Experimental study of CFRP cutting with nanosecond lasers†

SATO Yuji*, TSUKAMOTO Masahiro*, NARIYAMA Tatsuya**, NAKAI Kazuki***, TAKAHASHI Kenjiro* MASUNO Shinichiro* and NAKANO Hitoshi**

Abstract

A carbon fiber reinforced plastic [CFRP] is widely used for automobile, aircraft because of high strength, lightweight and weather resistance. The cutting of CFRP is difficult since it is composed of a complex matrix of carbon fiber and epoxy resin. In this paper, CFRP was cut with UV and IR nanosecond lasers. The ablation plume of CFRP was investigated with an ultra-high speed camera and a spectrometer under the laser irradiation. From the results, it was clear that the ablation dynamics differed with wavelength of the laser. It was confirmed that the ablation rate of the IR laser was 0.85 μm/ pulse larger than 0.6μm/ pulse for the UV laser.

KEY WORDS: (CFRP), (laser cutting), (HAZ), (laser ablation), (nanosecond laser),

1. Introduction

The use of carbon fiber reinforced plastic (CFRP) has new potential for saving of energy consumption for automobile, aircraft, and several industries because of having light weight and good properties [1]. CFRP is composed of two parts; carbon fiber as a reinforcement and a binding polymer, such as epoxy resin, polyester, vinyl-ester or nylon.

Generally, cutting techniques for CFRP are mechanical machining, water jet machining and electro-spark machining. These techniques raise a delamination and a nap after cutting. Tools also wear out during these processes [2-5]. The laser cutting technique is one of the useful tools for CFRP. J.Stock et.al have cut the CFRP with a CW fiber laser at the output power of 3 kW [6]. A. Klotzbach et al achieved a 50 m/min of cutting speed for CFRP by CO_2 laser irradiation [7]. Recently, the laser cutting and drilling of CFRP were reported as successful for high speed processing in the world.

By applying the laser cutting of CFRP, the matrix resin was quickly evaporated before cutting of the carbon fiber, which caused formation of a heat affected zone [HAZ] because of differences in thermal properties and laser absorption of carbon fiber and matrix resin. C. Emmelmann et al reported the HAZ became less than 20 μm with fiber lasers and pulse width of 1ns and 1ps, respectively [8]. However, there are no reports which investigate correlation between the laser ablation dynamics and laser wavelength which is required to decrease the HAZ.

In this study, CFRP plates were cut with nanosecond lasers of ultra violet ray (UV) and infrared ray (IR) to investigate the correlation between the ablation plume and the laser wavelength. The experimental results suggested that the HAZ of the UV laser became smaller than that of the IR laser.

2. Experimental

Based on those results, this paper presents investigations of laser ablation and cutting of CFRP. The CFRP material used was a multi-directional stack type consisting of carbon fiber and epoxy resin and its thickness was 0.6 mm.

Lasers were employed, which were nanosecond lasers at 1064 nm wavelength of a fundamental wave (ω) and 266 nm wavelength of forth harmonic generation (4ω). The experimental setup was shown in Fig. 1(a). The CFRP was set on the XY stage, the laser (SureliteⅢ, Continuum, ltd.) irradiates the sample passing the attenuator for adjusting the laser intensity. In cutting experiments, the laser beam was scanned on the CFRP by using the XY stage in air, as shown in Fig.1 (b). All the experiments were performed with same conditions, as shown in Table 1. The laser power, pulse width, frequency and scanning speed were 4.7×10^9 W/cm^2, 6 ns, 10 Hz, and 1.0 mm/sec, respectively. Spot diameters of both lasers were 100 μm of full width at half maximum (FWHM).

Emission spectrum and dynamics of ablation plume were measured at an oblique view to 45 degrees of the laser by a spectrometer (USB2000, Ocean optics com.) and an ultra-high speed camera (Ultra NEO, nac image

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* JWRI, Osaka University
** Kinki University
*** Graduate student, Osaka University

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technology co.jp). Exposure time and flame rate of the ultra-high speed camera were 5 ns and 2×10^9 fps respectively. After laser irradiation, the CFRP plated was observed with a laser microscope and SEM to investigate the ablation rate and HAZ.

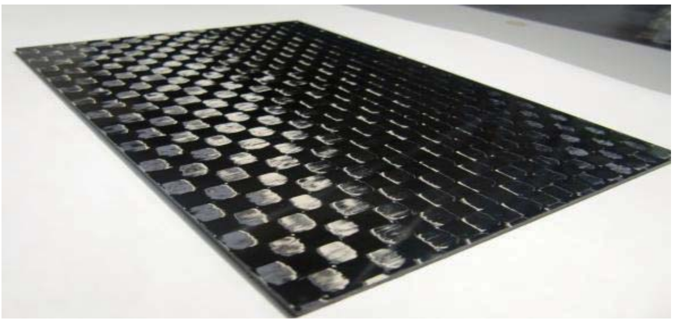

Fig.1 Photograph of CFRP.

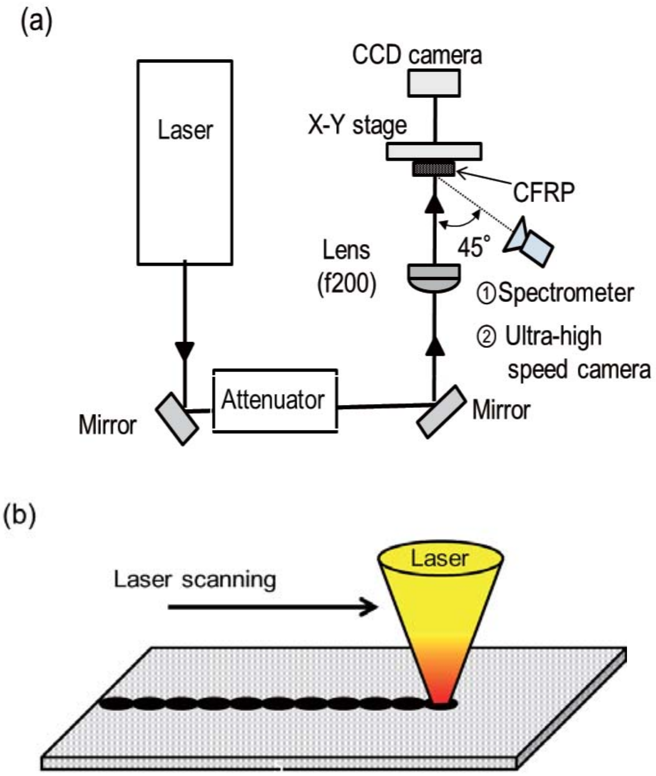

Fig.2 (a) Schematic diagram of experimental setup for Nd:YAG laser irradiation. (b) Scanning of the laser focusing spot to cut the CFRP.

3. Results and Discussion

3.1 Analysis of emission spectra

Spectral analysis was carried out to investigate the plume emission of CFRP with 1064 nm and 266 nm laser irradiations, as shown in Fig 3. The measurement was done using the fiber multi-channel spectrometer with an oblique view of the laser. Line spectra of O II , O I 、 and C II were observed at 384 nm, 550 nm and 510 nm, respectively. The laser ablation with both lasers was indicated to be evaporated and ionized carbon and oxygen atoms of CFRP at 4.7×10^9 W/cm^2.

The temperature of the laser irradiation spot was estimated by curve fitting the data of Fig.3 to obtain the wavelength at the curve peak λ_{max} = 450 nm, and by using Wien's law:

$$T = \frac{b}{\lambda_{max}}$$

where b=2.898 $\times 10^{-3}$ (mK) at constant, the spot temperature calculated to be 6000K.

Table.1 Experimental condition.

Wavelength (nm)	1064	266
Laser power (W/cm^2)	4.7×10^9	4.7×10^9
Pulse width (ns)	6	6
Frequency (Hz)	10	10
Intensity (mJ/pulse)	2.19	2.19
Focal length (mm)	200	200
Spot diameter (μm)	100	100
Scan speed (mm/sec)	1.0	1.0

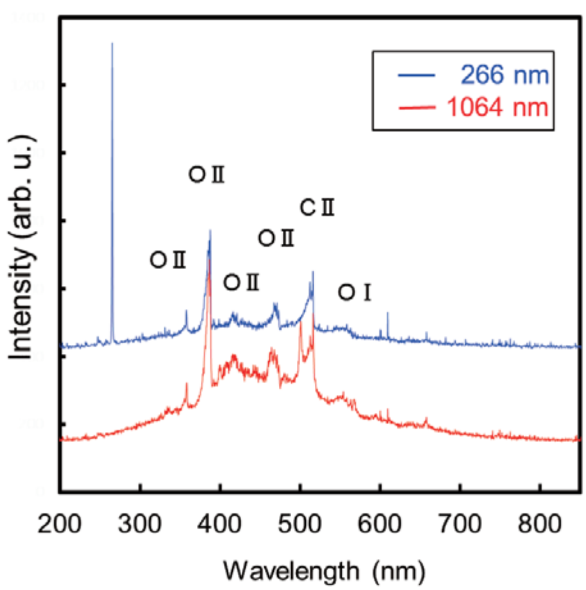

Fig.3 Ablation plume emission spectra of CFRP.

3.2 Measurement of ablation rate

Figure 4 shows the correlation between the laser ablation depth and laser shot number. Laser wavelengths were 266 nm and 1064 nm. As the results show the ablation depth of both lasers was increased with increasing the laser shot number. Ablation rate R_L, which means the ablation depth D divided by the laser shot number N, were calculated as follows equation;

$$R_L = \frac{D}{N}$$

The ablation depth for 1064 nm laser became 0.85 μm/pulse larger than that for 266 nm laser to 0.6 μm/pulse.

The cross area and kerf (abrasive parts) were measured and calculated by laser microscope, as shown in Table 2.

Cross area of 1064 nm was an amount about equal to that of 266 nm. These results indicate that the ablations differ with wavelength of laser. The cutting speed for 1064 nm is 1.3 times higher than that for 266 nm. The HAZ, which was defined to expose the carbon fiber after laser irradiation, were measured by a scanning electron microscope. The HAZ for 1064 nm laser and for 266 nm laser were compared. As the results show the HAZ for 1064 nm became 105 μm, of which 266 nm was decreased by 18 % to 88 μm.

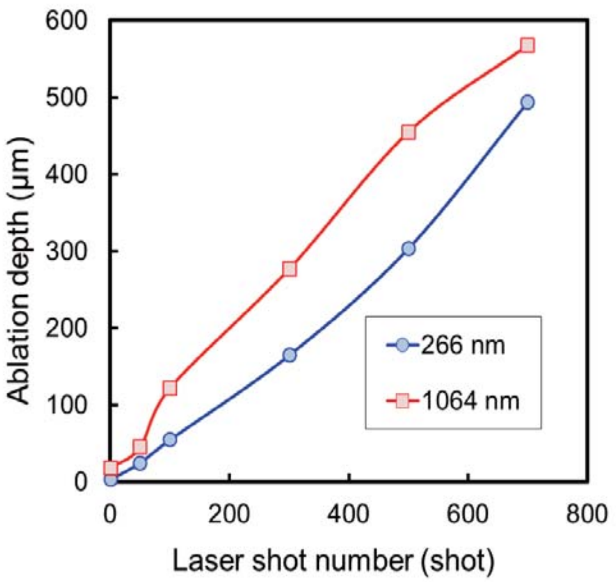

Fig.4 Correlation between the laser shot number and ablation depth.

Table 2 Average of ablation rate for CFRP with the laser irradiation at 4.7 x 10^9 W/cm^2 and 10 Hz.

	Ave. of ablation depth (μm/pulse)	Ave. of ablation area (μ m^2/pulse)	HAZ (μm)
1064 (nm)	0.85	101	105
266 (nm)	0.6	105	88

3.3 The investigation of ablation dynamics by with ultra-high speed camera

Fig. 5 shows photographs of the laser ablation plume captured by ultra-high speed camera at 10 ns of exposure time and 2x10^9 fps. The ablation plumes of both lasers were generated on the CFRP surface at 10 ns. The plume expanded gradually at 20 ns. At 30 ns, the plume faded away. For 266 nm laser irradiation, the plume spread widely like a semi-sphere. On the contrary, for the 1064 nm laser irradiation, the plume was blow out like a cone shape and plume size of 1064 nm was smaller than that of 266 nm.

Plume temperatures with 1064 nm laser or 266 nm laser were calculated as 6000 K in Fig.3 and ablation mass of both lasers were almost equal, as shown in Table 2. It was found the ablation density of 1064 nm laser was higher than that of 266 nm laser, as the laser plume was dependent upon temperature and pressure. These results indicated the 266nm laser is absorbed by the epoxy resin only on the CFRP surface to generate the ablation plume, and 1064 nm laser absorbs the carbon fiber in the CFRP to generate and burn out into the sample.

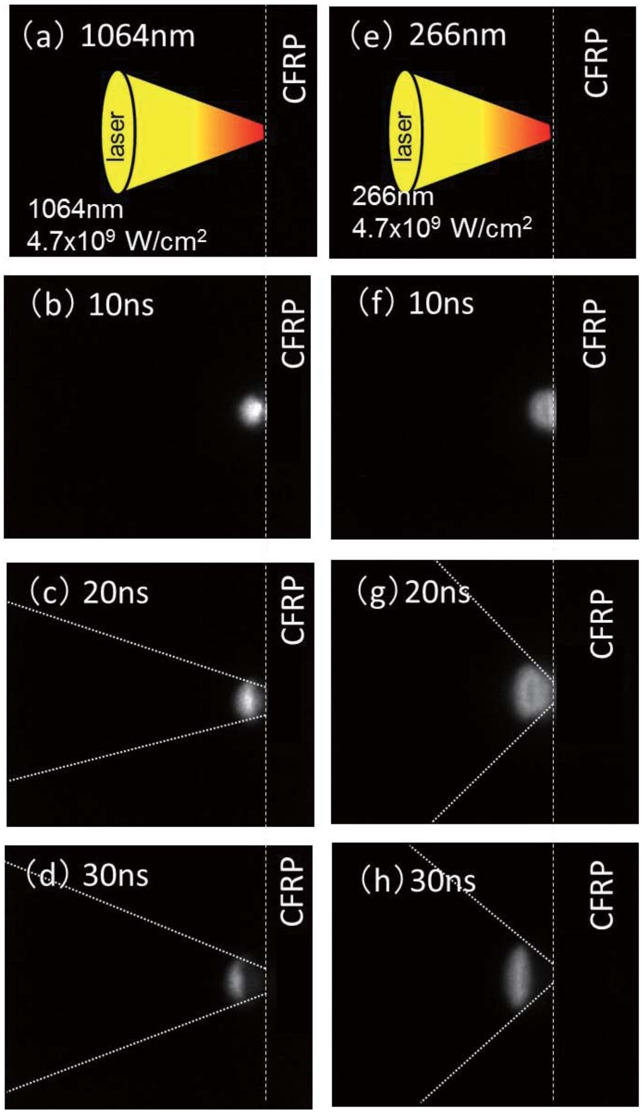

Fig.5 CFRP ablation with 1064 nm and 266 nm laser captured with the ultra-high speed camera, (a) 0 sec for 1064nm, (b) 10ns for 1064 nm, (c) 20ns for 1064nm, (d) 30ns for 1064 nm (d) 0 sec for 266nm, (e) 10ns for 266nm, (f) 20ns for 266nm, (g) 30ns for 266nm

4. Conclusion

We tried to cut the CFRP with two different nanosecond pulse lasers, whose wavelengths were 1064 nm and 266 nm respectively. The ablation plumes were investigated by spectroscopic analysis and ultra-high speed camera observation. The results revealed that the ablation dynamics differ with the wavelength of the laser. Furthermore, it was established that the cutting speed of 1064 nm became higher than that of 266 nm, although the HAZ of 1064 nm was larger than that of 266 nm.

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