Journal of Modern Processes in Manufacturing and Production, Volume 9, No. 1, Winter 2020

The Effect of Power and Maximum Cutting Speed on the Material Removal Rate and Cutting Volume Efficiency in CO_2 Laser Cutting of Polycarbonate Sheets

Majid Hashemzadeh[1*], Mehdi Mohammadi[1]
[1]Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran
[*]Email of Corresponding Author: m.hashemzadeh@pmc.iaun.ac.ir
Received: December 23, 2019; Accepted: March 18, 2020

Abstract

In the laser cutting process some well-known parameters, e.g. laser power and cutting speed, play major roles in the performance of the process. Each parameter or a combination of parameters can affect the material removal volume and cutting volume efficiency. The purpose of this research is to study the effect of power and maximum cutting speed on the material removal rate (MRR) and cutting volume efficiency (α_{Vol}) in CO_2 laser cutting of polycarbonate (PC) sheets. A CO_2 laser cutting machine with a maximum power of 130 W was used to cut PC sheets with thicknesses of 2 to 8 mm. The spot size of the focused beam was 0.1 mm on the upper surface of the sheet. The cutting experiments were carried out by varying the laser power from 20 to 100 W and the maximum cutting speed was found for each power. In the range of applied laser parameters for cutting of PC sheets, the results show that the MRR increases with power. The results also indicate that the MRR increases with maximum cutting speed and thickness. The cutting volume efficiency (α_{Vol}) increases with power until it reaches the apex of efficiency then, it slightly reduces with increasing power.

Keywords

CO_2 Laser Cutting, Polycarbonate (PC), Material Removal Rate (MRR), Cutting Volume Efficiency

1. Introduction

In the laser cutting process, a laser beam that is focused on the surface of the workpiece, melts and vaporizes a small zone of material. An assistant gas jet, which is aligned with the laser beam, simultaneously removes the molten and vaporized material from the cutting zone through the bottom of the kerf. Hence, cutting happens when the laser beam or CNC table (workpiece) moves at a specified speed [1,2]. In laser cutting process, many parameters (e.g. power density, wave length, focal point properties, cutting speed, assistant gas and material conditions) influence the cutting process in terms of kerf width, heat affected zone (HAZ), cut edge quality, cutting efficiency and material removal rate [3]. Nowadays, laser cutting is commercially applied for the rapid cutting of various materials. Doubtlessly, one of the most important groups of materials in the field of CO_2 laser cutting is non-metallic materials particularly polymers. The main reason for this is that the polymers are highly absorptive at the CO_2 laser wavelength of 10.6 µm [4] and so the cutting efficiency and cut quality are considerably high [5]. Laser cutting parameters influence the cutting process and there are many published results that present a framework of cutting parameters for a particular polymer [6,7]. Polycarbonate (PC) sheet is one of the most commercial engineering polymers that is always demanded to cut by laser. This polymer is classified into the group of amorphous polymers and presents excellent heat resistance, good dimensional stability, high impact strength, and excellent transparency. Polycarbonate sheets are often employed as a protective cover around CO_2 laser work stations because it combines transparency with good resistance to ablation by reflected laser beams [4].

Powell in chapter 4 of his book [4] has completely discussed the CO_2 laser cutting of polymers. In laser cutting of polymers, depending on the kind of polymer three groups of the material removal mechanism can be observed: 1- Melt shearing e.g. polypropylene (PP), polystyrene (PS) and polyethylene (PE), 2- Vaporization e.g. polymethyl methacrylate (PMMA) or acrylic and polyoxymethylene (POM) or polyacetal, 3- Chemical degradation e.g. phenolic or epoxy resins, poly vinyl chloride (PVC) and polyurethane (PU). Polycarbonate (PC) is cut by a combined mechanism of melt shearing and chemical degradation and has a different cut surface quality. This cut surface combines the ripples associated with melt shearing and a yellowish discoloration due to the dissociation or thermal degradation. During laser cutting of PC, the light-yellow toxic fumes are given off through the cutting zone so an appropriate fume extraction is essential [4]. The reason for the combined melt removal mechanism in PC may be related to the proximity of the melting point (230 - 330 °C [8]) to the thermal degradation temperature (420 to 620 °C [9]). When a focused laser beam irradiates the surface of the PC sheet, a melting zone is formed as the material surface temperature reaches the melting point and simultaneously the shearing material removal mechanism partially begins. Further increase in the laser interaction time or laser power density causes the melt temperature to reach the thermal degradation point. This leads the material removal mechanism to chemical dissociation in combination with melt shearing. Haddadi et al. [10] experimentally investigated into CO_2 laser cutting of polystyrene and optimized the cutting parameters to minimize the HAZ and kerf width. They found that the cutting mechanism changes from melting to evaporation as the laser power increases. Dubey and Yadava [11, 12] by using Taguchi methodology showed that the material removal rate during pulsed mode Nd: YAG laser cutting of 0.9 mm thick 8011-H14 aluminum is mainly affected by the cutting speed but the kerf wall taper is only influenced by the pulse frequency. Multiple beam technology provides an efficient combination of high cutting speed and material removal rate with good cut quality. Müller et al. [13] divided a single solid-state mode laser beam into some beams by using a diffractive optical element and showed that in laser cutting of wafer yield by increasing the number of beams, the material removal rate per pass can be increased. The material removal process during laser ablation using pulsed CO_2 laser interaction with graphite fiber-reinforced composite was investigated by Iorio et al. [14]. They realized that the material removal process was imperfect when the laser power and pulse duration were low. They concluded that the transfer of energy from the beam to the sample was varied over a range of energy levels due to significant differences in the physical properties of the composite's constituents. Cenna and Mathew [15] theoretically analyzed the upper and lower kerf width, the kerf wall angle, material removal rate, and transmitted energy into the kerf in laser cutting of fibre reinforced polymers (FRPs). In their analysis, they assumed that the laser energy is absorbed through the entire cutting zone. Two complicated material removal processes may happen during laser cutting of FRP composites, direct laser ablation or combination of laser ablation and heat conduction. During pulsed laser cutting of FRP, the fibres were chopped into small pieces and then ejected layer by layer through the cutting zone. The direction of fibres in the matrix influence the number of pulses delivered on a fibre which results in different material removal rates [16]. Davari et al. [17] compared CO_2 laser cutting of Teflon and Teflon-bronze composite sheets. Their results showed that the upper kerf width for both materials was in the order of 0.5 mm for a beam diameter of 0.35 mm. However, a comparison between two employed materials indicated that the presence of bronze particles in the reinforced Teflon causes an increase in the lower kerf width. Al-Sulaiman et al. [18] experimentally and analytically studied the CO_2 laser cutting of carbon/carbon multi-lamelled plain-weave structure and reported that the kerf width increases with power and the orientation of the carbon fiber axis have a significant effect on the kerf size. Moradi et al [19] used a 60 W CO_2 laser machine to cut injection moulded polycarbonate workpiece. They found that the laser cutting quality increases when the focal point is located in the depth of cut. They also indicated that the lower kerf width decreases as the laser focal plane position and laser power reduce. In another research [20] they concluded that when CO_2 laser cutting of polycarbonate, the upper and lower kerf width increases by increasing gas pressure and focal point position.

The main aim of this research is to investigate the influence of power and maximum cutting speed on the material removal rate (MRR) and cutting volume efficiency (α_{Vol}) in CO_2 laser cutting of polycarbonate sheets. The results can be applied for a better understanding of the laser cutting process in terms of appropriate selection of cutting parameters and material removal rate and cutting volume efficiency perspective. Similar work has not been addressed in literature so far.

2. Experimental Procedure

2.1. Cutting Experiments

A CO_2 laser cutting machine was used in this research. This machine was manufactured by Crystal Sign Company with a maximum nominal power of 130 W. Some features of this machine derived from the manufacturer's catalog are presented in Table 1.

Table1. General features of applied laser cutting machine

Descriptions	Values
Model	EZ-Z1390
Manufacturer	Crystal Sign Co.
Max. Power	130 W
Max. Speed	24000 mm/min
CNC Table	2 axes
Work envelope	1300 × 900 mm
Lens Diameter	20 mm
Focal length	65 mm

A lens with a focal length of 65 mm was applied and a CO_2 laser beam in a continuous wave mode was focused on the top surface of the sheet. The focused beam diameter on the sheet surface was 0.1 mm. The periodic preventive maintenance (PM) operation had been performed on the employed laser cutting machine a few days before our tests and so it is to say that the lasing cavity and other optics were in an appropriate condition. Other laser cutting parameters are illustrated in Table 2.

According to the purpose of this research and to reduce as much as possible the direct loss of laser beam in the cutting zone, the maximum cutting speeds for a variety of powers and thicknesses under the same laser cutting condition were determined for commercial polycarbonate sheets. When laser cutting with maximum cutting speed, it can be assumed that the entire incident laser energy is absorbed through the entire cutting zone [21]. To find the maximum cutting speed for a given power, the cutting speed was gradually increased until the situation of cut-no cut happened. The highest speed, which a through cut occurred, was the maximum cutting speed.

Table2. Applied laser cutting parameters

Cutting parameters	values
Sheet thickness	2-8 mm
Power	20-100 W
Cutting speed	180-2100 mm/min
Focal point position	Top surface of sheet
Assistant gas	Air
Gas pressure	1 bar
Nozzle diameter	1 mm
Stand-off distance	1 mm
Focused beam diameter	0.1 mm

2.2. Material

Commercial polycarbonate sheets with thicknesses of 2 to 8 mm were used in this research. Polycarbonate (PC) is basically categorized in thermoplastic polymers and it contains carbonate groups in its chemical structure [22, 23]. PC can also be sorted as an engineering polymer and it is relatively a strong and tough material with high impact resistance, excellent heat resistance, and self-extinguishing but with low scratch resistance [8]. Although some grades of PC are optically transparent to the visible light, they strongly absorb CO_2 laser radiations with wavelength of 10.5 μm [4]. Some mechanical and chemical properties of the polycarbonate sheet are shown in Table 3.

Table3. Some properties of polycarbonate [8, 9, 24]

Properties	values
Density	0.00121 g/mm^3
Refractive index (n)	1.585
Tensile strength (σ_t)	65 MPa
Hardness (Rockwell M)	70
glass-transition temperature Tg	147 °C
Heat deflection temperature	140 °C (at 0.45 MPa)
Melting point	230 - 330 °C
Degradation temperature	420 - 620 °C
Melting heat	134 J/g
Heat of combustion	31300 J/g

In order to ensure that the sheet surface is free from any dust or contamination, the surface of the sheets was cleaned by a piece of cotton before cutting.

2.3. Kerf width measurement

An optical microscope with a magnification of 100X was employed to measure the kerf width. Due to acceleration and deceleration of the CNC table, the middle of the cut path, where the cutting speed is generally constant, was selected as a position to be considered by using the microscope. In order to ensure the accuracy of measurement, the kerf was measured in three points on the middle of each cut path as shown in Figure 1. Then, the average of three measured values was reported as the results of the kerf width.

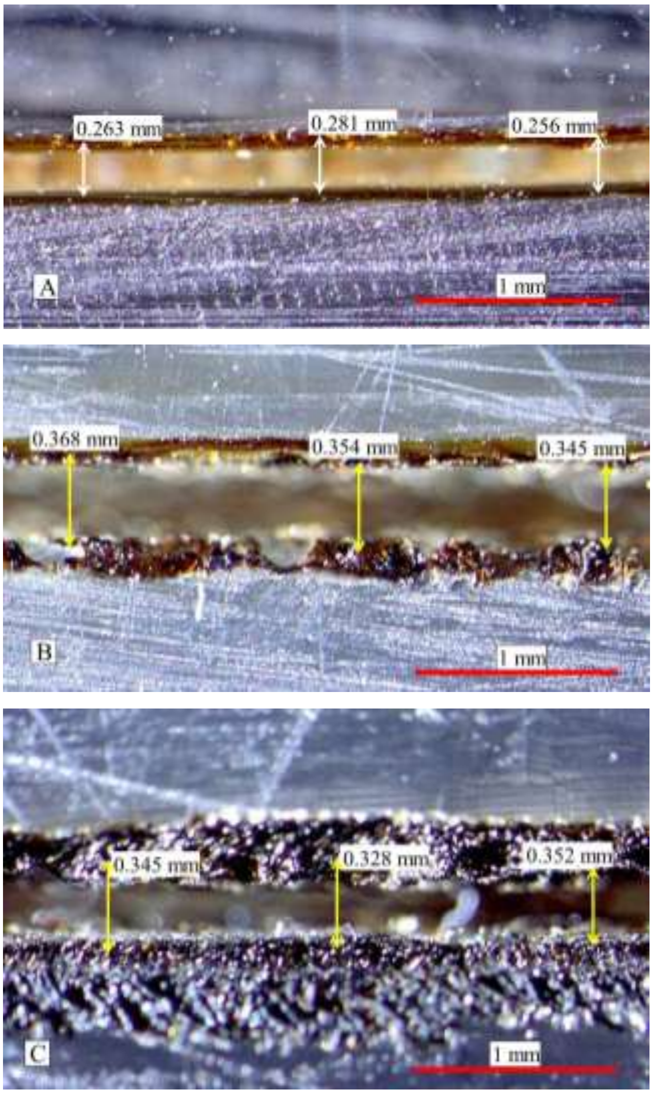

Figure1. Upper kerf width measurements at three points in the middle of the cut path where the cutting speed is steady. A) 2 mm thick, 45 W, 1200 mm/min. B) 6 mm thick, 45 W, 370 mm/min. C) 8 mm thick, 45 W, 300 mm/min. The dark zone surrounding the kerf is referring to HAZ and residual melt

3. Results and Discussion

3.1. Maximum Cutting Speed

In order to obtain results with acceptable accuracy, 76 cuts were totally performed in a day using the same environmental condition. This is well understood that the industrial cutting speed is generally less than the maximum cutting speed for any combination of laser-material. However, due to the purpose of this research, the maximum cutting speeds for various thicknesses of PC sheets were achieved experimentally using different powers. For a given power, when the cutting speed is at the highest value, it can be supposed that the amount of direct loss of incident laser energy is at the lowest value. Thus, it can be said that most of the laser energy input into the cutting front is consumed to melt and thermally decompose the material of workpiece. The employed combination of powers and maximum cutting speeds for a variety of PC sheet thicknesses is indicated in Table 4.

Table4. Maximum cutting speeds for a variety of powers and PC sheet thicknesses

2 mm		**3 mm**		**4 mm**		**6 mm**		**8 mm**	
Power (W)	Speed (mm/min)	Power (W)	Speed (mm/min)	Power (W)	Speed (mm/min)	Power (W)	Speed (mm/min)	Power (W)	Speed (mm/min)
20	180	25	360	30	420	35	280	30	180
25	300	30	540	35	540	40	320	35	240
30	540	35	660	40	600	45	370	40	270
35	720	40	780	45	660	50	402	45	300
40	1020	45	840	50	708	55	436	50	324
45	1200	50	900	55	744	60	464	55	348
50	1380	55	960	60	780	65	478	60	378
55	1500	60	1020	65	804	70	490	65	390
60	1650	65	1068	75	834	75	502	70	402
65	1720	70	1110	80	852	80	508	75	414
70	1790	75	1140	85	870	85	514	80	426
75	1850	80	1152	90	876	90	520	85	432
80	1910	85	1200	95	882	95	526	90	435
85	1950	90	1218	100	885	100	540	95	438
90	2020	95	1224	-	-	-	-	100	445
95	2060	100	1230	-	-	-	-	-	-
100	2100	-	-	-	-	-	-	-	-

Figure 2 and Figure 3 have been obtained using the results of Table 4. Figure 2 illustrates that in the range of employed laser conditions, how the maximum cutting speed changes with increasing power. As is seen in Figure 2, for a given thickness and regarding the cutting conditions, the maximum cutting speed enhances with power approximately in a logarithmic trend. This enhancement is because of this fact that as the laser power increases, the incoming energy to the cutting front becomes larger and the laser energy penetration is accelerated thus the cutting speed must be increased to maintain the cutting efficiency. The cutting speed must strike up a balance between the consumption of laser energy and any enlargement in the laser penetration.

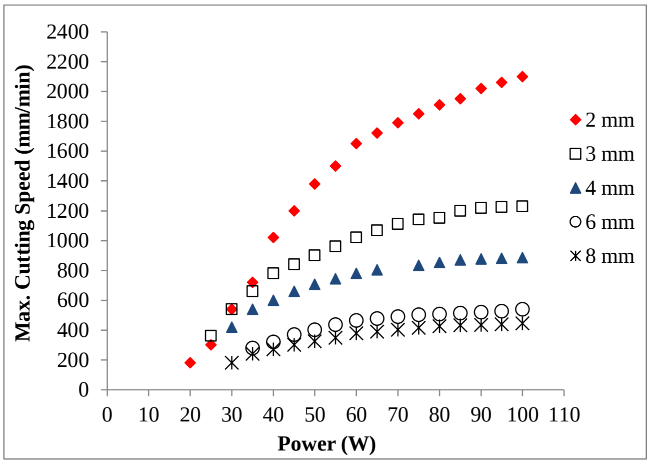

Figure2. Maximum cutting speed versus laser power for a variety of applied polycarbonate sheet thicknesses

The results from Figure 2 also show that the maximum cutting speed, overall, decreases with increasing PC sheet thickness. This is because, when the thickness of the sheet is increased, the interaction time between the laser beam and cutting front has to be enhanced to complete laser penetration; then the cutting speed must be decreased.

Figure 3 shows that for a given power, the cutting speed decrease with increasing sheet thickness. Using the results of Figure 3, it can be derived that the equation of cutting speed in terms of sheet thickness and power is as an exponential function. The equation can be written as follows [4]:

$$V = PQT^{-B} \qquad (1)$$

Where, V is the maximum cutting speed (mm/min), P is incident laser power (W), T is sheet thickness (mm), Q is a constant value that experimentally derived from the laser cutting of polycarbonate sheets using a particular laser-focusing optics combination. B is also a constant amount achieved in laser cutting of polycarbonate sheets.

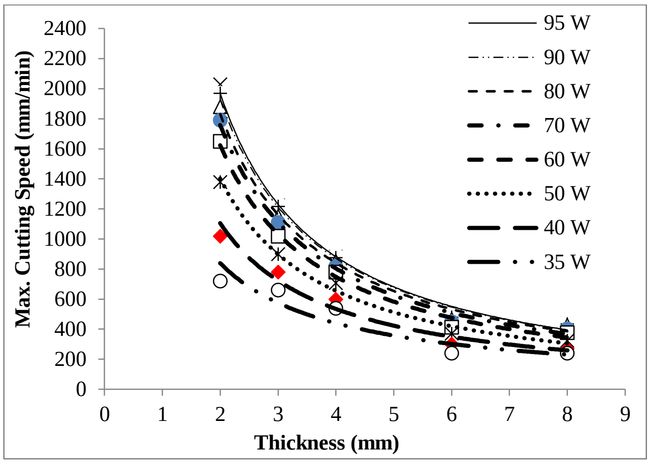

Figure3. Experimental maximum cutting speed versus sheet thickness for a variety of employed laser powers.

Using the results of experiments, some relevant numerical values of P, Q, and B to obtain a formula for maximum cutting speed in laser cutting of polycarbonate sheets are presented in Table 5.

Table5. Experimental values for P, Q, and B in laser cutting of polycarbonate sheet

P (W)	Q	B
35	43.95	0.881
40	56.14	1.026
50	58.81	1.072
60	57.10	1.082
70	56.8	1.107
80	47.05	1.102
90	47.75	1.136
95	46.05	1.142
Average	51.7	1.07

Using the values of Table 5 and in the range of employed laser cutting parameters, the equation of maximum cutting speed for laser cutting of polycarbonate sheets can be derived as follows:

$$V = 51.7\,P\,T^{-1.07} \quad , \quad \left\{\frac{mm}{min}\right\} \qquad (2)$$

Two points can be realised from this equation. First, the cutting speed is proportional to the laser power and sheet thickness. Second, the exponential curves of cutting speed versus material thickness have the same shape for most polymers e.g. polypropylene [4]. Figure 4, which has been achieved from Equation (2), shows the theoretical cutting speed versus polycarbonate sheet thickness for different applied powers. A comparison between Figure 3 and Figure 4 reveals that the discrepancy between theoretical and experimental cutting speed is in the range of -11% to 15.5%.

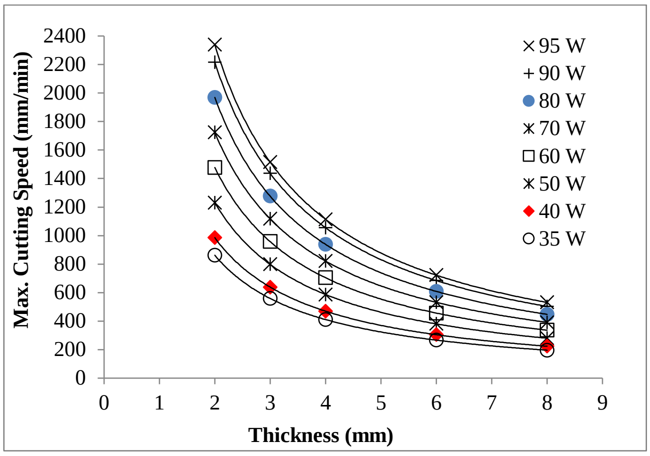

Figure4. Showing theoretical maximum cutting speed versus thickness for a variety of applied powers. Results come from Equation (2)

3.2. Kerf Width

The amounts of kerf width are fundamentally required to calculate the values of material removal, so, the upper and lower kerf widths for all applied sheet thicknesses and powers were observed. Examples of the kerf width results are illustrated in Figure 5 to Figure 8. These figures show the results of upper and lower kerf width measurement as a function of laser power and maximum cutting speed in laser cutting of 2- and 8-mm thick polycarbonate sheets. The results of kerf width measurements indicate that for a given thickness, with an increase in the power and cutting speed, overall, the upper and lower kerf width is almost constant just with some variations. As can be seen in Figure 5 and Figure 6 for a thickness of 2 mm, generally, the upper and lower kerf widths are in the order of 0.24 mm and 0.18 mm respectively. These values for an 8 mm thick sheet (Figure. 7 and Figure 8) are in the order of 0.34 mm and 0.20 mm.

The average kerf widths for all the samples involved in the trials are presented in Figure 9. It should be mentioned that, in the range of used laser conditions and with different cutting speeds and powers and for all applied thicknesses, the results in Figure 9 indicate that the upper kerf width is 1.3 to 1.7 times (1.5 in average) wider than the lower kerf width. Figure 9 also shows that as the sheet thickness increases, the average of upper and lower kerf widths almost widens, however, as seen, there is a slight decrease in the kerf widths when the thickness changes from 6 to 8 mm. This might imply that depending on the laser machine properties (maximum power, speed, optics, and gas pressure), the kerf width widens with increasing sheet thickness up to a certain threshold. It must be emphasized that the average kerf width is significantly wider than the focused beam diameter. To learn about the reason(s) for this significant enlargement in the kerf width, a deep study in the mechanism of kerf width widening is essential.

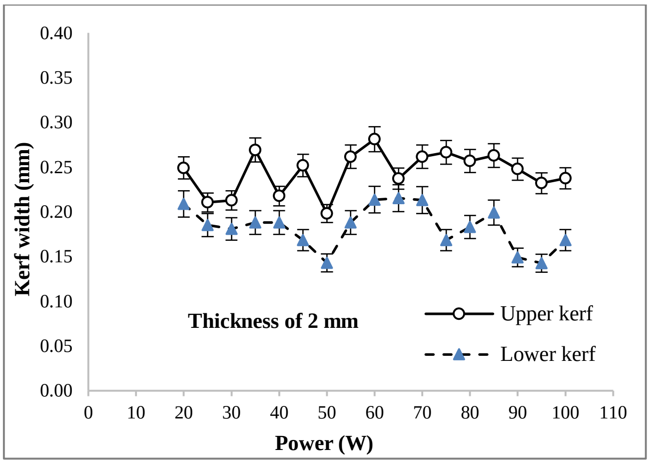

Figure5. Upper and lower kerf width of 2 mm-thick sheets as a function of laser power

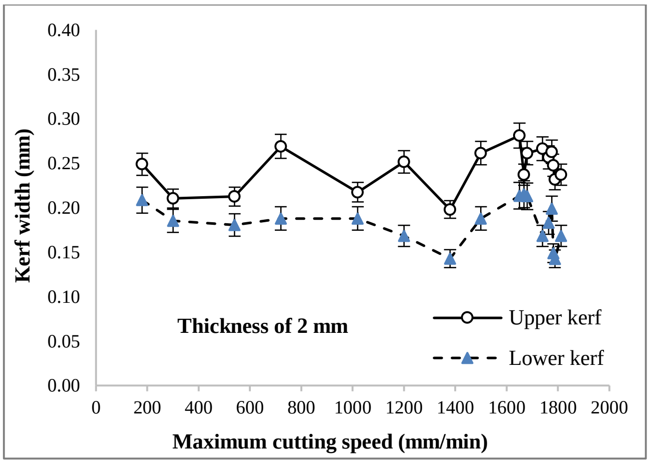

Figure6. Upper and lower kerf width of 2 mm-thick sheets versus maximum cutting speed

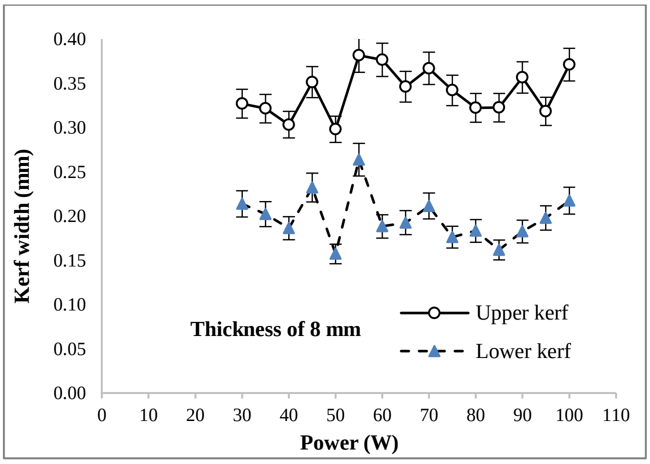

Figure7. Upper and lower kerf width of 8 mm-thick sheets as a function of laser power

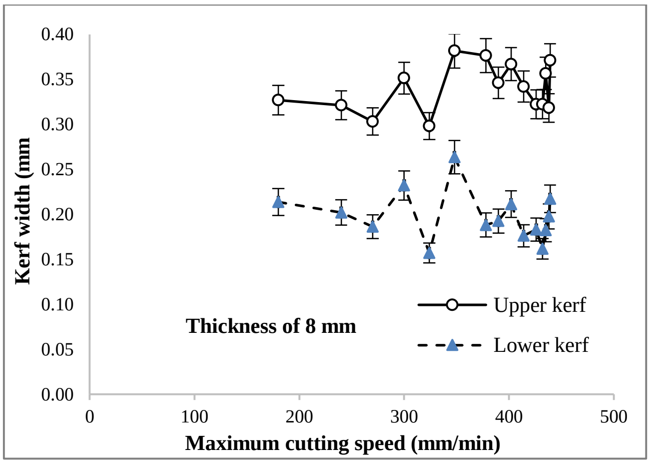

Figure8. Upper and lower kerf width of 8 mm-thick sheets versus maximum cutting speed

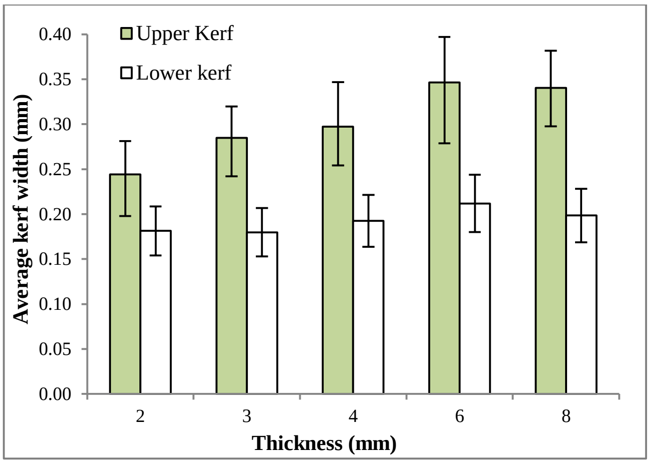

Figure9. The average upper and lower kerf width versus sheet thickness. The focused beam diameter was 0.1 mm

For a given power, the maximum cutting speed proportionally reduces with an increase in the sheet thickness (see Figure 3). As the maximum cutting speed decreases, the interaction time between the laser beam and polycarbonate molecules raises so the laser beam has more time to melt and decompose the molecules of polycarbonate. Any increase in the interaction time causes the lateral heat conduction to expand beyond the laser beam diameter. Hence, excessive melting and thermal dissociation of the polycarbonate molecules happens which brings about the widening of the kerf. Furthermore, the increasing tendency of the kerf width could be explained by the fact that a wider kerf is necessary for material removal in a thicker sheet. The wider kerf can provide more space for the enlarging of fume and possible plasma generated in the laser degradation process. This in turn, will result in more incident laser energy reaching the material and leads to a more efficient material removal rate. It is well understood that the melt flow behaviour and melt thermal condition in combination with the spatial distribution of the laser beam in the cutting zone also affect the kerf width widening [17].

Besides, for laser cutting of a thick sheet, more material is melted and decomposed in comparison with a thinner sheet; and the micrographs of the kerfs in Figure 1 indicate that the residual melt on the cut edge for a thicker sheet is more than that for a thinner sheet. These phenomena will make the heat-affected zone deeper for thick material as a result of heat conduction. Thicker residual melt on the cut edge can also restrict the kerf width widening for thicker sheets as it is seen in Figure 9.

3.3 Material Removal Rate and cutting volume efficiency

The material removal rate (MRR) is the volume of material that is removed from the kerf at the time that the laser beam moves a distance of its diameter. The material removal rate, in CO_2 laser cutting of PC sheets, is influenced by some well-known parameters, e.g. laser power, cutting speed, assist gas condition and beam diameter. The volume of removed material can be calculated by measuring the upper and lower kerf width. According to the results of kerf width measurements, the cross-section of cut kerf can simply be similar to a trapezoid in which the bigger width is located on the upper surface of the sheet and the smaller width is positioned on the lower surface as shown in Figure 10.

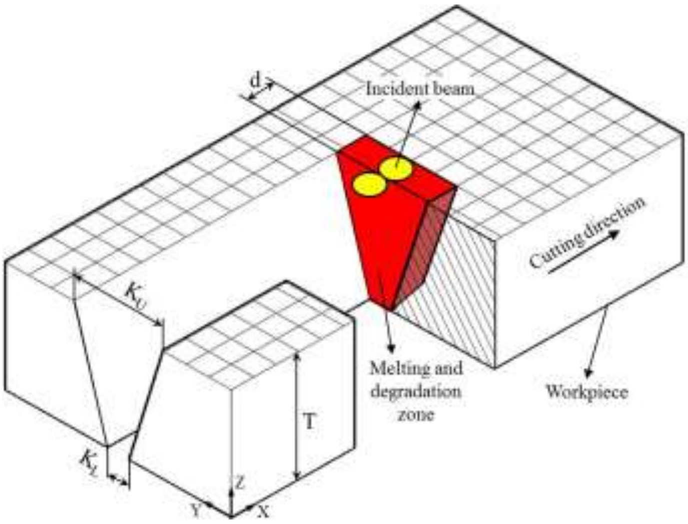

Figure10. Schematic interaction of the laser beam with workpiece in laser cutting as the laser beam moves a distance of its diameter. The cross-section of cut kerf simply can be similar to a trapezoid. The volume of removed material is then similar to a trapezoidal prism

The volume of removed material in this figure is indicated as a trapezoidal prism. The equation to calculate the volume of removed material (MR_V) is:

$$\mathrm{MR}_V = \left(\frac{K_U + K_L}{2}\right) \times T \times d \quad , \quad \{mm^3\} \qquad (3)$$

Where, K_U and K_L are the upper and lower kerf width respectively (mm), T is the sheet thickness (mm) and d is the focused beam diameter (mm).

The MRR can be calculated as follows:

$$MRR = \frac{MR_V}{t} = \left(\frac{K_U + K_L}{2}\right) \times T \times \frac{d}{t} = \left(\frac{K_U + K_L}{2}\right) \times T \times V = A_K \times V \quad , \quad \left\{\frac{mm^3}{sec}\right\} \qquad (4)$$

Where, t (sec) is the interaction time, V is the cutting speed (mm/s) and A_K is the cross-section area of the kerf (mm^2). The interaction time is the time that the focused laser beam moves a distance of its diameter ($t=d/V$).

From this point towards the end of this research, some equations are derived from the experimental results. These equations are only used to help us to describe the physics of the laser cutting process. We strongly emphasize that the form of these equations may vary from experiment to experiment.

Regarding Equation 4 and for a given thickness, MRR is enhanced as the cutting speed and/or the cross-section area of the kerf (A_K) increases. In the range of employed laser parameters, the results of CO_2 laser cutting of polycarbonate sheets indicate that the material removal rate (MRR) increases with power as shown in Figure 11. The results of experiments show that the kerf widths (Figure 5 to Figure 8) and so the cross-section areas of the kerfs (A_K) are almost constant with increasing power. Therefore, and as the experimental results confirm (Figure 2), the main reason for the enhancement of MRR with power is that, when the laser power increases, the maximum cutting speed relatively rises to maintain the equilibrium of the energy.

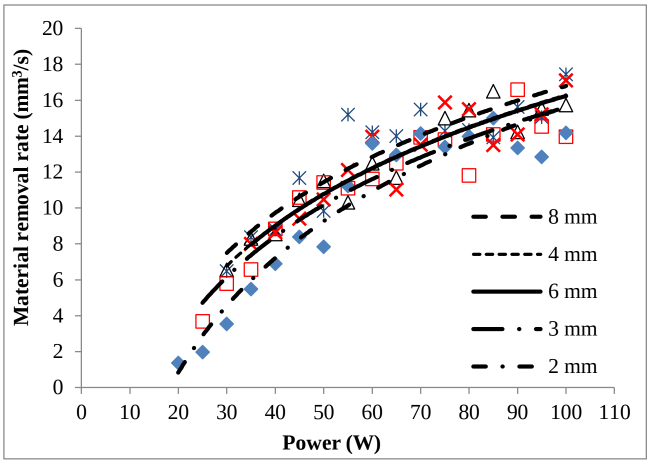

Figure11. Experimental results of material removal rate (MRR) as a function of laser power for all used sheet thicknesses

A logarithmic equation can be derived from Figure 11 as *MRR=F×Ln(P)-C*. In this equation, *P* is the laser power (W), *F* and *C* are the values that experimentally derived from the laser cutting of polycarbonate sheets using a particular laser-focusing optics combination. Considering all results and in the range of employed laser conditions with different maximum cutting speeds and different powers and for all used polycarbonate thicknesses, the average values *F* and *C* for are 8.5 and 21.84 respectively. Hence, the equation of MRR in laser cutting of polycarbonate sheet can be derived as follows:

$$MRR = 8.5 \ln P - 22.84 \quad , \quad \left\{\frac{mm^3}{sec}\right\} \tag{5}$$

According to Equation 5, two points can be noted. First, the material removal rate logarithmically changes with incident laser power. Second, *F* and *C* are obtained experimentally, so some laser cutting conditions e.g. power, cutting speed, laser-focusing optics combination, assist gas kind and pressure, stand of distance and material properties can influence the amount of *F* and *C*. These values are likely related to the cutting volume efficiency.

Study on the MRR can also help us to investigate the cutting efficiency in detail. The cutting volume efficiency can be calculated using the following equation:

$$\alpha_{Vol} = \frac{\left(\frac{K_U+K_L}{2}\right)\times T\times V}{P} = \frac{MRR}{P} \quad , \quad \left\{\frac{mm^3}{J}\right\} \tag{6}$$

The cutting volume efficiency (α_{Vol}) as a function of power for all employed sheet thicknesses is indicated in Figure 12. As can be seen, for all thicknesses and in the range of applied cutting parameters, the α_{Vol} increases with increasing power until it achieves an apex, then it slightly decreases as the power increases.

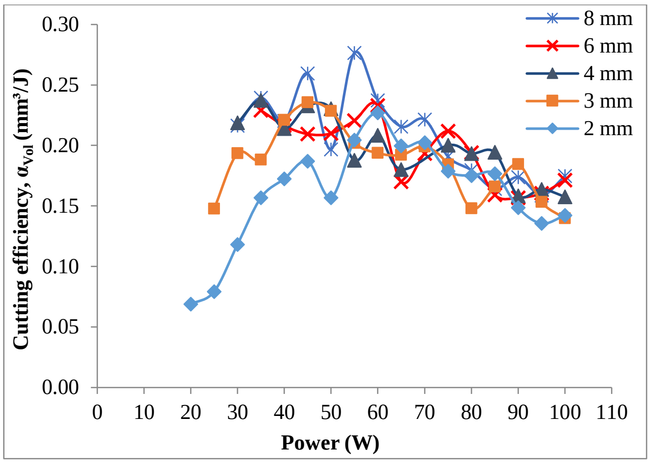

Figure12. Cutting volume efficiency versus power for a variety of sheet thickness

By using Equation 5 in Equation 6, the cutting volume efficiency (α_{Vol}) can be calculated as follows:

$$\alpha_{Vol} = \frac{8.5 \ln P - 22.84}{P} \quad , \quad \left\{\frac{mm^3}{J}\right\} \tag{7}$$

Regarding Equation 5 and Equation 7, a comparison between cutting volume efficiency and MRR as a function of power is shown in Figure 13. It can be seen that in the range of applied laser cutting parameters and for all employed sheet thicknesses, the MRR is enhanced with increasing power, whilst, the cutting volume efficiency (α_{Vol}) increases with power until it reaches the apex of efficiency (0.213 mm^3/J) in the power of 40 W. Then, the cutting efficiency slightly reduces with increasing power.

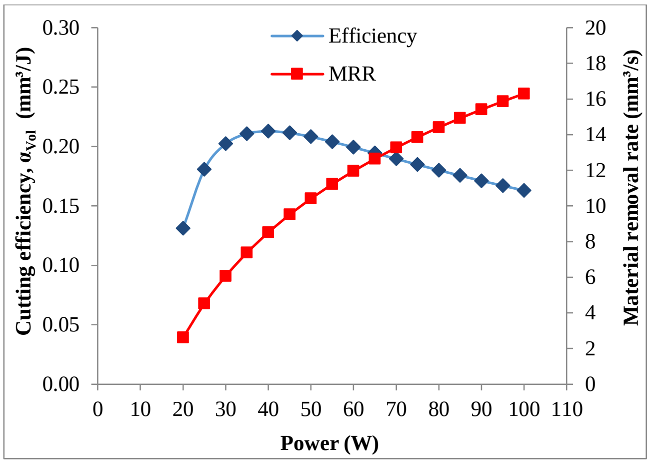

Figure13. Comparison between cutting volume efficiency (Equation 7) and MRR (Equation 5) versus laser power

A possible reason for the reduction of cutting volume efficiency can be related to the melt removal condition. Incompetent melt removal condition in laser cutting is solely due to insufficient assist gas pressure [4]. An insufficient melt removal condition causes a re-solidified melt attached to the bottom of the kerf, resulting in an incomplete cut. In this situation and due to the purpose of this research, the maximum cutting speed, for a given power, is decreased to make a through cut. This reduction in the maximum cutting speed mildly bends MRR graph and slightly decreases the α_{Vol} with increasing power.

Another possible reason for the reduction of cutting volume efficiency could be due to the attenuation of laser beam energy in the cutting zone. As it is already mentioned, Polycarbonate is cut by a combined mechanism of melt shearing and chemical degradation [4]. The presence of polymeric vapour in the cutting front may absorb a part of laser beam energy decreasing the incident laser power. In this case, the laser power must be increased for a given maximum cutting speed or the maximum cutting speed must be decreased for a given power which brings about a decrease in the cutting volume efficiency.

A comparison between cutting volume efficiency (α_{Vol}) and material removal rate (MRR) as a function of sheet thickness is indicated in Figure 14. As seen, in the range of employed polycarbonate sheet thicknesses and laser cutting parameters, MRR and α_{Vol} have almost the same trend versus sheet thickness. Both of them rise as the thickness increases to 4 mm then they are almost constant with increasing thickness.

It seems that the combination of incident power, maximum cutting speed, and melt removal situation is a reasonable principle cause for this trend. A deep study is essential to find out more about how a combination of power, speed and melt removal influences MRR and α_{Vol}. For this purpose, a study on the cross-section area of the kerf is necessary.

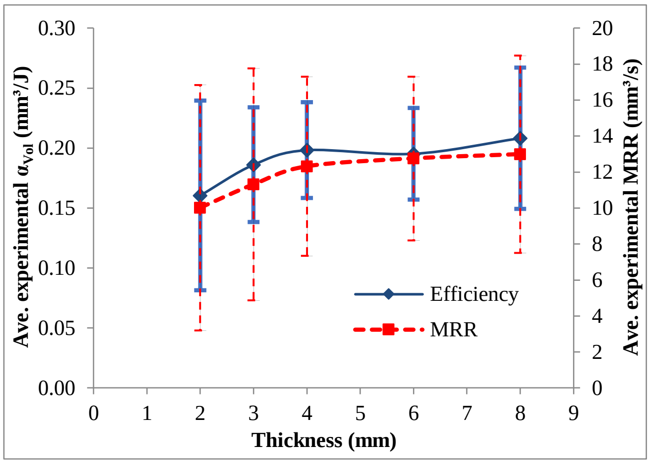

Figure14. Comparison between average experimental cutting volume efficiency (α_{Vol}) and MRR versus sheet thickness; Error bars obtained from experimental values.

Using the results of kerf width measurements, Figure 15 shows that the cross-section area of the kerf increases with thickness. As shown in Figure 15, the average cross-section area of the kerf can be calculated using the following equation:

$$A_K = 0.189\, T^{1.191} \quad , \quad \{mm^2\} \tag{8}$$

A comparison between Figure 15 and Figure 9 indicates that the expansion of A_K in a thickness of 6 mm and 8 mm should be solely due to the enlargement of the thickness because the kerf widths are almost constant in these thicknesses. In this research, the MRR and α_{Vol} remained almost constant when laser cutting the thickness of 6 and 8 mm. Although the A_K enlarges in these thicknesses, the MRR and α_{Vol} are approximately constant. This is because:

- For a given power, as the thickness increases, the maximum cutting speed decreases to maintain a sufficient melt removal condition (Figures 3 and 4).
- For a given maximum cutting speed, as the thickness increases, the laser power must be raised to sustain the cutting efficiency and maintain a competent melt removal condition (Figures 3 and 4).

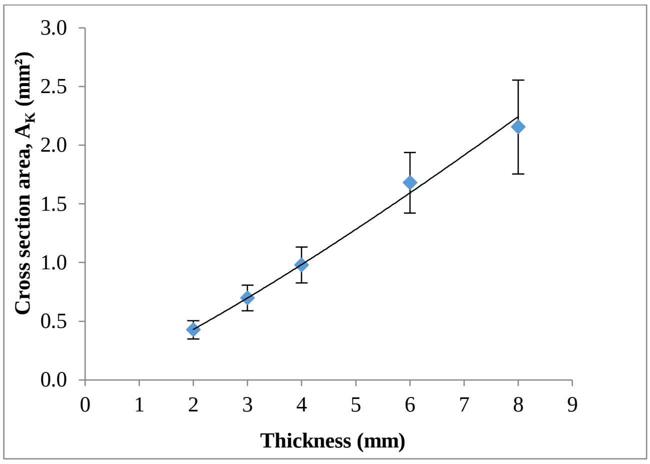

Figure15. Average experimental cross-section area of the kerf against sheet thickness. Error bars obtained from experimental values.

Using Equation 8 in Equation 4 we have:

$$MRR = (0.189\, T^{1.191}) \times V \qquad (9)$$

With using Equation 9 and Equation 2, another formula can be obtained for MRR as follows:

$$MRR = A_K \times V = 0.189\, T^{1.191} \times \frac{51.7\, P\, T^{-1.07}}{60} = 0.163\, PT^{0.121} \quad , \quad \left\{\frac{mm^3}{sec}\right\} \qquad (10)$$

In Equation 10, MRR is a function of power and thickness. With using this equation, the cutting volume efficiency is:

$$\alpha_{Vol} = 0.163 \times T^{0.121} \quad , \quad \left\{\frac{mm^3}{J}\right\} \qquad (11)$$

A comparison between Equation 11 and experimental α_{Vol} is indicated in Figure 16. As can be seen, the cutting volume efficiency almost tends to be constant as thickness increases from 6 to 8 mm.

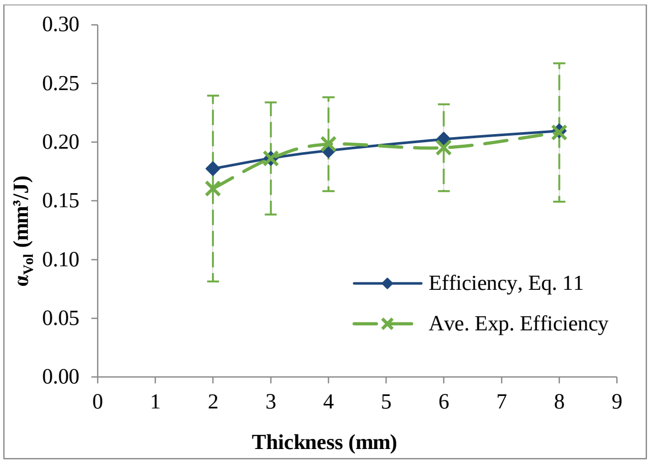

Figure16. Cutting volume efficiency versus sheet thickness; Error bars obtained from experimental values.

Till now, three equations (Equations 4, 5 and 9) have been deduced for MRR. Equation 4 is a base formula for MRR. In Equation 5, MRR is proportional to power while in Equation 9, MRR is related to thickness and maximum cutting speed. Using Equations 5 and 9, a formula for maximum cutting speed can be arranged as follows:

$$MRR_{Eq.5} = MRR_{Eq.9}$$

$$8.5\ \ln P - 21.84 = (0.189\, T^{1.191}) \times V$$

$$V = \frac{8.5 \ln P - 22.84}{0.189\, T^{1.191}} \quad , \quad \left\{\frac{mm}{sec}\right\} \qquad (12)$$

From Equation 12, the relation between maximum cutting speed and MRR in the range of employed laser parameters can be described by the following simple equation:

$$V = 5.29 \times MRR \times T^{-1.191} \quad , \quad \left\{\frac{mm}{sec}\right\} \qquad (13)$$

Equation 13 can be rearranged for MRR as follows:

$$MRR = \frac{V}{5.29} \times T^{1.191} \quad , \quad \left\{\frac{mm^3}{sec}\right\} \qquad (14)$$

Then, the cutting volume efficiency (α_{Vol}) can be calculated as:

$$\alpha_{Vol} = \frac{V \times T^{1.191}}{5.29 \times P} \quad , \quad \left\{\frac{mm^3}{J}\right\} \qquad (15)$$

To summarize to this point, three equations have been developed for cutting volume efficiency (α_{Vol}). Equation 6 is a base formula for α_{Vol}. In Equation 7, cutting volume efficiency is proportional to power while α_{Vol} in Equation 15 is related to the maximum cutting speed, thickness, and power. Figures 17 to 19 illustrate a comparison between experimental and estimated α_{Vol} (Equation 15) for thicknesses of 2, 4 and 8 mm respectively. As seen in Figure 17 to Figure 19, the theoretical cutting volume efficiency (α_{Vol}) has a good correlation with the experimental results.

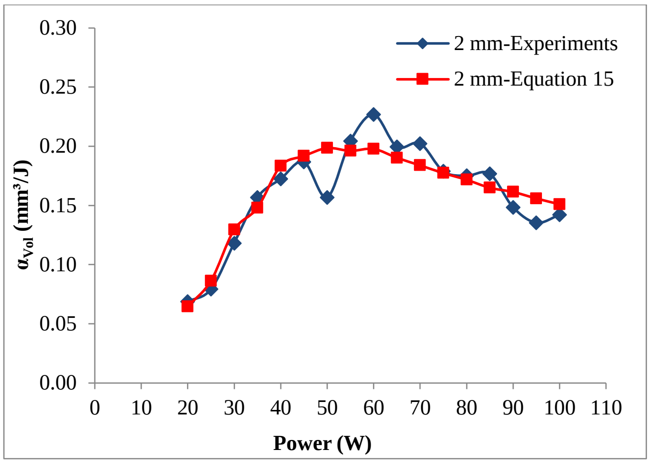

Figure17. Cutting volume efficiency versus power for the thickness of 2 mm

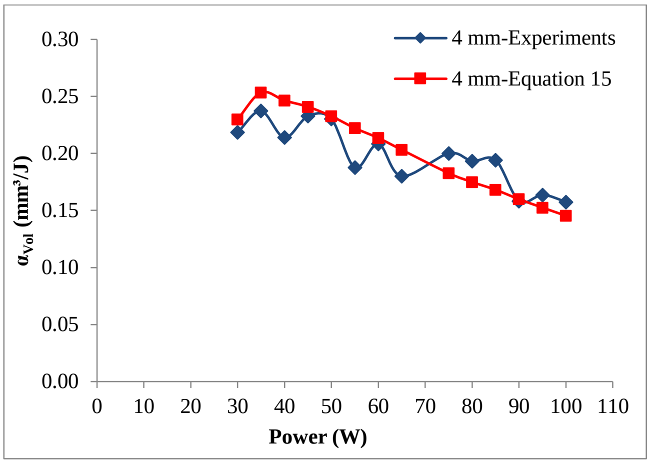

Figure18. Cutting volume efficiency versus power for the thickness of 4 mm

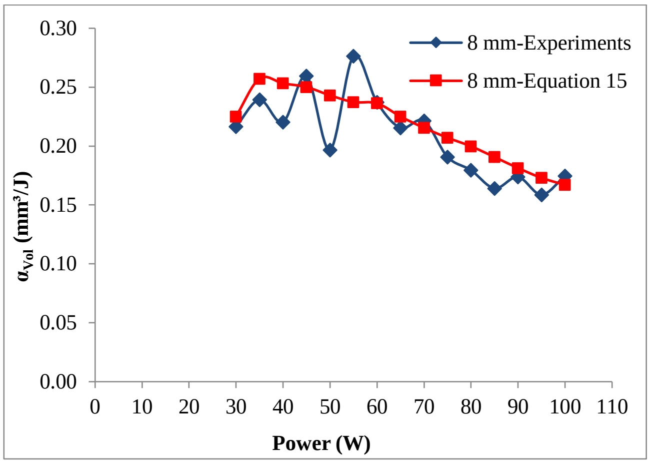

Figure19. Cutting volume efficiency versus power for the thickness of 8 mm

4. Conclusion

In the range of applied laser cutting conditions, parameters and CO_2 machine properties for cutting of polycarbonate sheet, some results can be concluded as below:

1. For a given thickness, overall, as the maximum cutting speed increases, the kerf width is almost maintained steady just with a variation.

2. The upper kerf width approximately 1.5 times wider than the lower kerf.
3. The experimental results show that, for a given power, the cutting speed exponentially decreases with increasing sheet thickness.
4. The experimental results of the material removal rate (MRR) increase logarithmically with power.
5. The experimental results of material removal rate (MRR) rise as the thickness increases to 4 mm then the MRR remains constant with increasing thickness.
6. The results of laser cutting tests show that the cutting volume efficiency (α_{Vol}) increases with power until it reaches the apex of efficiency then, it slightly reduces with increasing power.
7. Overall, the experimental results of cutting volume efficiency (α_{Vol}) indicate that the α_{Vol} slightly increases as the thickness increases from 2 to 6 mm then it is almost kept constant as the thickness increases from 6 to 8 mm.

5. References

[1] Riveiro, A., Quintero, F., Lusquiños, F., del Val, J., Comesaña, R., Boutinguiza, M. and Pou, J. 2012. Experimental study on the CO_2 laser cutting of carbon fiber reinforced plastic composite. Composites Part A: Applied Science and Manufacturing. 43(8), 1400–1409.

[2] Caiazzo, F., Curcio, F., Daurelio, G. and Minutolo, F. M. C. 2005 Laser cutting of different polymeric plastics (PE, PP and PC) by a CO2 laser beam, J. Mater. Process. Technol. 159(3):279–285.

[3] Steen, W. M. 1991. Laser Material Processing. Springer.

[4] Powell, J. 1998. CO2 laser cutting, Second edition, Springer, London.

[5] Davim, J. P., Barricas, N., Conceição, M. and Oliveira, C. 2008. Some experimental studies on CO2 laser cutting quality of polymeric materials. J. Mater. Process. Technol.198(1–3):99–104.

[6] Kurt, M., Kaynak, Y., Bagci, E., Demirer, H. and Kurt, M. 2009. Dimensional analyses and surface quality of the laser cutting process for engineering plastics, Int. J. Adv. Manuf. Technol. 41(3–4):259–267.

[7] Caiazzo, F., Curcio, F., Daurelio, G. and Minutolo, F. M. C. 2005. Laser cutting of different polymeric plastics (PE, PP and PC) by a CO2 laser beam, J. Mater. Process. Technol.159(3):279–285.

[8] Schwartz, S. S. and Goodman, S. H. 1982. Plastic Materials and Processes, Van Norstrand Retnhold.

[9] Vogel, C., Mueller, A., Lehmann, D. and Taeger, F., 2012. Characterization of the Burning Behaviour of Plastics by a New Method. Open Journal of Polymer Chemistry.2(2):86-90.

[10] Haddadi, E., Moradi, M., Karimzad Ghavidel, A., Karimzad Ghavidel, A. and Meiabadi, S. 2019. Experimental and Parametric Evaluation of Cut Quality Characteristics in CO2 Laser Cutting of Polystyrene. Optik. 184:103-114.

[11] Dubey, A. and Yadava, V. 2008. Robust parameter design and multi-objective optimization of laser beam cutting for aluminium alloy sheet. The International Journal of Advanced Manufacturing Technology. 38: 268–277.

[12] Dubey, A. K. and Yadava, V. 2008 Optimization of kerf quality during pulsed laser cutting of aluminium alloy sheet. Journal of Materials Processing Technology. 204:412–418.

[13] Müller, M. C. R., Hendriks R. and Chall, H P. 2006. Significant step in wafer yield optimization and operation cost reduction due to dicing innovation. Proceedings on The International Conference on Compound Semiconductor Manufacturing Technology, CS ManTeCH Conference. Vancouver, Canada. pp 141–144.

[14] DeIorio, I., DiIlio, A. and Tagliaferri, V. 1987. Cut edge quality of GFRP by pulsed laser-material interaction analysis. Proceedings of LAMP, high Temperature Society of Japan. 279–284.

[15] Cenna, A.A. and Mathew, P. 1997. Evaluation of cut quality of fibre reinforced plastics –a review. International Journal of Machine Tools and Manufacture. 37(6):723–736.

[16] Lawrence, J., Pou, J., Low, D. K. Y. and Toyserkani, E. 2010. Advances in laser materials processing, Woodhead Publishing.

[17] Davari, M. and Hashemzadeh, M. 2018. The effect of bronze particles on CO2 laser cutting of reinforced polytetrafluoroethylene. Int J Adv Manuf Technol. 96:4029–4039.

[18] Al-Sulaiman, F.A., Yilbas, B.S. and Ahsan, M. 2006. CO2 laser cutting of a carbon/carbon multi-lamelled plain-weave structure. J Mater Process Technol. 173(3):345–351.

[19] Moradi, M., Mehrabi, O., Azdast, T. and Benyounis, K.Y., 2017. Enhancement of low power CO2 laser cutting process for injection molded polycarbonate. Optics & Laser Technology. 96: 208–218.

[20] Moradi, M., Mehrabi, O., Azdast, T. and Benyounis, K.Y. 2017. The effect of low power CO2 laser cutting process parameters on polycarbonate cut quality produced by injection molding. Modares Mechanical Engineering. 17(2):93-100.

[21] Hashemzadeh, M., Suder, W., Williams, S., Powell, J., Kaplan, A.F.H., Voisey, K.T. 2014. The Application of Specific Point Energy Analysis to Laser Cutting with 1µm Laser Radiation. Physics Procedia. 56:909-918.

[22] Brydson, J. A. 1989. Plastic Materials, Fifth edition. Butterworth.

[23] Campo, E. A. 2006. The Complete Part Design Handbook for Injection Molding of Thermoplastics, Hanser.

[24] Walter, R. N., Hackett, S. M. and Lyon, R. E. 2000. Heats of combustion of high temperature polymers, Fire and Materials, Volume 24, Issue 5, pp 245-252.