The Effect of Power, Maximum Cutting Speed and Specific Point Energy on the Material Rremoval Rate and Cutting Volume Efficiency in CO_2 Laser Cutting of Polyamide Sheets

Majid Hashemzadeh[1*], Reza Pourshaban[1]
[1]Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran
*Email of Corresponding Author: mahashemzadeh@yahoo.com
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Abstract
Material removal rate (MRR) and cutting volume efficiency (α_{Vol}) in laser cutting of commercial polyamide (Nylon) sheets have been studied in this research. A CO_2 laser cutting machine with the power of 100 W was used to cut polyamide (PA) sheets with thicknesses of 2 to 8 mm. The beam spot size on the upper surface of the sheet was 0.1 mm. The maximum cutting speeds for a variety of powers and thicknesses were specified under the same other laser cutting parameters. The specific point energy (Esp) was calculated for every combination of maximum cutting speed and power. Results show that for a given power, the maximum cutting speed exponentially decreases with increasing sheet thickness. The MRR increases logarithmically with power and for a given power, it rises as the sheet thickness decreases. The α_{Vol} increases with power until it reaches the apex of efficiency, then it slightly reduces with increasing power. Overall, the α_{Vol} decreases with increasing sheet thickness and Esp.

Keywords
CO_2 Laser Cutting, Polyamide (PA), Material Removal Rate, Kerf Width

1. Introduction

In laser cutting, a laser beam is focused on the surface of the sheet, and the energy of the laser is absorbed by the material according to the Fresnel absorption [1]. The absorption of laser beam energy brings about heating in a very thin surface layer of the sheet. The temperature of a small zone of the material rapidly rises to the melting point if the power intensity and irradiation time are adequate [2]. Then, the volume of the melting zone rapidly enlarges in depth and width as the laser beam more penetrates the molten material [3]. Meanwhile, the assist gas pressure causes an upward melt flow along the wall of the hole. As the laser irradiation continues and depending on the laser energy density, the laser beam can decompose the molecular bond and so the material evaporation begins. Since the laser beam melts the lower surface of the sheet, due to the gas pressure the direction of melt flow is changed to downward, and melt ejection occurs through the bottom of the sheet resulting in breakthrough [3]. After a breakthrough, the cutting process will start if the laser beam or the workpiece (CNC table) moves at an appropriate speed [4, 5]. During laser cutting, the surface of the cut front is irradiated by the laser beam, and a thin layer of the melt is formed on this surface. Simultaneously, the melted layer flows downward on the cut front and it is pushed out from the bottom of the cut zone by assist gas pressure. It has been verified that depending on the cutting speed, the cut front inclines and kinks during laser cutting [6, 7] and so, the loss of laser beam energy becomes less when the cutting speed increases to the maximum cutting speed [8, 9].

The mechanism of melting and melt removal depends on the material properties, optical considerations, laser beam conditions, and cutting parameters. The material removal mechanism in laser cutting of polymers is segregated into three groups: 1- Melt shearing e.g. polyamide (PA), 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, polyvinyl chloride (PVC) and polyurethane (PU) [10]. In laser cutting of most thermoplastics e.g. polyamide (nylon), depending on the cutting parameters and the surface tension of the melted polymer, the assist gas is unable to remove all the liquid polymer from the cutting zone, and always a thin layer is left on the surface of kerf wall. The melted polymer leaves the cut zone as droplets and/or tiny strings. These droplets or tiny strings sometimes remain attached to the lower edge of the kerf. However, these residual and re-solidified filaments are almost fragile and in some cases, they may need removal from the lower edge of the kerf by scraping [10].

In an experimental investigation on CO_2 laser cutting of polystyrene, Haddadi et al. [11] optimized the cutting parameters to minimize the HAZ and kerf width. They resulted that when the laser power rises, the cutting mechanism alters from melting to evaporation. Zhai et al. [12] experimentally compared 1064 nm nanosecond and 800 nm femtosecond pulsed laser cutting of polyamide rods in air. They found that femtosecond laser cutting had better cut quality and achieved non-thermal processing of PA. Moreover, in femtosecond laser cutting, the higher cutting speed can reduce the roughness of the cut surface and can improve the quality of cut surface morphology. Riveiro et al. [13] experimentally studied on the continuous and pulsed mode CO_2 laser cutting of 3 mm-thick carbon fiber reinforced (CFRP) plastic composite sheets. They found that a minimum heat affected zone was achieved using a high-beam quality in pulsed mode. Davari et al. [14] compared CO_2 laser cutting of Teflon and Teflon-bronze composite sheets. They indicated 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 used materials showed that due to the presence of bronze particles in the reinforced Teflon, the lower kerf width is wider than that for non-reinforced Teflon. Moradi et al. [15] used a 60 W CO_2 laser machine to investigate the laser cutting of injection moulded polycarbonate workpiece. They experimentally showed that the laser cutting quality enhances when the focal point is located in the depth of cut. They also indicated that the lower kerf width reduces as the laser focal plane position and laser power decreases. They also in another experimental research [16] concluded that in CO_2 laser cutting of polycarbonate, the upper and lower kerf width increases by increasing gas pressure and focal point position. Banerjee et al. [17] reported the application of the low-power CO_2 laser-cutting process to fluoroelastomer (FKM), polyamide 6 (PA6), PA6/FKM thermoplastic elastomers (TPEs), and thermoplastic vulcanizate (TPV). They measured kerf width, melted transverse area, and melted volume per unit time and found that a smaller melted area and melted volume per unit time are achieved for TPE when compared with those values for PA6. They also indicated that the HAZ and surface roughness largely decreased in TPE when compared with PA6. DeIorio et al. [18] studied the material removal process during laser ablation using pulsed CO_2 laser interaction with graphite fiber-reinforced composite. They revealed that the material removal process was defective when the laser power and pulse duration were low. They concluded that the transfer of energy from the beam to the workpiece was various over a range of energy levels due to significant differences in the physical properties of the composite's constituents.

The main purpose of this research is to investigate the effect of power, maximum cutting speed, and specific point energy on the material removal rate (MRR) and cutting volume efficiency (αVol) in CO_2 laser cutting of polyamide (nylon) sheets. The results can be applied not only for laser cutting technicians in industries but also 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. Material

Commercial polyamide sheets with thicknesses of 2 to 8 mm were applied in this research. Polyamide (PA) is often called nylon and is one of the thermoplastic polymers. Nylon contains repeating amide molecule (-CO-NH-) linkages in its chemical structure [19, 20]. PA also is one of the engineering polymers and it is relatively a strong and tough material with high impact resistance, excellent heat resistance, and self-extinguishing but with low scratch resistance [21]. PA is not optically transparent to the visible light and it strongly absorbs CO_2 laser radiations with a wavelength of 10.5 µm [10]. The melt removal mechanism of PA in laser cutting is based on melt shearing [10]. Some mechanical and chemical properties of the polyamide sheet are shown in Table 1.

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 doing experiments.

Table1. Some properties of polyamide [21, 22]

Property	**value**
Density	0.00114 g/mm^3
Refractive index (n)	1.54
Tensile strength (σ_t)	82.7 MPa
Hardness Rockwell	M52
glass-transition temperature Tg	70 °C
Heat deflection temperature	121 °C (at 0.45 MPa)
Melting point	250 - 264 °C
Degradation temperature	500 - 600 °C
Melting heat	230 J/g
Heat of combustion	31400 J/g

2.2. Cutting Experiments

A CO_2 laser cutting machine was employed in this research. This machine was manufactured by Crystal Sign Company with a maximum nominal power of 100 W. Some features of this machine derived from the manufacturer’s catalog are presented in Table 2. The periodic preventive maintenance (PM) operation had been carried out on the used laser cutting machine a couple of weeks before doing this research and so, it is to say that the lasing cavity and other optics were inappropriate conditions.

Table2. General characteristic of applied laser cutting machine

Model	Manufacturer	Max. Power	Max. Speed	work envelope	Lens Dia.	Focal length
EZ-Z1390	Crystal Sign Co.	100 W	24000 mm/min	2 axes (X,Y) CNC 1300 × 900 mm	20 mm	65 mm

A cutting head, that was equipped with a 65 mm focal length lens, was applied and the 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. Other laser cutting parameters are illustrated in Table 3.

Table3. The applied laser cutting parameters

Cutting parameter	value
Sheet thickness (mm)	2-8
Power (w)	20-83
Cutting speed (mm/min)	138-1320
Focal length (mm)	65
Focal point position	Top surface
Assist gas	Air
Gas pressure (bar)	1
Nozzle diameter (mm)	1
Stand-off distance (mm)	1
Beam diameter (mm)	0.1

Due to the aim of this research and to decrease the direct loss of laser beam energy in the cut front, the maximum cutting speeds for a variety of powers and thicknesses under the same other laser cutting parameters were specified for commercial polyamide sheets. With using the maximum cutting speed, it can be assumed that the full incident laser beam energy is absorbed into the entire cutting zone [8, 9]. In order 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 complete cut occurred, was the maximum cutting speed.

2.3. Kerf Width Measurement

In order to assess the material removal rate and the cutting efficiency, the upper and lower kerf width must be measured. 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. An optical microscope with a magnification of 100X was employed to measure the kerf width. In order to ensure the accuracy of measurement, the kerf width was measured in three points in 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.

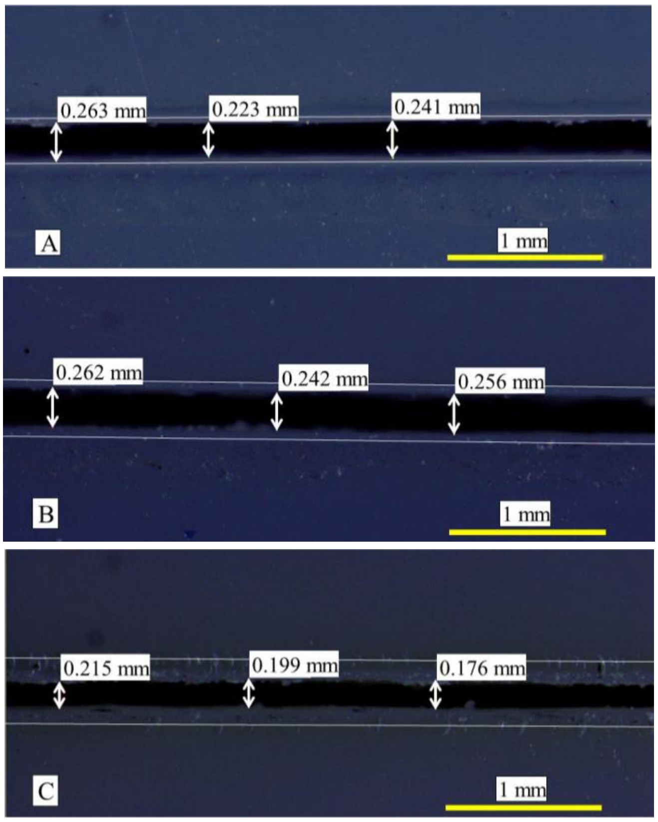

Figure1. Showing upper kerf width measurements at three points in the middle of the cut path where the cutting speed is steady. A) 2 mm thick, 63 W, 1260 mm/min. B) 4 mm thick, 63 W, 510 mm/min. C) 8 mm thick, 63 W, 193 mm/min. The heat-affected zone is indicated with a white line.

3. Results and Discussion

3.1. Maximum Cutting Speed

In this research, 55 cuts were performed in a day using the same environment condition in order to get results with appropriate accuracy. In general, the industrial cutting speed is less than the maximum cutting speed for any combination of laser-material. However, because of the aim of this research (reduction of laser energy loss), the maximum cutting speeds with using different powers were obtained experimentally for various thicknesses of nylon sheets. In laser cutting with using the maximum cutting speed for a given power, it can be supposed that the amount of direct loss of incident laser beam energy is at the lowest value [8, 9]. Hence, it can be stated that most of the laser energy input into the cutting front is consumed to melt and thermally decompose the material of the workpiece. The combination of powers and maximum cutting speeds applied for a variety of PA sheet thicknesses is indicated in Table 4.

Figures 2 and 3 have been achieved using the results of Table 4. Figure 2 indicates that in the range of applied laser conditions, the maximum cutting speed rises with increasing power. As is seen in Figure 2, for a given thickness, the maximum cutting speed is raised with power approximately in a logarithmic trend. This increment in the cutting speed is due to this fact that as the laser power increases, the incoming energy to the cut front becomes larger and the laser energy penetration is accelerated, and thus the cutting speed must be increased to maintain the cutting efficiency. In other words, cutting speed must execute a balance between the consumption of laser energy and any enlargement in the laser penetration.

Table4. Maximum cutting speeds for a variety of powers and PA 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	300	29	300	34	300	39	180	34	138
24	360	34	360	39	330	44	240	39	150
29	480	39	420	44	390	51	258	44	168
34	720	44	480	49	420	53	270	49	180
39	780	49	540	54	450	57	276	53	189
44	840	59	555	59	480	63	279	55	189
49	900	63	570	63	510	68	282	59	191.5
54	1140	68	579	68	528	73	283	63	193
59	1200	73	588	73	552	78	284	68	194.5
63	1260	78	594	78	564	83	285	73	195
68	1290			83	576			78	195.5
73	1320							83	196

The results from Figure 2 also indicate that the maximum cutting speed, overall, decreases with increasing sheet thickness. This is because, when the sheet thickness is increased, the interaction time between the laser beam and cutting zone must be increased in order to complete laser penetration; then the cutting speed has to be reduced.

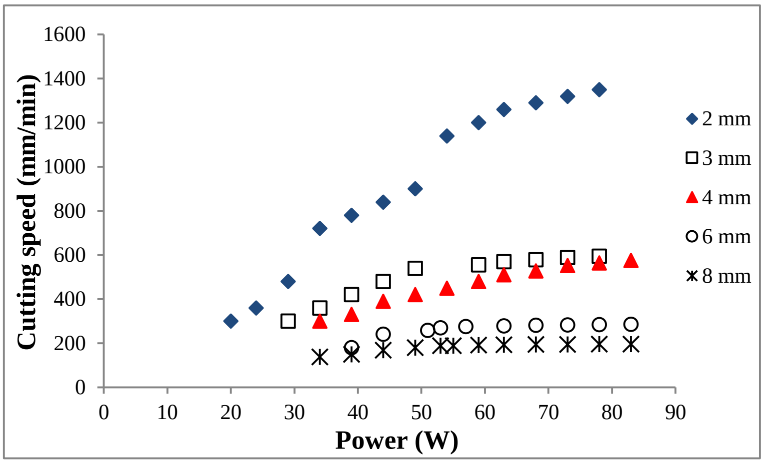

Figure 2. Maximum cutting speed versus laser power for a variety of applied polyamide 66 sheet thicknesses

Figure 3 illustrates that for a specified power, the cutting speed reduces with increasing sheet thickness. According to this figure, the equation of cutting speed in terms of sheet thickness and power can be derived 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.

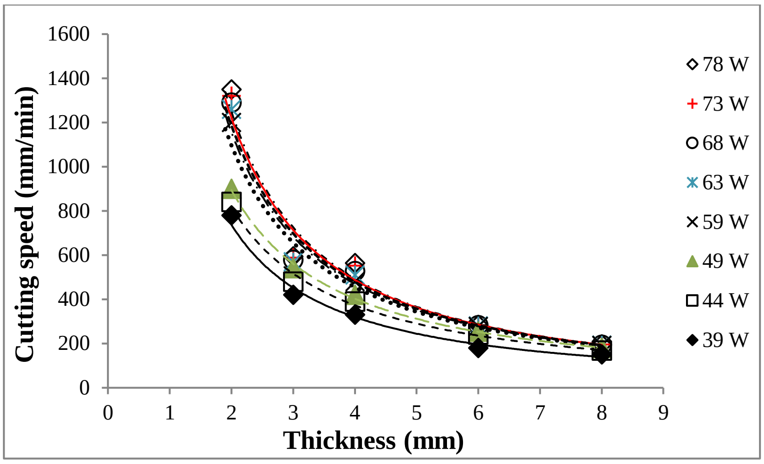

Figure 3. Maximum cutting speed versus applied polyamide sheet thicknesses for a variety of employed laser power

In order to obtain a formula for maximum cutting speed in laser cutting of polyamide sheets, the values of P, Q, and B in Equation (1) can be found using the results of experiments. Some relevant numerical values of P, Q, and B are presented in Table 5.

Table 5. Some experimental values of P, Q, and B in laser cutting of polyamide sheet

P (W)	Q	B
39	43.56	1.204
44	40.72	1.132
49	40.48	1.149
59	44.75	1.267
63	45.01	1.297
68	43.22	1.309
73	41.92	1.324
78	40.49	1.338
Average	**42.52**	**1.25**

Using the values of Table5 and in the range of applied laser cutting conditions, the Equation (1) for laser cutting of polyamide sheets can be rewritten as follows:

$$V = 45.52\, P\, T^{-1.25} \quad , \quad \left\{\frac{mm}{min}\right\} \qquad (2)$$

From Equation (2), two subjects can be pointed. 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]. Using Equation (2), the theoretical maximum cutting speed for different applied powers versus polyamide sheet thickness is shown in Figure 4. A comparison between Figurea 3 and 4 reveal that the discrepancy between theoretical (Equation (2)) and the experimental cutting speed is in the range of -16% to 6.5%.

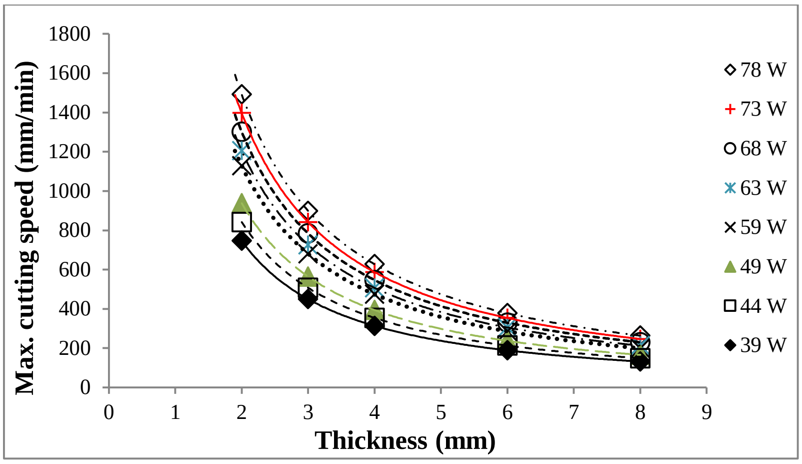

Figure 4. Theoretical maximum cutting speed (Eq.2) versus thickness for a variety of applied power

3.2 Kerf Width

In order to calculate the values of material removal, the amounts of kerf width are essential so, the upper and lower kerf widths for all applied sheet thicknesses and powers were observed. Examples of the kerf width results are indicated in Figure 5.

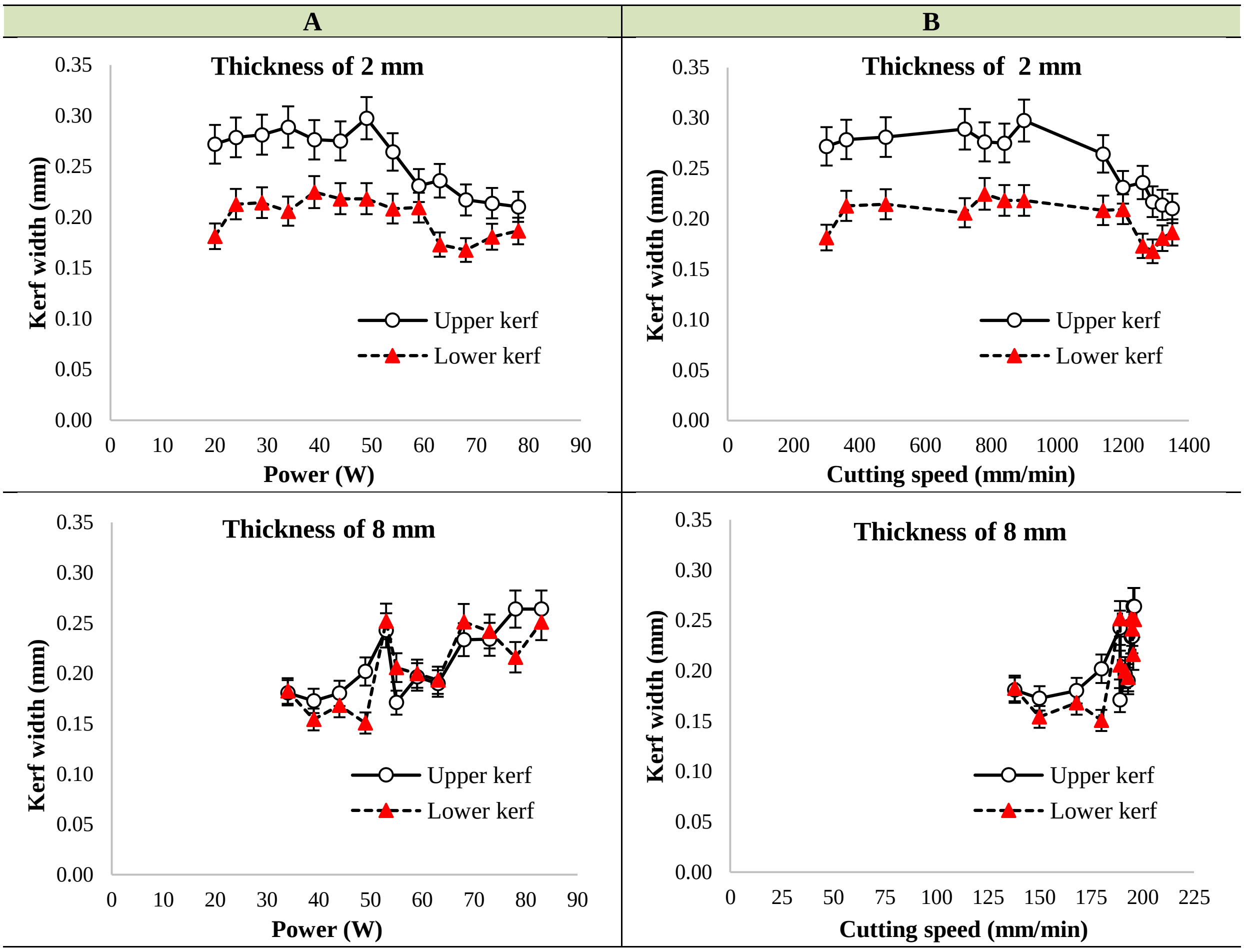

Figure 5. Upper and lower kerf width of polyamide sheet as a function of A) laser power and B) cutting speed for two thicknesses of 2 mm and 8 mm; the focused beam diameter was 0.1 mm

This figure (Figure 5) shows 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 polyamide sheets. As can be seen for the thickness of 2 mm, on average, the upper and lower kerf widths are in the order of 0.26 mm and 0.20 mm respectively. These values for an 8 mm thick sheet are in the order of 0.21 mm and 0.20 mm.

The average kerf widths for all the samples involved in the experiments are presented in Figure 6. As can be seen, the upper and lower kerf widths in thicknesses of 6 and 8 mm are almost equal. Considering all cutting parameters and in the range of applied thicknesses, the results of Figure 6 indicate that the upper kerf width is 1.0 to 1.5 times (1.25 in average) wider than the lower kerf width. This figure 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 3 to 8 mm. This might suggest 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. In order to know more about the reason(s) for this significant enlargement in the kerf width, a deep study in the mechanism of kerf width widening is necessary.

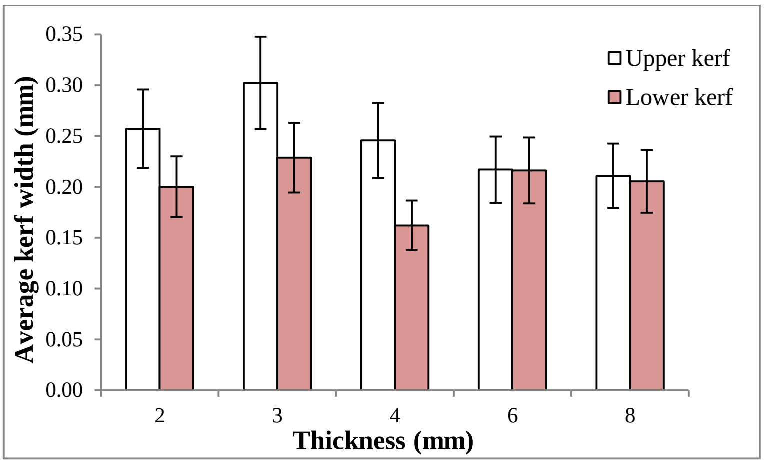

Figure 6. The upper and lower kerf width versus polyamide sheet thickness. The focused beam diameter was 0.1 mm.

For a specified power, as the sheet thickness increases, the maximum cutting speed proportionally reduces (see Figure 3). As the maximum cutting speed decreases, the interaction time between the laser beam and polyamide molecules rises so the laser beam has more time to melt and disintegrate the molecule linkages of polyamide. 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 polyamide molecule linkages happen which brings about the thickening of the melt layer. As the melt layer increases, the mechanism of melt removal needs more gas pressure to remove the thick melt layer, while the pressure of the gas is constant. Owing to these reasons, all the melt cannot be pushed out through the bottom of the kerf. The residual melt solidifies on the kerf walls causes a reduction in the kerf width. Therefore, the kerf width decreases, and the lower and upper kerf width become almost equal as the thickness increases. In this situation, the increments of cutting speed are not noticeable in comparison with the power changes (Figure 2, the thickness of 8 and 6 mm). In other words, in laser cutting of polyamide with 1 bar assist gas pressure, with an increase in the power, the cutting speed does not significantly change. The micrographs of the kerfs in Figure 1 also indicate that the residual melt on the cut edge for a thicker sheet is more than that for a thinner sheet.

3-3. Material Removal Rate (MRR) and cutting volume efficiency

The material removal rate (MRR) is the volume of material that is removed from the cutting zone at the time that the laser beam moves a distance of its diameter. Some well-known parameters, e.g. laser power, cutting speed, assist gas condition and beam diameter can affect the MRR. The volume of removed material can be calculated by measuring the upper and lower kerf width. The cross-section of cut kerf can simply be supposed as 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 7.

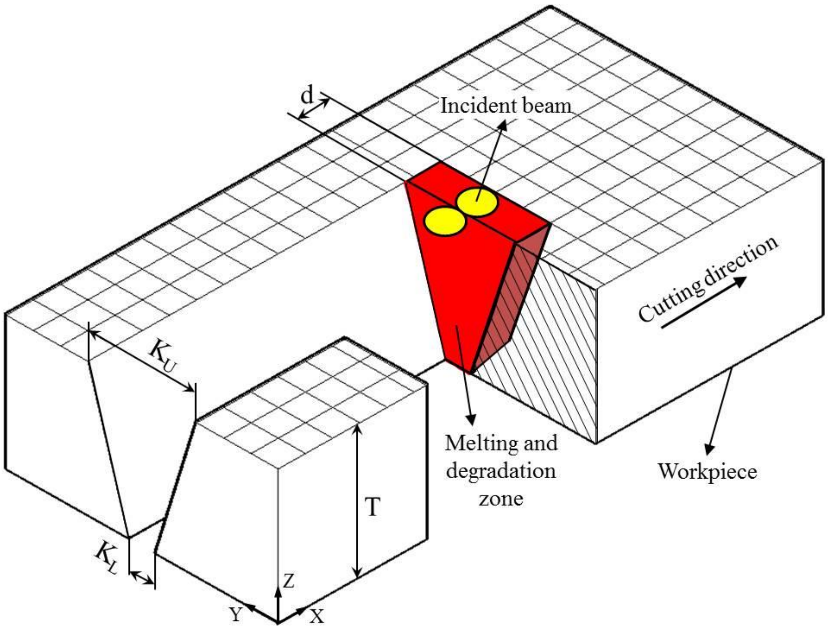

Figure 7. Schematic interaction of the laser beam with the workpiece in laser cutting as the laser beam moves a distance of its diameter. The cross-section of cut kerf simply can be similar to a trapezoid. The volume of removed material is then similar to a trapezoidal prism [23].

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:

$$MR_V = \left(\frac{K_U + K_L}{2}\right) \times T \times d \quad , \quad \{mm^3\} \tag{3}$$

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 material removal rate can be calculated as follows:

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

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 only 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.

Based on Equation (4) and for a specified thickness, material removal rate (MRR) is changed when the cutting speed and/or the cross-section area of the kerf (A_K) changes. In the range of employed laser parameters, the results of CO_2 laser cutting of polyamide sheets indicate that the material removal rate (MRR) increases with power as shown in Figure 8. The results of experiments show that the kerf widths (Figure 5) 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 balance of the energy. However, as seen in Figure 2, when laser cutting of thicker nylons (e.g. 6 mm and 8 mm), with an increase in the power, the cutting speed does not significantly change. In the range of used laser cutting conditions and as can be seen in Figure 8, for a given power, the amount of MRR reduces with increasing thickness.

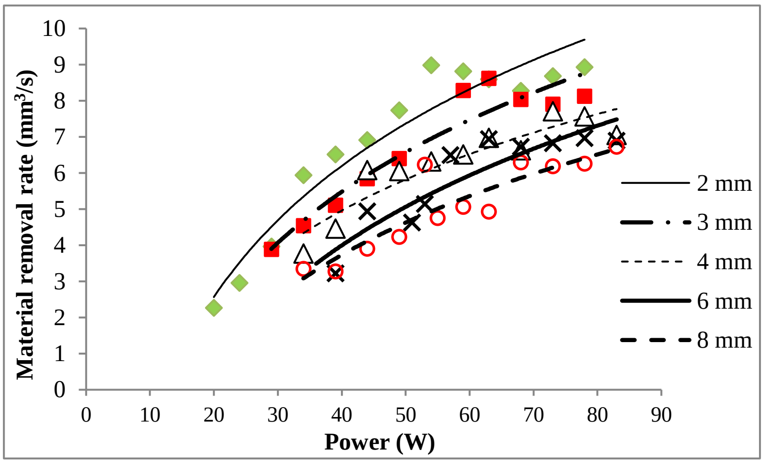

Figure 8. Material removal rate (MRR) as a function of laser power for all used polyamide sheet thicknesses

A logarithmic equation can be derived from Figure 8 as $MRR=F\times Ln(P)-C$. In this equation, *P* is the laser power (W), *F* and *C* are the values that experimentally derived from the laser cutting of nylon 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 polyamide thicknesses, the average values *F* and *C* for are 4.6 and 12 respectively. Hence, the equation of MRR in laser cutting of polyamide sheet can be derived as follows:

$$MRR = 3.9 \ln P - 9.3, \quad \left\{\frac{mm^3}{sec}\right\} \qquad (5)$$

According to Equation (5), two subjects 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 affect the amount of *F* and *C*. These values are likely related to the cutting volume efficiency.

A 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 9. As can be seen, for all thicknesses and in the range of applied laser cutting conditions, the α_{Vol} increases with power until achieves an apex, then it slightly decreases as the power increases.

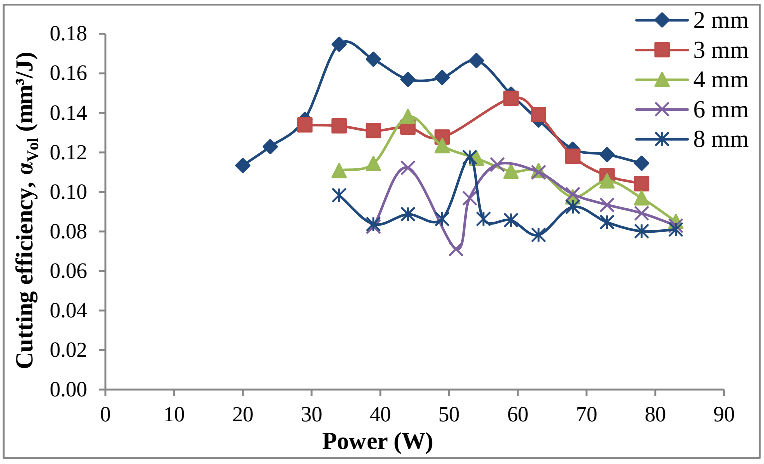

Figure 9. Experimental cutting volume efficiency versus power for a variety of sheet thickness

The cutting volume efficiency (α_{Vol}) can be estimated using Equation (5) and Equation (6) as follows:

$$\alpha_{Vol} = \frac{3.9\ln P - 9.3}{P} \quad , \quad \left\{\frac{mm^3}{J}\right\} \tag{7}$$

A comparison between cutting volume efficiency and MRR as a function of power using Equations (5) and (7) is shown in Figure 10. As seen, 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 (0.132 mm^3/J) in the power of 29 W. Then, the cutting efficiency slightly reduces with increasing power. A possible reason for the reduction of cutting volume efficiency can be related to the melt removal condition. Insufficient melt removal condition in laser cutting is solely due to inadequate assist gas pressure [4]. An incompetent melt removal condition means that all the melt cannot be pushed out through the bottom of the kerf. Owing to this, a residual melt solidifies on the kerf walls causes a reduction in the kerf width. Moreover, a re-solidified melt is 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 reduced to make a through cut. This reduction in the maximum cutting speed mildly bends the MRR graph and slightly decreases the α_{Vol} with increasing power.

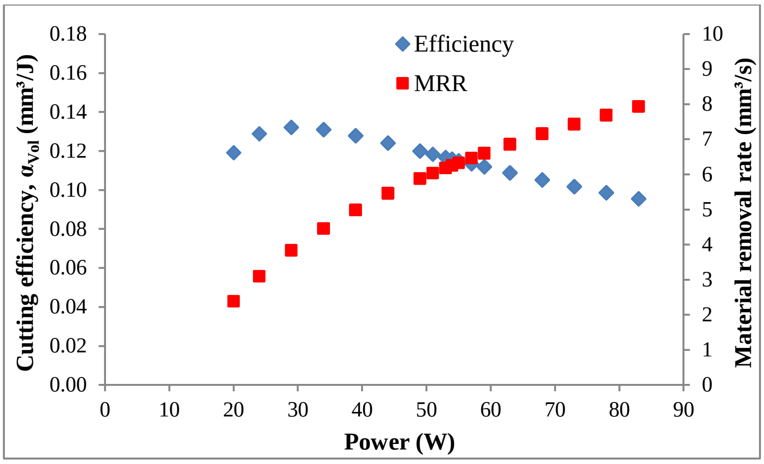

Figure 10. Comparison between cutting volume efficiency (Equation (7)) and MRR (Equation (5)) versus laser power

In laser cutting, the energy delivered to the cutting zone in the interaction time of t is called specific point energy (Esp) [my thesis] which can be calculated by Equation 8. The interaction time is the time that the laser beam moves a distance of its diameter.

$$E_{SP} = P.t = \frac{P.d}{V} \quad , \quad \{J\} \tag{8}$$

Where P is the laser power (W), t is the interaction time (sec), d is the focused beam diameter (mm) and V is the cutting speed (mm/s). This energy is consumed to melt the material of the workpiece. A main question is that, is all the input laser energy into the cutting zone consumed for melting the material. In order to answer this question, first, we need to know how much energy is essential to melt the polyamide molecule linkages at interaction time. Equation 9 calculates this as below:

$$E_m = MR_V \times \rho \times mh = \left(\frac{K_U + K_L}{2}\right) \times T \times d \times \rho \times 230 \quad , \quad \{J\} \tag{9}$$

Where, ρ is the volume density (g/mm^3), mh is the melting heat and for polyamide, it is 230 J/g. Figure 11 shows the energy ratio of Esp/Em versus sheet thickness for three amounts of different MRR. As can be seen, the energy ratio is not affected by MRR. However, for all MRRs, the energy ratio increases with increasing thickness. In the range of employed laser conditions and selected MRRs, the energy ratio increases from about 22 to 47 as the sheet thickness increases from 2 to 8 mm. This means the amount of input laser energy into the cutting zone is 22 to 47 times more than the melting energy necessary for melting the material of the workpiece. In other words, it seems that there was lots of energy wastage during the cutting experiments. However, it must be emphasized that we used maximum cutting speed in order to reduce as much as possible the wastage of laser energy. In this case, if we suppose that the loss of energy from the bottom of the workpiece is negligible so it can be stated that the wastage of energy is due to the reflections and excessive melting of the material. The reflection happens as the laser irradiates the surface of the workpiece. The excessive melting of material is the same as residual melt layers that cannot be removed from the bottom cutting zone. These residual melting layers solidify again on the kerf wall.

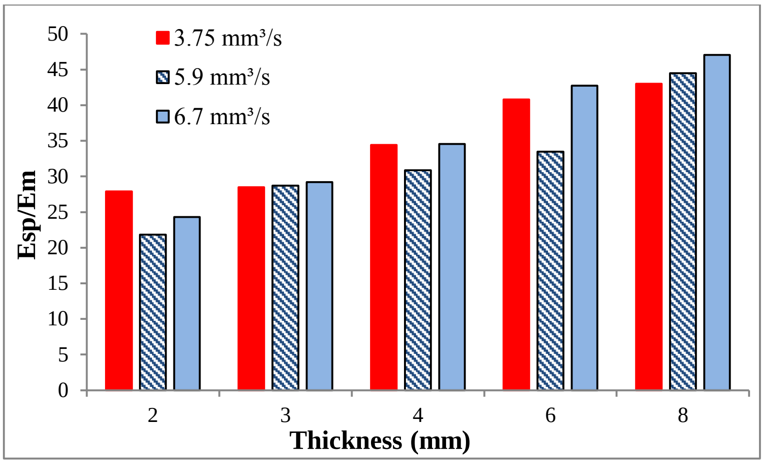

Figure 11. The energy ratio (specific point energy per melting energy, E_{sp}/E_m) versus polyamide sheet thickness for a different amount of MRRs

In the range of applied laser parameters and thicknesses, cutting volume efficiency (α_{Vol}) decreases with increasing Esp as indicated in Figure 12. According to this figure, the equation of cutting volume efficiency in terms of Esp can be derived as an exponential function. The equation can be written as follows:

$$\alpha_{Vol} = 0.104\, E_{sp}{}^{-0.286} \quad , \quad \left\{\frac{mm^3}{J}\right\} \tag{10}$$

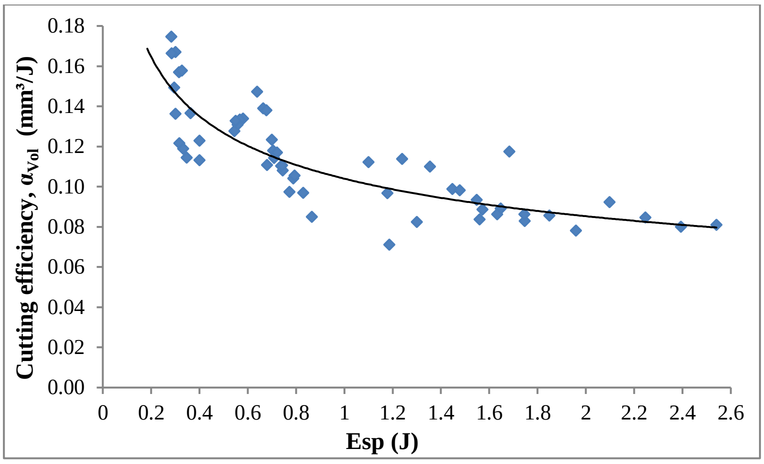

Figure 12. Cutting volume efficiency versus specific point energy

Using Equation (8) we have:

$$\alpha_{Vol} = 0.104 \left(\frac{Pd}{V}\right)^{-0.286} \quad , \quad \left\{\frac{mm^3}{J}\right\} \tag{11}$$

The focused beam diameter (d) in this research is 0.1 mm so Equation (11) can be rewritten as follows:

$$\alpha_{Vol} = 0.2 \left(\frac{P}{V}\right)^{-0.286} \quad , \quad \left\{\frac{mm^3}{J}\right\} \tag{12}$$

Using Equation (12), Figure 13 indicates that in the range of employed laser cutting conditions, the cutting volume efficiency decreases as the thickness increases. Insufficient melt removal can be a possible reason for this reduction in cutting volume efficiency.

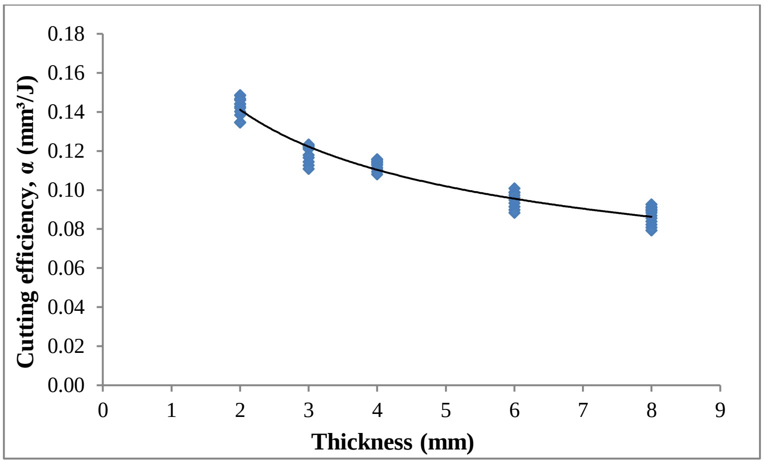

Figure 13. Cutting volume efficiency versus thickness

4. Conclusion

CO_2 laser cutting of polyamide (nylon) sheets with thicknesses of 2 to 8 mm have been reported in this research. All experiments were established on the maximum cutting speed for a given power. In the range of employed laser cutting conditions, parameters, and CO_2 machine properties, some results can be concluded as below:

1. The experimental results show that, for a given power, the maximum cutting speed exponentially decreases with increasing sheet thickness.
2. In thinner sheets e.g. 2 to 4 mm the upper kerf is wider than the lower kerf, but as the thickness increase to 6 and 8 mm the upper kerf width is almost in the range of the lower kerf width.
3. The material removal rate (MRR) increases logarithmically with power.
4. For a given power, the MRR rises as the sheet thickness decreases.
5. 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.
6. For a given power, the cutting volume efficiency (α_{Vol}) rises as the sheet thickness decreases.
7. For a given MRR, the ratio of Esp/Em enhances as the sheet thickness increases.
8. The cutting volume efficiency (α_{Vol}) reduces with increasing specific point energy (Esp).
9. Overall, the cutting volume efficiency (α_{Vol}) decreases with increasing sheet thickness.

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