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An Exploratory Study - Critical Laser Processing of Composite Materials

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Abstract

This paper reports an exploratory study of the laser composite cutting process. The laser cutting of composite is a multi-factor process and correct combination of the parameters is needed to achieve high quality and optimum process efficiency. Laser machining based non-contact type advanced machining process with several advantages such as no tool wear, fast, precise and virtually force-free manufacturing method. Laser cutting involves thermal energy process and it does not depend on the strength and hardness of the work piece. In recent years the researchers have explored a number of ways to improve the cut quality of composite materials in different type of lasers. In this paper, an exploratory study is done on critical laser processing of composite materials optimization by other researches which made from available data especially from ScienceDirect Journal Database. This study predominantly focuses to investigate the correlation between laser machining parameter with the responses. The paper also highlights the experimental control parameters of composite laser machining with responses.

1. Introduction

The word laser was originally spelled LASER and is an acronym for Light Amplification by Stimulated Emission of Radiation. A ruby crystal is the world's first laser was established [1]. It is essentially a coherent, convergent, and monochromatic beam of electromagnetic radiation with wavelength ranging from ultraviolet to infrared. Since the development of the first ruby laser in 1960, the laser action has been demonstrated in hundreds of materials. However, the range and variety of active materials for commercial lasers are still limited [1]. There are three common types of lasers used in laser cutting: (1) CO_2 laser; (2) Nd-YAG; and (3) fibre laser.

1.1. CO_2 laser

CO2 laser is one of the most main lasers in the laser machining of material is shown in figure 1. However, the laser radiation at 10.6 µm is the strongest and forms the generally usual mode of operation [1]. They are commercially available, with high laser powers of 20kW and more. Moreover, both the matrix and the fibre of the composite are greatly absorbing for the CO2 wavelength of 10.6 mm. The system chosen due to very compact laser with low investment and operating costs [2].

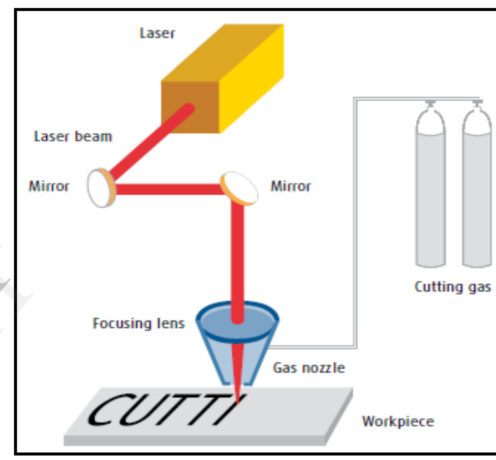

Figure 1. CO_2 laser

1.2. Nd:YAG laser

Nd:YAG laser consist of crystalline YAG with a chemical formula Y3Al5O12 as a host material. Such systems offer significant advantages such as ease of achieving population inversions. Hence, simple designs of flashlamps with a modest amount of pumping energy are sufficient to achieve the efficient population inversions [1]. According to Herzog et al. [2], Nd:YAG lasers, in comparison, have a wavelength of 1.064 mm, for which the matrix is highly transparent. The laser energy is consequently absorbed mainly by the fibre. The system used here can run in a pulsed mode with very high pulse peak powers of up to 18kW. This has two effects: it leads to really high intensities within the laser pulses, and part of the heat can be removed from the processing region by conduction in the time between two pulses. The schematic of Nd:YAG laser is shown in figure 2.

1.3. Fibre laser

Disk laser systems are a comparatively new development. As for the Nd:YAG lasers, they discharge in the NIR (l ¼ 1.03 mm) range which means that absorption in the CFRP will be dominated by the fibre, too. Due to their different resonator set-up, the beam quality of disk lasers are more advanced than that of comparable Nd:YAG systems. The schematic of fibre laser is shown in figure 3.

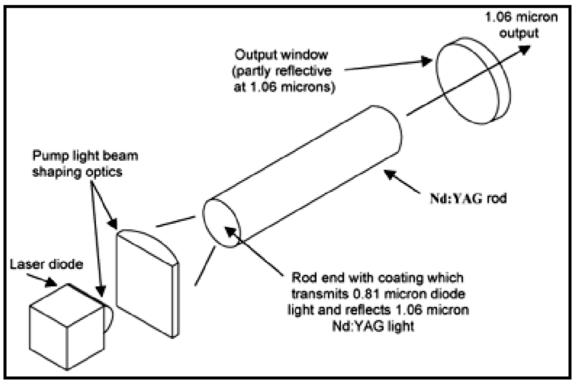

Figure 2. Nd:YAG laser

Therefore, high intensities can be reached by the system used. Providing 3 kW, the disk laser was the laser with the highest medium output power used here. This leads to high process speeds up to 10 m/min for a CFRP of 1.5mm in thickness [2].

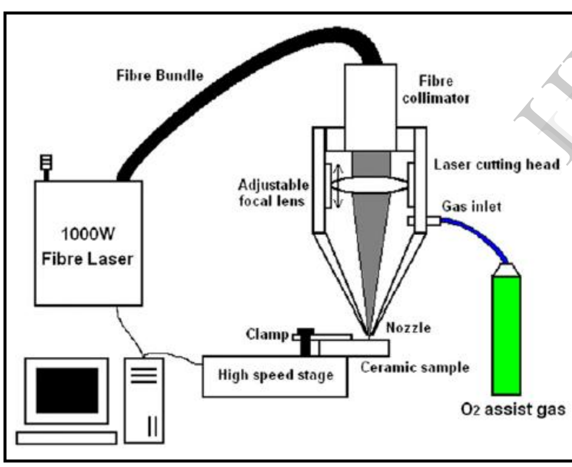

Figure 3. Fibre laser

In the modern advancing technology, the application of composite materials is increasing due to improved end product quality, low cost and short processing time. The application of composite materials in many modern industries has become more crucial, such as aerospace, automotive, electrical component, infrastructure, marine, military, railway and sport [2-5]. The composite materials represent a class of advanced materials with unique properties obtained by combining two or more constituent materials. Due to commonly differing properties of the constituent phases in the composite, the manufacturing composites present important challenges. Depending on the type of constituent materials (matrix and reinforcing phases), the composite materials have commonly differing manufacturing routes [1].

1.4. Problem associated with composite cutting

Further investigation is required for selection of the cutting parameters due to thermal behaviour on anisotropic and heterogeneous feature of CFRP material [6-9]. Detailed study is necessary on thermal effect by lasers composite cutting was suggested by Herzog et al. [2]. The cut quality is influenced significantly by thermal behaviour, which causes thermal damage such as matrix decomposition, matrix recession and delamination was studies by Pan and Hocheng [10]. Most previous studies on composite were conducted by laser machining does not show great potential due to poor cut quality [5, 11-13] and causing charring, fibre spalling and low productivity [14,15]. Cutting processes by laser machining of composite materials with conventional cutting methods produce tool wear, damages such as delamination and fibre pull out [16-19]. In addition, machining is not suitable when a very small complex shape is required [20]. Laser cutting is a possible alternative which does not involve any mechanical cutting forces or tool wear, as well as obtain complex shape too.

Consequently machining processes such as mechanical cutting and water-jet cutting technique are commonly being used for the machining of CFRP today, but they have faced difficulty on the wastewater disposal and high tool wear, etc. according to Ushida et al. [21]. Laser machining on wood composite is being a complicated process due to engage a chemical reaction and also influenced by several factors such as: composition, density, internal bond strength, moisture and thermal conductivity. According to Fatimah et al. [4], polymer difficult to process due to the matrix structure such as fibre orientation, lamination, matrix properties and relative volume fraction. As well produced penetration energy during CO_2 involves in cutting of polymer composite.

In this work, an exploratory study is done on critical laser processing of composite materials optimization by other researches which made from available data. The paper also highlights the method used for analysis process parameters on experimental investigations. This study predominantly focuses to investigate the correlation between laser machining parameter with the responses. The paper also highlights the experimental control parameters of composite laser machining with responses.

2. Investigations of laser cut quality

From the literature review, it is clear that a number of experimental investigations in laser cutting have been carried out. Kerf width is one of the important responses in cut quality. According to Eltawahni et al. [3] a study using CO_2 laser cutting of (4, 6, 9 mm) of medium density fibreboard (MDF) shows that surface roughness value reduces as the focal point position and laser power were increased and cutting speed and gas pressure were decreased. Parameter focal point position is the major factor affected the upper kerf. The observation concludes that upper kerf decreases as the focal point increases. Other hand, main factor affected on the lower kerf is laser power and cutting speed. It is been observed lower kerf decrease when laser power decreases, but reversely to cutting speeds. The ratio decreases as the focal point position and laser power increases, nevertheless, the laser power effect reduces as the material becomes thicker, and also it was found that an increase in cutting speed until a certain point around 3875 mm/min will decreases the ratio after which it starts to decrease. It was found through experimental studies that response surface methodology (RSM) used as analytical method to statistically signify the input design parameters with the responses. There are also another studies that used same analytical tool to determine main parameter influences with minimum number of experinments [7].

It revealed that cutting of 1.5mm thick of CFRP (carbon fibre-reinforced plastics) by using pulsed Nd:YAG gives better HAZ compared to disk laser and CO_2 laser. The result of the experiment showed that static strength is obtained reached maximum to 1000MPa by Nd:YAG laser, while for disk laser is around 950MPa, and for CO_2 laser around 900MPa. Considering the HAZ and kerf width, Nd:YAG laser and disk laser has produces better value compared to abrasive water-jet and milling technique. It was also noted that a higher HAZ produces aggravate tensile strength was proven by Herzog et al. [2].

An experimental study was done by Muller and Monaghan [18] to investigate the machinability of Electro Discharge Machining (EDM), laser cutting and Abrasive Water Jet (AWJ) on SiC particle reinforced aluminium matrix composites (PRMMC). The result showed that EDM suitable for machining but the process is very slow. They found that existence crater on the surface, the size of crater increase proportional to the discharge energy. Laser machining offers significant productivity advantages for rough cut-off applications, but produces more HAZ compared to EDM [30]. Conversely, laser machining able to reduce the recast layer [29] It is proven that application of laser suitable for high feed rates and can obtain a cut with small values of kerf width, but striation patterns on the cut surface (dross attachment) were observed. In the case AWJ cutting did not result in any thermal damage and no burr attachment was observed, but the surface was relatively rough and slotted-edge damage was noted at the top of the cut surface.

Al-Sulaiman et al. [6] concluded that fibre orientation in the work piece with mention to the work piece motion has a significant effect on the kerf pattern. Kerf width size obtained from an experiment with different power intensities for three thermal conductivities. The result shows that the kerf width size can be decreased by decreasing the laser power meanwhile an increase in thermal conductivity will reduce the kerf width size.

Mathew et al. [7] investigated selection of cutting parameter towards cut quality on CFRP composite sheet 3mm thick. In this study, discovered that pulse repetition rate (RR) and cutting speed is the two major parameters play a significant role in affecting the HAZ. Smaller HAZ obtain when used higher pulse energy at lower RR. Meanwhile the higher cutting speed gives a smaller HAZ due to less interaction time and it is in agreement with what observed by Iorio et al. [19] using same Nd:YAG source. They also found that RR and pulse energy to be a most influencing parameter affecting the kerf width. Next, increase in pulse energy guide to more material removal and increase in kerf width. Another response, taper is obtained to be minimized at the middle range of RR and at lower pulse energy, higher pulse duration and cutting speed. But taper angle tends to enhance at the increase of cutting speed parameter according to Iorio et al. [19].

Riveiro et al. [8] studied the effect of CFRP cut quality by CO_2 laser cutting in both continuous wave (CW) and pulsed mode. The most influencing parameter on the cut quality is laser power. As result from CW, laser power is more affected at kerf width in the entry side compare to exit side. It was observed that the HAZ is proportional to the laser power. Meanwhile, taper angle is inversely proportional to the laser. The higher the laser power is, the smaller the taper angle is. The result from pulsed mode showed that the duty cycle is a very significant parameter determining the kerf width. Where the pulse frequency slightly decreases the kerf width, pulse energy is opposite from that. The narrow cuts obtain in kerf width when used middle value of duty cycle. When evaluating the taper angle, duty cycle and pulse energy linearly increase the taper angle, while pulse frequency linearly decreases the taper angle. Duty cycle also main influencing parameter affected HAZ, the increasing of this parameter tend to increase the HAZ to the maximum rate. Finally, concluded that the present of HAZ cannot be avoided but can be reduced by selecting the proper processing parameters.

Negarestani et al. [9] conducted research on the effect of assist gas pressure on quality of the cut CFRP material; they are pure oxygen, pure nitrogen and 50% oxygen-50% nitrogen. The result showed that 12.5% oxygen-87.5% nitrogen of 8 bar pressure given the optimum parameter arrangement to improve quality in laser cutting of CFRP. From optimum parameter, noted that the fibre pull out was reduced almost 55%.

El-Taweel et al. [5] research on CO_2 laser cutting of Kevlar-49 composite. The Taguchi technique used to identify the effect of laser parameters; laser power, cutting speed, material thickness, gas pressure and laser mode on the quality of cut, namely; kerf width, dross height and slope of the cut. The Taguchi method is a powerful tool based experiment used to find the optimal condition for improving the cutting quality. For kerf width, cutting speed and gas pressure increase lead to kerf width decrease, but laser power and material thickness reversely effect on it. Dross height was found to be directly proportional to the laser power and material thickness meanwhile, inversely proportional to cutting speed and gas pressure. The third output response is slope of the cut, was clearly shown that this response increase with the increasing of laser power and material thickness. Nevertheless, slope of the cut decreases as the cutting speed and gas pressure increase. Finally researcher concluded that laser power is the most important parameter affected quality of cut for Kevlar-49 composite then followed by material thickness, assistance gas pressure, cutting speed and then laser mode. The study to obtain optimum value of kerf width suggests that optimal setting for the laser power - 800 W, cutting speed - 30 m/min, material thickness - 1 mm and assistance gas pressure – 16 bar.

The use of solid state Nd:YAG laser in cutting operation of CFRP sheet was investigated in [20]. It was shown that the minimum kerf width were obtained by decreasing the spot overlap or enhance the cutting speed by using Nd:YAG laser. In the case the taper angle tends to increase. While HAZ tend to be minimized by reducing the spot overlap [16] or increasing the cutting speed. As above statement also proven by Hira and Tsuboi [22] that HAZ decreased with increasing of cutting speed but using fibre laser.

Kevlar and mild steel composite of CO_2 laser cutting was conducted by Al-Sulaiman et al. [13]. Duty cycle is the significant cutting parameter in determining the kerf width and dross height. The result shown that increasing the duty cycle is tend to increase the kerf width or decreasing the dross as well. There was a quantitative analysis made to find cut quality of 4mm of mullite-alumina ceramic composite by using Nd:YAG laser cutting. In their study, discovered that pulse frequency and cutting speed play a significant role in affecting the HAZ while assist gas pressure no essential effect on HAZ. It was also observed that cutting speed is a role of gas pressure and power [31].

3. Discussion

From the analyses, it is obvious that various experimental investigations in composite laser cutting have been carried out. Table 1 shows the summary of experimentally manipulated parameters in composite laser machining from year 1985-2012 practically publisher by ScienceDirect Database. There were 25 researches conducted investigation to determine the significant design parameters and responses involved. Table summarize brings the outcome to the further critically investigate.

The influence of input machining parameters on the responses in percentage is shown in figure 4. Selection of cutting parameter have been proven by Mathew et al. [7] that improve the laser cut quality with respect to surface quality and dimensional accuracy. The significant parameters used in composite laser cutting were found to be; laser power (56%), cutting speed (48%) and gas pressure (36%) while, duty cycle (8%), wavelength (12%) and peak power (12%) obtain with least affects.

The responses were critically investigated in order to obtain excellent cutting quality among composite laser machining parameters is shown in figure 5. It shows that the most responses investigate were; HAZ (60%), kerf width (56%) and microstructure (20%) towards laser cutting enhancement parameter approach. Also observed that the least responses investigate were; striation formation (8%), dross height (8%) and material removal rate (8%). Studies towards minimizing the taper angle are become priority for cutting process in order to characterize the cut quality by reflects to the optimum result.

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Table 1. Experimental manipulated parameters composite laser machining from years (1985-2012) according to available data especially from ScienceDirect database.

Type of Laser	Ref.	Input Parameters											Output Parameters							
		MP	LP	PF	WL	PE	FS	PD	DC	PP	CS	GP	HAZ	KW	SF	MS	MR	TA	SR	DH
CO_2	[2]	✓		✓						✓	✓	✓	✓							
	[18]		✓												✓				✓	
	[11]		✓		✓								✓	✓						
	[8]		✓	✓		✓			✓			✓	✓	✓				✓		
	[5]		✓								✓	✓		✓				✓		✓
	[4]						✓									✓				
	[25]		✓									✓		✓						
	[12]		✓											✓						
	[13]								✓				✓	✓						✓
	[17]										✓									
	[26]		✓											✓						
	[10]		✓								✓		✓							
	[14]		✓										✓							
	[27]		✓								✓			✓			✓			
	[6]		✓											✓	✓					
	[3]		✓				✓				✓	✓		✓					✓	
Nd:YAG	[2]	✓		✓						✓	✓	✓	✓							
	[7]					✓		✓			✓	✓	✓					✓		
	[19]							✓			✓		✓	✓				✓		
	[21]						✓									✓				
	[9]			✓		✓					✓	✓	✓							
	[15]												✓			✓	✓			
	[28]				✓	✓										✓				
	[20]	✓		✓		✓							✓	✓						
	[16]					✓		✓					✓	✓						
Fibre	[2]	✓		✓						✓	✓	✓	✓							
	[11]		✓		✓								✓	✓						
	[22]		✓								✓					✓				

There are: **MP**-mean power; **LP**-laser power; **PF**-pulse frequency; **WL**-wavelength; **PE**-pulse energy; **FS**-focus spot; **PD**-pulse duration; **DC**-duty cycle; **PP**-peak power; **CS**-cutting speed; **GP**-gas pressure; **KW**-kerf width; **SF**-striation formation; **MS**-microstructure; **MR**-material removal rate; **TA**-taper angle; **SR**-surface roughness; and **DH**-dross height

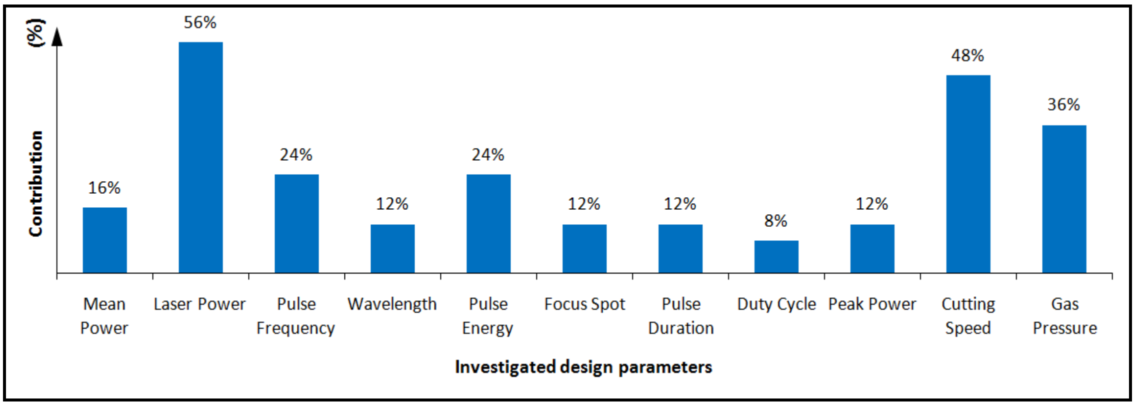

Figure 4. Critically investigated design parameters in laser processing of composite materials

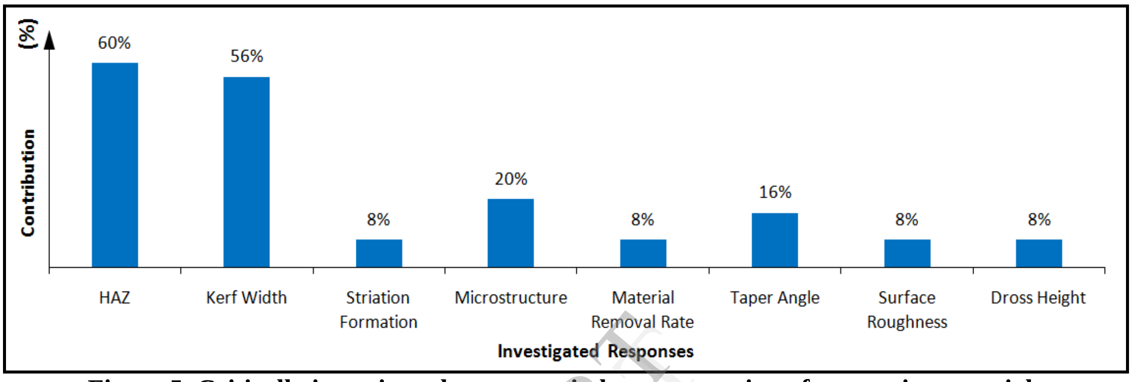

Figure 5. Critically investigated responses in laser processing of composite materials

4. Conclusion

An exploratory study of the laser composite cutting process is presented in this paper. The investigation of three main laser machining; CO_2, Nd:YAG and fiber laser from available data especially from ScienceDirect Journal Database have been discussed. The objective was to study critical laser processing of composite materials optimization by other researcher, the problem occurred during cutting composite, and correlation between laser machining parameter with the responses. CO_2 is currently used widely for machining of composites than others. This is reflected in the number of publications concerned with these processes. The main factors which affect the quality of cutting: laser power, cutting speed and gas pressure. On the other hand, the important influence quality characteristic studies are HAZ, kerf width and taper angle. Technique of experimental was also found used to be a very important tool for improving the process performance. By using different techniques efficiency of experimental is increased by reducing the loss of quality.

Quality improvement of the laser cutting process is becoming increasingly more important. Machining of composite materials is difficult to carry out due to the anisotropic and non-homogeneous structure of composites. Laser and water-jet machining are currently used extensively in industry of composite cutting. Problems with delamination, wastewater disposal, cutting speed limitation and crack due to shock wave impact during water-jet machining have been identified. The major concern with laser machining is the introduce heat affected zone (HAZ). However this problem can be eliminated by proper selection of operating parameters.

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