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CO₂ Laser Cutting of Thermoplastic Material - A Review

Maisuriya Kirankumar I¹, A. M Varsi²

PG Student, Department of Mechanical Engineering, S.N. Patel Institute of Technology & Research Centre, Bardoli,
Gujarat, India¹

Assistant Professor, Department of Mechanical Engineering, S. N. Patel Institute of Technology & Research Centre,
Bardoli, Gujarat, India²

ABSTRACT: Laser Beam Machining (LBM) is one of the most use thermal base non-contacting type advance manufacturing process which can be apply for almost whole range of material. Laser beam is focussed for melting and vaporizing the unwanted material from the parent material. It is suitable for geometrically complex profile cutting and making miniature holes in sheet metal. Among various type of lasers used for machining in industries, CO₂ is most established. In recent years, researchers have explored a number of ways to improve the LBM process performance considerably by proper selection of laser beam parameters, material parameters and operating parameters. This paper reviews the research work carried out so far in the area of LBM of thermoplastic material. It reports about the experimental and theoretical studies of LBM to improve the process performance.

KEYWORDS: - Advance machining, Laser cutting, CO₂ laser, Thermoplastic material, Number of pass, melting

I. INTRODUCTION

In a recent year many advance manufacturing processes are being used in the industry such as; electro-discharge machining, beam machining processes such as Laser beam machining (LBM), electron beam machining, ion beam machining and plasma beam machining, electrochemical machining, chemical machining processes, ultrasonic machining (USM), and jet machining processes, but these processes have their own limitations regarding workpiece material, shapes, etc. LBM is one of the advance manufacturing processes (AMPs) which are used for shaping almost whole range of engineering materials. The laser beam are widely used for cutting, drilling, marking, welding, sintering and heat treatment. The laser is also used to perform turning as well as milling operations but major application of laser beam is mainly in cutting of metallic and non-metallic sheets [1]. When the laser beam gets focused on the workpiece, the material removal takes place by the method of melting and vaporization. The material removal takes place by the suction process of compressor attached with the laser machine. In order to required depth, the probe has to be moved number of times for a given set of parameters. Laser machining is accomplished when the workpiece absorbs laser energy and this portion energy gets converted into thermal energy. The high peak intensity of the pulse generates strong evaporation pressure which is responsible for ejection of this molten material and material loss at the surface due to evaporation for generation of machined depth [2]. LBM has wide applications in the field of automobile sectors, aircrafts industry, electronic industry, civil structure, nuclear sector and house appliances. PMMA possesses high absorbance in the mid-infrared zone which makes it particularly suitable for CO₂ laser machining [3]. Unlike other polymers, such as polycarbonate (PC) and polypropylene (PP), it results in a minimum heat affected zone (HAZ) and better surface finish subjected to CO₂ laser processing [4]. PMMA has low heat capacity and low heat conduction. Therefore, any absorbed energy will immediately result in rising local temperature without creating thermal cracks [5].

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The principle of laser cutting

Laser cutting is a thermal separation process. Our pulsed lasers permit a controlled heat entry which is optimum for fine cutting. The high peak performance of our laser permits a maximum cut depth of up to 10mm. As the laser beam can be focused on a very small diameter for high precision, fine cuts are possible with a minimum cut width of up to 15 μm (0.0006 in). In addition, the heat-affected zone along the cut is very small (up to 2μm). The high energy depth in the focus point of the laser beam causes the material to melt and evaporate. By using an active or neutral process gas, for example, oxygen, nitrogen, or argon, the melted material is blown out. If the work piece or laser beam is now moved, a cut is created. The smallest possible cut width is dependent on both the beam characteristics and the material and material strength [35].

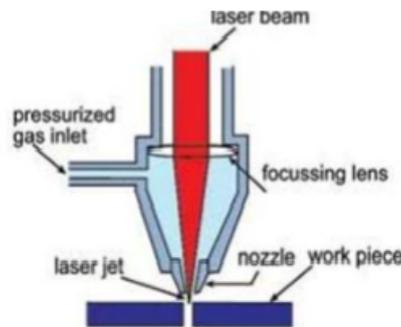


Fig 1. Laser machine^[30]

II. LITERATURE REVIEW

Black [6] had proposed the relationship between cutting speed and depth of cut for through cutting of the ceramic tile materials at constant cutting power (500 W). He has proposed the following empirical equation based on extensive database:

..... (1)

$$V = 12.618 * 10^3 d^{-B}$$

Where, B is the analytical constant whose value is 1.982.

Experiments were performed by A. A. Shaikh, et al [7] on acrylic sheet by varying power and traverse speed for a single pass cutting. The experimental results show that the depth of cut increase with increase in power whereas depth of cut decreases with increase in speed.

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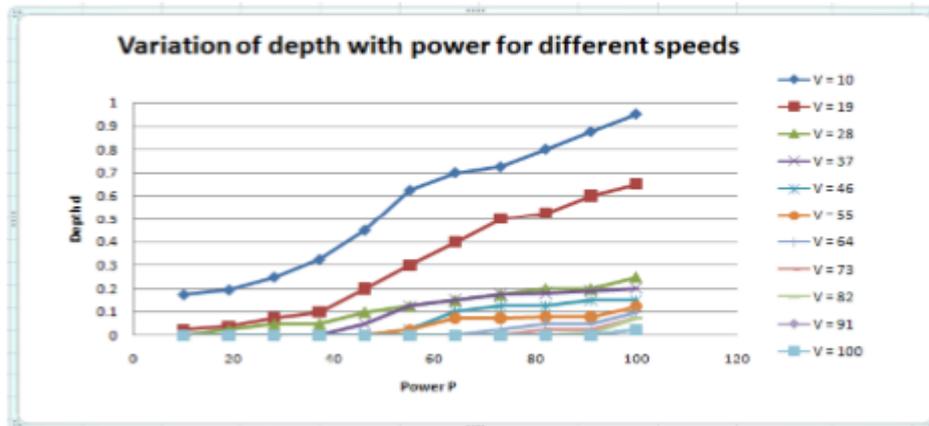


Fig. 2: Effect of power on depth of cut for different speeds [7]

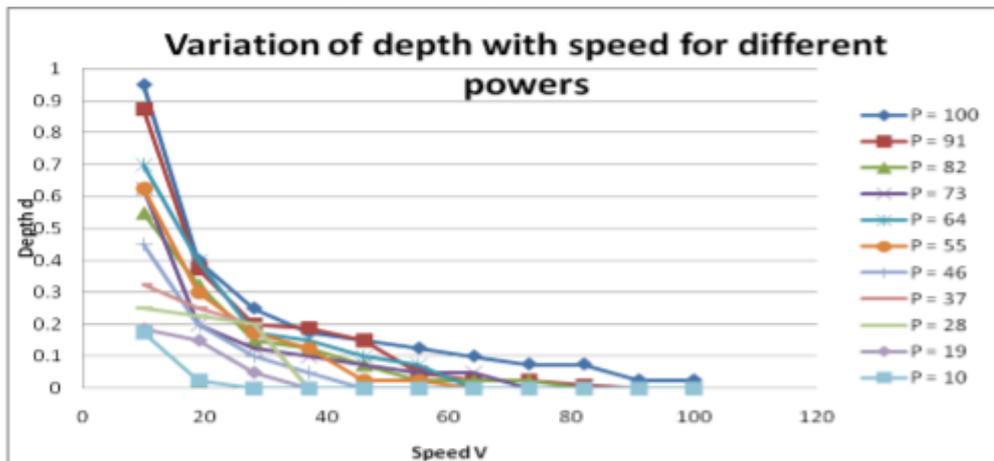


Fig. 3: Effect on speed on depth of cut for different powers [7]

Experiments were performed by Arif M. Varsi, et al [8] on acrylic sheet by varying power and traverse speed for a multi pass cutting. The experimental results show that the depth of cut increase with increase in power whereas depth of cut decreases with increase in speed.

L. Ramoli, et al [9] studied CO₂ laser machining of a suitable amorphous polymer (PMMA) for a rapid fabrication of miniaturized structures such as micro fluidic devices. Results revealed that the depth of a layer is inversely proportional to the scanning step. The reason for this behaviour can be attributed to thermal accumulation due to the much greater number of passes needed to machine the same rectangular layer using small values of the scanning step. As a result, the irradiation time increases and a large amount of heat cannot be eliminated by conduction due to the low thermal diffusivity of PMMA.

Nayak, et al [10] stated that PMMA has the tendency to show a singular behaviour when subjected to CO₂ laser radiation, where it undergoes softening and degradation. The degradation initiates the formation of H₂ gas and the softening eases the gas expansion. This results in small bubbles production in the HAZ region, characterized by a thin layer of porous material.

Zhou and Mahdavian [11] showed that the effect of cutting speed was more significant than that of laser power on the depth of cut of PMMA. The variation in cut depth was more pronounced for cutting speed less than 20 mm/s. The study however did not consider the effect of assist gas for removing molten plastic. By neglecting the effect of assist gas

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pressure, the cut depth was found to decrease exponentially with cutting speed at various laser power ranging from 6 W to 60 W. In addition, a theoretical model was introduced to estimate the depth of cut as a function of material properties and cutting speed. The model however did not include the influence of laser power.

Yilbas, et al [12] examined CO₂ laser cutting of sheets of mild steel and titanium while varying the cutting speed along with the mixture of argon and oxygen gas as an assist gas during cutting. When the partial pressure of O₂ in the gas mixture was increased, the high temperature oxidation increases resulting in excess energy, increasing the rate of melting and evaporation. This also increases the plasma size and reduces the transmittance. When air pressure in the gas mixture was increased, the transmittance increases and the cutting quality improve.

Shashi Prakash et al. (2015) [13] investigated the theoretical models for predicted micro channel profile and depth have been proposed. Single pass Laser processing model had been proposed based on energy balance and two pass Laser process for micro channel fabrication produces smoother micro channel with better surface topography. Spectroscopic test were determined the absorptivity and simultaneous thermo gravimetric analysis test were determined the thermo-physical properties. Results revealed that the predicted models was used to find close agreement with the actual values.

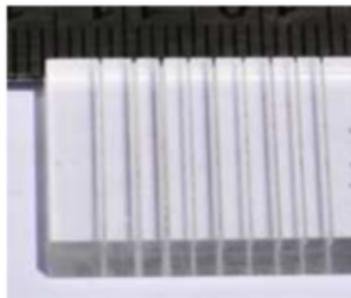


Fig. 4: Fabrication micro channel on PMMA sheet ^[13]

B. D. Prajapati, et al [14] studied the effect of laser machining processing parameters such as laser power, gas pressure, cutting speed and thickness effect on measured response such as surface roughness. The experiment was designed by Taguchi L₂₇ orthogonal array. Results revealed that the cutting speed and thickness of plate had high contribution on surface roughness for both materials.

L.D. Scintilla, et al [15] studied the influence of processing parameters and laser source type on cutting edge quality of AZ31 magnesium alloy sheets and observe differences in cutting efficiency between fiber and CO₂ lasers. It was also observed that fiber laser allows to obtain best quality of cutting edge and although dross height is lower for CO₂ laser cut, the attached dross on the lower part of the cutting edge is discontinuous, slightly adherent and easily removable. An increase in cutting speed has the effect of reducing the extension of striations, roughness and dross height.

Chen, et al [16] studied Grey relational analysis to optimize CO₂ laser cutting of 6 mm thick PMMA. By considering two performance characteristics such as high transmittance ratio and small surface roughness, the optimized parameters were determined at medium assisted-gas flow rate, minimum defocussing distance, low pulse frequency and high cutting speed. Of these factors, assisted-gas flow rate and beam defocussing distance have the dominant influence on the quality of cut surface.

H. A. Eltawhni, et al [17] studied the effect of process parameters such as laser power, cutting speed and focal point position effect on measured surface roughness, lower kerf and upper kerf. Results revealed that the roughness decreased as the laser power increased and it increased as the cutting speed increased.

Milos Madic, et al [18] studied empirical modeling of surface roughness in CO₂ laser cutting of mild steel using the multiple regression analysis (MRA) and artificial neural network (ANN). It can be observed that the surface roughness is highly sensitive to the selected laser cutting parameters. An increase in the cutting speed leads to the decrease in the surface roughness.

M. Boujelbene et al. [19] studied the CO₂ Laser cutting of 3 mm thick of titanium alloy sheet grade 5 Ti-6Al-4V. Presented a study to evaluate the effect of Laser power, cutting speed and gas pressure on heat affected zone and kerf width quality. Output variables were analyzed and optimized using the taguchi method. The Results revealed that the

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HAZ increased with Laser power increased and it decreased with cutting speed increased. The kerf width was proportional to Laser power and gas pressure also inversely proportional to the cutting speed.

H.A. Eltawahni, et al [20] presents a means for selecting the process parameters for laser cutting of MDF based on the design of experiments (DOE) approach, where CO₂ laser was used to cut various thicknesses of MDF panels. The process factors investigated are: laser power, cutting speed, air pressure and focal point position.

H.A. Eltawahni, et al. [21] studied the process parameters for Laser cutting of MDF based on the design of experiments (DOE). The process factors investigated were: Laser power, cutting speed, air pressure and focal point position. The effect of each factor on the qualities measures was determined. The Results revealed that the upper kerf decreased with cutting speed and air pressure increased, and it increased as the Laser power increased. The lower kerf width decreased with cutting speed increased, and it increased with Laser power increased. The ratio decreased with focal point position and Laser power increased.

Mahmoud Moradi, et al. [22] investigated by using design of experiments (DOE) with considering Laser cutting speed, Laser power and focal plane position as process input parameters and kerf geometry dimensions such as top and bottom kerf width, ratio of the upper kerf to lower kerf, upper heat affected zone (HAZ) and surface roughness of the kerf wall as process output responses. A 60 Watts CO₂ Laser cutting machine is used for cutting the injection molded samples of polycarbonate sheet with the thickness of 3.2 mm. The Results revealed that decreasing the Laser focal plane position and Laser power, the bottom kerf width will be decreased. Also the bottom kerf width decreased by increasing the cutting speed.

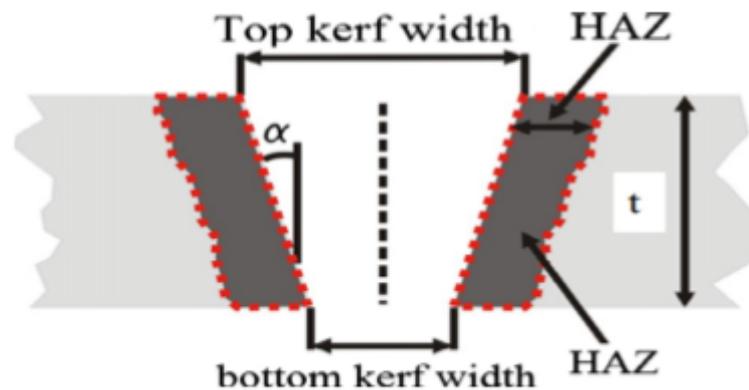


Fig. 5: Geometrical features of the cross section of the kerf ^[22]

A Parthiban, et al [23] investigated the Box- Behenken design for cutting of AISI 316L 2mm thickness stainless sheet. They developed a mathematical model kerf width for straight and curved profile through response surface methodology. The developed mathematical models for straight and curved profile have been compared. The numerical optimization technique has been used to find out optimum Laser cutting parameter for both straight and curved profile cut. Results revealed that the minimum of kerf width 0.3281 mm for straight profile and kerf width 0.3120 mm for curved profile. When the process parameters such as Laser power 2807.45 W, cutting speed 5500 mm/min and gas pressure 0.9 MPa.

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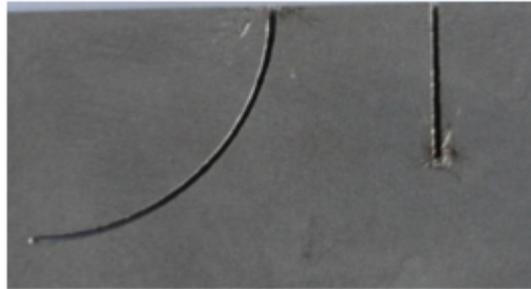


Fig. 6: Photo of straight and curved profile cut ^[23]

I. A. Choudhury, et al [24] had investigated about CO₂ laser cutting of three polymeric materials each with the aim of evaluating the effect of the main input laser cutting parameters (laser power, cutting speed and compressed air pressure) on laser cutting quality of the different polymers and developing model equations relating input process parameters with the output.

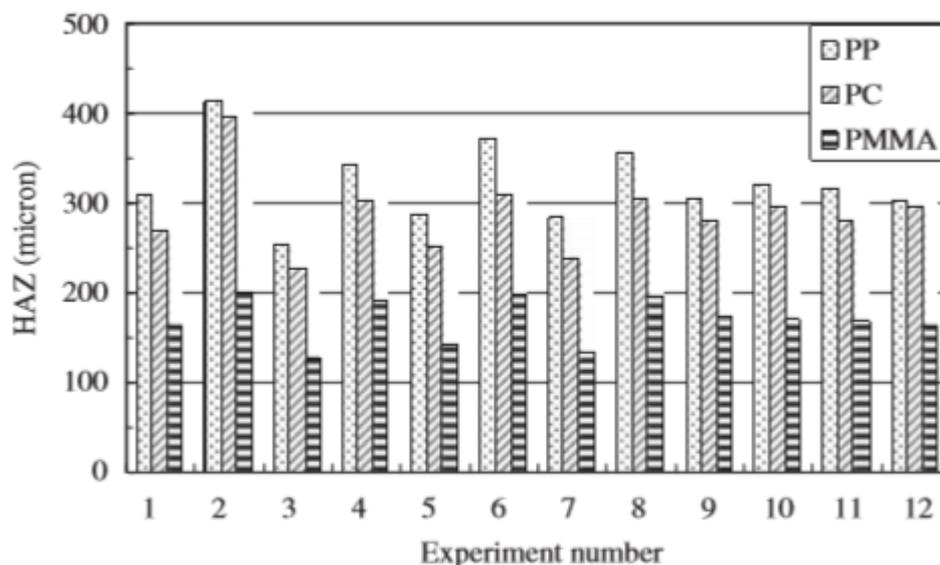


Fig. 7: dimension of HAZ (μm) for each type of polymer cut by laser ^[24]

J. Paulo Davim, et al [25] presents a preliminary study to evaluate the effect of the processing parameters (laser power and cutting velocity) under the quality of the cut for several polymeric materials.

B. Tirumala Rao, et al [26] presented work which aimed at studying the dynamic behaviour of melt ejection in laser cutting of titanium sheet for obtaining dross-free cuts with minimum heat affected zone (HAZ). The results reveals use of He as the shear gas brought about significant reduction in dross formation. Shear gas not only serves to drag the melt out of the kerf but also causes cooling of the melt front. Cooling effect of the shear gas becomes relatively more dominant at higher gas pressures. This effect seems to be responsible for relatively lower rise in maximum cutting speed at higher gas pressure while using air as the shear gas.

Davim et al. [27] evaluated the effect of cutting velocity and laser power on surface qualities of a two-dimensional irregular PMMA substrate, namely surface roughness, dimensional precision and HAZ. Nitrogen was used as an assist gas for the experiments at a constant pressure of 0.5 bar. It was found that the HAZ increases with laser power but

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decreases with cutting velocity. On the contrary, the surface roughness increases with a decrease in laser power and increase of cutting velocity.

Krzysztof Jarosz, et al [28] studied the effect of cutting speed on heat-affected zone (HAZ) and surface roughness in Laser cutting of AISI316L stainless steel. Test samples were cut with varying cutting speed, while other process parameters remained constant. Surface roughness of each test sample was measured in several places along cut depth. The Results revealed that the HAZ increased with cutting speed decreased. The highest reached cutting speed 16.5 mm/s produce cut surface with good roughness and negligible HAZ. The lower cutting speed 9.17 mm/s produces cut surface with lower roughness but visible heat-affected zone, approximately 20% of the cut surface. Lowest researched cutting speed 1.84 mm/s has no practical use.

K.F. Tamrin et al. [29] studied grey relational analysis to determine a single optimized set of cutting parameters for three different thermoplastic. The set of the optimizing processing parameters were determined based on the highest relational grade and was found at low Laser power (200 w), highest cutting speed (0.4 mm/s) and low compressed air pressure (2.5 bar). The influence of each cutting parameters on cut quality is also studied quantitatively using ANOVA technique. Results revealed that the Laser power has dominant effect on HAZ as compared to the cutting speed and air pressure for all thermoplastics.

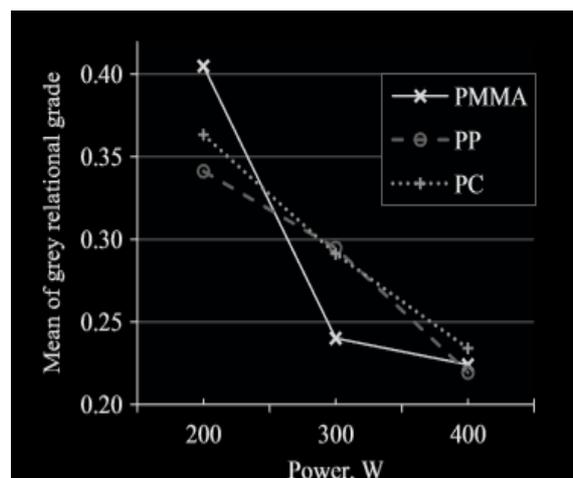


Fig. 8: Influence of Laser power on grey relational grade of different Thermo plastics ^[29]

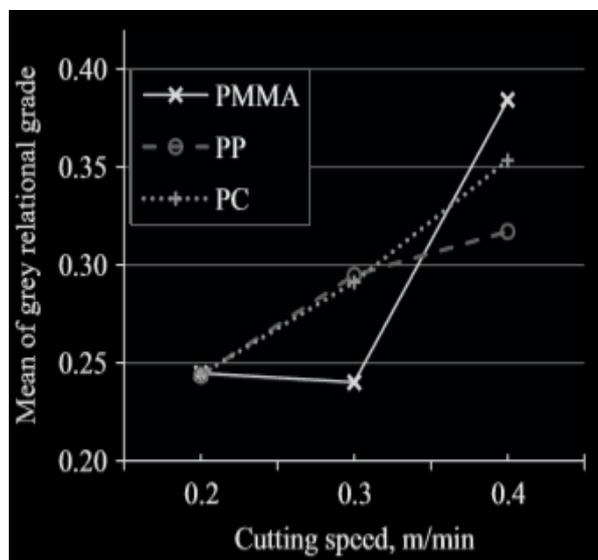


Fig. 9: Influence of cutting speed on grey relational grade of different thermo plastics ^[29]

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Abdul Fattah Mohd Tahir, et al [31] investigated of kerf width and HAZ of ultrahigh strength 22mnB5 steel cutting. Material cutting was conducted using a 4 kW CO₂ laser machine with 10.6 μm wavelength with the laser spot size of 0.2 mm. Also a response surface methodology using three level Box-Behenken design of experiment was developed with three factors of peak power, cutting speed and duty cycle.

Model equation was developed for each response based on equation (2) that consist of main factor effects, quadratic effect and interaction effect.

$$y = b_0 + \sum b_i X_i + \sum b_{ii} X_{ii}^2 + \sum b_{ij} X_i X_j + \epsilon \quad \dots\dots\dots (2)$$

Bhuvnesh Bhardwaj, et al [32] investigated the effect of Laser cutting parameters such as Laser power, cutting speed, focal point position and gas pressure on kerf width using the taguchi method L₁₆. The entire Laser cutting experiments was carried out on AISI304L stainless steel. The Results revealed that the kerf width increased with increased Laser power and gas pressure. The kerf width decreased with increased cutting speed and focal point position. Also found the cutting speed was dominating factor that affect the kerf width.

N. Rajaram, et al [33] studied 4130 steel were cut on a CO₂ Laser cutting system. The combined effects of power and feed rate on kerf width, surface roughness, striation frequency and the size of heat affected zone. Regression analysis was used to develop models that describe the effect of the independent process parameters on Laser cut quality. The Results revealed that the low power levels, increased feed rate led to a slight decreased in kerf width and a slight decrease in HAZ. At high power levels, increased feed rate with decreased in kerf width and a slight increase in HAZ. Increased feed rate with increased surface roughness and striation frequency. Power has a small effect on surface roughness, and no effect at all on striation frequency.

Ahmet Cekic et al [34] investigated mathematical models of value changes for surface roughness (Ra, μm) and heat affected zone width (HAZ, mm) during high-alloyed steel 1.4828 Laser cutting using oxygen as an assistance gas. Multiple linear regression analysis is used, with four independent variables that were varied at five levels. Following parameters were such as cutting speed (V), assist gas pressure (p), focus position (fs) and stand-off (Nd). The Results revealed that basis of the experimental data and mathematical models, optimum parameters of cutting high-alloy steel 1.4828 with thickness of 3 mm with CO₂ Laser with the assistance of O₂ as an assist gas in order of achieving a minimum width of cut, HAZ, as well as optimal surface roughness.

III. CONCLUSION

PMMA thermoplastic material can be cut by many methods but to obtain high accuracy and precision, laser cutting is the most convenient. The laser beam cutting process is characterized by large number of process parameters that determines efficiency, economy and quality of whole process and hence, researchers have tried to optimize the process through experiment based, analytical, and AI based modelling and optimization techniques for finding optimal and near optimal process parameters. It is commonly found that the laser engraved depth became deeper for either higher laser power or a lower feed speed ratio. Engraved depth increase at high laser power and for higher engraving speed, surface roughness decreases. Also for higher power, it is observed that HAZ is found to be more with slow speed and vice versa. Hence, it can be recommended to go for high power, low speed for achieving the required quality characteristics.

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