

3.1 Laser Cutting

Figure 2 shows the cross-sections of machining-cut, 0.8 kW CO_2 laser-cut, 0.3 kW fiber laser-cut and 2 kW fiber laser-cut specimens using an optical microscopy. As shown in (a), the machining-cut specimen procedures a cut of high quality. No delamination or free fiber is observed, but a small portion of burrs or chipping which is likely to be from resin matrix constituents. In (b)-(d), the laser-cut specimens all clearly exhibit a thermal damage with micro-cracking or free fibers. The CO_2 laser-cut specimen shows the free fibers in the two outer laminas and the visible cracking. The cutting specimen of 0.3 kW or 2 kW fiber laser also shows the free fibers in the two outer laminas and cracking in the inter-lamina.

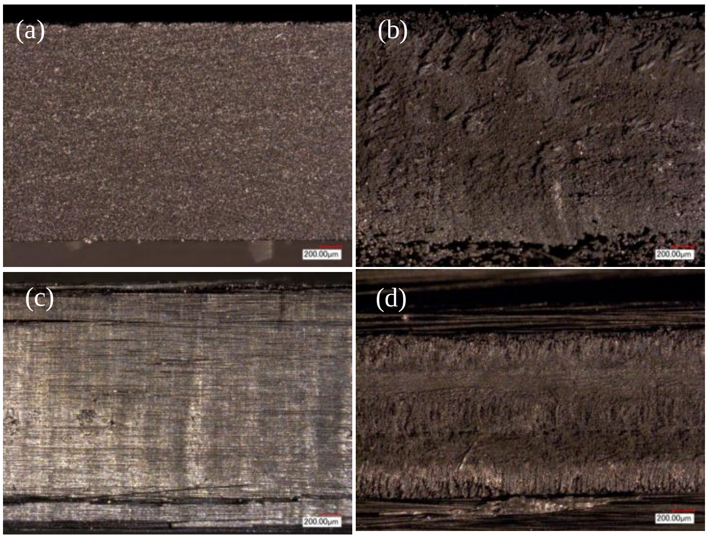

Figure 2. Observation of the cross-section of cutting surface by (a) machining-cut, (b) 0.8kW CO_2 laser-cut, (c) 0.3kW fiber laser-cut and (d) 2kW fiber laser-cut.

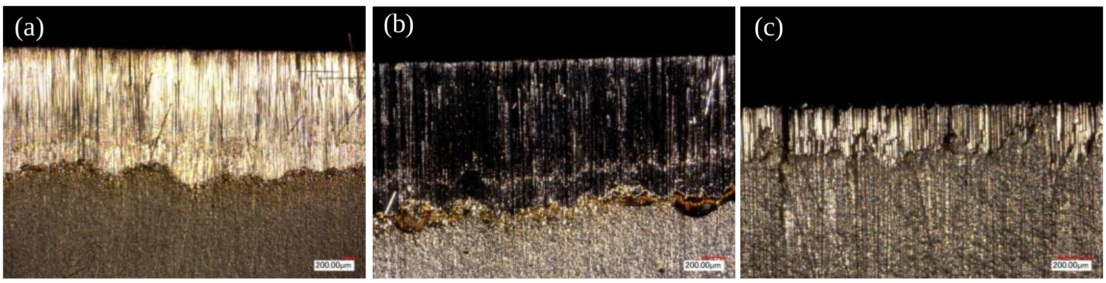

Figure 3. Observation of the cutting edge of (a) 0.8kW CO_2 laser-cut, (b) 0.3kW fiber laser-cut and (c) 2kW fiber laser-cut .

Figure 3 shows the cutting edge using CO_2 laser and fiber lasers process specimens. As shown in (a)-(c), the thermal damage (calls heat affected zone, HAZ) can be clearly identified. The

CO_2 laser-cut specimen is observed that the resin matrix is melted and literally vaporized to a certain point in the material. The carbon fiber is exposed on the surface. In (b) and (c), the 0.3 kW or 2 kW fiber laser-cut specimens also shows the melted resin matrix and exposed carbon fibers on the surface.

As compared the laser-cut specimens with each other, the 2 kW fiber laser obviously produces the smaller HAZ than the CO_2 laser or 0.3 kW fiber laser. The average HAZ extension of the fiber laser-cut specimens was approximately 0.27 mm of 2 kW and 0.39 mm of 0.3 kW. While, that of CO_2 laser-cut specimens was approximately 0.79 mm. This may be an effect of the wavelength, where the fiber laser radiation should be absorbed favorably, or simply due to the smaller focus.

3.2 Tensile properties

Figure 4 shows the stress-strain curve under static tensile test of cross-ply CFRP after machining-cut. The values were always from failure of the last stress. The specimen tested at room temperature is fractured during almost linear response. The maximum stress is approximately 580 MPa. In the case of specimens tested at 110 °C and 110 °C in moisture, it is seen that an initial linear response is followed by a non-linear behavior. These failure stresses are approximately 480 MPa and 380 MPa, which the induced moisture is decreased the tensile stress.

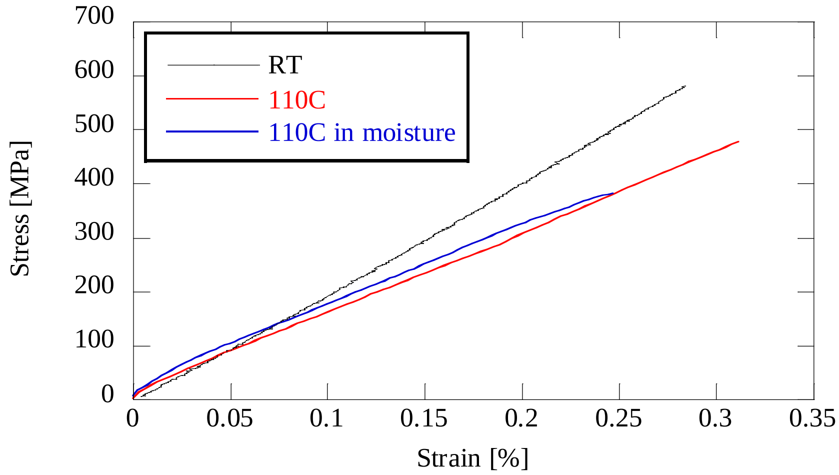

Figure 4. Stress-strain curves under static tensile test at room temperature, 110ºC and 110ºC in moisture of cross-ply CFRP after machining-cut.

3.3 Fatigue properties

Figure 5 shows S-N diagrams obtained in fatigue tests. The specimens were subjected to tensile cyclic loads having a triangle wave at a frequency of 0.01 Hz and stress ratio of 0.1. The test condition was set at the temperature of 110 ºC, the humidity of 50 % and the pressure of 0.002 MPa. The specimens were obtained the number of repetitions until breaking in the fatigue test. Figure shows data of CFRP specimens after machining-cut, the CO_2 laser-cut, the 0.3 kW fiber laser-cut (0.3kWSMFL) and the 2 kW fiber laser-cut (2kWSMFL). As shown in this figure, when the cyclic maximum stress that 0.6 – 0.85 of the mean value of the static tensile strength is given, it is found that the number of loading cycles to failure is distributed to 1 – 10^5 times. Although it is difficult for the number of data to judge it might be few and clearly, it can be assumed that the fatigue life of machining-cut specimen is longer than those of laser-cut specimens and the fatigue life of CO_2 laser-cut specimen is shorter than those of fiber laser-cut specimens. These results show that the fatigue life of cross-ply CFRP is improved if the materials are not subjected to moisture at the humidity of 50 %.

Figure 6 shows the fatigue strength at around 2000-3000 cycles of machining-cut and CO_2 laser-cut specimens. The maximum strength is produced by the specimen from machining-cut tested at room temperature. With increasing temperature up to 110 °C, the fatigue strength of machining-cut specimen decreases around 30 % reduction. In addition, with increasing the humidity of 50 %, the value is decreased to 35 % reduction as compared with the data of CFRP at room temperature. The specimen produced by CO_2 laser-cut reaches the smallest value. It is approximately 44 % reduction of the fatigue strength under the temperature of 110 °C and the humidity of 50 % compared with data of machining-cut at room temperature.
The photographs of internal damage state for cross-ply CFRP after CO_2 laser-cut are shown in figure 7. According to the observation, a lot of transverse cracks and local delamination initiates for the CO_2 laser-cut specimens. However, the machining-cut specimens were a little, as compared with CO_2 laser-cut specimens.

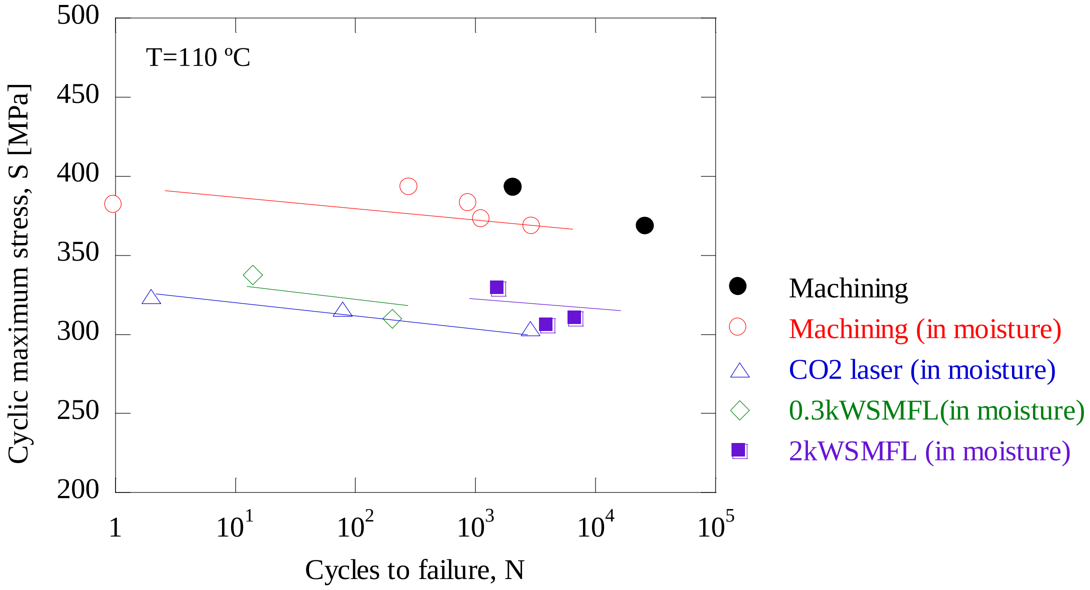

Figure 5. S-N diagram of cross-ply CFRP after machining-cut, CO_2 laser-cut, 0.3kW fiber laser-cut and 2kW fiber laser-cut. Fatigue tests were conducted under 110ºC or 110ºC in moisture (Rh=50%).

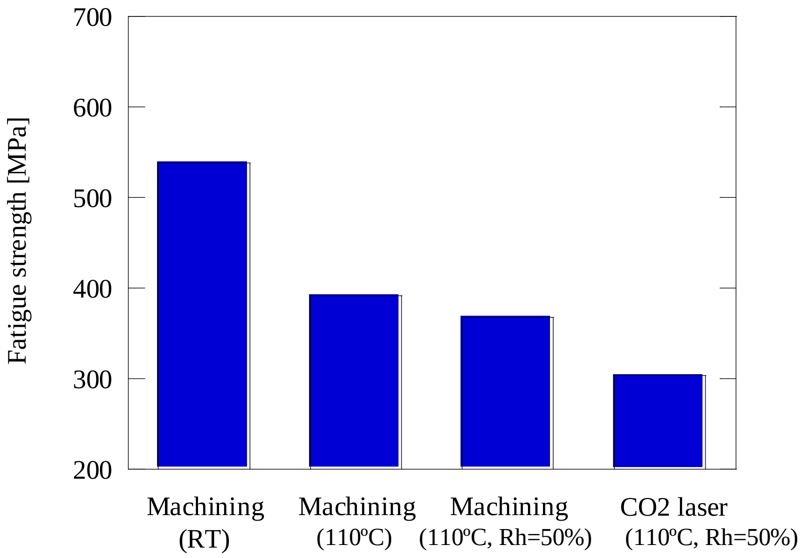

Figure 6. Fatigue strength at around 2000-3000 cycles. of cross-ply CFRP after machining-cut or CO_2 laser-cut. Fatigue tests were conducted at 110ºC or 110ºC in moisture (Rh=50%).

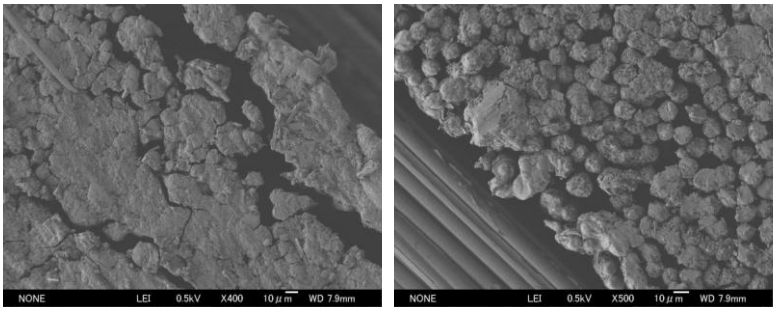

Figure 7. Photograph of failure damage state for cross-ply CFRP (σ_{max}=304 MPa, N=3000 cycles, T=110ºC in moisture (Rh=50%)).

4 Conclusion

The environmental effects of tensile and fatigue properties of cross-ply CFRP after laser-cut processes; 0.8 kW of CO_2 laser, 0.3 kW of CW single-mode fiber laser, 2 kW of CW single-mode fiber laser and machining were investigated. The following summary can be drawn:

1. The laser processing such as CO_2 laser or CW single-mode fiber lasers led to the thermal damage in the cutting edges of CFRP. The CO_2 laser-cut specimen was observed large melted matrix degradation and exposed free fibers. While, the specimen of CW single-mode fiber laser-cut for 2 kW and 7 m/min exhibited much smaller damage than other laser-cut specimens.
2. The temperature of 110 ºC and moisture with the humidity of 50 % led to the reduction of tensile strength compared with room temperature. The maximum stress was approximately 580 MPa tested at room temperature. In the case of specimens tested at 110ºC and 110ºC in moisture, these failure stresses were approximately 480 MPa and 380 MPa showing an initial linear response was followed by a non-linear behavior.
3. From S-N diagrams obtained in fatigue tests, the fatigue life of machining-cut specimen was longer than those of laser-cut specimens and the fatigue life of CO_2 laser-cut specimen was shorter than those of fiber laser-cut specimens. These results showed that the fatigue life of cross-ply CFRP was improved if the materials are not subjected to moisture.
4. The maximum fatigue strength was produced by the specimen from machining-cut tested at room temperature. With increasing temperature to 110 ºC and the humidity of 50 %, the fatigue strength decreased abound 30-35 % reduction as compared with the specimen at room temperature. The CO_2 laser-cut specimen reached the smallest value of 44 % reduction.

Acknowledgments

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References

[1] Kimpara I., Matsui J. *Plastics and FRCM as Lightweight Materials for Automobiles*, CMC Publishing, Tokyo (2010).
[2] Beardmore P., Johnson C.F. The potential for composites in structural automotive applications, *Composites Science and Technology*, **26**, pp.251-281 (1986).
[3] Chawla K.K. *Composite Materials*, Springer, NewYork (2001).

[4] Bhatnagar N., Ramakrishnan N., Naik N.K., Komanduri R. On the mechaning of fiber reinforced plastic (FRP) composite laminates, *International Journal of Machine Tools and Manufacture*, **35**, pp.701-716 (1995).
[5] Moeller R. *Machining of composites with abrasive waterjets*, in Proceeding of *CFK-Valley Stade Convenstion*, Stade, Germany, (2007).
[6] Harada Y., Suzuki T., Teramoto T. Evaluation of Cutting Process on the Tensile and Fatigue Strength of CFRP Composites, *Material Science Forum*, **706-709**, pp.649-654 (2012).
[7] Harada Y., Kawai K., Nishino M., Niino H., Suzuki T., Teramoto T. Effect of Fiber Orientation on Tensile Properties of Carbon Fiber Reinforced Plastic (CFRP) using Laser Cutting Process in "Proceesing of *12th Japan International SAMPE Symposium & Exhibition*, Tokyo, Japan, (2011).