Dimensional processing of composite materials by picosecond pulsed ytterbium fiber laser

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Abstract. In this paper, an experimental study of laser dimensional processing of thermoset carbon fiber reinforced plastics with a thickness of 2 and 3 mm was performed. In the process of work test rig setup based on picosecond pulsed fiber laser with 1.06 microns wavelength and 30 W average power was developed. Experimental tests were carried out at the maximum average power, with laser beam moved by a galvanometric mirrors system. Cutting tests were executed with different scanning velocity, using different laser modes, number of repetitions, hatching distance and focal plane position without process gas. As a result of the research recommendations for the selection processing mode parameters, providing minimal heat affected zone, good kerf geometry and high cutting speed were produced.

1. Introduction
The widespread introduction of composite materials due to their high performance properties raises the problem of their processing. The carbon fiber reinforced plastics (CFRP) with 2 and 3 mm thickness based on thermosetting binders are widely used in various constructions [1]. At the final stage of the manufacture of items from CFRP, there is a need for additional processing for forming windows, through holes and other elements that are impossible or impractical to produce in the preform stages. Traditionally, mechanical and abrasive water jet machining is used to perform these operations [2]. They have some significant shortcomings – high tool wear, high cost of consumables, delamination due to vibration and shock loadings, some limitations on the cutting contour and treatment of complex shape details. Laser machining by industrial ytterbium fiber lasers is a contact-free, flexible, stable processing method requiring no consumables. A comparative analysis of the characteristics of these treatment methods is presented in the article [3]. These sources reveal that laser processing is one of the promising directions for eliminating lacks of conventional machining methods.

The main technological problems of laser treatment are formation of heat affected zone (HAZ) and defects of cutting kerf geometry (taper and roughness). The HAZ is formed due to high heterogeneity and anisotropy of thermophysical properties of CFRP. In HAZ area adhesion strength between carbon fibers and matrix is broken, this dramatically reduces material strength properties. Taper and roughness of the cutting kerf determine detail accuracy grade and grade of finish. So to achieve high quality of CFRP laser machining, it is necessary to carry out complex experimental research to optimize technological parameters and processing logic. The use of pulsed-periodic laser sources can almost completely eliminate the HAZ and substantially improve the quality. For this reason, machining was carried out on a modern industrial pulsed laser with 1.06 microns wavelength.
2. Experimental setup

Experimental investigations of laser machining CFRP were carried out on the system consisting of the following key components:

1. Picosecond industrial ytterbium fiber laser YLPP-1-150-30M (IPG) with $\lambda = 1.06$ microns wavelength and 30 W average power. Typical operating modes of this laser are shown in table 1;
2. A two-axis high-speed and high-accuracy scan head with a clear mirror aperture of 12 mm;
3. F-Theta lens with effective focal length EFL = 330 mm and processing field size 220 x 220 mm;

| Mode number | Average power (W) | Frequency (kHz) | Pulse duration (ns) | Pulse energy (mJ) |
|-------------|-------------------|-----------------|---------------------|-------------------|
| T1          | 30                | 600             | 0.15                | 0.05              |
| T2          | 100               | 1               | 1                   | 0.3               |
| T3          | 60                | 2               | 0.5                 |                   |
| T4          | 30                | 5               | 1                   |                   |

The choice of the laser and the scanning optical system was due to necessity to provide high power density in the focused spot for material removal due to mechanism of evaporation and short interaction time between laser and CFRP specimen because the reduction of heat accumulation effect. The evaluation of the main characteristics of the experimental setup (focus spot diameter, depth of focus, pulse power density) were carried out according to the known equations (1–3) [4]:

$$ D = \frac{4 \cdot \lambda}{\pi D_0} \cdot M^2 \cdot F \approx 100 \mu m, $$

$$ 2 \cdot z_0 = \frac{\pi D_0^2}{4 \lambda} \approx 14 \text{ mm}, $$

$$ W_{pulse} = \frac{P_{avg}}{f \cdot \tau \cdot S} \approx 10^9 \frac{W}{cm^2}. $$

Where $\lambda = 1.06 \mu m$ – laser wavelength; $D_0$ – diameter of the collimated beam; $M^2$ – beam quality parameter; $F$ – focal length of the F-Theta lens; $P_{avg}$ – average laser power; $f$ – pulse repetition rate; $\tau$ – pulse duration; $S$ – area of the focused laser spot. The block diagram of the experimental setup is shown in figure 1.

![Figure 1. The block diagram of experimental setup.](image-url)
In the investigation, we use CFRP with 2 and 3 mm thickness produced by direct compression molding. Reinforcing fiber – Toray T700, binding epoxy matrix – Hexcel M21. The mass content of reinforcing in the material is 65%. Orthotropic reinforcement scheme. The structure of the investigated material is schematically shown in figure 2.

3. Method of evaluation of processing quality
The main criteria to evaluate the quality of laser processing CFRP parts are shown in figure 3. These criteria are discussed in detail in the articles [5, 6].

Estimation of the kerf width and HAZ on the sample surface was carried out with the optical microscope Olympus GX-51. Defects of internal structure were investigated on microsections of the cutting kerf cross-section with the same optical microscope. Estimation of the kerf taper was carried out using a contour measuring station Mitutoyo Contracer CV-2100. The roughness was measured with a surface analyzer (profilometer) Proton Model 130. The investigation of the kerf surface was also carried out using electronic scanning microscope Zeiss Gemini Merlin Compact VP-60-13.

4. Experimental results
In the research, the cutting of CFRP specimens was carried out in a straight line 30 mm length due to mechanism of evaporation in a multipass mode by the hatching algorithm without the assist gas in the air atmosphere. The algorithm for single pass processing is schematically represented in figure 4.

As a result of a large number of experiments, the recommended technological parameters and the processing algorithm were determined: average laser power 30 W; pulse repetition rate 30 kHz; pulse width 5 ns; scanning speed 0.5–1.5 m/s; hatching distance 25–50 μm. These settings provide high-quality CFRP parts on the chosen criteria. The results of machining 2 and 3 mm thick CFRP are shown in figure 5 and figure 6.
Figure 4. Machining method.

Figure 5. The surface of the CFRP sample from the beam entrance (a) and exit (b); microsection of the cutting kerf cross-section (c); kerf surface on an electronic scanning microscope (d), (e); the result of roughness measuring (f); the result of taper measuring (e).
Figure 6. The result of roughness measuring (a); microsection of the cutting kerf cross-section (b); the surface of the CFRP sample from the beam entrance (c); the result of taper measuring (d); kerf surface on an electronic scanning microscope (e, f, g); the surface of the CFRP sample from the beam exit (h).

5. Conclusions

In the course of this research work, a test rig setup based on picosecond fiber laser model YLPP-1-150-30-M (IPG) with wavelength $\lambda = 1.06 \mu m$ and average power 30 W was developed. Using this equipment the experimental evaluation of laser dimensional processing modes CFRP with 2 and 3 mm thickness was carried out. The high-quality of CFRP was provided at the recommended technological parameters and laser processing algorithm. The HAZ (zone of full and partial matrix thermal destruction) was less than 50 $\mu m$. The taper of the cutting kerf wall was less than 100 $\mu m$. The laser machining provided roughness grade 9 in accordance with ISO 1302. The cutting speed was about 10 mm/min. On microsections of the cutting kerf cross-section and its surface, there are no visible signs of delamination. These results testify to the prospects of high-quality machining composite materials by short pulse industrial fiber lasers.

References

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