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COMPARATIVE ASSESSMENT OF CONTINUOUS AND PULSED FIBER-LASER CUTTING OF CFRP LAMINATES

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Abstract: An experimental comparison of continuous-wave and pulsed fiber-laser cutting of a 1 mm carbon-fiber-reinforced polymer (CFRP) laminate is presented. A total of 96 cutting conditions were produced by varying laser power, scanning speed, and the number of passes in both operating modes. Cut performance was quantified by the kerf width together with the thermally affected regions measured on the upper and lower surfaces (HAZ and HAZ_S). Statistical evaluation showed that beam power primarily controls kerf formation, whereas scanning speed has the strongest effect on the extent of thermal damage. Additional passes can facilitate material separation, but some multi-pass pulsed conditions caused local burning because of accumulated heat. The continuous-wave regime generally generated a smaller kerf, while pulsed operation limited the thermally affected region more effectively. The findings describe the process trade-off between dimensional accuracy, penetration capability, and thermal integrity and can be used when selecting parameters for fiber-laser machining of CFRP.

Keywords: CFRP laminate, fiber-laser machining, continuous-wave cutting, pulsed cutting, kerf geometry, thermal damage

1 Introduction

Carbon-fiber-reinforced polymers (CFRP) are widely used in lightweight structural applications because they combine high specific strength and stiffness with low density and good corrosion resistance. Their heterogeneous and anisotropic structure, however, makes machining difficult and can promote defects such as delamination, fiber pull-out, matrix damage, and geometrical inaccuracies. A recent review of CFRP edge-trimming technologies emphasizes that machining performance is strongly affected by the interaction between the cutting process and the fiber-reinforced architecture [1]. Related studies have also shown that fiber orientation and specimen geometry can substantially modify stress transfer and the mechanical response of reinforced polymer structures [2], [3].

Laser processing offers a non-contact alternative to conventional CFRP machining, but the large differences in the thermal and optical behaviour of the polymer matrix and carbon fibers make process-window selection critical. Li et al. [4] demonstrated the feasibility of continuous-wave fiber-laser cutting of CFRP using single- and multi-pass strategies and showed that thermal damage depends strongly on the selected cutting conditions. Oh et al. [5] subsequently evaluated laser power, scanning speed, and the number of passes over a broad process window and identified scanning speed as a dominant factor in limiting thermally induced damage.

Pulsed and modified beam-delivery strategies have been investigated to reduce the thermal load introduced during CFRP cutting. Leone et al. [6] used a quasi-continuous-wave fiber laser and demonstrated that pulse-related parameters can significantly affect kerf geometry and the heat-affected zone. Kelsey et al. [7] compared single- and multi-pass cutting strategies with a continuous-wave fiber laser, while Elkington et al. [8] investigated water-jet-guided

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nanosecond laser cutting as an approach for controlling the process-affected region in thicker CFRP. More recently, Zhang et al. [9] showed that ultra-short-pulsed processing can strongly limit heat accumulation and thermal damage when suitable pulse fluence, overlap, and pass count are selected.

The strong dependence of laser-cut quality on process parameters is also evident in metallic materials. Statistical optimization of fiber-laser cutting has shown that focal position, assist-gas pressure, and cutting speed can significantly influence dimensional accuracy [10], [11], while comparative fiber- and CO_2-laser processing of Hardox 450 confirmed that the selected laser source and cutting conditions affect the resulting thermal and material response [12]. Despite the available CFRP studies, direct comparison of continuous-wave and power-modulated/pulsed operation under an identical parameter matrix remains useful for clarifying the trade-off between kerf geometry, penetration capability, and thermal damage. The present study therefore evaluates the effects of laser power, scanning speed, and number of passes on kerf width, upper- and lower-surface heat-affected zones, and cut-through behaviour in both CW and PM operation. Regression analysis is subsequently used to identify the variables that dominate the measured responses.

2 Material and methods

A 1 mm thick CFRP laminate was used as the workpiece material. The composite consists of a polymer matrix and carbon-fiber reinforcement. Because of this heterogeneous and anisotropic structure, its mechanical and machining behaviour depends on the reinforcement architecture, fiber orientation, and load transfer between the matrix and fibers [1], [2], [3].

Cutting trials were conducted on a Fiber Laser MSF 3001.15L system [13], shown in Fig. 1. The machine is equipped with a HighYag FSC-Bimo2 direct cutting head and an IPG Photonics YLS-10000-CUT fiber-laser source.



Fig. 1 Fiber Laser MSF 3001.15L

The experimental matrix was defined by three controllable variables: laser power, scanning speed, and the number of beam passes along the same trajectory. Four power levels and four speed levels were combined with three pass-count levels. The numerical settings used in the experiment are listed in Table 1.

The complete matrix was executed separately for CW and PM operation. Each unique setting was applied once, producing 48 specimens per mode and 96 specimens overall. The optical system used a 175 mm focusing lens and a 100 mm collimating lens. Nitrogen at 0.5 bar served as the assist gas, and the pulse frequency in PM operation was fixed at 5000 Hz. Every specimen contained a straight 20 mm cut. A piercing sequence preceded cutting in both modes to limit

contamination of the protective window: piercing was maintained for 0.1 s, movement from the 10 mm piercing position to the 2 mm cutting height required 0.1 s, a further 0.1 s delay was applied before cutting, and piercing power was set to 3000 W.

Table 1 Proposed levels of the independent variables

FACTORS		FACTOR LEVELS			
		0	**1**	**2**	**3**
Laser power (W)	**A**	200	400	800	1600
Cutting speed (mm/min)	**B**	125	250	500	1000
Number of laser passes	**C**	1	5	10	-

Kerf dimensions were determined with a Keyence IM-7030 image-measurement system. Thermal effects were assessed with a SmartScope MVP optical microscope operated with Measure-X® software. This system was used to quantify the affected-zone width on both the incident surface (HAZ) and the opposite surface (HAZ_S). Several positions along each cut were examined to capture local variation. The resulting measurements were first reviewed graphically and were then processed in Minitab using analysis of variance and regression modelling to identify the variables responsible for the largest changes in kerf width, HAZ, and HAZ_S.

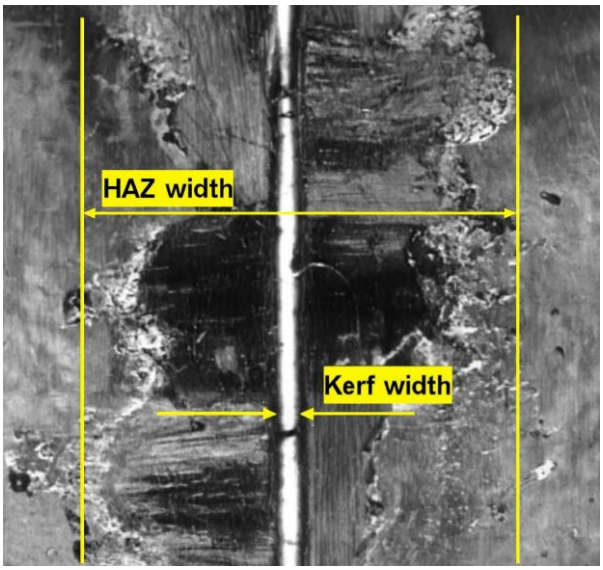


Fig. 2 Measurement scheme for kerf width and the upper- and lower-surface thermally affected zones

3 Experiment

Single-pass CW cutting produced complete separation only for two parameter combinations. Both occurred at a scanning speed of 1000 mm/min, with laser powers of 800 W and 1600 W (Fig. 3), the remaining single-pass trials did not penetrate the laminate along the full cut. After five passes, the condition 400 W and 125 mm/min generated a visibly enlarged cutting gap (Fig. 4). Repeating the beam path ten times increased the number of fully separated specimens, and penetration was obtained even at 200 W combined with 125 mm/min (Fig. 5). These observations indicate that accumulated energy from successive CW passes can compensate for low instantaneous power, although the additional heat also changes the cut geometry.

Among the CW measurements, the narrowest kerf was 0.042 mm and occurred at 200 W, 500 mm/min, and one pass. The minimum upper-surface HAZ, 2.363 mm, was measured at 200 W and 1000 mm/min after five passes. For the lower surface, the smallest HAZ_S value was 2.714 mm at 800 W, 1000 mm/min, and a single pass.

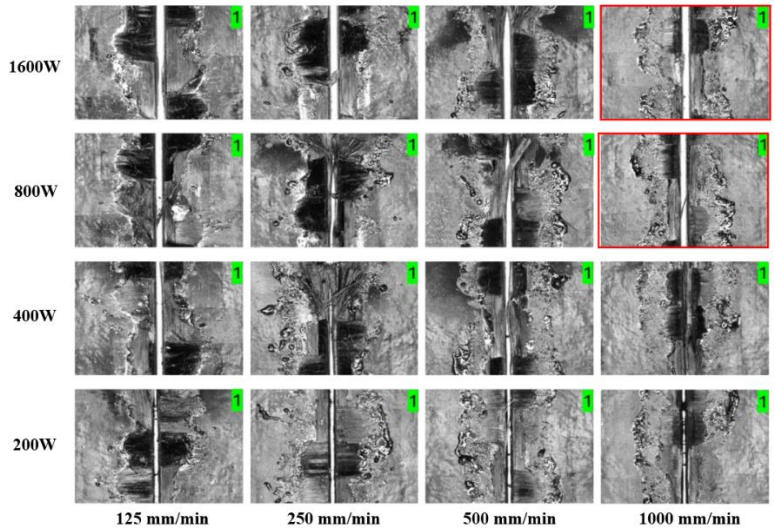


Fig. 3 CW-mode cut specimens obtained after one laser pass

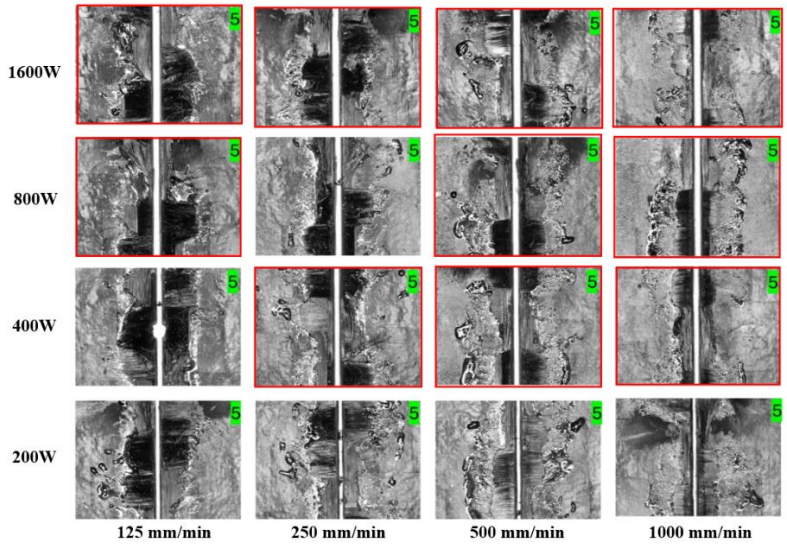


Fig. 4 CW-mode cut specimens obtained after five laser passes

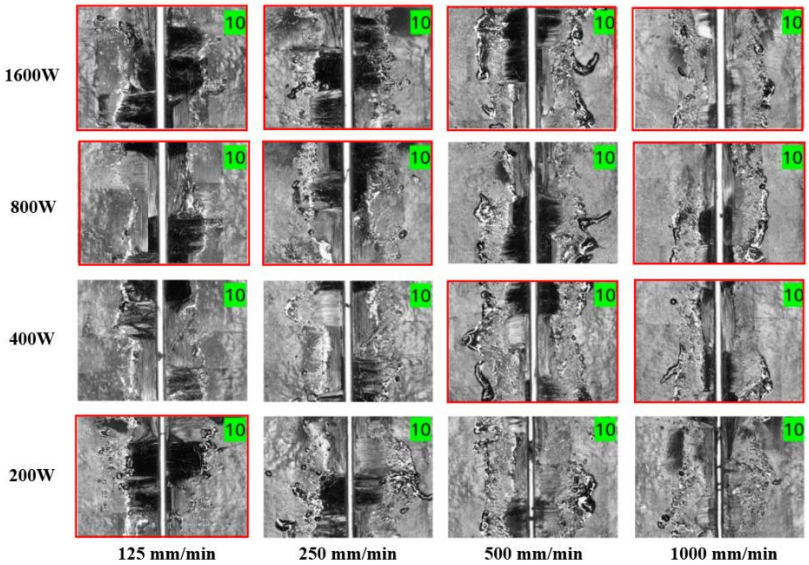


Fig. 5 CW-mode cut specimens obtained after ten laser passes

The penetration behavior differed in PM operation. With only one pass, full-length separation was recorded for a single condition: 1600 W at 500 mm/min (Fig. 6). Multi-pass cutting did not improve monotonically with pass count; full cuts were observed more often after five passes than after ten (Figs. 7 and 8). Moreover, at 1000 mm/min with five passes, settings of 400 W, 800 W, and 1600 W caused strong burning within the kerf. Under these conditions, repeated pulsed energy delivery promoted local thermal deterioration instead of efficient removal. Consequently, increasing the number of passes cannot be regarded as an automatically beneficial strategy for PM cutting.

The smallest kerf measured in PM operation was 0.088 mm at 200 W, 500 mm/min, and one pass. The lowest HAZ value was 2.249 mm for 200 W, 1000 mm/min, and one pass. A minimum HAZ_S of 2.942 mm was obtained at 1600 W and 1000 mm/min, also with a single pass.

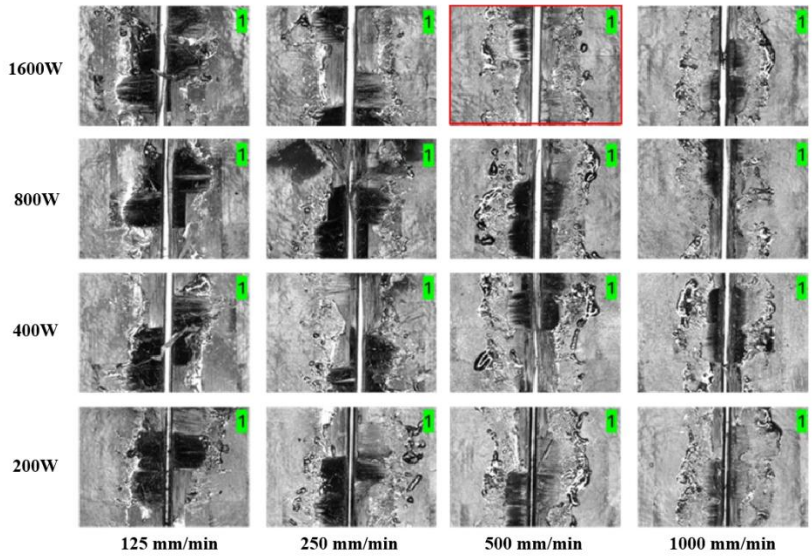


Fig. 6 PM-mode cut specimens obtained after one laser pass

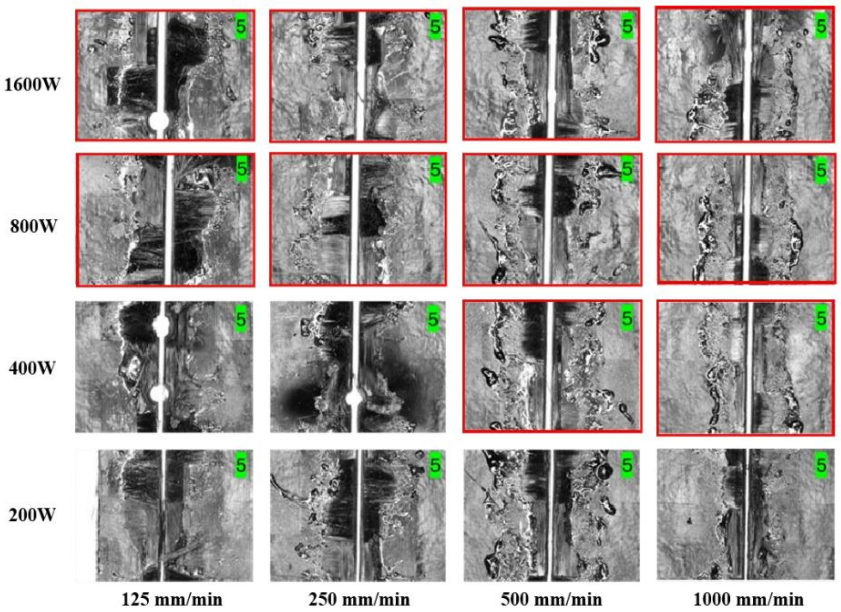


Fig. 7 PM-mode cut specimens obtained after five laser passes

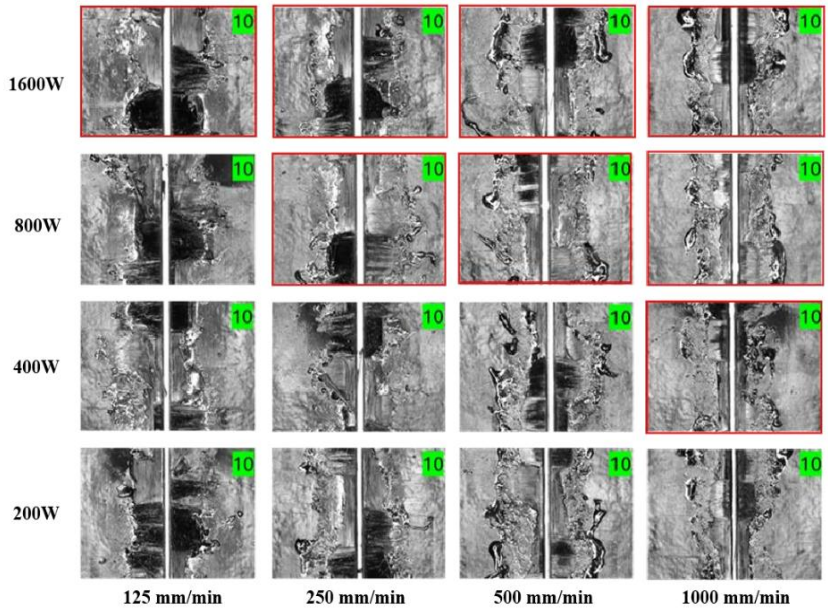


Fig. 8 PM-mode cut specimens obtained after ten laser passes

Taken together, the cutting trials show that useful parameter selection requires simultaneous consideration of power, travel speed, and repeated exposure. Greater energy input can improve penetration, but beyond a suitable range the extra thermal load ceases to contribute effectively to removal and instead increases matrix damage and burning.

4 Results and discussion

To compare the importance of the input variables, their effects were ordered from rank 1 for the strongest influence to rank 3 for the weakest. The resulting ranking is given in Table 2. The same pattern was obtained for both operating modes: laser power ranked first for kerf width, while scanning speed ranked first for both HAZ indicators. Pass count contributed least to kerf width and to the upper-surface HAZ. In contrast, laser power was the lowest-ranked variable for HAZ_S.

Table 2 Relative ranking of process-variable effects

Mode	Parameter	Kerf width	HAZ	HAZ_S
CW	Laser power	1	2	3
CW	Scanning speed	2	1	1
CW	Number of passes	3	3	2
PM	Laser power	1	2	3
PM	Scanning speed	2	1	1
PM	Number of passes	3	3	2

Because the complete dataset contains several responses and a large number of measurements, PM kerf width was used as an illustrative case for the detailed plots. The main-effects diagram in Figure 9 shows the strongest change in the response across the laser-power levels. By comparison, changing the number of passes produces the smallest shift in the mean kerf width.

To further evaluate the statistical importance of the investigated process variables, a Pareto chart of standardized effects for PM kerf width was constructed, as shown in Figure 10. The reference line at a standardized effect of 2.02 represents the threshold for statistical significance. Laser power (A) exhibits by far the largest standardized effect, confirming that it is the dominant factor affecting kerf width. The quadratic term of laser power (A^2) represents the

second most influential contribution, indicating a nonlinear relationship between laser power and kerf formation within the investigated range. The number of laser beam passes (C) and scanning speed (B) show considerably smaller effects; however, both exceed the significance reference line and can therefore also be considered statistically significant. These results further confirm the dominant role of laser power in determining the kerf width during pulsed-mode fiber-laser cutting.

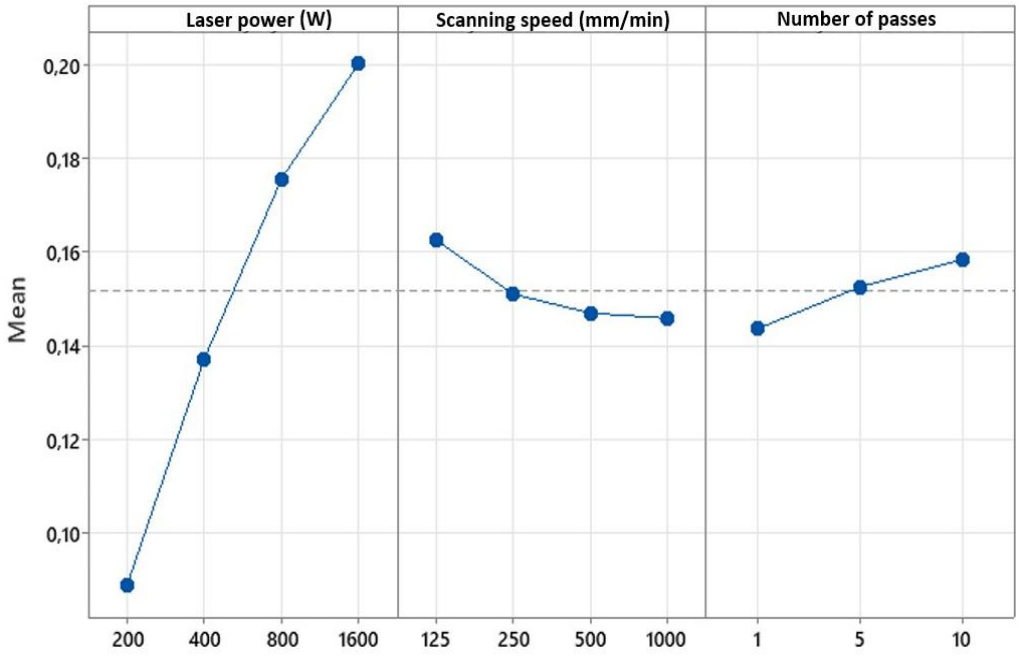


Fig. 9 Main effects plot for PM kerf width

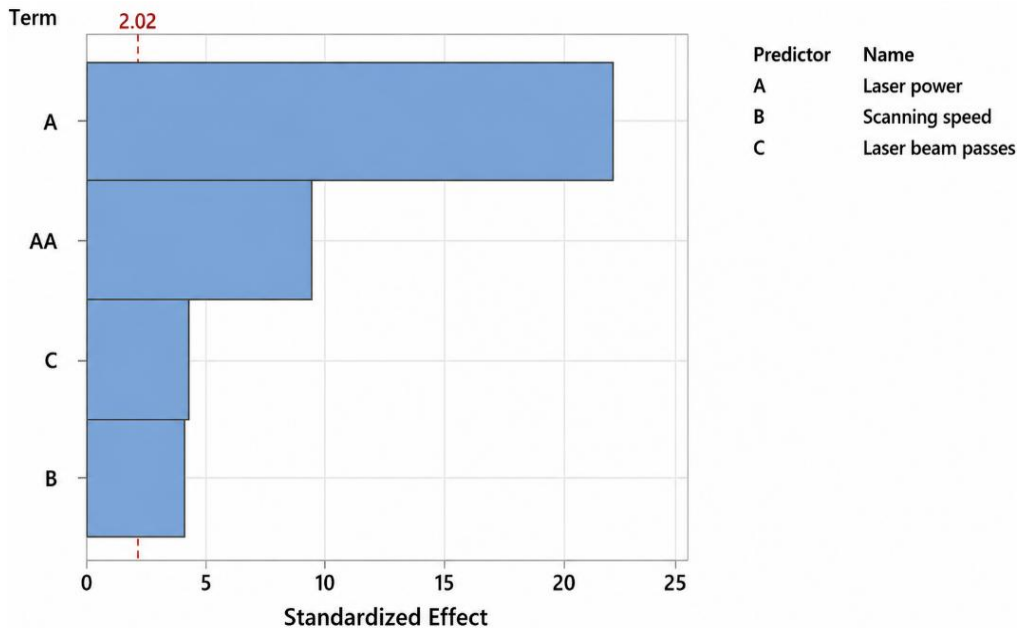


Fig. 10 Pareto chart of standardized effects for PM kerf width

Figure 11 contains the residual diagnostics for the PM kerf-width regression. No clear ordered pattern is visible in the residual sequence or in the residual-versus-fit distribution. Together with the approximately regular probability behavior, these plots indicate that the fitted model is adequate for interpreting the effects of the selected process variables within the tested range.

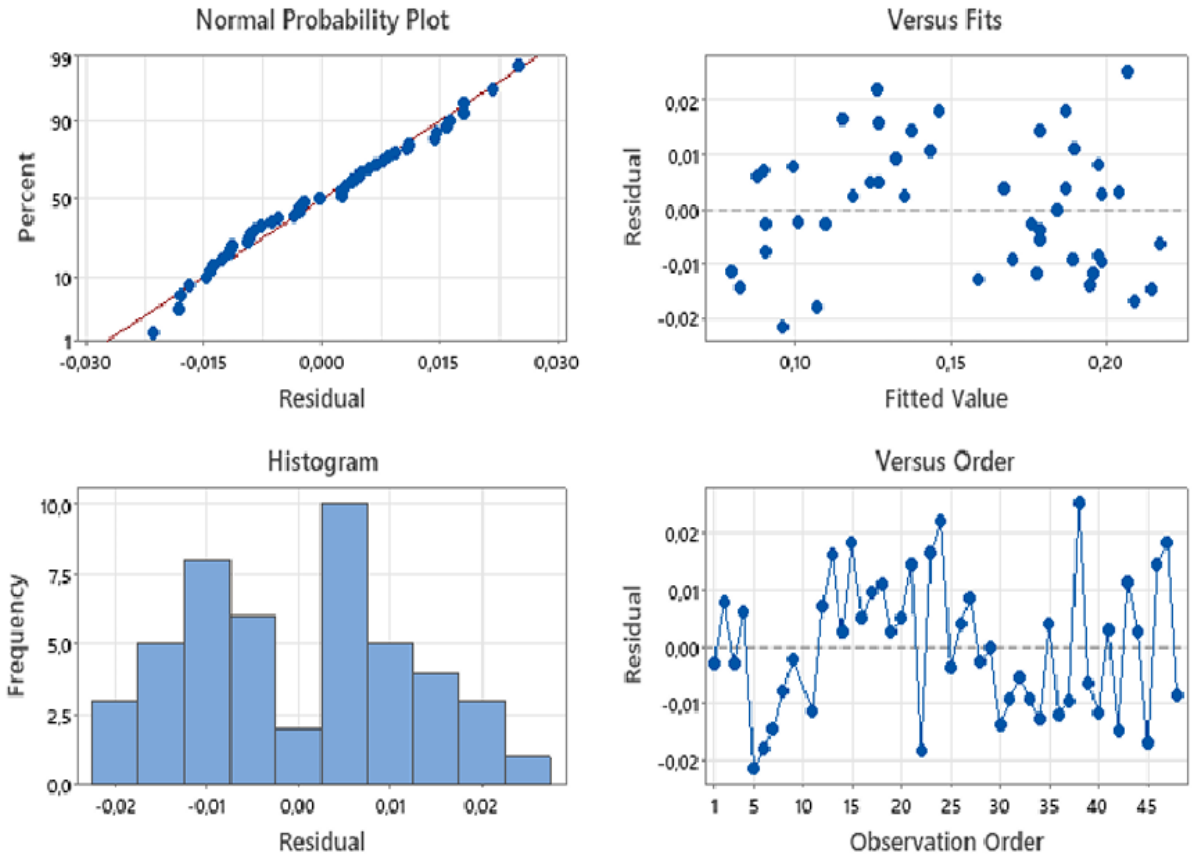


Fig. 11 Residual diagnostics for the PM kerf-width regression model

The regression model confirms that laser power is the dominant parameter affecting PM kerf width, while scanning speed and the number of passes have smaller but statistically significant effects. The model summary presented in Table 3 indicates a high goodness of fit.

Table 3 Summary of the model

S	R-sq	R-sq(adj)	R-sq(pred)
0.0123630	93.02%	92.35%	91.15%

The statistical results summarized in Table 4 support the ranking obtained from the mean-effect comparison. The table presents the coded regression coefficients, their standard errors, t-values, and statistical significance. All retained terms satisfy the adopted significance criterion of $\alpha = 0.05$. In both CW and PM cutting, the largest contribution to kerf-width variation is associated with laser power, whereas scanning speed provides the principal contribution to changes in HAZ and HAZ_S.

The observed trends are consistent with the principal mechanisms reported in previous CFRP laser-cutting studies. The dominant influence of scanning speed on thermal damage agrees with the findings of Oh et al. [5], who identified beam-travel speed as a key variable for reducing matrix damage. The influence of repeated exposure on penetration and thermal accumulation is also consistent with the single- and multi-pass observations reported by Li et al. [4] and Kelsey et al. [7]. The smaller thermally affected region obtained under PM operation is qualitatively consistent with QCW results reported by Leone et al. [6], where shorter energy-delivery intervals were used to limit HAZ formation. Studies using water-jet-guided nanosecond [8] and femtosecond [9] laser processing further support the general conclusion that reducing uncontrolled heat accumulation is essential for preserving the surrounding CFRP structure. Direct numerical comparison between these studies is limited by differences in laminate thickness, laser source, wavelength, pulse characteristics, and measurement methodology.

Table 4 Regression coefficients and statistical significance of the evaluated responses

Mode	Response	Term	Coef.	SE Coef.	T-value	p-value
CW	Kerf w.	Constant	0.166	0.0062	26.62	<0.001
	Kerf w.	Laser power	0.054	0.0038	14.37	<0.001
	Kerf w.	Scan. speed	−0.014	0.0038	−3.79	<0.001
	Kerf w.	Laser power²	−0.019	0.0040	-4.88	<0.001
	HAZ	Constant	3.235	0.0447	72.39	<0.001
	HAZ	Laser power	0.106	0.0255	4.16	<0.001
	HAZ	Scan. speed	−0.566	0.0354	−16.03	<0.001
	HAZ	Scan. speed²	0.095	0.0377	2.54	0.015
	HAZ_S	Constant	3.555	0.106	33.53	<0.001
	HAZ_S	Laser power	0.129	0.0606	2.14	0.038
	HAZ_S	Scan. speed	−1.066	0.0839	−12.71	<0.001
	HAZ_S	Scan. speed²	0.595	0.0893	6.67	<0.001
PM	Kerf w.	Constant	0.176	0.0031	55.32	<0.001
	Kerf w.	Laser power	0.054	0.0024	22.02	<0.001
	Kerf w.	Laser power^2	-0.02547	0.0027	-9.46	<0.001
	Kerf w.	Scan. speed	−0.007	0.0018	−4.13	<0.001
	Kerf w.	No. passes	0.007	0.0018	4.29	<0.001
	HAZ	Constant	3.249	0.0452	71.86	<0.001
	HAZ	Laser power	0.098	0.0258	3.79	<0.001
	HAZ	Scan. speed	−0.605	0.0358	−16.94	<0.001
	HAZ	No. passes	−0.077	0.0258	−2.99	0.005
	HAZ	Scan. speed²	0.094	0.0381	2.49	0.017
	HAZ_S	Constant	3.612	0.118	30.62	<0.001
	HAZ_S	Scan. speed	−0.998	0.0934	−10.69	<0.001
	HAZ_S	Scan. speed²	0.714	0.0994	7.19	<0.001

CONCLUSION

The experiments establish different operating characteristics for CW and PM fiber-laser cutting of the tested CFRP laminate. Kerf formation is most sensitive to laser power, and higher power generally enlarges the cut gap.

Thermal damage on both laminate surfaces is controlled mainly by scanning speed. Faster beam movement reduces the residence time of the heat source and therefore limits the affected region. Repeated passes can assist penetration, particularly in CW operation, but the PM trials show that excessive repeated exposure may produce local burning and matrix deterioration instead of further useful removal. The observed damage consisted primarily of degradation of the polymer matrix together with fiber pull-out. From a process-selection perspective, CW operation offers the advantage of a narrower kerf but imposes a greater thermal load, whereas PM operation better restricts the heat-affected region while producing a wider cut. Accordingly, the preferred operating mode depends on whether dimensional precision or preservation of the surrounding composite structure is the dominant requirement.

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