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Laser Induced Thermal Effects and Accuracy in Polycarbonate Cutting

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***Abstract* – This research investigates into the CO2 laser cutting process applied to polycarbonate materials of varying thicknesses. Investigating laser power, cutting speed, standoff distance, and cutting diameter, the study focuses on responses such as heat-affected zones and kerf diameters. Through advanced microscopy and coordinate measuring tools, interaction effects were assessed using variance analysis. Measurements were made using Meiji Techno MT7000 Metallurgical Microscope and the CRYSTA-Apex S 900 CNC Coordinate Measuring Machine. Interactions effects of data were calculated by analysis of variance. Notably, higher cutting speeds coupled with lower laser power yielded optimal heat-affected zones. Standoff distance emerged as a critical factor influencing material cut-through capacity. The results show that optimum levels of heat affected zone were possible by applying higher cutting speeds and lower laser power. Standoff distance had the most impact on the ability of the material to be cut through.**

Keywords— CO2 Laser, Polycarbonate, Standoff Distance, HAZ, Kerf Diameter.

I. INTRODUCTION

Lasers of various types and properties have been utilized to produce a variety of components for automotive, aerospace, electronics, and biomedical industry. To produce high-quality products through laser cutting, the optimal combination of input parameters must be determined through trial and error until the desired results are achieved. To reduce the number of attempts needed to obtain the desired outputs, the study of laser cutting input parameters effects on its output results is necessary. Different input parameters affect the output of the laser cutting in different ways. Laser cutting of polymeric materials remains an aspect that could be enhanced to produce higher quality outputs. In this research, the effects of parameters, laser power using current, cutting speed, and standoff distance on the kerf diameter of polycarbonate materials was investigated. Experiments were conducted on two different thickness of polycarbonate sheets and three different diameter holes. Circular cut profile examined using a coordinate measuring machine (CMM) and a metallurgical microscope. The quality of circular holes of specimens will be examined by measuring dimensional accuracy and heat affected zones.

Polycarbonate is a thermoplastic material that is widely used in a variety of applications due to its unique properties [1]. It has a high impact strength and is resistant to breakage and cracking, making it ideal for use in a variety of structural and protective applications [2]. Additionally, polycarbonate has a high transparency, making it suitable for use in transparent applications such as windows, screens, and other products that require transparency [3]. Laser cutting is a precise manufacturing process that uses the concentrated light beam to cut through a wide range of materials. Additionally, it allows for a greater degree of automation, which improves productivity and efficiency

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[4]. The use of laser cutting for the processing of polycarbonate sheets has a relatively short history [5]. Laser cutting technology itself is a relatively recent development [6]. Laser cutting of polycarbonate sheets has several advantages over traditional cutting methods, including the ability to cut complex shapes with high precision, the ability to cut through thick materials, and the ability to cut at high speeds [7].

Laser cutting technology has only recently begun to be utilized for processing polycarbonate sheets [8]. Laser cutting of polycarbonate has grown significantly in recent years due to the increasing demand for high-precision polycarbonate components and the growing availability of laser-cutting equipment [9]. Further research is needed to continue to improve the efficiency and effectiveness of laser cutting for polycarbonate sheets [10]. Laser cutting is a widely used manufacturing technique that involves the use of a focused laser beam to cut materials into specific shapes and sizes. However, a few factors, such as the power of laser, speed of laser, focal length, gas pressure, material thickness, and material characteristics, can affect the precision and quality of the laser cutting process. An optimum combination of process parameters will be identified after conducting the experiment.

II. Materials and methods

EZLaser 4040 50W laser cutter incorporates a computer numerical control (CNC) system that uses a low powered laser with a focused beam to cut or engrave materials to form simple and complex shapes. Meiji Techno MT70000 metallurgical microscope is a high-power microscope that is designed with the purpose of observing opaque substances. It uses reflected white light and is equipped with a high-power light source. The microscope has a bright-field mode that delivers clear and high-resolution images. Additionally, its super widefield high eyepoint eyepieces (SWH10X, F.N.22) enable users to view the magnified materials smoothly and easily. Crysta-Apex S 900 CNC coordinate measuring machine detects individual points on the surface of a physical object and measures their geometry. Polycarbonate (1 mm to 2 mm) with thermal conductivity, 0.190 W/mK; tensile strength, 65.5 MPa was used. Minitab, a software application for data analysis, statistical analysis, and process improvement, to boost quality and cut expenses.

The laser beam delivery system provides a cutting speed range of 0-50 mm/s, with an optimal speed between 5-20 mm/s cutting polymeric material. This sleek and lightweight system uses a 50W laser at a 450nm wavelength. The laser's focal point is typically set 6mm from the nozzle tip, ensuring precise targeting on the material [11]. With a remarkable positioning precision of less than 0.01mm, it generates a spot size that varies between 75 and 125 microns. Given the study's focus on thin material, inconsistencies in cutting diameter from entry to exit surfaces weren't deemed significant. Selection of laser cutting input parameters was made based on the summary of findings from previous research literature. Laser power and cutting speed were popular input parameters which were present in previous studies thus these parameters were chosen to be studied in this research. On the other hand, standoff distances and material thicknesses did not feature that often in previous studies. Heat-affected zone (HAZ) analysis and average kerf diameter (KD- avg), were important output responses that needed to be studied and analysed. Kerf diameter was measured from the cutting profile using CMM. HAZ results were obtained through microscopic measurements of the affected area of the cutting profiles.

TABLE 1. Experiment parameters

Input Parameter	*Levels*		
	1	*2*	*3*
Laser Power (W)	30	40	50
Cutting Speed (mm/s)	8	12	15
Diameter (mm)	10	18	25

III. Results & Discussion

The experiments have been conducted according to the experiment parameters [12, 13] in Table 1 with 3 levels for laser power (LP), cutting speed (CS), diameter of holes, 2 thickness sheet and 2 levels for the standoff distance (SOD). The circular laser cutting of a hole by maneuvering the laser beam in both x and y directions, while the table remains stationary. Dimensional accuracy is significantly influenced by the kerf width; a narrower kerf width enhances the precision [14]. The cutting speed is hole's periphery speed, as the linear x-y movements. The interpolation movement influence on kerf width is studied by cutting different diameter holes. The data obtained from experimental measurements were tabulated in Tables 2. Mean effect plots and interaction plots are used to interpret the interaction effects between input parameters and the output parameters.

A. *1mm thickness*

Figure 1(a) shows the heat-affected zone measurements for the 10mm diameter hole that was cut using laser power (LP) of 30A, 15 mm/s speed and a standoff distance (SOD) of 7 mm. The HAZ measurements consist of wavy cutting-edge regions. Measurements were taken at random points across the cutting edge 12 times and the average data recorded. HAZ appears to have a better quality of cutting edge compared to the HAZ in Figure 1(b). Also, the surrounding region around its cutting edge appears to have fewer sightings of solidified molten material. respectively, laser power (LP) of 30,40 and 50 A, cutting speed (CS) of 8,12,15 mm/s and diameter (DIA) of 10, 18 and 25 mm.

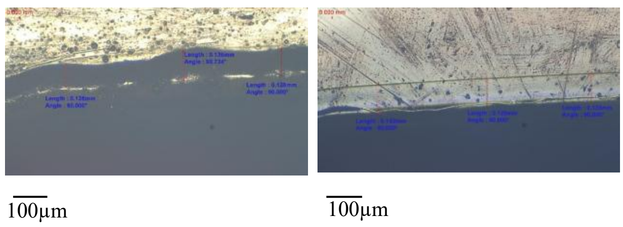


FIGURE 1. HAZ measurements for 10mm diameter hole (a) LP 30A, CS 15 mm/s, 7mm SOD (b) LP 30A, CS 15 mm/s, 5 mm SOD

TABLE 2. Experiment plan and measured data

Trial No.	*DIA*	*LP*	*CS*	*1 mm thickness*				*2 mm thickness*			
				7 mm SOD		*5 mm SOD*		*7 mm SOD*		*5 mm SOD*	
				HAZ	*KD-avg*	*HAZ*	*KD-avg*	*HAZ*	*KD-avg*	*HAZ*	*KD-avg*
	mm	*A*	*mm/s*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*
1	10	30	8	0.15	10.18	0.16	10.48	0.22	10.25	0.22	10.25
2	10	30	12	0.16	10.25	0.16	10.49	0.21	10.26	0.21	-
3	10	30	15	0.15	10.30	0.16	10.50	0.21	10.25	0.21	-
4	10	40	8	0.17	10.25	0.18	10.60	0.24	10.25	0.24	10.37
5	10	40	12	0.17	10.29	0.18	10.65	0.23	10.32	0.24	10.24
6	10	40	15	0.18	10.32	0.18	10.66	0.23	10.09	0.23	-
7	10	50	8	0.20	10.25	0.21	10.54	0.27	10.28	0.27	10.30
8	10	50	12	0.20	10.34	0.20	10.52	0.26	10.31	0.26	10.30
9	10	50	15	0.19	10.31	0.19	10.52	0.24	10.08	0.26	-
10	18	30	8	0.15	10.24	0.16	10.69	0.22	10.32	0.23	10.32
11	18	30	12	0.15	10.30	0.15	10.80	0.21	10.32	0.22	-
12	18	30	15	0.16	10.36	0.16	10.82	0.20	10.31	0.21	-
13	18	40	8	0.18	10.36	0.18	10.62	0.25	10.32	0.25	10.34
14	18	40	12	0.17	10.37	0.18	10.65	0.24	10.35	0.24	10.30
15	18	40	15	0.18	10.34	0.18	10.65	0.22	10.16	0.22	-
16	18	50	8	0.19	10.37	0.20	10.50	0.27	10.36	0.26	10.33
17	18	50	12	0.18	10.38	0.18	10.54	0.27	10.38	0.27	10.28
18	18	50	15	0.19	10.35	0.18	10.55	0.25	10.08	0.254	-
19	25	30	8	0.16	10.32	0.15	10.56	0.21	10.39	0.21	10.34
20	25	30	12	0.15	10.41	0.15	10.52	0.19	10.41	0.21	-
21	25	30	15	0.14	10.33	0.15	10.55	0.19	10.41	0.19	-
22	25	40	8	0.17	10.32	0.17	10.54	0.24	10.44	0.22	10.30
23	25	40	12	0.17	10.38	0.17	10.62	0.22	10.40	0.23	10.34
24	25	40	15	0.16	10.37	0.16	10.63	0.21	10.27	0.22	-
25	25	50	8	0.19	10.45	0.20	10.55	0.27	10.44	0.26	10.28
26	25	50	12	0.19	10.35	0.19	10.65	0.25	10.48	0.25	10.23
27	25	50	15	0.17	10.33	0.17	10.66	0.24	10.25	0.25	-

Heat Affected Zone (HAZ)

Table 2 shows the heat-affected zone (HAZ) measurements and the kerf diameter (KD avg) measurements for polycarbonate material of thickness 1mm with standoff distances (SD) of 7mm and 5mm.

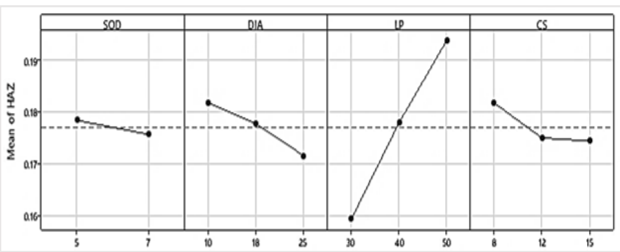
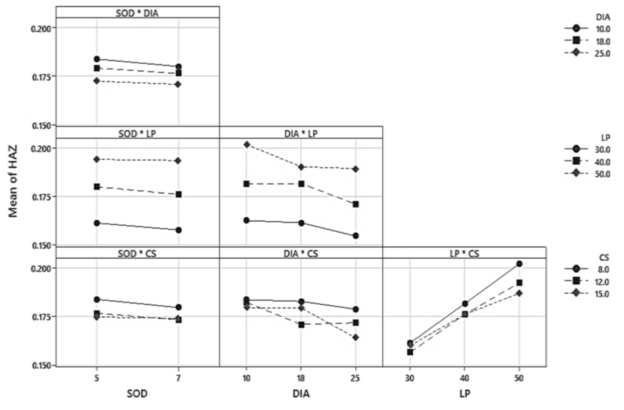


FIGURE 2. Main effects plot of HAZ for 1mm PC sheet

As shown in Figure 2 main effect plot for 1mm thickness polycarbonate material, laser power appears to have the biggest effect on the HAZ. From plots, it can be said that heat-affected zone is linearly proportional to laser power such that when laser power increases, the measurements of the heat-affected zone also increase. For the diameter of holes, it is observed that the heat-affected zone decreases as the diameter of holes increases. In the case of cutting speed, the heat affected zone values reduce moderately when cutting speed is increased from 8 to 12 mm/s but shows minimal change when the cutting speed is increased from 12 to 15 mm/s. Standoff distance has the minimum influence on the HAZ.

Figure 3, the Interaction plot for the HAZ means is observed which shows the link between the factors and the responses. If the lines are parallel, the interaction does not have a significant impact. If not parallel, there is a considerable impact on the response. The strength of the interaction increases with the degree of non-parallelism between the lines.



Based on the interaction plot in Figure 3 it is seen that standoff distance is insignificant towards the heat-affected zone. Variations in diameter against the current and speed of cutting are slightly significant whereas the combinations of power and speed are the most significant factors on HAZ.

FIGURE 3. Interaction plot for HAZ of 1mm

For 1mm thickness, the largest HAZ measurement of 0.211 mm was identified at the 10mm diameter hole, 50A laser power, 8 mm/s cutting speed and 5mm nozzle gap. The smallest HAZ measurement of 0.149mm was measured for hole diameter 25mm, 30A laser power, 15 mm/s cutting speed and 7mm gap. The mean HAZ for 1mm thickness was 0.1771mm.

Kerf Diameter (KD-avg)

The kerf diameter was measured using the Coordinate Measuring Machine (CMM) The kerf diameter values were measured on top and bottom surfaces of cut holes. The kerf diameter values tabulated in Table 2 is the average of the top kerf diameter and the bottom kerf diameter.

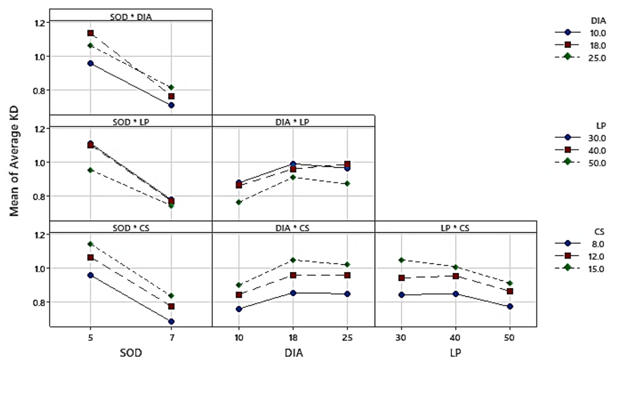


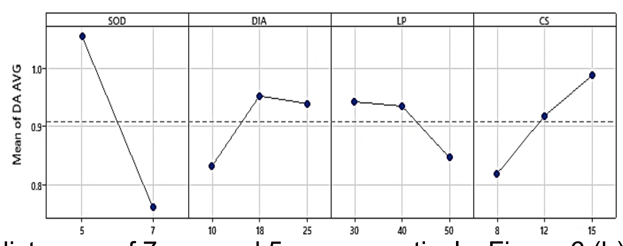
FIGURE 4, Main effect plot for average kerf diameter for 1mm

Figure 4 shows the main effect plot for the average kerf diameter of the 1mm thickness polycarbonate sheet. From the graphs, it is observed that standoff distance has the most effect on the average kerf diameter. Standoff distance is linearly proportional with the average kerf diameter. When the standoff distance is reduced, the average kerf diameter also reduces. The parameter with the second most influence on the average kerf diameter is speed of cutting. When the cutting speed increases, KD-ave, increases linearly with it. For laser power, the average kerf diameter reduces in a small scale from 30A to 40A. From 40A to 50A, there is a notable reduction in the average kerf diameter. In the case of diameter of holes, the average kerf width for the 10mm holes is the smallest. There is a significant increase of average kerf width when the diameter of holes is increased to 18mm then a slight reduction when the hole size is increased to 25mm. This occurrence can be explained in that interaction time of the laser cutter and the material is lowest when cutting smaller holes thus reducing the chances of error of laser beam defects which may occur. Figure 5 shows the kerf diameter interaction plots between factors. The standoff distance is shown to have the biggest impact on the average kerf diameter with its highest values of average kerf diameter. A large reduction in average kerf diameter is noticed when the standoff distance is increased from 5 to 7 mm. This could be attributed to large pressure differences and turbulence of the laser beam because of the changes in distance between the nozzle and the workpiece.

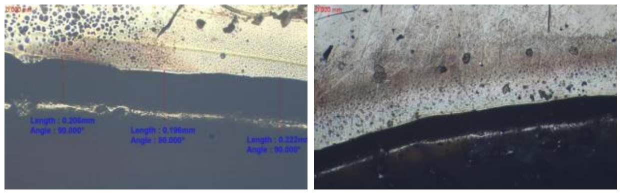
FIGURE 5. Kerf diameter interaction plot for 1mm

B. 2mm thickness

The results of heat-affected zone measurement and dimensional accuracy data in the form of average kerf diameter for the 2mm thick polycarbonate sheet are discussed in this. Figure 9 shows a sample result obtained from the laser cutting of a hole with laser power of 30A, cutting speed of 15 mm/s and standoff distance of 7 mm. The sample is like the sample result shown in Figure 1 for the 1mm thickness polycarbonate sheet. Which indicates that by increasing the thickness, the HAZ region increases moderately. Table 2 shows the results of heat-affected zone and KD-ave measured data obtained for standoff



distances of 7 mm and 5mm respectively. Figure 6 (b) shows the similar cut hole as per Figure 1(b) but with a laser power of 40W. The surface of the cutting edge shows more charring and burn marks compared to the hole cut at a lower laser power. This is because of the increased heat input because of higher laser power absorbed.



100μm 100μm

FIGURE 6. Result sample (a) LP 30W, CS 15 mm/s, 7mm SOD (b) LP 40W, CS 15 mm/s, 7mm SOD

Figure 7 shows the main effect plots for heat-affected zone for the 2mm thick polycarbonate sheet. Laser power has the highest impact on the HAZ as they are linearly proportional to one another. When power increases so does the HAZ. Cutting speed is inversely proportional to the HAZ. Cutting speed increased, HAZ decreased. For the diameter of holes of 10 mm to 18 mm there appears to be little change in the HAZ but once the hole diameter increases from 18 mm to 25 mm the HAZ is reduced clearly. Standoff distance shows the least significance on the HAZ. Figure 8 shows plots of the laser input factors on HAZ for the 2 mm thickness polycarbonate sheet.

HAZ

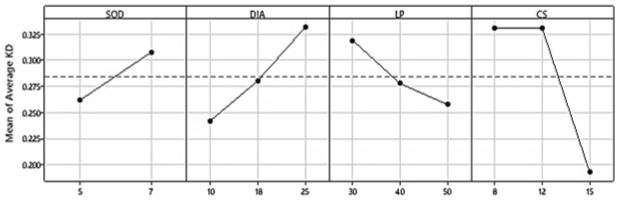


FIGURE 7. Main effect plot for HAZ of 2mm thickness

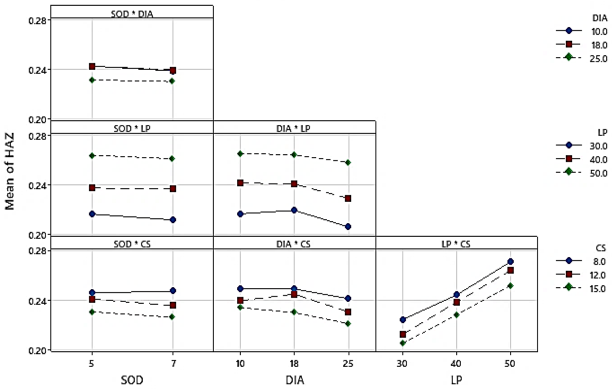


FIGURE 8. HAZ interaction plot for 2mm thickness

Kerf Diameter

Figure 9 shows the plot for the average kerf diameter of the 2 mm thick polycarbonate sheet. Cutting speed had the highest impact on the average kerf diameter. For several holes cut at higher cutting speeds of 12 mm/s to 15 mm/s, the holes were unable to be cut through fully. Diameter of holes had the second highest impact on the average kerf diameter. The diameter of holes increased linearly with large increments in the average kerf diameter. For laser power, when it increased the average kerf diameter decreased which makes their relationship inversely proportional. Figure 10 shows the interaction plot between factors for the average kerf diameter of 2mm thickness polycarbonate sheet.

Heat Affected Zone (HAZ)

The mean HAZ for 1 mm thickness was 0.177 mm. The mean HAZ for 2 mm thickness was 0.238 mm. For all sheet thicknesses (1mm, 2mm) the largest HAZ measurements were identified at the parameter combination of (10 Dia, 50 LP, 8 CS, 5 SOD). For all sheet thicknesses (1 mm, 2 mm) the smallest HAZ measurements were identified at the parameter combination of hole diameter (25 mm diameter, 30 LP, 15 CS and 7 SOD). For all sheet thicknesses, when laser power increases, the HAZ increases and when cutting speed increases, the HAZ decreases. For all sheet thicknesses, it is observed that the when standoff distance increases there is a small yet insignificant decrease in the HAZ. For sheet thicknesses of 1mm and 2mm, when diameter of holes increases the HAZ decreases.

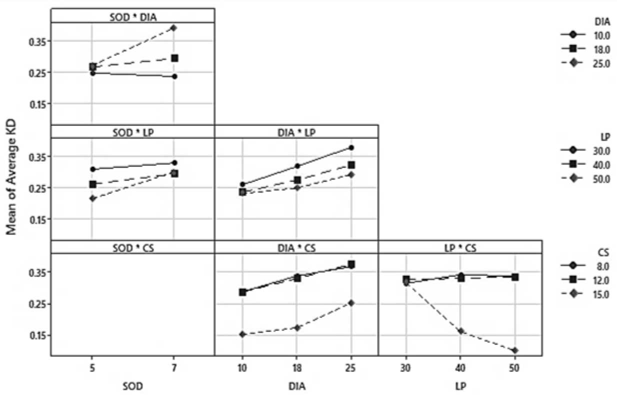


FIGURE 9. Main effects plot for average kerf diameter of 2mm

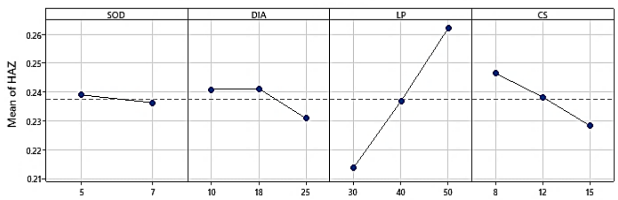


FIGURE 10. Interaction plot for average kerf diameter of 2mm

Average Kerf Diameter (KD avg):

The mean kerf diameter for 1mm thickness was 0.908 mm. The mean kerf diameter for 2 mm thickness was 1.070 mm. For 1mm sheet thickness the smallest average kerf diameter was obtained at (10 Dia, 30 LP, 8 CS, 7 SOD). For 2mm sheet thickness the smallest average kerf diameter was obtained at (10 Dia, 50 LP, 15 CS, 7 SOD). For 1mm sheet thickness the largest average kerf diameter was obtained at (18 Dia, 30 LP, 15 CS,5 SOD). For 2mm sheet thickness the largest average kerf diameter was obtained at (25 Dia, 40 LP, 12 CS, 5 SOD). Standoff distance appears to have the highest contribution to the dimensional accuracy of polycarbonate cutting of circular holes at thicknesses above 1mm. It is observed how the decrease in standoff distance results in the cutting of the holes at higher cutting speeds to not penetrate through the material. It is understood that as the standoff distance increases, the pressure of the beam increases thus leading to better cutting quality. As the pressure of the beam increases, the laser can penetrate through the material and perform better cutting of specimens [15].

Heat affected zone across all thicknesses is seen to be similar in that at lower cutting speeds and higher laser power, the laser beam heat input is increased, and the material is exposed to the heat for a longer time since the time to complete the cutting will take longer. Therefore, the material absorbs higher heat energy which results in larger widths of heat affected zone around the circular cutting profiles. When the thickness of the material was increased, the heat affected zone also increased due to the polycarbonate materials low thermal diffusivity which meant that for thicker polycarbonate variations, the ability for the heat to flow within it was reduced thus creating larger heat affected zones at the edges of the circular cutting profiles. This theory is in line with past research on heat affected zones in laser cutting. [16].

It is observed that the smaller diameter holes of 10 mm and 18 mm had lower levels of kerf diameter compared to the 25 mm holes. This occurrence is due to the laser cutter moving in a shorter path to complete the cutting for the smaller holes compared to the 25 mm holes. As the laser travels a longer distance and time the laser beam faces higher chances of inconsistencies in its delivery of laser beam wavelength due to variations of pressure due to air flow, variations due to surrounding temperature as well as variations of laser beam power delivery due to a build-up of fume particles getting stuck to the focusing lens of the laser which can affect the accuracy of cutting of the laser cutter [17]. The study revealed that some cuttings were not successful due to joining at the hot melt condition.

IV. Conclusion

In conclusion, the results of this experiment demonstrate that polycarbonate material with thicknesses ranging from 1mm and 2mm can be successfully cut using a 50W CO2 laser. The main finding of this report is that low-powered CO2 lasers are capable of cutting polycarbonate materials of varying thicknesses with the proper setting of input parameters. This study was limited to the examination of the heat affected zone (HAZ) and kerf diameter measurement. For all thicknesses, it is observed that when laser power increases, the HAZ increases and when cutting speed increases, the HAZ decreases. It is observed that when standoff distance increases there is a small yet insignificant decrease in the HAZ and diameter of holes increases the HAZ decreases. Standoff distance appears to have the highest contribution to the kerf diameter accuracy of polycarbonate cutting. Moreover, the observations made in this study were consistent with previous research on the topic.

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Author Contributions

Chockalingam: Conceptualization, Data Curation, Methodology, Validation, Writing – Original Draft Preparation;

Dhanush Mahendren: Data collection, Writing – Review & Editing.

Conflict of Interests

No conflict of interest was disclosed.

Ethics Statements

There are no ethical considerations to declare. This work does not involve human subjects, animals, or data from any social media platforms.

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