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# Fiber laser cutting of CFRP laminates with single- and multi-pass strategy: A feasibility study

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ABSTRACT

Experimental data is presented relating to hole quality and feasibility studies when using continuous wave (CW) fiber laser to cut CFRP laminates (6.0 mm diameter hole) with single- and multi-pass strategy. The effect of typical processing parameters including laser power and cutting speed on thermal defect was also investigated. The statistical significance of individual cutting parameters was determined using main effects plot together with ANOVA analysis. Three methods were proposed to characterize HAZ based on the feature of thermal defect. According to statistical analysis, both cutting speed and laser power were significant with respect to HAZ (recorded at hole exit). The minimal value of HAZ was recorded with laser power of 650 W and cutting speed of 1100 mm/min. Energy per unit length ($E_l$) should be set above 40 J/mm to ensure cutting through CFRP laminates using fiber laser in high efficient machining process. Multi-pass strategy was investigated without setting pause/break time between each pass in order to increase cutting efficiency. Results showed limited improvement in terms of the level of HAZ even with cutting speed up to 10,000 mm/min, while machining time was significantly reduced to cut 6.0 mm diameter hole compared with single-pass strategy. For machining small holes with diameter down to 2.0 mm, high power fiber laser was not preferred due to severe thermal defect observed at hole entry and exit.



## 1. Introduction

The superior fatigue performance and high specific strength of carbon fiber reinforced plastics (CFRP) have made them favorable for several structural applications, including automobile panel and aircraft wing components, where they are replacing conventional metallic alloys [1,2]. Joining of such parts is mainly dependent on mechanical bolting/riveting, which depends critically on the quality of machined holes. Conventional machining techniques including drilling and helical milling are widely used to process CFRP composites, the inevitable problems however are severe tool wear and high level of cutting forces due to mechanical loading and high strength of fibers. Abrasive water jet (AWJ) is considered as an alternative to cut CFRP without interfering with its inherent structure, which also does not produce heat damage, while moisture absorption and delamination greatly reduce the mechanical properties and reliability [3,4]. In recent years, laser technology has been greatly improved with optics' development. Cutting composites with laser system is a non-contacting and non-abrasive machining progress exhibiting unique advantages including eliminating tool wear, vibration and cutting force. In addition, laser cutting is more suitable for large-scale and high-efficiency production on account of fast cutting speed and high level of laser power.

Due to the advantages of the laser cutting, a few researchers focus on obtaining superior cutting quality with laser in the field of cutting composites. Al-Sulaiman et al. [5] applied $CO_2$ laser for cutting CFRP and observed HAZ, delamination, collapse, striation and fiber-end swelling on the cut surface using SEM and optical microscope. It was also found that fiber orientation with reference to the workpiece motion during the cutting process had a significant effect on kerf formation. Among the defects generated when cutting CFRP using laser, the level of HAZ is a significant evaluation index for machining quality and the static strength of CFRP laminate is mainly dependent on the dimensions of HAZ [6]. In order to improve cutting quality, optimized machining parameters and various processing technology including picosecond and ultraviolet laser were investigated, which could achieve better machining quality. Increasing cutting speed and decreasing laser power could evidently decrease heat defects. This was due to the fact that low power and high-speed inputted relatively less energy to CFRP workpiece, which resulted in low level of heat damage [7,8].

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**Table 1**
Typical thermal property of matrix and fiber materials.

| Material | Conductivity (W/m K) | Heat capacity (J/kg K) | Vaporization temperature (°C) | Thermal diffusivity ($cm^2/s$) $\times 10^{-3}$ | Heat of vaporization (J/g) | Density ($g/cm^3$) |
|---|---|---|---|---|---|---|
| Epoxy | 0.2 | 1100 | 400 | 1.2 | 1100 | 1.2 |
| Carbon fiber | 10 | 710 | 3300 | 380 | 43,000 | 1.9 |

Many innovative processing technologies were also applied to improve machining quality. Salama et al. [9] found that the strategy of using multiple ring/pass could increase the ablation depth and material removal rate in comparison to those using single ring/pass trepanning. Gräf et al. [10] trepanned small holes using a novel Q-switched $CO_2$ laser with a very short pulse duration of about 300 ns, a high peak power of up to 60 kW and a high average power of the pulsed laser radiation. It was concluded that decreased pulse widths and increased peak power led to a remarkable enhancement of quality and precision of thermal $CO_2$ laser trepanning processes. Either the short duration or the multiple ring/pass strategy could decrease the dimension of HAZ, but these processes were relatively time consuming and inefficient. In terms of sample's mechanical properties in post machining process, Herzog et al. [6] found that the tensile strength of CFRP workpiece recorded with large level of HAZ (~1 mm) was similar to those machined with abrasive water jet and conventional milling. It was indicated that high power laser was feasible for cutting CFRP composite without diminishing mechanical properties when applying optimized processing parameters.

The aim of this study is to investigate surface quality of machined holes in CFRP laminates using high power fiber laser. It also evaluated different methods to quantify thermal defect and analyzed the effect of cutting parameters on hole quality. Based on experimental and statistical analysis, optimal machining parameters were identified and the results would give guidance for further study and practical applications. Besides, some contrastive trials concerning multi-pass strategy and small diameter holes are conducted for feasibility studies.

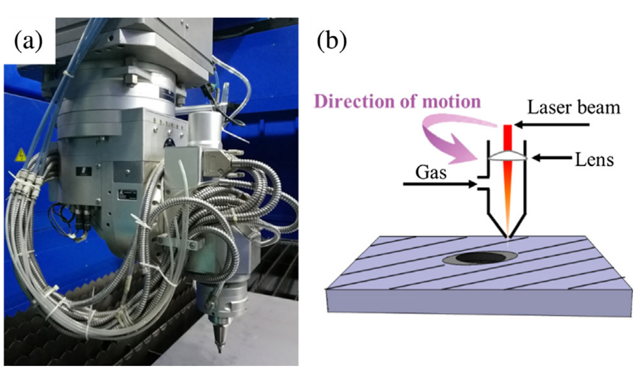


**Fig. 1.** (a). Laser cutting head and (b) schematic of thermal damage during laser cutting of CFRP laminate.

## 2. Material and methods

### 2.1. Workpiece material

Workpiece materials used in the experiment were CFRP laminates with lay-up configuration of $[+45/-45]_{2s}$, producing final plate thicknesses of 2 mm. The laminates were manufactured via high pressure resin transfer molding (HP-RTM) process, which was running at 120 °C for injecting resin and then holding for 240 s for curing. The CFRP laminates were made of high tensile strength carbon fiber impregnated with AM8930A/B epoxy resin (supplied by Wells Advanced Materials) having fiber weight fraction of 45%. Plates measuring 260 mm × 50 mm were cut and prepared for experimental trials. The typical thermal properties of matrix and fibers are detailed in Table 1.

### 2.2. Laser system

High power fiber laser IPG YLS-5000 was employed for the experiment, which was efficient and widely used in industries. It supplied the maximum output power of 5 kW and emitted continuous wave with the wavelength of 1070 ± 10 nm. The relative movement of workpiece with regard to the laser beam was achieved by an X-Y-Z CNC laser head. The stand-off was set at 2 mm to put the focus position on the sample surface, which was likely to process narrow, smooth and straight kerf [11]. Since the presence of oxygen into the inert gas was shown to have a clear influence on the fibers pull-out [12], 4 bar nitrogen was employed as the auxiliary gas in order to minimize its nature influence on the process, which was selected based on preliminary trials, indicating that lower level of gas pressure (down to 1 bar) produced larger thermal damage and high pressure (up to 8 bar) promoted large erosion in the entry surface due to the higher dynamic pressure of the jet onto the cutting front. The laser head and schematic of thermal damage are shown in Fig. 1. The level and feature of heat damage recorded at hole entry was various, as high thermal conductivity along fiber orientation led to severe surface damage in this direction.

### 2.3. Experiment design and data analysis

Three sets of experiment were conducted for contrastive analysis and feasibility study, which included the following design. The detailed factors and corresponding levels are shown in Table 2.

**Table 2**
Detailed parameters and corresponding levels in the experiment.

| Hole diameter (mm) | Cutting strategy | Variables | Levels | | |
|---|---|---|---|---|---|
| | | | 1 | 2 | 3 |
| 6.0 mm | Single-pass | Laser power (W) | 650 | 950 | 1250 |
| | | Cutting speed (mm/min) | 500 | 800 | 1000 |
| 6.0 mm | Multi-pass | Laser power (W) | 650 | 950 | |
| | | Cutting speed (mm/min) | 8000 | 10,000 | |
| 2.0 mm | Single pass | Laser power (W) | 650 | 950 | |
| | | Cutting speed (mm/min) | 500 | 800 | 1000 |