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Experimental and Statistical Analysis of Kerf Taper during CO₂ Laser Machining of Cylindrical Blind Pocket-Technical Paper

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ABSTRACT: Laser cutting is one of the most widely used thermal energy based non-contact type method to achieve good precise cutting of complicated shapes. The main objective of this work is to carry out parametric study for kerf taper angle which is the inherent characteristics during CO₂ laser machining of Polymethylmethacrylate (PMMA) material. The parameters to be varied are laser power, scanning speed and number of passes of laser beam probe. The influence of cutting parameters on the kerf taper angle will be studied. The full factorial methodology will be developed to decide the experimental runs for machining blind cylindrical pockets on PMMA material. The ANOVA will be performed to investigate the effect of the laser cutting parameters on the kerf taper angle during machining of cylindrical blind pocket on PMMA. The optimization of process parameters will be carried out through regression analysis. The model developed will serve as a base to predict the kerf taper angle by varying process parameters before actual machining is carried out.

KEYWORDS: CO₂ laser cutting, PMMA, Kerf Taper

I. INTRODUCTION

Laser which stands for Light Amplification by Stimulated Emission of Radiation, is an electrical optical device that produces coherent radiation. A laser is a device that creates and amplifies a narrow intense beam of coherent light. Nowadays Lasers are widely used in industry for cutting and boring metals and other materials it is used in surgery in communications, scientific research, and holography. They are an integral part of such familiar devices as bar code scanners used in supermarkets, scanners, laser printers, and compact disc players. Laser cutting devices are proving beneficial in a wide array of industries. The laser cutting method uses a non-contact approach when cutting the material. Due to this, the wear and tear associated with conventional methods is absent, preventing the product from any damage and deformation. The laser process also delivers a finish quality unmatched by any other process.

Among different types of lasers CO₂ and Nd:YAG lasers have low beam power, better efficiency and good beam quality. Because of material versatility, no change of tool or wear, high material utilization with production flexibility, high accuracy and edge quality, laser beam cutting appears to be superior to any cutting process whether traditional or non-traditional.

In the case of laser cutting of polymeric materials, Caiazzo et al. [2] Have presented the application of CO₂ laser cutting of three thermoplastic polymers of thickness ranging 2–10 mm. They examined laser power, cutting speed, gas pressure and thickness of work materials as the input cutting variables. They have found that laser cutting workability of polycarbonate (PC) was high, that of polypropylene (PP) was medium and that of polyethylene (PE) was low. The laser cutting process provides a good PMMA cutting face without ejecting debris. Wang et al. [3]. Davim et al. [7] evaluated the effect of laser power and cutting velocity on the quality of cut for different polymeric materials. They observed that

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laser cutting workability of PMMA was very high, PC was high, PP was medium and reinforced thermoset plastic was low. In investigating cutting quality of PMMA with CO₂ laser. Patel and Sanghavi [11] studied effect of process parameters such as feed rate, input power and process parameters input power is the most predominant parameter that affects the cut quality like kerf width and surface roughness using ANOVA. Dhaval P. Patel and Mrugesh B. Khatri [12] investigated CO₂ laser cutting process for Stainless Steel (S.S) and Mild Steel (M.S) and found that Kerf width generally increases with increase in assist gas pressure and laser power and decrease in cutting speed. Dubey and Yadava [11] proposed laser cutting of nickel-based super alloy sheet, using a hybrid Taguchi method and principal component analysis. Their report included discussion of the quality characteristics of kerf width, kerf deviation, and kerf taper. Yuan and Das [5] proposed an analytical model for low power CO₂ laser ablation of PMMA. The model included heat conduction as well as energy loss in the decomposition of PMMA. The model has been found to be suitable for sub-micron range micro channels of widths ranging from 44 to 240 μm and of depths varying from 22 to 130 μm . Samant and Dahotre [19] established that multi-pass processing results in minimum thermal damage and cracking. The basic reason for reduced thermal damage may be attributed to lower thermal energy deposition in each pass compared to single-pass processing. In spite of significant advantages of multi-pass processing for microchannel fabrication on PMMA, no detailed experimental study of multi-pass CO₂ laser microchanneling on PMMA. Eltawahni et al. [8] have investigated the effect of CO₂ laser cutting of ultrahigh molecular weight polyethylene. They reported that the focal point position has the key role on the kerf size and on the ratio between the upper kerf to the lower kerf. They listed the optimum sets of cutting conditions, which would lead to best quality and another list for minimum cost. Kurt et al. [10] have concluded that the laser power and cutting speed must be regulated and optimized in order to obtain not only the desired dimensions but also optimum surface quality and roughness values. The effect of gas pressure on desired dimensions was found to be negligible. Better surface quality was obtained with low frequency of striation. However, very few attempts were made to minimize the kerf taper on PMMA material through CO₂ laser cutting.

II. EXPERIMENTATION AND MEASUREMENTS

A 25W CO₂ laser machine is used for the maximum engraving speed of Laser Pro Mercury is 1066 mm/sec (42inch/sec). When engraving an A4 (18 x 28 cm) size square with 250dpi at full speed, it takes Laser Pro Mercury about 18 minutes to complete. Compressed air was used as shield gas. The shield gas in CO₂ laser cutting primarily removes molten material from the cut zone and at the same time protects the lens from smoke emitted due to vaporization of the material. Moreover, it enables effective coupling of the laser beam with the parent material.

III. MECHANICAL AND THERMAL PROPERTIES OF THE POLYMER

| Polymer | Yield Strength (MPa) | Ultimate Tensile Strength | Density (g/cm ³) | T _{mp} (°C) |
|---------|----------------------|---------------------------|------------------------------|----------------------|
| PMMA | 53.8–73.1 | 48.3–72.4 | 1.19 | 160 |

Table 1

Polymethylmethacrylate (PMMA) is a hard and stiff material with a very good weather resistance property having the chemical designation as C₅H₈O₂. The material is clear as glass and extensively used for optical applications. It has good tensile and flexural strengths. The impact resistance is 10 times higher than glass. PMMA has the highest surface hardness of all common thermoplastics and is also highly scratch resistant. All three materials are in sheet form with a thickness of 6 mm. These polymeric materials are widely used in the manufacturing industries and have wide

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applications in optics, vehicles, electrical engineering appliances, office equipment's, medicine and others.

IV. MATERIAL (PMMA)



Figure 1Machined profile

V. INPUT PROCESSING VARIABLES

Table 2

Levels of independent input machining parameters.

| Factor Designation | Level of factors | | | | |
|---------------------|------------------|----|----|----|----|
| POWER (P) % | 55 | 64 | 73 | 82 | 91 |
| CUTTING SPEED (V) % | 19 | 28 | 37 | 46 | 55 |
| NUMBER OF PASS (n) | 1 | 2 | 3 | 4 | 5 |

The experiments have been carried out according to the full factorial method. Response surface modeling was used to establish the mathematical relationship of kerf taper and the input machining parameters (laser power, laser cutting speed and number of pass). The relationship between the response and the input independent machining parameters can be represented by the equation given as

$$\tan \alpha = \left(\frac{K_T - K_B}{2d} \right) \text{----- (1)}$$

During laser beam machining, the major cut quality characteristics are kerf width, kerf taper, surface roughness and HAZ. The kerf taper angle is one of the most important quality characteristics because it is one of the measures for the geometrical accuracy of the machined cavities. Due to Gaussian beam distribution of the laser, the kerf taper is the inherent cut characteristics obtained on the machined surfaces as shown in Fig. The kerf taper angle (α) is calculated from the formula given by Eq. 1The experimental runs were decided with the help of full factorial design matrix as shown in Table 5.6 Due to non-linear characteristics of laser beam and complex behavior of the kerf taper angle with the control parameters, the number of levels of each factor was taken as 5. Where, K_T represents upper kerf width, K_B represents lower kerf width and d represents the depth of the machined cavities. The values of K_T , K_B and d are measured with the help of Dr. PICZA scanning software. The details.

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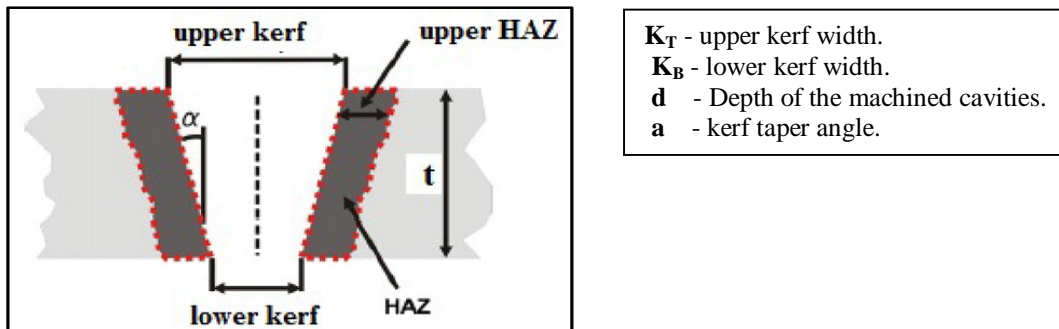


Figure 2 Schematic diagram of kerf taper

VI. EXPERIMENTAL SETUP



Variation of kerf taper with number of passes

The variation in the kerf taper angle with number of passes for constant power and variable speeds are shown in Fig. From Fig. (a), it is found that when the power is kept at high value (i.e $P=91\%$), a decrease in the value of kerf taper angle is observed for low speed (i.e $V=19\%$). With an increase in the values of speed, the kerf taper also increases gradually. The high laser power results in more transfer of heat energy to the profile which evaporates more amount of material. On the contrary, the lower speed also plays a significant role reducing the kerf angle along with higher power. The low speed gives much time to the laser to remain in contact with the profile, thereby; the heat concentration by the laser is more focused resulting in low kerf taper. Again, for the same constant power of 91%, it is found that as the value of speed goes on increasing, kerf taper also goes on increasing. The reason for the increase in the kerf taper with increase in speed is that the heat concentration by the laser goes on decreasing resulting in less evaporation of material. This results in an increase in the kerf taper gradually. Same trend of observations are seen in Fig. (b), (c), (d) and (e). It can be seen that as the value of power goes on decreasing, there is an increase in the value of kerf taper angle for constant variation of speed.

The number of passes of the laser probe also plays a significant role in the kerf taper variation. It is seen from the trends that there is a linear relation between the kerf taper and the number of passes. As the number of passes goes on increasing, the kerf taper goes on decreasing for constant power and variable speed. With an increase in the number of passes, the stand-off distance goes on increasing resulting in less supply of heat energy to the profile. This results in

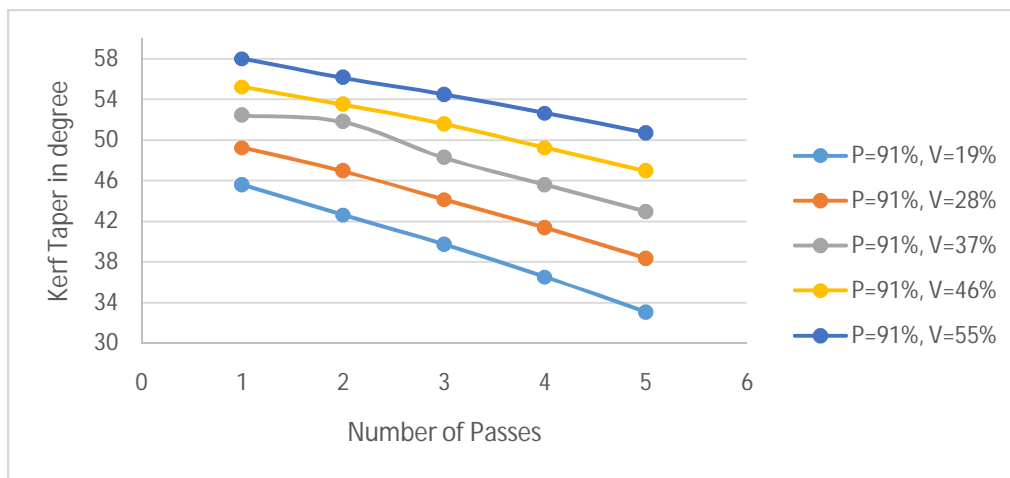
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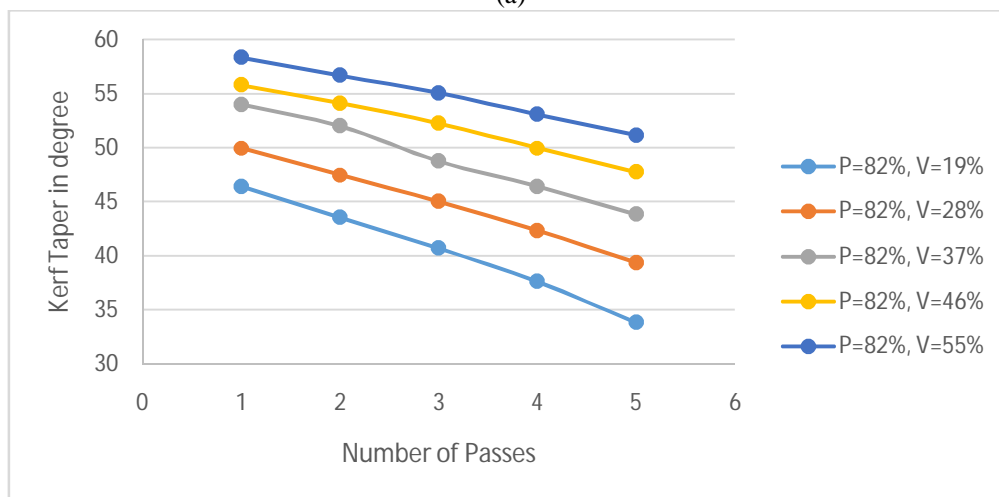
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less evaporation of material producing small kerf tapers as compared to first pass. The average kerf taper for high power (i.e $P=91\%$) and low speed (i.e $V=19\%$) is found to be 39.5° whereas for low power (i.e $P=55\%$) and high speed (i.e $V=55\%$), the average kerf taper is found to be 56.4° . Hence, it can be said that for minimizing the kerf taper, the value of power should be high and the speed should be kept low with high number of passes.



(a)



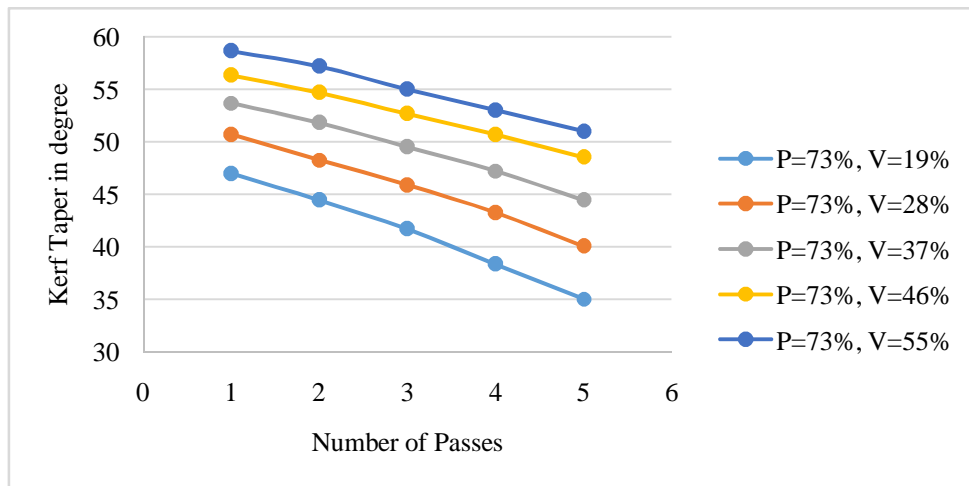
(b)

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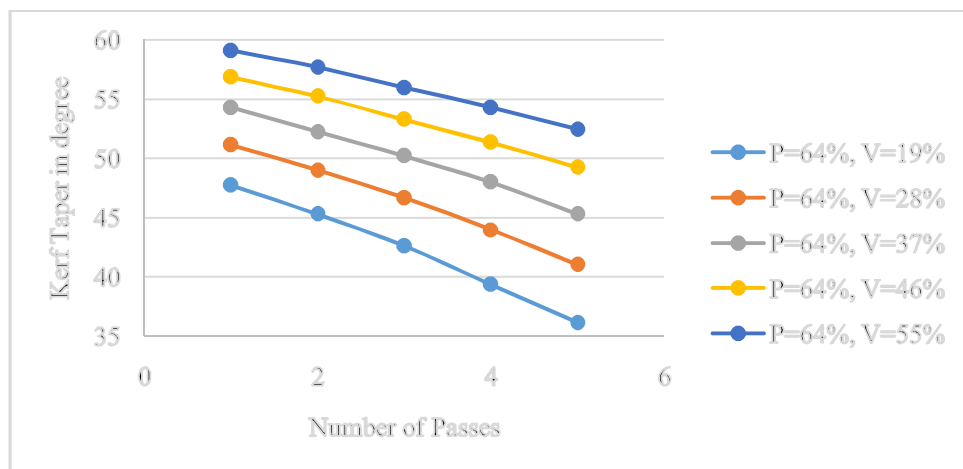
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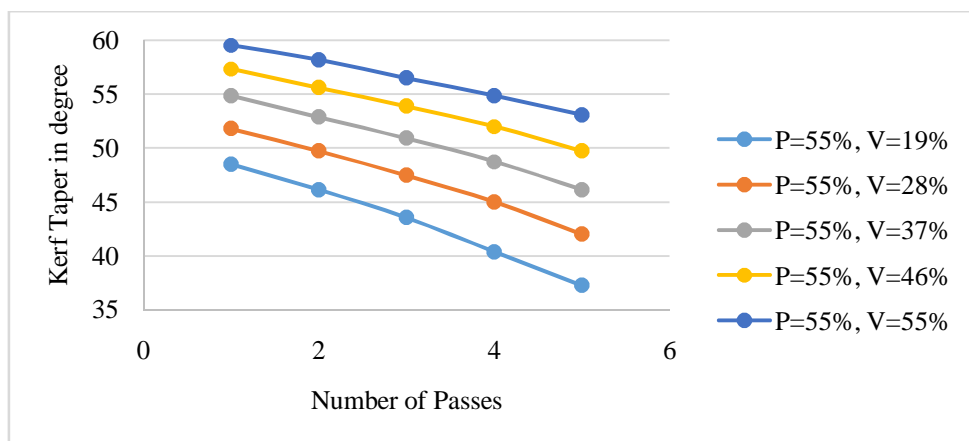
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(c)



(d)



(e)

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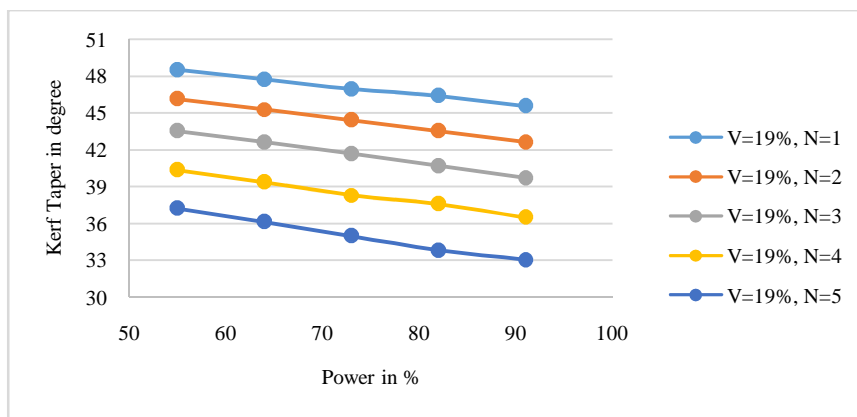
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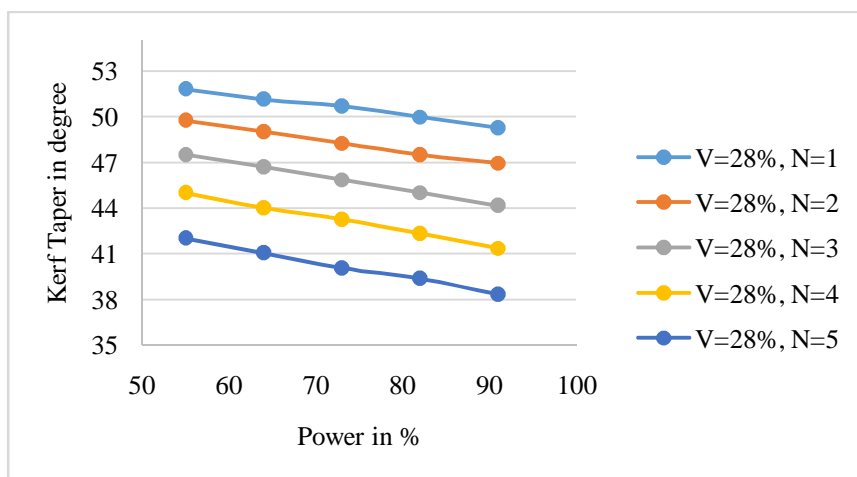
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Variation of kerf taper with laser power

The most parameter is the laser power which significantly contributes to the kerf taper angle. Fig. shows the variation of kerf taper with laser power for 5 numbers of passes with constant speed. From the graph (Fig. (a-e)), it is found that kerf taper angle is significantly reduced with increase in laser power. During the high power setting, the heat supplied by the laser beam penetrates maximum through the thickness of the profile. This results in wider kerf with low kerf taper. Consequently, the material removal rate increases during high power operation which reduces the taper formation. As shown in Fig. (a), it can be seen that the kerf taper is minimum for low speed, high power and more number of passes. As the power goes on decreasing for the same low speed and with the decrease in the number of passes, the kerf taper increases gradually. The minimum taper angle is found to be 33° for 91% power, 19% speed and 5 numbers of passes whereas the maximum taper angle is 49° for 55% power, 19% speed and 1 number of pass. Similar types of trends are observed in the Fig. 8 (b), (c), (d) and (e). The increase in the cutting speed for the same variation of power and number of passes results in increase in the kerf taper angle of the profile. Due to the higher cutting speed, the laser beam probe moves faster over the profile such that less time is achieved at a single location. This results in higher kerf taper as the beam energy absorption time is very less due to which the heat is not fully transmitted over the thickness of the profile. For higher speeds shown in Fig. 8 (e), the maximum kerf taper is found to be 60° while minimum kerf taper is 50° . Hence, it can be said that smaller kerf taper can be achieved at higher laser power, lower cutting speed with higher number of passes.



(a)



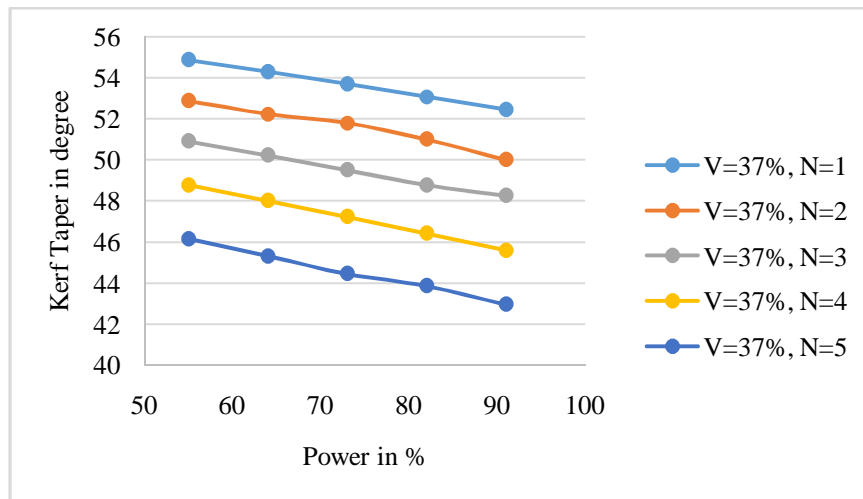
(b)

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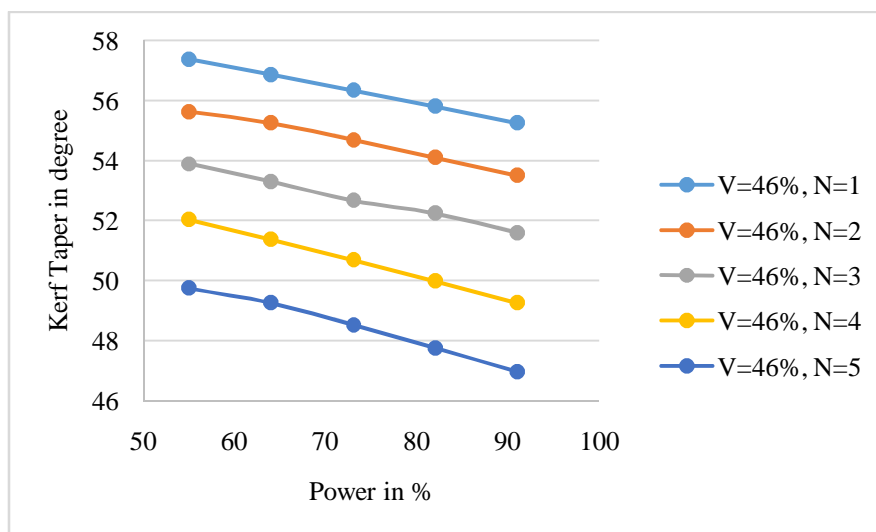
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(c)



(d)

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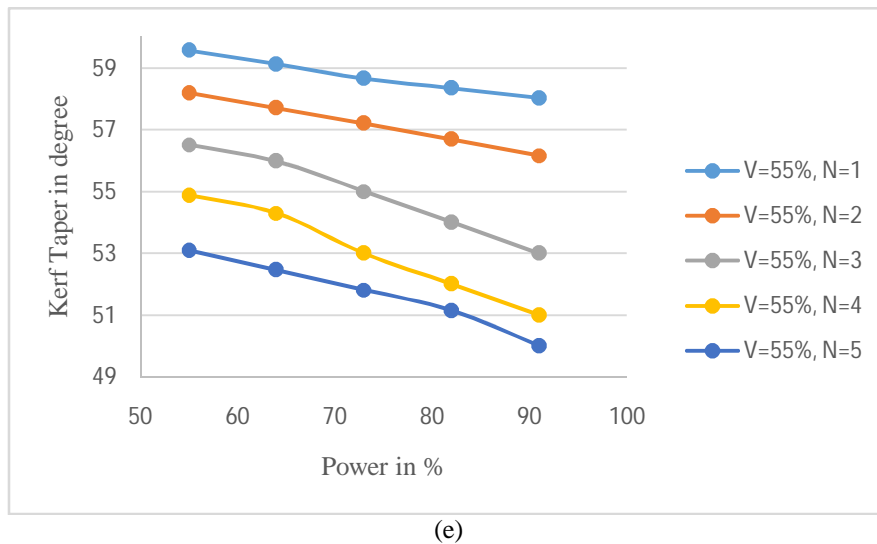
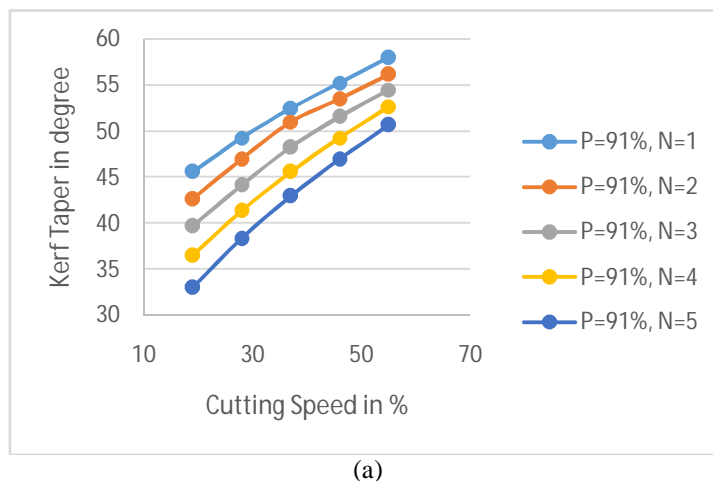


Fig. Influence of laser power on kerf taper (a) V=19%, (b) V=28%, (c) V=37%, (d) V=46% and(e) V=55%

Variation of kerf taper with cutting speed

Though laser beam power is the most significant process parameter affecting the kerf taper, the cutting speed also plays an important role in determining the kerf taper characteristics. The variation of kerf taper with cutting speed for constant power with 5 numbers of passes is shown in Fig. The increase in the cutting speed for constant power (i.e P=91%) with 5 numbers of passes results in a linear increase in the kerf taper angle as shown in Fig. (a). The minimum kerf taper comes to be 46° (at V=19%) and the maximum value comes to be 58° (at V=55%) for first pass. Subsequently, as the number of passes goes on increasing, the kerf taper is found to be decreasing gradually. The value of kerf taper is found to be 33° (minimum) at V=19% and 51° (maximum) at V=55% for fifth pass. Similar types of trends are observed for other values of power as shown in Fig. (b-e). It is observed from the trends that higher cutting speed yields larger kerf taper as compared to lower speeds. The reason behind this trend can be highlighted with the argument that as the cutting speed increases; the rate of laser energy available to the profile section reduces due to less interaction of the beam with the surface. This results in lower rate of temperature rise over the surface as well as the diffusion energy transfer in the depth direction which give rise to higher kerf taper.

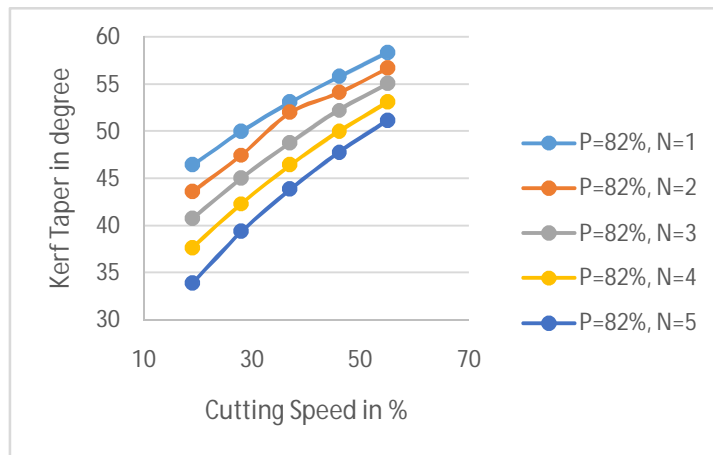


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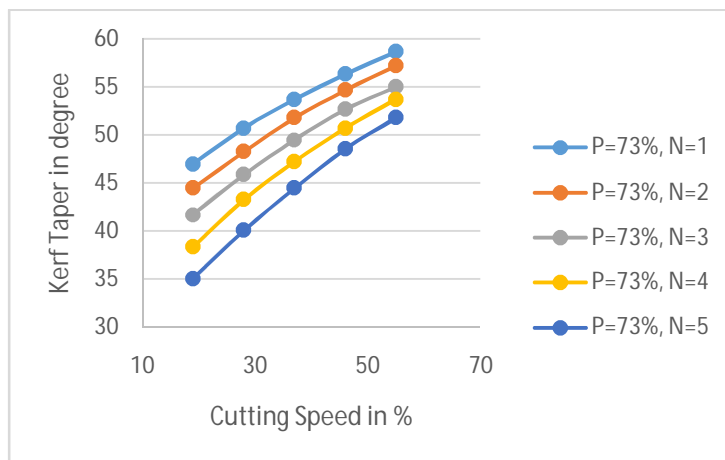
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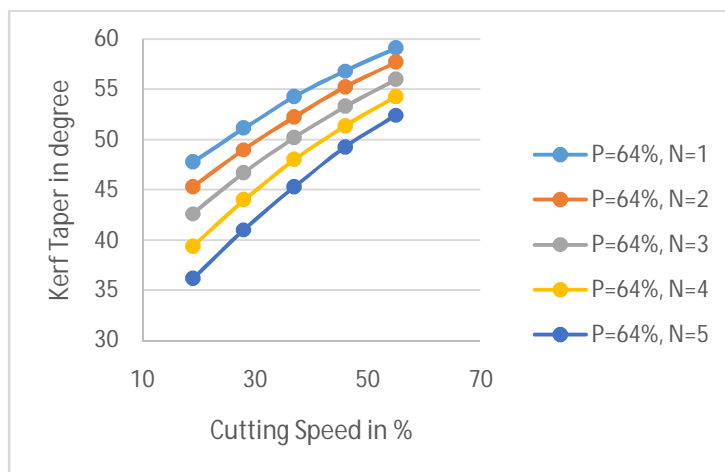
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(b)



(c)



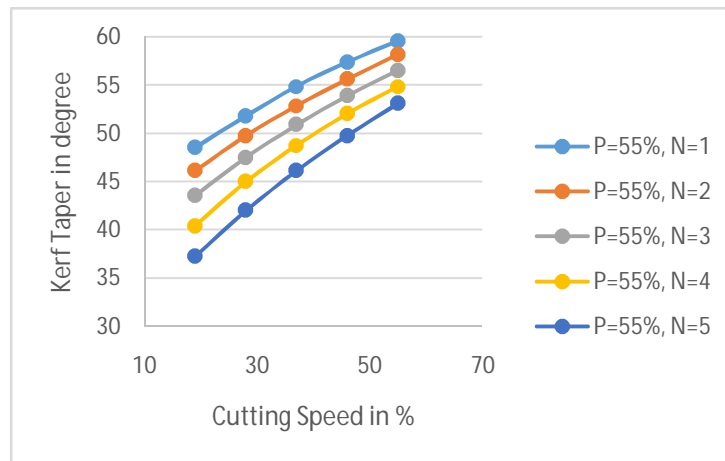
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(e)

Fig. Influence of cutting speed on kerf taper (a) P=91%, (b) P=82%, (c) P=73%, (d) P=64% and(e) P=55%

VII. SCANNED MACHINE PROFILE

Laser machining of PMMA (6 mm thickness) was carried out for different combinations of power, speed and number of passes (shown in Table 1) according to full factorial methodology. Profile of the machined cavities was carried out on the needle scanner. The machined profiles obtained on the needle scanner are shown in Fig. It can be readily seen from Fig. (a) That as the number of passes goes on increasing, the depth of cavity also goes on increasing for various parametric combinations of power and speed. Also, it is observed from Fig. (e) that with decrease in the power results in lowering the depth of cavity. This may be due to the fact that low power does not provide sufficient beam energy to evaporate the material for the same number of passes and the cutting speed.

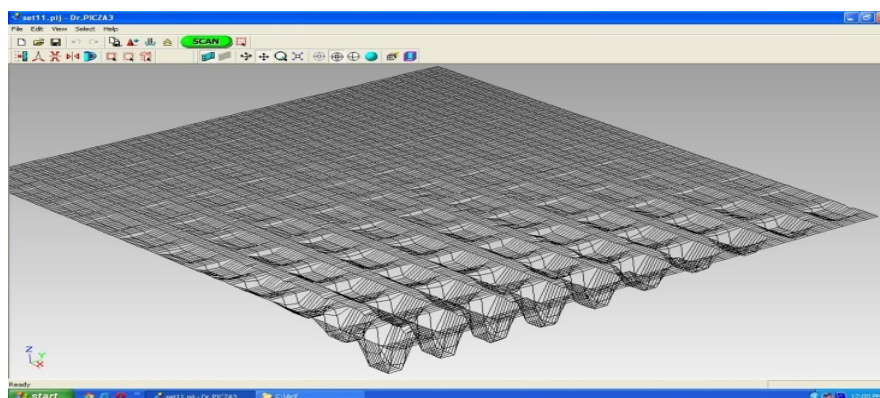


Figure 5 Scanned machined profile

VIII. CONCLUSION

1. Laser beam power has a significant effect on the kerf taper angle. An increase in the power results in a significant reduction in kerf taper angle.
2. Cutting speed also plays a major role in kerf taper formation. A decrease in the value of cutting speed results

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in minimization of kerf taper.

3. Number of passes of laser probe also has a significant influence on the kerf taper. With an increase in the number of passes, the kerf taper is found to be decreasing for constant power and speed setting.

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