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Optimization of Laser Cutting Parameters on the Laminated Carbon Fibre Reinforced Plastics (CFRP) Composites Using DOE Technique

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Abstract. Nowadays, carbon fiber reinforced plastics (CFRP) composites is widely used in the aerospace industry due to its excellent mechanical properties. In laser cutting process, high powers are used to cut materials then material melts and burns leaving edges with a high quality finish. To fulfill the high demand of cutting quality, a set of laser cutting parameters of CFRP material are studied. The objective of this experiment is to obtain an optimum laser cutting parameter thus minimizing the cutting defects particularly on kerf width at the top and bottom surfaces. The analysis of process parameter was carried out using DOE, Design Expert 6.0.8. Cutting speed, pulse duration, pulse repetition rate and pulse energy were analyzed at two levels. By the optimizing the parameter setting, significant improvement in cutting quality has been achieved.

Introduction

Carbon fiber reinforced plastics (CFRP) have increasingly widened their use in aerospace application due to the high strength and lightweight. Even though near-net manufacturing of composite materials is possible, cutting and drilling will remain unavoidable operations. Cutting and drilling of CFRP composites with conventional cutting methods produce tool wear and damages such as delamination and fibre pull out [1]. Moreover, machining is not suitable when a very small complex shape is required.

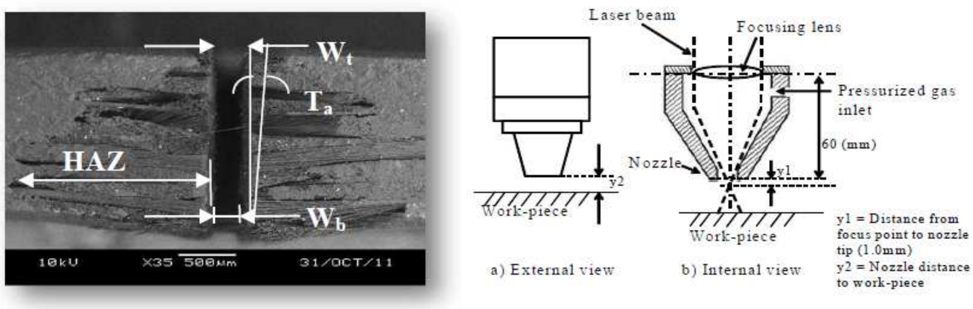
Laser cutting is the main production for thin sheet workpiece. These workpiece can be cut by several types of laser such as Nd:YAG laser, fiber laser or by water-jet guided Nd:YAG laser which produces narrower kerf width [2]. The narrower the kerf width, the lower the energy input for the workpiece, because of melting lower amount of material. Lower energy input means narrower heat affected zone, lower heat-caused distortion and more accurate workpiece profile [3]. The used of pulsed Nd:YAG laser in cutting operation of CFRP was investigated in [4]. According Leone et al, narrow kerf width and smaller heat affected zone was depends on beam intensity and better focusing. Applications of laser cutting in carbon fiber reinforced plastics have grown considerably in many industries. Nowadays, the most commonly used laser for thin workpiece cutting is Nd:YAG laser with 1064 nm wavelength. The objective of this study is to investigate the significant parameters on kerf width at the top and bottom surface using full factorial method.

Experimental Setup

CFRP composite with thickness 1.5 – 3.0 mm were used as the studied material. The material in this cutting experiment was BMS8-256, epoxy pre-impregnated carbon fiber tapes and woven fabrics. Type of preparing for this material was unidirectional and its fiber orientations during the fabrication process was 45°, 90°, -45° and 0°. The resin used for this material is epoxy and curing temperature at 177 °C. Nd:YAG laser machine (Model GSI-JK300HPS) was used for the experiments. The laser was operated at a wavelength of 1064 nm and 810 mm region for light energy. The maximum average output power is 300 W. Two level of each input process parameter have been selected with considering the interaction effects. The considered process parameters and their levels are listed in Table 1. The result were evaluated by using optical microscopy to assess the kerf width at the top and bottom surface, heat affected zone and taper angle, as shown in Figure 1.

Table 1: Input process parameters and their levels used in the Design of Experiment

Symbols	Input parameters	Unit	Level 1	Level 2
A	Pulse Energy	J	1.4	2.2
B	Pulse repetition Rate	Hz	35	45
C	Pulse Duration	ms	0.5	0.8
D	Cutting Speed	mm/min	30	48



(a) (b)

Figure 1 (a) Image of kerf geometry W_t: Top kerf width, W_b Bottom kerf width, T_a Taper angle and (b) Laser beam setup (focus distance)

Results and Discussion

Design of experiment (DOE) analysis. A 2 level full factorial analysis with 1 center points was conducted in order to gain the optimum process condition. These optimum conditions were then used for further analysis on the cutting process of the CFRPs. Design Expert 6.0.8 software was used to design the experiment with four parametric factors such as cutting speed, pulse energy, pulse repetition rate and pulse duration. The cutting speed ranges were confirmed following initial trial runs to realize the cut through condition at maximum and minimum levels of the system. The factors and their levels are given in Table 1 and also presents the results indicating the effect of pulse energy (A), pulse repetition rate (B), pulse duration (C) and cutting speed (D) on kerf width, heat affected zone and taper angle. In laser cutting process, lower value of kerf width, minimum of heat affected zone and narrow taper angle are an indication of better performance.

Effect on kerf width (Top). The result of ANOVA for top kerf width have been given in Table 2, which also shows the pulse repetition rate, pulse duration, the interaction between the pulse energy and pulse repetition rate and pulse duration between cutting speed are the most significant parameter.

Table 2: Result an ANOVA for kerf width (Top).

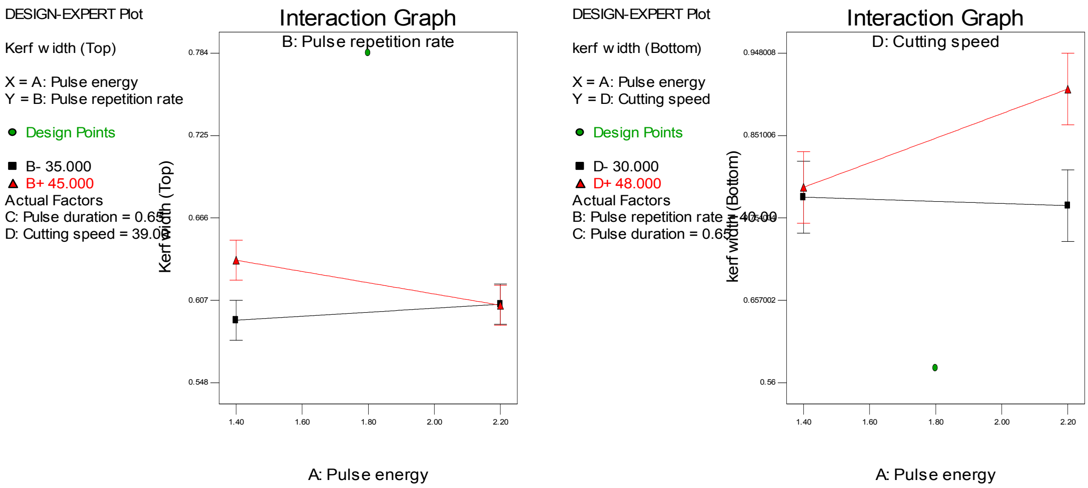
Source	**Sum of squares**	**Degree of freedom**	**Mean square**	**F-value**	**Prob>F**
Model	0.014	9	1.518E-03	5.44	0.0260 Significant
A	4.306E-004	1	4.306E-004	1.54	0.2607
B	1.785E-003	1	1.785E-003	6.39	0.0448
C	3.57E-003	1	3.57E-003	12.78	0.0117
D	5.641E-004	1	5.641E-003	2.02	0.2051
AB	1.91E-003	1	1.914E-03	6.85	0.0397
AC	1.425E-003	1	1.425E-003	5.10	0.0647
BC	1.501E-004	1	1.501E-004	0.54	0.4912
CD	2.998E-003	1	2.998E-003	10.73	0.0169
ABC	8.266E-04	1	8.266E-004	2.96	0.1362
Curvature	0.029	1	0.029	103.12	<0.0001 Significant
Residual	1.676E-003	6	2.79E-004		
Cor Total	0.044	16			

Effect on kerf width (Bottom). The result of ANOVA for top kerf width have been given in Table 3, which also shows the cutting speed and the interaction between the pulse energy and cutting speed are the most significant parameter.

Table 3: Result of ANOVA for kerf width (Bottom)

Source	Sum of squares	Degree of freedom	Mean square	F-value	Prob>F
Model	0.10	9	0.012	4.75	<0.0357 Significant
A	0.011	1	0.011	4.62	0.0752
B	0.011	1	0.011	4.71	0.0731
C	0.014	1	0.014	5.63	0.0533
D	0.022	1	0.022	9.14	0.0233
AB	1.914E-003	1	1.914E-0.03	0.79	0.4082
AC	0.013	1	0.013	5.25	0.0618
AD	0.016	1	0.016	6.53	0.0432
BD	6.28E-004	1	6.28E-003	2.59	0.1584
ABD	8.51E-004	1	8.51E-003	3.51	0.1100
Curvature	0.051	1	0.051	21.22	0.0037 Significant
Residual	0.015	6	2.422E-003		
Cor Total	0.17	16			

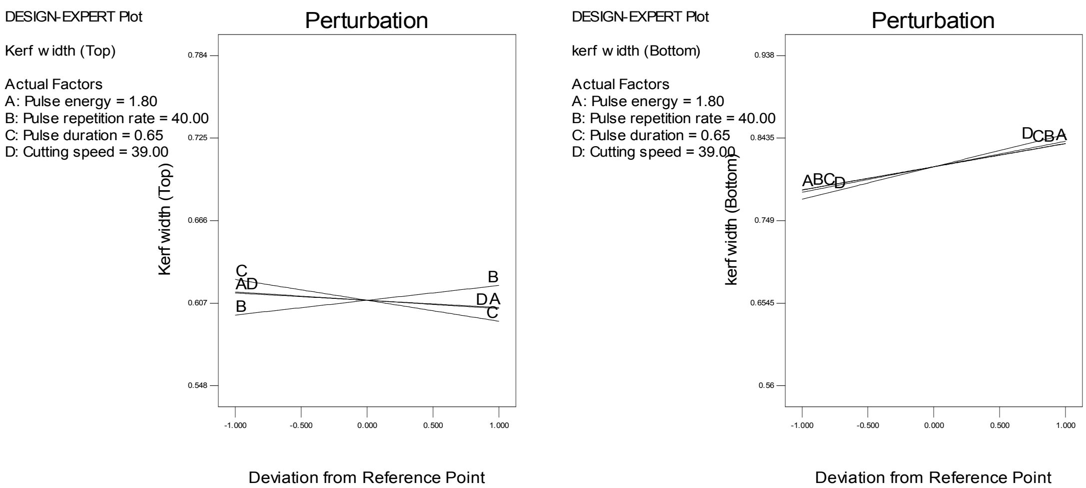
Interaction Factor. For interaction factor of top and bottom kerf width, the plot show on Figure 2, the interaction of pulse energy and pulse repetition rate was found as the significant factor influencing the kerf width for top and bottom.



(a) (b)

Figure 2: Interaction graph for kerf width a) top and b) bottom

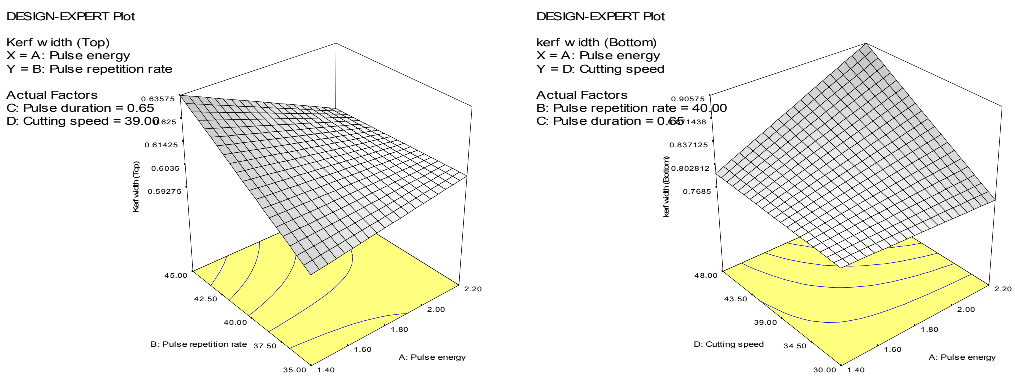
Perturbation analysis. The perturbation plots for the coded values of the process factors and their influence on the top kerf width are showed in Figure 3. The graph is a helpful tool in statistical analysis that facilitates observation of the effect all numeric factors on the response under analysis.



(a) (b)

Figure 3: Perturbation plot for kerf width a) top and b) bottom

Parameter Optimization. The analysis of the result showed that the kerf width on the top surface is mostly influenced by the pulse repetition rate and pulse energy. The relationship of these factors is given in the Figure 4. It can be observed, the top kerf width sensitive to the pulse repetition rate and pulse energy. Decreasing the pulse repetition rate the kerf width decrease. However, increasing the pulse energy, increased the kerf width less significantly as compared to the increase pulse repetition rate. This can be linked to the fact the power density is directly proportional to pulse energy. Whereas, for the bottom kerf width the significant factors are cutting speed and pulse energy. When the cutting speed decreases, the bottom kerf width will decrease. Furthermore, there is similarity with the top kerf width which increasing the pulse energy, increased the kerf width.



(a) (b)

Figure 4: 3D surface plot for kerf width a) top and b) bottom

Conclusion

The following conclusion are drawn from this study;

1. Based on the analysis of variance, pulse repetition rate and pulse duration was found to be the most significant effect on the cutting parameter for minimizing the value of top kerf width.
2. The optimum setting of the laser cutting parameters was found at pulse energy at 1.4 J, pulse repetition rate at 40 Hz, pulse duration at 0.80 ms and cutting speed at 48 mm/min.
3. Kerf width is critical quality of interest, which cannot be removed completely but can be minimized up to the certain range.

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