CO2 laser cutting of glass-fibre-reinforced unsaturated polyester (GFRUP): an experimental investigation

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Abstract

Glass-fibre reinforced unsaturated polyester (GFRUP) is one of the thermoset composites that has many applications in manufacturing productions. CO₂ laser cutting of this composite has been significantly developed in industries. It is believed that the presence of glass fibre network in the matrix of thermoset affects the laser cutting process of this composite. In addition, the three-dimensional matrix of monomers along with carbon atoms in the atomic network's joints can also influence the laser cutting parameters. The aim of this research is to experimentally investigate the effect of these complicated structural properties on the CO₂ laser cutting of GFRUP sheets. First, the maximum cutting speeds, in which the cut occurs, were obtained for various sheet thicknesses using a variety of powers. The kerf width was measured with using an optical stereo-microscope. Then, the laser cutting mechanism was discussed using the SEM of the cut edge surfaces. The volume cutting efficiency was also studied. The results indicate that the upper kerf width is wider than the lower kerf width. The upper kerf width is larger than the spot size of 0.3 mm. The chaotic striations on the cut edge surface are the re-solidified glass fibres and can be seen as something like stalactites which are in black due to the carbon dust. Opening of the lower kerf due to the shrinkage of the re-solidified glass fibre is reported as a phenomenon. The cutting efficiency decreases as sheet thickness increases.

1. Introduction

Nowadays, the unsaturated polyester (UP) resin is one of the major thermosetting resins that used in conjunction with glass fibre (GF) reinforcement. Glass-fibre reinforced unsaturated polyester (GFRUP) is one of the specifically appropriate composite thermoset polymers for particularly technical applications due to their non-melting, high thermal and chemical resistance, stiffness, surface hardness, dimensional stability and low flammability [1]. Due to these extraordinary mechanical properties, this composite is vastly applied for manufacturing various parts in aerospace industries, ship, submarine, train and automotive [1,2]. Basically, the glass-fibre-reinforced polymer is a composite manufactured combining two phases namely a polymer matrix and a fine GF network scattered into it. Under the microscope, it is clear that these two phases remain separate and distinct and it is well understood that this nonhomogeneous field is necessary to obtain the remarkable mechanical properties [3]. Besides this, the significant differences between melting properties of polyester and glass fibre significantly affect the process of laser cutting [4]. Today, CO₂ laser cutting is commercially used for rapid cutting of different non-metallic materials particularly polymers and composites. This is well known that polymers are highly absorptive at the wavelength of 10.6 μm [5] and so the cut edge quality and especially the cutting efficiency are high when cutting with CO₂ laser [6]. In laser cutting of a single phase plastic (e.g. Teflon), generally, processing parameters and laser conditions influence the cutting performance particularly cutting efficiency, cut edge quality, and kerf width and there are many published researches which present a framework of cutting parameters for a particular polymer [7-9]. However, in laser cutting of composite polymers which are reinforced by high reflective metal particles (e.g. bronze) and/or hard fibers (e.g. carbon and glass) the structure properties extremely affect the process of laser cutting [10,11]. This is

due to the significant differences between physical properties of polymer matrix and reinforcement materials as the published results from other researchers indicate [6-17]. In CO₂ laser cutting of Teflon and Teflon-bronze composite sheets, Davari et al. [10] showed that the upper kerf width for both materials was in order of 0.5 mm for a beam diameter of 0.35 mm. However, comparison between two employed materials confirmed that due to the presence of bronze particles in the reinforced Teflon, the lower kerf width is wider than that for non-reinforced Teflon. Moreover, for a given power and the same thickness, the maximum cutting speed for non-reinforced Teflon is higher than that for Teflon-bronze sheets. Riveiro et al. [12] investigated into CO₂ laser cutting of carbon fiber reinforced plastic (CFRP) composites. They assessed the cut quality in terms of kerf width, perpendicularity of cut and HAZ. Then, they concluded that the laser cutting of CFRP is difficult due to the different physical properties between the carbon fibers and the epoxy matrix. In CO₂ laser cutting of fibre-reinforced polyesters, Tagliaferr et al. [13] resulted that the thermal properties of the fibres and polymer matrix are the major factors which affect cutting performance. Solati et al. [14] in CO₂ laser drilling of GFRP composites found that the optimum laser drilling parameters resulted higher tensile strength and lower surface roughness in drilled GFRP laminate compared to the conventional drilling. Tamrin et al. [15] experimentally and numerically analyzed low power laser cutting of cotton fibre laminate (CFL) and they observed that protruding fibres along with bubbles and crack happened on the laser cut edge of the sample causing significant strength loss of fibres and epoxy. Nagesh et al. [16] experimentally researched on the influence of the addition of nanofillers on the quality of laser cutting of vinylester/glass nanocomposites. They found that nickel nanopowder made uniform distribution of smaller globules of char to protect the fibres whilst carbon black brought about thick char material and allowed glass fibre to melt.

As far as the structure properties of the polymer composites can determine the process of laser cutting in terms of cut edge quality and kerf width, this research experimentally studies on the laser cutting of glass-fibre-reinforced unsaturated polyester to better understand the cutting mechanism. Moreover, some novel results of this research can be useful for laser cutting specialists.

2. Experimental Procedures

2.1 Cutting experiments

CO₂ laser cutting machine employed in this research is a 1.5-kW laser machine manufactured by AMADA Laser Company. Some features of this machine derived from the manufacturer's catalog are presented in Table 1. Before going through the results, it must be emphasized as a caution that the laser cutting of glass-fibre-reinforced unsaturated polyester sheet produce lots of smoke, so, air ventilation system must be used. In addition, a suitable assist-gas pressure should be applied in order to protect the lens.

Table 1 General characteristics of the employed laser machine

Model	Manufacturer	CNC Table	Max. Power	Max. speed	Max. Thick. (Steel)	Max. sheet size
LC-655	AMADA	X:2540 mm Y:1500 mm Z: 114 mm	1500 W	5000 mm/min	6 mm	2540*1270 mm

Figure 1 shows the employed cutting head when laser cutting of 8 mm thick sheet with power of 1300 W and cutting speed of 170 mm/min

A lens with focal length of 101 mm was applied and the laser beam in a continuous wave mode (C.W.) was focused on the top surface of the sheets. The maximum cutting speeds for variety of powers and thicknesses under the same laser cutting condition were achieved. In order to determine the maximum cutting speed, for a given power, the cutting speed was gradually increased. The highest speed, in which the cut occurred, was the maximum cutting speed. Some laser cutting parameters are shown in Table 2.

Table 2 cutting parameters

Processing Parameters	Value
Sheet thickness (mm)	2,4,6,8
Power (w)	300-1500
Cutting speed (mm/min)	100-5000
Focal length (mm)	101.6
Focal position	Top surface
Assist gas	Filtered air
Gas pressure (bar)	4
Nozzle diameter (mm)	2
Stand-off distance (mm)	1
Beam diameter (mm)	0.3

2.2 Material

Glass-fibre-reinforced unsaturated polyester (GFRUP) sheets with different thicknesses were used in this research. The length and wide of all employed sheets were the same as 300 and 200 mm respectively. In order to clarify the physical and chemical properties of the used GFRUP in this research, some relevant information is indicated in Table 3. Typical thermal properties of composite material constituents are shown in Table 4.

Table 3 Relevant information of employed GFRUP sheets

Thickness (mm)	Number of laminate	Sheet weight (gr)	Glass fiber (wt%)	Polyester (wt%)	Cobalt (wt%)	Peroxide Acid (wt%)
2	3	204	43.62	55.02	0.27	1.09
4	6	341	52.47	46.34	0.23	0.96
6	9	588	45.76	52.93	0.26	1.05
8	12	745	47.91	50.81	0.25	1.03

Table 4 Typical thermal properties of composite material constituents [13]

	Density (g/cm ³)	Conductivity (W/m°K)	Specific Heat (J/g °K)	Diffusivity (cm ² /s)*10 ⁻³	Vaporization Temp. (°C)	Heat of vaporization (J/g)
Resin	1.25	0.20	12	1.3	350-500	1000
Glass fiber	2.55	1.0	0.85	4.6	2300	31000
Glass/resin	1.90	0.4-0.6	1.0	2.1-3.2	-	-

2.3 Kerf width measurement

An optical stereo microscope model Olympus SZX16 with magnification of 7x to 115x was applied to measure the kerf width. The CNC machine's table generally has acceleration and deceleration at the beginning and the end of cutting process respectively. Hence, the kerf width was measured at the middle of the cut path where the cutting speed is steady as shown in Fig. 2. In order to ensure the accuracy of measurement, the kerf was measured in three points on the middle of each cut path (Fig. 2). Then, the average of three measured values was calculated and reported as the results of kerf width.

3. Results And Discussion

3.1 Maximum cutting speed

Regarding the satisfaction of laser energy consumption and requirements of cutting efficiency, the cutting parameters (e.g cutting speed and power) should be in the range of optimum values. This is well known that for a given power when laser cutting at the maximum speed, the laser energy loss is at lowest value [5]. In this research, the maximum cutting speeds for various thicknesses of glass-fibre-reinforced unsaturated polyester sheets were obtained experimentally using variety of powers. The results are indicated in Table 5. In order to present the results with an acceptable accuracy, many cuts using variety of powers were produced to obtain the maximum cutting speed for each power. As seen in this Table, there are 25 samples were finally obtained with maximum cutting speed for given powers which all samples were cut in a day using the same environmental condition. The results in Table 4 can also be applied for commercial laser cutting. In commercial laser cutting, manufacturers usually use a cutting speed of 80 to 85% of the maximum cutting speed for a given power [5].

Due to some technical limitations (i.e., maximum cutting speed and minimum power), laser cutting of 8 mm thick composite polyester sheet limited just to four results as can be seen in Table 5. The achievable minimum cutting speed on the employed laser machine's CNC table was 100 mm/min and for this speed, the laser cutting of 8 mm thick achieved power of 900 W. On the other hand, the maximum power for the employed laser machine was 1500 W. For this power, the maximum cutting speed was obtained 200 mm/min.

Figure 3 indicates the maximum cutting speed versus power for different employed thicknesses. As seen, for a given thickness, the maximum cutting speed rises with power.

Table 5 Maximum cutting speeds for different thicknesses and powers

Thickness (mm)	Power (W)	Maximum cutting speed (mm/min)
2	300	1000
	400	1500
	500	2400
	700	3000
	800	3500
	900	4500
	1000	5000
4	300	450
	500	700
	700	900
	900	1200
	1100	1600
	1300	2000
	1500	2500
6	300	200
	500	400
	700	500
	900	600
	1100	700
	1300	900
	1500	1000
8	900	100
	1100	140
	1300	170
	1500	200

This is because, as the power increases, the incoming energy to the cutting zone grows and the laser penetration is accelerated, so the cutting speed must be enhanced to maintain the cutting efficiency. Figure 3 also shows that, overall, the maximum cutting speed range reduces with increasing thickness. This is due to this fact that as the thickness is increased, the interaction time between the laser beam and the cutting front must be enhanced to complete laser penetration, hence the cutting speed has to be decreased.

The ratio of power to thickness (P/T) as function of maximum cutting speed can be an approximate scale for laser energy consumption in every millimeter of the laser beam penetration into the depth of sheet. Figure 4 indicates the ratio of P/T as a function of maximum cutting speed for all employed thicknesses. As seen, the ratio of P/T basically increases with increasing maximum cutting speed. In addition, for a given cutting speed, the P/T generally grows with increasing thickness. For instance, at the cutting speed of 1000 mm/min, the P/T for 2 mm thick is 150 W/mm while it is 250 W/mm for 6 mm. Moreover, for a given P/T , the cutting speed reduces with increasing thickness. For example, at the P/T of 250 W/mm, when the sheet thickness increases from 2 to 6 mm, the maximum cutting speed decreases from 2400 to 1000 mm/min. The main reason for all results above is that, fundamentally, the cutting speed must establish a balance between the consumption of laser energy and any increase in the laser

penetration. If so, when the sheet thickness and/or input power is changed to increase the P/T, the cutting speed must be enhanced to maintain the cutting efficiency.

3.2 Cut surface features

Micro-photos from the surface of the cut edges which were taken by an optical stereo microscope show that the characteristic of cut surface is very complicated to describe as indicated in Fig 5. As seen, the cut edge is generally covered with chaotic re-solidified polymer. Unlike the cutting pattern that we could see on the cut edge of some materials (e.g., mild steel), there is not any clear pattern of the re-solidified melt flow on the cut surface of this composite. Then, it will be very difficult to distinguish the cutting direction from the cut edge pattern. In addition, the cut edge surface has been covered with carbon, which can blacken your finger if you draw finger on the cut surface. Qualitatively, it is to say that the amount of this carbon increases with increasing thickness.

Scanning electron micrographs (SEM) of the surfaces cut at different cutting speeds and powers indicate in Fig. 6 - 10. The striations on the cut surface are the re-solidified glass fibres and can be seen as something like stalactites which are in black due to the carbon dust. The chaotic striations lie almost perpendicular to the cutting direction and seem to be bent a little towards the back of cutting direction.

The morphology of the cut edge is strongly influenced by the re-solidified glass fibre melts which are covered by the very fine carbon particles. In this case, it is complicated to describe the cutting front situation (e.g., inclination angle, material flow) from the angle of the striations on the cut edge.

3.3 Kerf width

Study on the kerf widening can help us to analyze the material removal rate and cutting efficiency. The upper and lower kerf widths for all employed sheet thicknesses and powers are investigated. Figure 11 shows kerf width results versus maximum cutting speeds for all applied thicknesses. As can be seen in Fig. 11, in the range of employed cutting conditions and for all applied thicknesses, the upper kerf width is wider than the lower kerf. Furthermore, the upper kerf width for all employed thicknesses is wider than the focused spot size. In this research the focused beam diameter on the surface of sheet is 0.30 mm. For thickness of 2 mm, the upper and lower kerf widths are in the range of 0.48 and 0.2 mm respectively. For thickness of 4 mm, the upper and lower kerf width slightly widen in order of 0.52 mm and 0.25 mm respectively. When laser cutting of 6 mm, the upper and lower kerf widths are in the order of 0.6 mm and 0.3 mm and when laser cutting 8 mm thick sheet the upper and lower kerf are in the range of 0.62 and 0.45 mm. In order to realize the reason(s) for this enlargement in the upper kerf width, a deep study in the mechanism of kerf width widening is necessary. When the laser beam is focused on the sheet surface, the incident laser energy is absorbed by the composite polyester according to the laser absorption coefficient. Composite polymers (e.g., glass-fibre-reinforced unsaturated polyester) usually exhibit a high absorption when interact with CO₂ laser beam with wavelength of 10.6 μm [13]. In other word, the amount of direct transmitted laser power in combination with beam reflectance for glass fibre/carbon reinforced polymers at wavelength of 10.6 μm is very low [17]. The absorbed laser beam energy causes material

heating in the thin surface layer of the sheet and the temperature rapidly increases to the chemical degradation point. Polyester, as the matrix of the used composite sheet, is a kind of thermoset. The molecular structure of thermoset plastics consist of a three-dimensional matrix of monomers along with carbon atoms in the network's joints. Due to this fact, thermosets generally cannot be softened or re-melt when its temperature increases. Hence, in laser cutting of thermosets, the laser cannot melt and eject a certain volume of polymer molecules as does for thermoplastics. The mechanism of laser cutting for thermosets is based on chemical degradation. This chemical degradation consumes the laser energy more than that is taken up by melting mechanism [5]. This causes that the cutting speed is much decreased and cutting zone temperature is increased. Any increase in the cutting zone temperature can give rise to a kerf width widening. Moreover, laser cutting of thermoset tends to produce a carbon based smoke during cutting. The residual carbon deposit on the cut edge can verify this (see figure 5). The presence of carbon dust in the cutting zone can affect the kerf width widening. Although, carbon particles are generally characterized by a thermal heat conductivity of $0.3 - 3.48 \text{ W/m}^{\circ}\text{K}$ [18,19], the hot carbon particles in the cutting zone can dissipate the laser heat in the upper melting zone possibly by combination of conduction, radiation, and convection. Hence, the laser heat can be spread through the cutting front into the surrounding material by the hot carbon particles results in an increase in the upper kerf width.

As can be seen in Figure 11, in the range of applied maximum cutting speeds and laser conditions, the lower kerf width for all employed thicknesses is less than the upper kerf width. The main reasons for this, can be related the amount laser energy that reaches to the bottom of kerf. As mentioned earlier in this section, the presence of carbon dust in the cutting zone can absorb the laser energy and so, the influence of laser beam to sustain the chemical degradation of the material near the bottom of the kerf decreases. Hence, the lower kerf width tends to be narrower.

As seen (Fig.11), the lower kerf width increases with thickness. As the sheet thickness increases from 2 to 8 mm, the lower kerf width is widened from 0.2 mm to about 0.45 mm. When the sheet thickness increases, the maximum cutting speed is reduced and the laser power is increased. This cutting condition is necessary in order to maintain the cutting process. An increase in the input laser power along with an increase in the interaction time between laser beam and material will give rise to more chemical degradation near the bottom of the kerf, result in enlargement of the kerf width.

During laser cutting of GFRUP, a novel phenomenon was observed. There were a few cuts that firstly appeared to be incomplete cuts, but 20 to 240 seconds after cutting, they became complete cuts. This phenomenon was mostly observed when laser cutting of 6 and 8 mm thick sheets. We filmed this phenomenon and Figure 12 indicates some snapshots of the kerf opening phenomenon. In figure 12, A) was cut on a 6 mm thick sheet by 1500 W and 1100 mm/min and B) shows the cut path after about 30 seconds. With the same thickness, C) was cut by 1100 W and 900 mm/min and D) illustrates this cut after about 35 seconds. The opening of the kerf fundamentally occurs in the lower kerf and stops after a few seconds since beginning. This phenomenon cannot be related to the distortion of the sheet after laser cutting; because, firstly, the sheet is so thick and secondly, the distance between cuts is so enough

that the cutting zone heat cannot warp the sheet. This phenomenon is possibly related to the shrinkage of molten glass fibres remaining on the cut edge surface during solidification. As mentioned earlier in this section, all of the incoming laser power to the cutting zone cannot reach the bottom of the cutting front. Therefore, the temperature of molten glass fibre near the bottom of the cut edge decreases. Hence, the viscosity of the molten glass fibre increases. This viscous molten glass fibre cannot be removed from the bottom of kerf by the assist gas pressure and so, sticks to the bottom of the kerf, gives rise to an unsuccessful cut or a cut-no cut situation. Observation of the cut edge by SEM indicates the re-solidified glass fibre, clinging to the cut edge (Figure 6, 10). Finally, the shrinkage happens during the solidification of this molten glass fibre and so, the lower kerf begins to open.

3.4 Cutting efficiency

Many laser cutter specialists would like to know that how much cut edge they can produce with each Joule of laser energy as they want to optimize the laser cutting costs. In this section, the cutting efficiency is investigated when laser cutting of GFRUP. This measure of efficiency can be described by the following equation [20]:

$$\alpha_{vol} = \frac{\left(\frac{K_U + K_L}{2}\right) \times T \times V}{P} = \frac{MRR}{P}, \quad \left\{ \frac{mm^3}{J} \right\}$$

Where, α_{vol} is the cutting volume efficiency (mm^3/s), K_U and K_L is the upper and lower kerf width (mm), T is the sheet thickness (mm), V is the cutting speed (mm/s), P is the laser power (W) and MRR stands for material removal rate (mm^3/s). MRR is the volume of melt ejected from the cut zone per second.

Regarding the equation above, the average kerf widths for all cuts in this research were calculated simply using the results of kerf widths measurement from Figure 11. It should be noted here that the results in this study are based on the maximum cutting speeds in which the laser energy losses possibly are in the minimum. In the range of employed laser cutting conditions, Fig. 13 indicates the cutting volume efficiency versus sheet thickness for all applied powers and cutting speeds.

As seen, the cutting volume efficiency decreases as sheet thickness increases. There are some reasons for this.

- When the sheet thickness increases, the maximum cutting speed, for a given power, decreases and the interaction time increases to sustain a successful cutting process. This means that the laser beam spends more time on the cutting front to penetrate the entire sheet thickness, results in an efficiency reduction.
- When the sheet thickness increases, the volume of carbon dust in the cutting zone enlarges. Although the assist gas pressure tries to remove the carbon fume from the cutting zone, the presence of carbon dust in front of laser beam during material degradation process in the cutting front can

strongly absorb a part of laser energy. Hence, the energy delivered to the cutting zone must be increased. This dissipation in energy supplied to the cutting front results in a reduced cutting efficiency.

The energy delivered to the cutting zone in the interaction time of t_I is named specific point energy (E_{SP}) [21] which can be calculated by the following equation:

$$E_{SP} = P \cdot t_I = \frac{P \cdot d}{V} , \{J\}$$

Where, P is the laser power (W), d is the focused beam diameter (mm) and V is the cutting speed (mm/s). Fig. 14 shows that the specific point energy increases with sheet thickness. As seen, when the sheet thickness increases from 6 to 8 mm, there is a significant enlargement in the specific point energy from about 30 J to 150 J. As the specific point energy increases the cutting efficiency decreases (Fig 15).

4. Conclusions

An Experimental investigation into CO₂ laser cutting of glass fibre reinforced unsaturated polyester (GFRUP) sheets with thicknesses of 2 to 8 mm was reported, Specific observations and conclusions are the following:

- In the range of employed cutting parameters and thicknesses, the upper kerf width is larger than the lower kerf width.
- With using a spot size of 0.30 mm, the upper kerf width increases from about 0.5 to 0.65 mm as the sheet thickness increases from 2 to 8 mm.
- The lower kerf width increases from 0.2 mm to about 0.45 mm as the sheet thickness increases from 2 to 8 mm.
- There were a few cuts that firstly appeared to be incomplete cuts, but 20 to 240 seconds after cutting, they became complete cuts. This phenomenon is possibly related to the shrinkage of the molten glass fibres remaining on the bottom of kerf wall during solidification.
- The cut edge surface is almost covered with a very fine carbon dust and qualitatively increases with sheet thickness.
- The chaotic striations on the cut surface are the remaining re-solidified glass fibres and can be seen as something like stalactites which are in black due to the carbon dust.
- Cutting volume efficiency decreases with increasing sheet thickness.

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Figures

Figure 1

Cutting head when laser cutting of 8 mm thick sheet, 1300 W, 170 mm/min

Figure 2

Three cut paths on the top surface of 4 mm thick GFRUP and the position of kerf width measurement in the middle of cut path. 1st cut: 700 W, 800 mm/min, 2nd cut: 700W, 900 mm/min and 3rd cut: 500 W, 800 mm/min. The distance between each cut is 15 mm.

Figure 3

Maximum cutting speed versus power for different employed thicknesses

Figure 4

The ratio of power to the thickness (P/T) for GFRUP versus maximum cutting speed

Figure 5

The surface of GFRUP cut edges are often accompanied by a residual carbon deposit on the cut edge. Cutting direction is from right to left. A) 2 mm, 500W, 2400 mm/s, B) 4 mm, 500 W, 700 mm/s, C) 6 mm, 1500 W, 500 mm/s, D) 8 mm, 1300 W, 100 mm/s

Figure 6

SEM of cut surface, 2 mm thick, 1500 W, 2500 mm/min. Re-solidified glass fibre can be seen as something like stalactites.

Figure 7

SEM of cut surface, 2 mm thick, 1500 W, 700 mm/min. Re-solidified glass fibre can be seen as something like stalactites.

Figure 8

SEM of cut surface, 2 mm thick, 1500 W, 3500 mm/min. Re-solidified glass fibre can be seen as something like stalactites.

Figure 9

SEM of cut surface, 6 mm thick, 1500 W, 500 mm/min. Re-solidified glass fibre can be seen as something like stalactites.

Figure 10

SEM of cut surface, 6 mm thick, 1500 W, 200 mm/min. Re-solidified glass fibre can be seen as something like stalactites.

Figure 11

Upper and lower kerf width of GFRUP sheet as a function of maximum cutting speed for all used thicknesses (2-8 mm) for variety of powers (300-1500 W). Focused spot size is 0.30 mm on the surface of the sheet

Figure 12

The phenomenon of the lower kerf opening, A) Cut with 1500 W, 110 mm/min. B) Cut path A after 30 seconds. C) Cut with 1100 W, 900 mm/min. D) Cut path C after 35 seconds.

Figure 13

Cutting volume efficiency versus sheet thickness for all employed powers and maximum cutting speed

Figure 14

Effect of specific point energy on the sheet thickness

Figure 15