Optimization of Processing Parameters for Picosecond Laser Cutting of Carbon Fiber Reinforced Polymers

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Abstract. With the increasingly widespread use of carbon fiber reinforced polymer in aerospace and automotive fields, the problem of difficult processing of carbon fiber reinforced polymer has become more prominent. Although laser processing can achieve more ideal processing results, the existence of the heat-affected zone has a negative impact on the use of the material. Therefore, the primary objective of this study is to reduce the width of the heat-affected zone in laser-cut carbon fiber reinforced polymer. The effect of process parameters on the heat-affected zone and the kerf width was first investigated. After that, the heat-affected zone width prediction model and the kerf width prediction model were developed based on the response surface method, and the process parameters were optimized. Finally, the excellent cutting results with almost no heat-affected zone were obtained.

Keywords: Carbon fiber reinforced polymers; heat affected zone; processing parameters; laser cutting.

1. Introduction

With the rapid development of the aerospace field, carbon fiber reinforced polymer (CFRP) has gradually replaced traditional metal materials due to their advantages of low density and high strength, and have developed into the fourth widely used aerospace structural material after aluminum alloy, titanium alloy and alloy steel [1-3]. Additionally, CFRP is becoming increasingly prevalent in high-end sporting goods and cars [4]. The advantages of CFRP, such as light weight, high strength, high hardness, good fracture resistance, corrosion resistance, fatigue resistance, vibration resistance and wear resistance, make it the ideal material for aircraft structural components. CFRP has surpassed metal as the primary structural material in many critical components of the new A350 and B787 aircraft, with a composition of more than 50% [5]. However, due to the material's heterogeneity, anisotropy, and high strength, there are issues with delamination, fiber pullout, burrs, and tool wear when processing CFRP using conventional processing techniques[6]. Numerous novel processing methods have been used to CFRP processing in recent years, including electric discharge machining (EDM), abrasive water jet machining (AWJM), ultrasonic vibration-assisted machining (UVAM) and laser processing [5, 7]. Among these, laser processing is regarded to be the most appropriate technique owing to its benefits such as avoiding tool wear and high efficiency.

However, the heat-affected zone (HAZ) produced in laser processing would cause the reduction of the mechanical characteristics of the material and lower the service life. Due to the fact that carbon fiber takes longer to vaporize than resin, a significant amount of heat is transmitted through carbon fiber and released into the matrix under the beam-material interaction, causing the matrix on both sides of the kerf to be ablated and pyrolyzed, and the fiber is exposed, forming the HAZ [8]. Thus, it is critical to minimize the breadth of the HAZ during carbon fiber reinforced composite laser processing.

In general, the HAZ may be decreased by shortening the beam-material interaction time or cooling the material from the external environment, such as via the use of ultra-short pulse lasers or water jet aided laser processing [9, 10]. In addition, the HAZ can be significantly reduced by optimizing processing parameters. Freitaga et al. pointed out that the HAZ will increase with the increase of pulse energy, pulse duration, average power and repetition frequency [11]. In the study of Hu et al., one-factor experimental design was utilized to investigate the influence of process parameters including laser power, hatch distance and cutting speed on the pulsed laser–material interaction. The process parameters were optimized by using central composite design of Response Surface Methodology [12]. The research of Xu et al. demonstrates that the carbon fiber retains a relatively complete degree of exposure when the pulse energy is low [13]. Jung et al. investigated the effect of cutting speed, time interval, defocus, and other processing parameters on cutting quality, observing that a faster cutting speed results in a smaller heat affected zone and slit width [14].

From the above considerations, it results that, it is critical to choose the right process parameters for high-quality CFRP laser cutting. Additionally, for various machines and materials, the processing parameters required to achieve the best cutting quality vary. Therefore, this article focuses on the selection of process parameters for picosecond laser cutting CFRP.

Aim of the work is to investigate the influence of process parameters (laser power, pulse frequency, scanning speed) of a high-power picosecond laser on the HAZ and to optimize the process parameters. In section II, a picosecond laser was used to carry out the cutting experiment of CFRP; in section III, the influence of process parameters on HAZ and slit width was discussed in detail, and the prediction model of HAZ and kerf width was established, and the process parameters were optimized. Conclusions are drawn in Section IV.

2. Experimental approach

A picosecond laser (Hyper Rapid 50 by Coherent), working at the fundamental wavelength of 1064 nm, was used in the experiments. The duration is less than 15 picoseconds, which can significantly reduce the HAZ. In Table 1 the main characteristics of the laser are reported. The scanning procedure is carried out using a two-dimensional scanning galvanometer. The beam waist diameter of the laser beam is about 20 μm.

Table 1 Laser system characteristics.

Characteristics	Value
Wavelength (nm)	1064
Pulse duration (ps)	<15
Average power (W)	0~50
Divergence angle (mrad)	<1
Repetitive rate (kHz)	10~1000
Beam quality parameter (M2)	≤1.2

The investigated material used in this paper is a CFRP sheet of 0.6 mm thickness. The fiberboard is composed of five layers. Two outside twill weave laminates contribute to the material's strength, while the interior twill weave laminates are unidirectional in the 0° and 90° directions. The plates were obtained by autoclave cure at 150 °C and 7 bar. The adopted reinforcing material was T300 carbon fibre (Toray, Japan), while the matrix was a HMF 934 epoxy resin. In Table 2 the main characteristics of the carbon fiber and epoxy resin are reported.

Table 2 Characteristics of the carbon fiber and epoxy resin

Characteristics	Epoxy resin	Fiber carbon
Density, ρ (kg/m3)	1300	1760
Tensile strength, Rm (MPa)	82.7	3530
Elastic modulus, E (GPa)	4.1	230
Thermal conductivity (Wm-1k-1)	0.08	50 (Axial)/5 (Radial)
Specific heat capacity (Jkg-1K-1)	700	1200
Evaporation temperature (K)	653	3573
damage temperature (K)	443	2973

Previous studies have shown that the selection of process parameters has a significant impact on cutting quality. In this article, the laser power, pulse frequency and scanning speed are taken into consideration. According to preliminary experiments, laser power (P, 10 W, 25 W and 40 W), pulse frequency (f, 200 kHz, 500 kHz and 800 kHz), and scanning speed (v, 200 mm/s, 1000 mm/s and 1800 mm/s) were taken into account in this study. In order to further study the influence of various processing parameters on the HAZ and kerf width, and establish a more accurate processing model, a full factorial experimental design was adopt. Multiple scans were performed with each set of process parameters to ensure that the material is cut through. Due to the thin thickness of the CFRP utilized in this study, the lower kerf width is almost identical to upper kerf width. Therefore, only the upper kerf width and HAZ were investigated. The transfer of laser energy in CFRP is mainly along the direction of fiber laying, and the heat transfer speed in carbon fiber is much faster than that in resin, resulting in a wider HAZ along the fiber direction [15]. As a result, only the kerf width and HAZ were assessed in this research at the region where the laser scanning direction is perpendicular to the fiber bundle (Fig. XX). The HAZ and kerf width were measured by an optical microscope (BX53MRF-S, OLYMPUS).

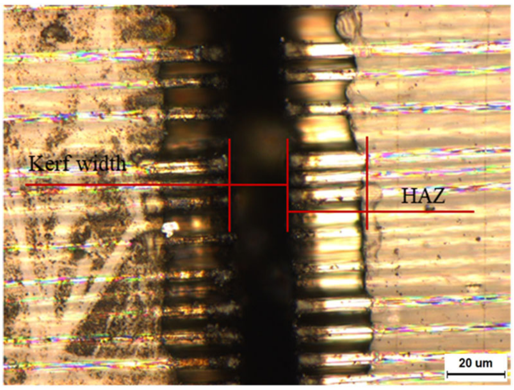

Fig. 1 HAZ and kerf width measurement

3. Results and discussion

3.1 Effect of process parameters on HAZ and kerf width

To investigate the impact of laser power on HAZ and slit width, the pulse frequency and scanning speed were set to 500kHz and 1000mm/s, respectively, and CFRP cutting tests were conducted using various laser powers. As shown in Fig.2. a), increasing the laser power from 10W to 25W results in a substantial increase in the HAZ, from 31 μm to about 67 μm. As laser power increases, the rate at which the HAZ increases lowers. As the laser power increases, the amount of energy that can be delivered to the material in a short period of time increases significantly, and the amount of heat transferred to the matrix at both sides of the kerf along the carbon fiber increases obviously, forming a more visible HAZ. However, the increasing trend of the kerf width with the laser power is not obvious, and it is stable between 20 μm and 30 μm. This may be because the energy density required for carbon fiber vaporization and separation is relatively high, and the energy of the laser beam is mainly concentrated within the beam waist diameter (20 μm), and the energy transmitted through the carbon fiber is not enough to cause carbon fiber vaporization.

Compared with the laser power, the HAZ increases slightly with the pulse frequency. And the kerf width rises very little as the pulse frequency increases. An increase in pulse frequency shortens the distance between two laser pulse bombardment sites and increases the accumulation of heat, thus having an effect on the HAZ and the kerf width. However, since the laser used is a picosecond laser, the time of each laser bombardment is extremely short, so increasing only the pulse frequency will not bring about a rapid growth of the HAZ.

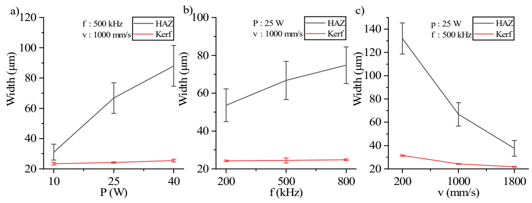

Fig. 2 Effect of process parameters on HAZ and kerf width a) laser power b) pulse frequency c) scanning speed

It is obvious from Fig. 2c) that the scanning speed has the most significant effect on HAZ and kerf width. Both HAZ and kerf width decreased significantly with the increase of the scanning speed. This is mainly due to the fact that the HAZ and kerf width of CFRP increase with increasing laser heat input (P/v) because of longer interaction period between the laser and the CFRPs at lower cutting speed [14]. And when the laser power is constant and the scanning speed increases, the laser heat input decreases, so the HAZ and kerf width decreases.

3.2 Prediction models

To explore the connection between HAZ and kerf width and process parameters in more detail, the prediction models for the HAZ and the kerf width were developed using the response surface method. The result obtained is shown in Eq. (1).

$$\begin{aligned} HAZ &= 75.382 + 2.656p - 0.004f - 0.081v + 0.001pf - 0.001pv - 0.00002fv \\ &\quad -0.021p^2 + 0.00003f^2 + 0.00002v^2 \\ Kerf\ width &= 28.065 + 0.048p - 0.0005f - 0.004v \end{aligned} \tag{1}$$

ANOVA is one of the most commonly used statistical methods to determine the performance of the model and determine the influence of machining parameters on the surface integrity [16]. Therefore, ANOVA was used to test the performance of the two models. The ANOVAs of the HAZ at 95% confidence level are shown in Table 3.

Table 3 Analysis of variance (ANOVA) table for HAZ and Kerf width. (SS, DF and MS denote summation of squares, degrees of freedom, and mean squares, respectively.)

	Source	SS	DF	MS	F	p-value	
HAZ	Model	55674.5	9	6186.1	240.4	4.0599E-16	significant
	P	10853.6	1	10853.6	421.8	1.94E-13	
	f	2280.4	1	2280.4	88.6	3.7264E-08	
	v	39668.1	1	39668.1	1541.5	4.0112E-18	
	Error	437.5	17	25.7			
	Total	56111.9	26				
	R^2	0.982		Adjusted R^2		0.978	
	Predicted R^2	0.968		Adeq Precision		54.0221	
Kerf Width	Model	191.5	3	63.8	23.1	3.9566E-07	significant
	P	9.4	1	9.4	3.4	0.07809596	
	f	0.3	1	0.3	0.1	0.7366143	
	v	181.8	1	181.8	65.8	3.3629E-08	
	Error	63.5	23	2.8			
	Total	255.0	26				
	R^2	0.751		Adjusted R^2		0.719	
	Predicted R^2	0.659		Adeq Precision		12.6128	

In the model for HAZ, the p-value is much less than 0.05, f-value is up to 240.4, which indicates that the model for HAZ is significant. In addition, the p-values of laser power, pulse frequency and scanning speed are much less than 0.05, which indicates that these parameters are significant. The Predicted R^2 of 0.968 is in reasonable agreement with the Adjusted R^2 of 0.978, and the difference between them is less than 0.2. Adeq Precision measures the signal to noise ratio. The ratio of 54.022 indicates an adequate signal. The above analysis study demonstrates that the model developed can be used to accurately reflect the actual actual processing situation. Similarly, the ANOVA results for the kerf width prediction model also prove that the developed model can accurately predict the kerf width.

Additionally, the f-value can reflect the ability of each processing parameter to influence the heat-affected zone width and the slit width. It can be found that the scanning speed is the process parameter that has the greatest influence on the HAZ and the kerf width, followed by the laser power, while the pulse frequency has a relatively weak ability to influence the HAZ and the kerf width, which is consistent with the analysis results in Section 3.1. In addition, in the analysis of variance for the HAZ model, the f-values for each process parameter are significantly higher than those in the kerf width, which indicates a more significant effect of the process parameters on the HAZ.

On the other hand, the plotting the normal plot of residuals provides a more intuitive response to the adequacy of the model. Fig. 3 illustrates that all residuals of both the HAZ prediction model and the kerf width prediction model are near straight lines, indicating that the errors are regularly distributed. It can be considered that the HAZ prediction model and the kerf width prediction model are sufficient.

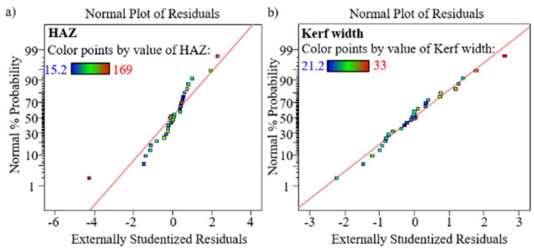

Fig.3 Normal probabilities of residuals for taper percentage a) HAZ b) kerf width

In addition, several sets of process parameters were randomly generated within the allowed range of each process parameter to verify the predictive performance of the developed model. The obtained results are shown in Fig. 4.

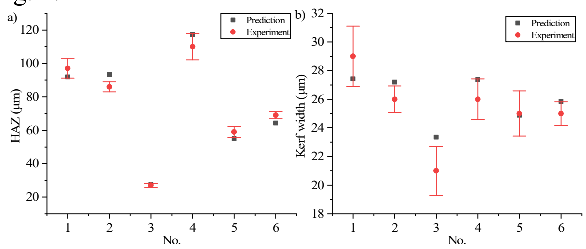

Fig. 4 Validation of model prediction results a) HAZ b) kerf width

As shown in Fig. 4, the predicted results for HAZ and kerf width using the developed model are extremely similar to the actual experiments. The established HAZ prediction model has higher prediction accuracy, and the difference between its predicted and actual values is quite small. Especially for the prediction of HAZ of the third group of machining parameters, the predicted value is almost identical to the actual value, and the maximum prediction error appeared in the prediction of HAZ of the fourth most group of machining parameters, and the maximum error is about 7 μm. It is within the acceptable range. It is expected that the model has reliable prediction accuracy, and one of the reasons for the deviation in the prediction is that there is also a small difference in the properties of the CFRPs, and thus there will be some deviation using the same process parameters. The predicted results for the kerf width are also basically consistent with the actual experimental results. In the predictions for groups 2, 3, 4 and 6 process parameters, the predictions were slightly larger than the actual experimental results. The largest prediction error occurs in the prediction of the kerf width for the third set of process parameters, and the maximum error is only 1.7 μm, which is acceptable for the prediction of the kerf width. From this, it can be concluded that the established HAZ prediction model and the kerf width prediction model both have high prediction accuracy.

3.3 Optimization of process parameters

The optimization of process parameters can effectively reduce the HAZ and the kerf width. Therefore, the optimal process parameters were obtained by using the expectation function method for multi-response optimization using Design Expert software. The optimization objective is to minimize the HAZ and the kerf width, and the constraints are that each process parameter needs to be within the appropriate range. The obtained optimization results are shown in Fig. 5.

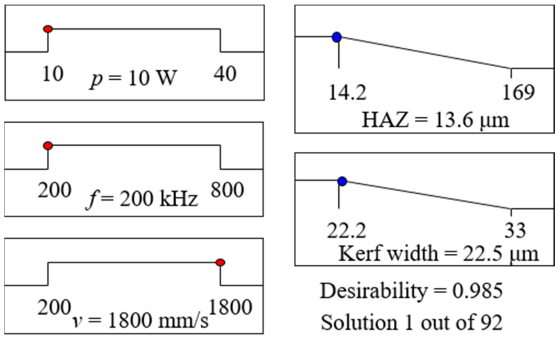

Fig. 5 Process parameter optimization results

The optimized laser power, pulse frequency and scanning speed are 10 W, 200 kHz and 1800 mm/s. The results obtained from the optimization can be explained by the laws of influence of processing parameters on HAZ and kerf width. The reduction of power, the reduction of pulse repetition frequency and the increase of scanning speed all contribute to the reduction of heat affected zone width and slit width.

The obtained kerf width is expected to be 22.5 μm and the HAZ is expected to be 13.6 μm. The machining results using the optimized machining parameters are shown in Fig. 6a). The obtained kerf width is 24 μm and the HAZ is 13.3 μm. The predicted value for the kerf width is 6.25% smaller than the experimental value, and the predicted value for the HAZ is 2.26% larger than the experimental value. The prediction errors are small and within acceptable limits. Fig. 6b) shows the results obtained by cutting CFRP using unoptimized process parameters. The comparison shows that the optimized process parameters significantly reduce the HAZ, while the reduction of the kerf width is not significant.

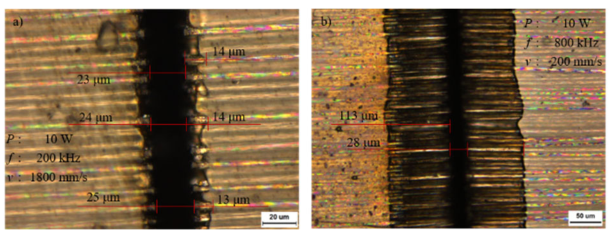

Fig. 6 Comparison of cutting quality a) with parameter optimization b) without parameter optimization

4. Summary

In this paper, the effects of laser process parameters on the HAZ and kerf width of CFRPs were investigated, and a HAZ prediction model and a kerf width prediction model were established and the process parameters were optimized. The main conclusions obtained are as follows:

- The scanning speed has the greatest effect on the HAZ and the kerf width, followed by the laser power and pulse frequency.
- The HAZ is strongly influenced by the process parameters, while the kerf width is relatively less influenced by the process parameters.
- There is a clear relationship between HAZ and kerf width and process parameters, and the cutting quality can be predicted by the established HAZ prediction model and the kerf width prediction model.
- The HAZ and the kerf width can be effectively reduced by optimizing the process parameters.

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