

Formation of microgrooves on glass and PMMA using low power CO₂ laser

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This article is aimed to present an improvised technique for inducing periodic structures on glass and Polymethyl methacrylate (PMMA) using low power CW CO₂ laser. Glass processing methods are widely recognized as engraving, drilling, cutting, and marking. In this current investigation, a focused laser beam with varying laser power of 0.8W to 2.5W was targeted to form the regular and tidy periodic structures on glass and PMMA. The writing speed is varied from 0.5 mm/s to 4.0 mm/s. The emergence of micro grooves is very sensitive to laser power and scanning velocity, therefore the depths of microchannels have been discussed in terms of these parameters. The XYRIS 2000 CL 3D surface profiler has been used for analyzing glass profile while scanning electron microscope SEM has been used for analyzing profiles of PMMA. In order to achieve the larger channel depth, the low power and low scanning speed has been used. For machining PMMA the depth of trenches is found to be nearly 2mm which is nearly cutting depth. The channel depth of PMMA has increased when the writing speed is decreased. A sub-micron grating structure on glass with the period of 1μm has been observed having depth of 1.5μm. Moreover the optimum condition for laser power and scanning speed is also achieved.

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1. Introduction

Laser micromachining for non-metallic materials such as soda–lime glass and Polymethyl methacrylate (PMMA) are widely studied by using femtosecond laser[1]. Laser micromachining is a promising technique for the fabrication of periodic structures and polymer devices employing microchannels due to the precision, reliability and contactless processing[2]. Recently many studies have been carried out for the fabrication of microchannels on glass and PMMA[3]. For the formation of periodic structures, several techniques had been employed such as lithography[4-5], holography [6] and etching [7-8]. The desired periodic pattern on workpiece depends on laser parameters such as scanning speed, laser power and focal length. UV and near IR lasers are extensively used for the machining of non-metallic materials (soda lime glass and polymer) and fabrication of microfluidic devices with low absorption rate in the visible wavelength range [9]. Microfluidic devices are hence frequently used for integrated circuits in microelectronics and for biological and chemical analysis [10].

The fabrication of microgrooves on polymers for microfluidic devices depends on input laser parameters and interaction time [11]. Furthermore, laser ablation brings lots of potential advantages such as simplicity, flexibility and high speed of the process, over the other conventional micro fabrication techniques [12]. Fabrication of microgrooves and development of model for measurement of penetration depth has been carried out by Zhao [13] and Buerhop [14]. The earlier techniques

used for the microfabrication usually consist of complex optical arrangements which are difficult to illustrate the complete fabrication mechanism as well as the cost of production is found to be much higher. The mask based micromachining methods [15-16] are generally limited due to their specific pattern availability hence are not suitable enough for introducing variety of shapes in patterns. A CO₂ laser with a wavelength of 10.6μm for the fabrication of microstructures looks challenging at first sight though the fabrication process is still not completely understood. The direct laser writing scheme enables the micromachining to be free of any complex optical arrangements used in other conventional methods. Therefore, this current study introduces a simple, effective, low cost and maskless direct writing method based on single pass. The surface morphology with progressive changes has been effectively carried out by using low power CO₂ laser where the profile size is reduced to even much smaller than the original wavelength of the CO₂ laser.

2. Experimental setup

The experimental setup for laser induced periodic structures consists of low power 10W CW CO₂ laser operating at the wavelength of 10.6μm with corresponding photon energy of 0.12eV. Figure 1 shows the schematic of laser system used for micromachining. The beam is polarized at TEM₀₀ gaussian temporal mode. The theoretical spot size can be obtained from the relation

$M^2=1.3$. The laser beam is directed by turning mirror at 90° towards the laser beam nozzle which has a ZnSe lens of 25mm of focal length. The system consists of rectangular xy stage with translational speed of 0-5mm/s which is controlled by computer program (MEOS). A laser is excited by the mixture of three gases (N_2 , He and CO_2). The maximum output power for this system is 10W which is measured by using Ophir power meter ranging from 0-30W. The upper surface of the target is parallel to the beam waist. The optimum value of the beam waist can be obtained by rotating the laser nozzle to either clock wise or anti-clock wise direction. The laser system is designed to

operate in multipath scanning method as it moves to various paths in overall scanning.

In this study, two materials are used such as soda lime glass and Polymethyl methacrylate (PMMA). The target materials glass and PMMA are submitted to multipath scanning with the interaction area of 10mm x 10mm x 1mm and 3.8mm x 5mm x 2mm respectively. The glass was carefully cleaned in ultrasonic bath with acetone and then ethanol while PMMA by detergent. The surface morphology is carried out by using Hitachi tabletop scanning electron microscope (SEM) TM 3000 and surface profiler (taicaan 2000CL 3D).

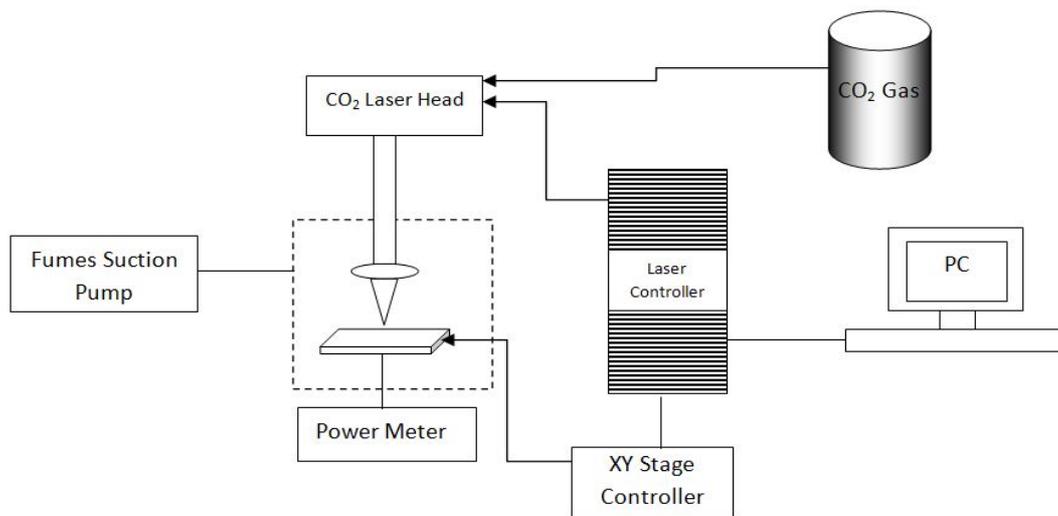


Fig.1. Schematic for periodic structures formation

3. Results

Several experiments have been performed to achieve the optimum condition for inducing microstructures. The experiments were performed by moving the sample under the laser irradiation followed by tuning the sample with 90° , then moving sample again under the laser irradiation. When the low power CO_2 laser is focused on the glass workpiece, two tidy periodic structures have been formed named as pattern 1 and pattern 2 as shown in the Fig.2.

From pattern 1, Fig.2, a small portion has been taken for analysis; this small patch of pattern 1 is divided into further three trenches namely (A, B and C) which are indicated in the dotted square boxes as shown in the Fig.3 Table 1 shows the irradiation processing parameters for patterns 1 and 2 which are essential for obtaining optimum condition.

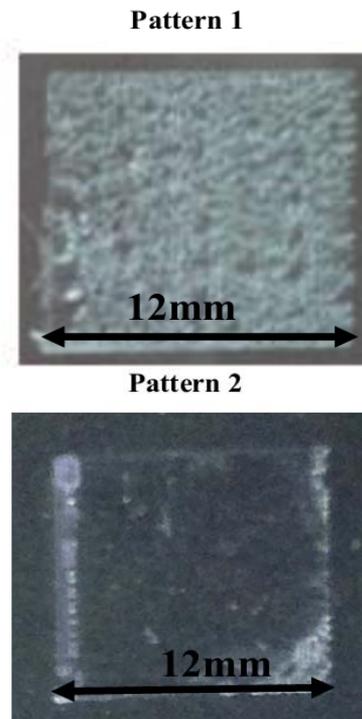


Fig.2: Formation of microstructures on glass substrate

Table 1. Processing Parameters for Pattern 1 and 2.

Processing Parameters	Pattern 1			Pattern 2
	Trench A	Trench B	Trench C	
Focal Spot Size (µm)	30	30	30	30
Laser Power (W)	1.30	1.35	1.40	0.7
Scanning Speed (mm/s)	3	3	3	3
Focusing Distance (mm)	20	20	20	20
Vacuum for Laser (mbar)	24.60	25.0	25.8	22.7
Tube Current (mA)	35	35	36	35
Tube Voltage(V)	2.0	1.98	1.95	1.75

The area for analysis is shown in the Fig. 3 is in the form of dotted box which has been magnified further in Figure 3(b), (c) and (d) to clearly indicate the surface profile region of trenches (A, B and C). For each trench, the surface profile has been taken separately and analysed. These successive straight trenches are about 1mm apart by one single pass and translational speed of 3mm/s. The structures are formed when the laser energy is above the threshold corresponding to the ablation threshold which is the minimum amount of power that is able to induce structure on material.

Fig 4(a) shows the profile for Trench A of pattern 1. It can be seen that the depth and width of trench is found to be 33.37 and 18.5 µm respectively. The laser power for the trench A is taken as 1.3 Watts. The shape and size of the profile is influenced by focal length of the lens. Figure 4(b) shows the Trench B profile of the pattern A. In this measurement, the depth and width of the fabricated microstructures is found to be 35.18 and 21.80 µm respectively. Fig 4(c) shows the 2D profile with the uniformity and smoothness along the trench B and the process involves precise arrangements of input parameters like laser power, scanning speed and distance of the lens to the workpiece.

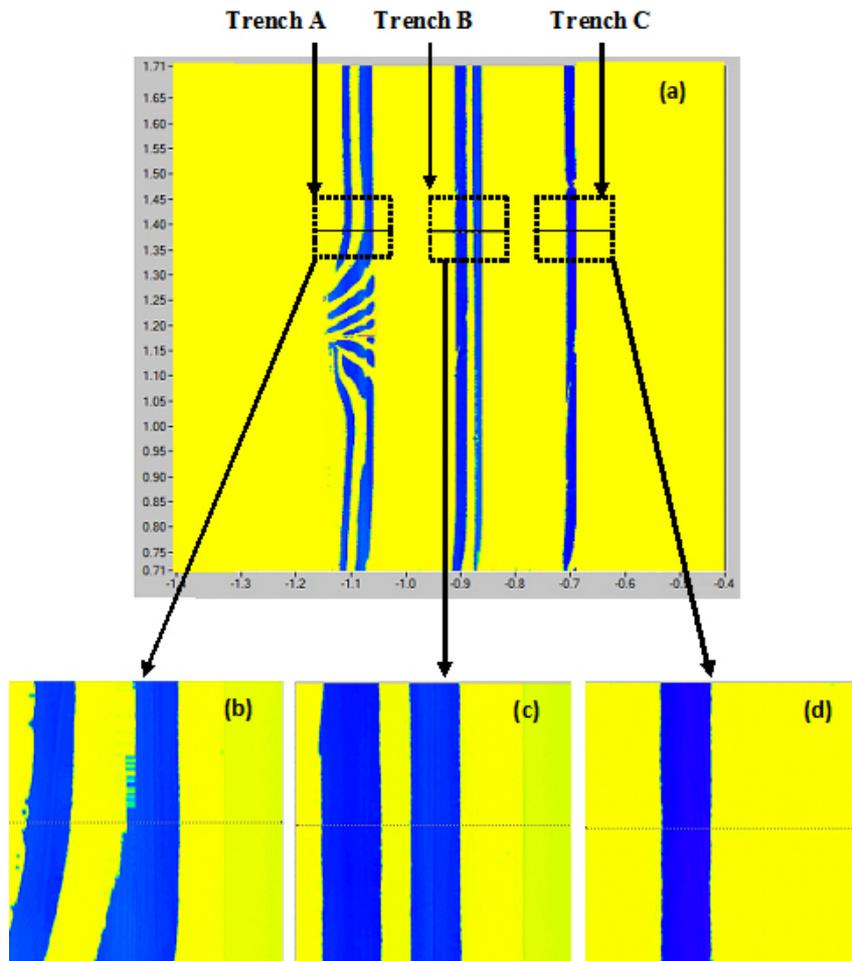


Fig.3(a). Micrograph of Pattern 1; (b), (c) and (d) are magnified Trenches.

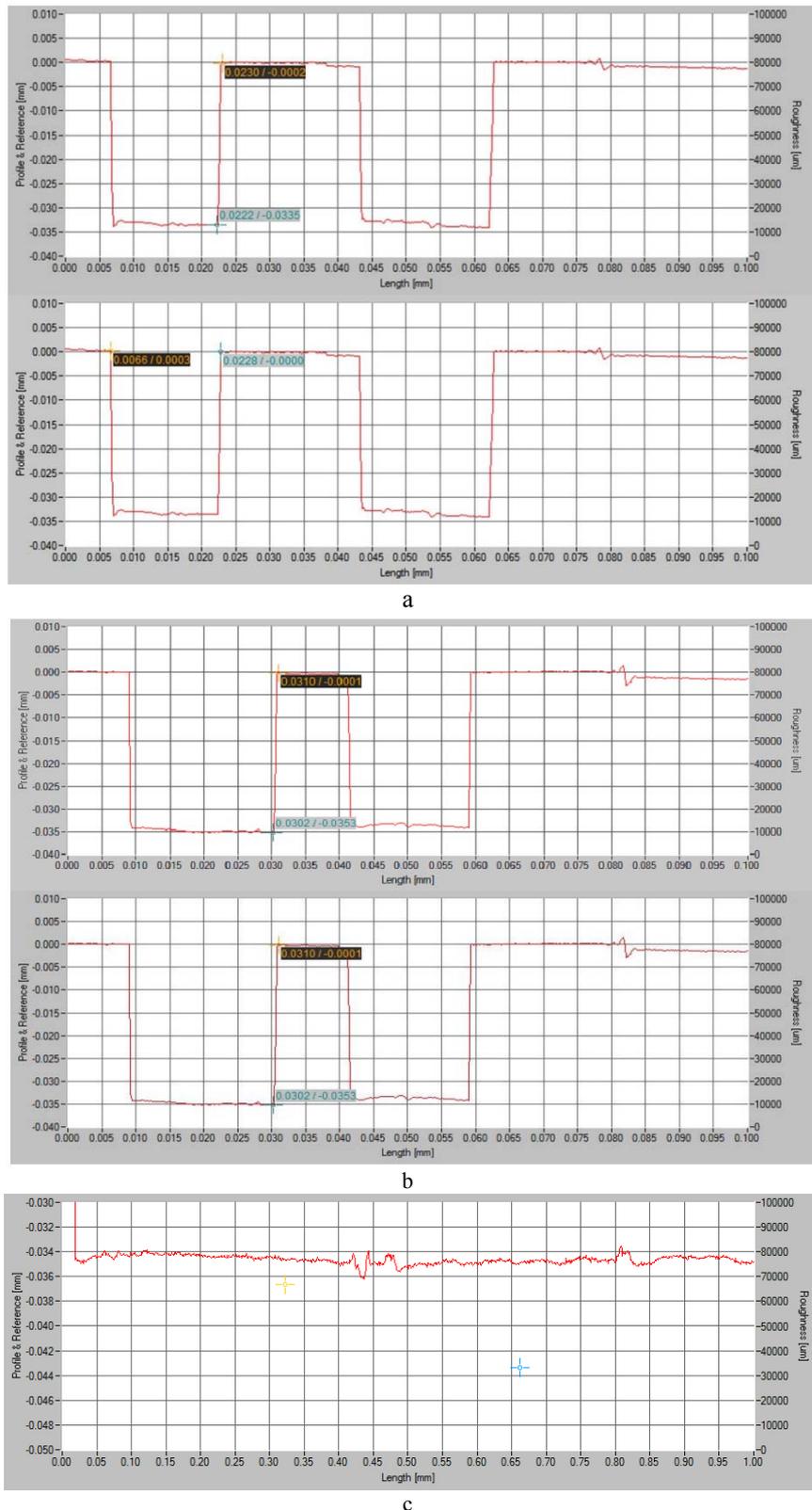


Fig.4 (a): Measurements for depth and width of Trench A, pattern 1, (b) Measurements for Depth and Width of Trench B, pattern 1, (c) 2D profile of Trench B, pattern 1.

The edging effect occurred in this measurement shown in Fig. 4(d) is due to lower data spacing in y-direction. The overall line spacing is approximately 10 microns for all three trenches. The sample spacing for x-

direction is taken as 0.2µm and for y-direction it is taken as 1µm. The total area under observation for this trench is 100µm x 100µm.

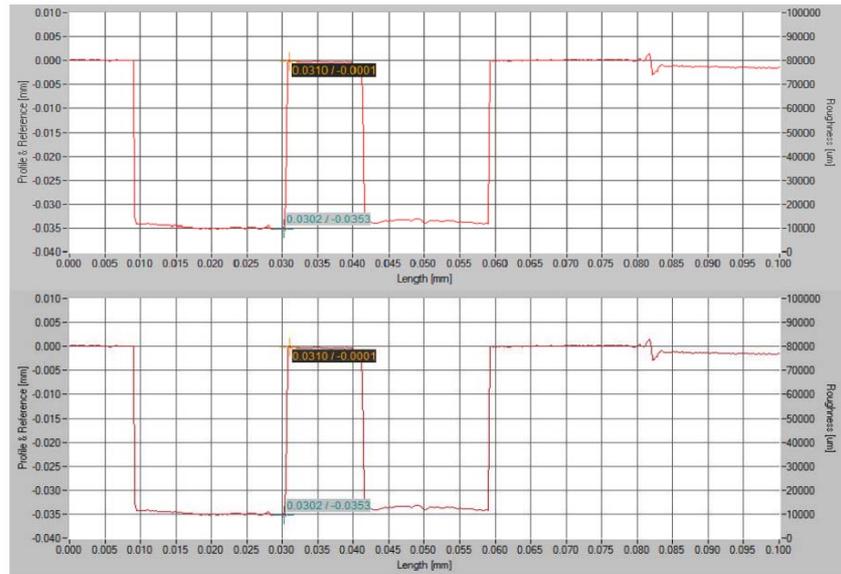


Fig.4 (d): Measurements for depth and width of Trench C, pattern 1.

Fig 4(d) shows the surface profile for trench C of pattern 1. A single trench has been observed by single laser pass utilising laser power of 1.3W. The scanning speed in this case is taken as 3mm/s. Table 2 shows the processing parameters for trench A, B and trench C. In this measurement the depth and width of the fabricated microstructures is found to be 37.35 and 18.20 µm respectively. A small variance is observed in the measurements taken for trench A, B and C which is shown in Table 2.

Table.2. Profile features for tranches (A, B and C), pattern 1.

Trench No	Width (µm)	Depth (µm)	Period (µm)
A	18.50	33.37	52.37
B	21.80	35.18	47.18
C	18.20	37.35	-

Fig 5 shows the 3-D profile of pattern 2. In pattern 2, the lowest power of 0.7W has been used with the scanning speed of 3mm/s. The machined area undergoes single pass and it is such region where the profile obtained has period less than the wavelength of CO₂ laser. The surface morphology has been examined by taicaan surface profiler taicaan 2000CL 3D.

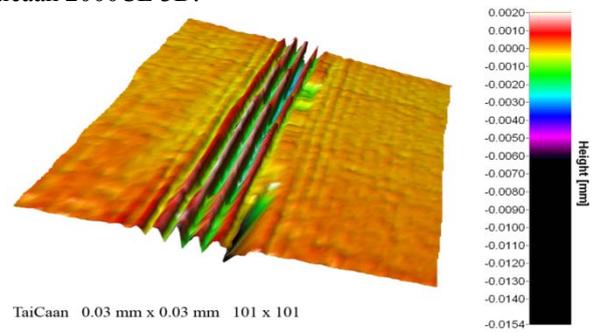


Fig. 5. Cross-sectional 3-D Profile of formed structure for pattern 2

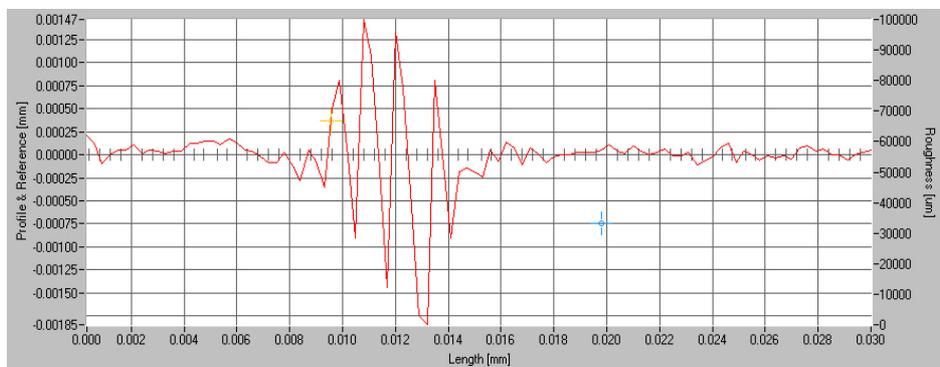


Fig. 5 (a). Graphical representation of formed structure for pattern 2

Fig.5 (a) shows the image of the graph obtained from, Taicaan surface profiler for CO₂ laser induced periodic

structures. The pattern observed here has the period of 1µm whereas the amplitude is 1.5µm. This is the

minimum amount of period obtained so far using direct CO₂ laser irradiation.

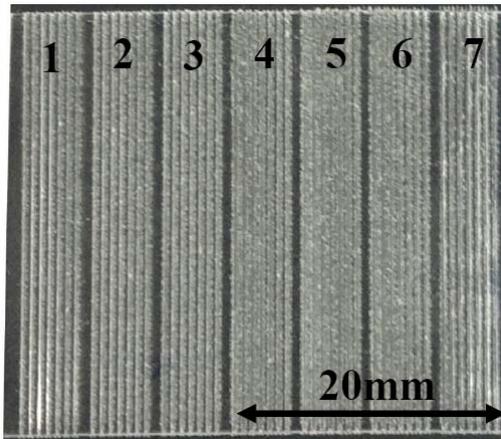


Fig.6. Micro-channels on PMMA (Patterns 1-7)

Fig 6 shows the image of micro-channels formed on Polymethyl methacrylate (PMMA) using direct CO₂ laser writing method. Four pieces of PMMA having 2mm of thickness and length of 4x5mm have been taken. Laser scanning speed was varied from 0.5 mm/s to 4.0mm/s. The laser power was varied from 1W to 2.5W. The first sample was treated with the scanning speed of 0.5mm/s to 4.0mm/s keeping the power constant for the first patch of grooves. The groove density for above samples is 7 per 5mm. The method used for glass and PMMA is same but with different laser power and scanning speed. In the first patch of the Fig 6, the scanning speed is taken at 4mm/s which is reduced to 3.5mm/s in the 2nd patch and so on for other patches. The surface morphology and cross-sectional depth of the each groove has been taken by SEM. The graph showing relationship between laser scanning speed and groove depth is described in Fig 7.

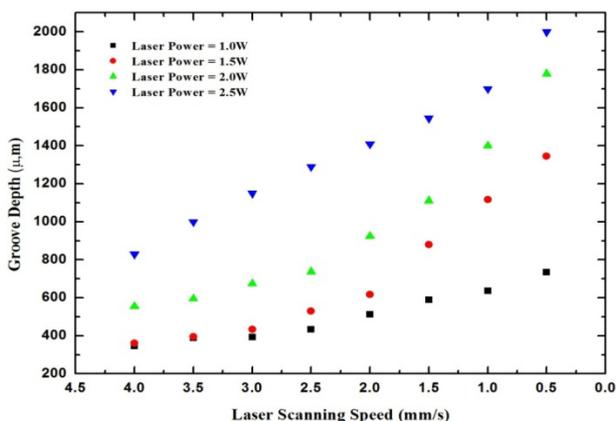


Fig.7. Depth of micro-channel vs. laser scanning speed

Fig 8 shows the cross-sectional surface morphology of formed microchannels on PMMA. Since the profile of the CO₂ laser beam is gaussian, this resembles the shape of the grooving Profile found for TEM00 gaussian mode.

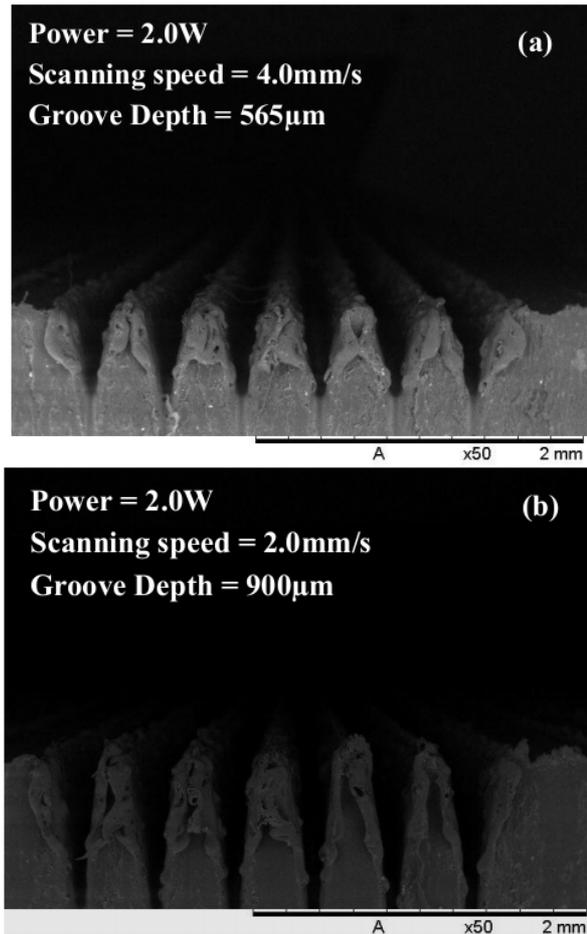


Fig. 8 (a), (b). SEM image of Cross-sectional surface morphology of formed Trenches

4. Discussion

When the CO₂ laser is focused on the glass workpiece; it is mostly absorbed and results in heating up the material. The heating up of the material created the heat affected zone in the interaction area of the workpiece. The micromachining of glass and PMMA is efficiently done using focusing method where the beam is focused on the material before going into any laser treatment hence the distance between the laser and workpiece is maintained throughout the whole investigation. A CO₂ laser induces large amount of temperature gradient on the material. This large temperature gradient causes a stress α which is proportional to E and δT , where α is the expansion coefficient, E is Young's modulus and δT is the temperature gradient. The glasses which are having high value of expansion coefficient are more sensitive to thermal stress as compared to the glasses having lower values of expansion coefficient [14].

The occurrence of periodic structure takes place in such areas of workpiece where the field is most intense. It is clear from the Fig.5 that a structure having period of 1µm has been observed with the amplitude of 1.5 µm. This is due to the low power area which is very small and decreases very sharply while higher power area is large as

in the case of PMMA and it does not increase sharply. Hence in a low power region where the absorbed energy exceeds to threshold value, a periodic structure is observed however at low power, the highest temperature of laser beam is not sufficient to deposit required amount of energy that can deform the surface to induce some patterns. The increase in the temperature of CO₂ laser beam results in decrease in viscosity with increase in the linear expansion of glass. When the laser power is close to optimum parameters, the temperature is then sufficient to deform the surface of glass with decreased viscosity. On the other hand the low scanning speed of translational stage makes the material slightly easy to deform at lower viscosity with high temperature but the possibility cannot be ignored that low scanning speeds will might cause the periodic lines to intertwine.

When the low power CO₂ laser is focused on the glass workpiece, a tidy periodic structure has been formed as shown in the Fig.3 and 6. The CO₂ laser micromachining is based on photothermal process due to the fact that it has long wavelength of 10.6 μm. This cause the development of heat affected zone (HAZ) on glass which ultimately increases due to the increase in laser power. At lower speed the air flow finds more time to eject the molten material out that sticks to the both sides in trenches. Consequently while at fast scanning speeds the laser beam finds less time to get it absorbed inside the material results in the microchannel to be less wide and deep as shown in Fig 9.

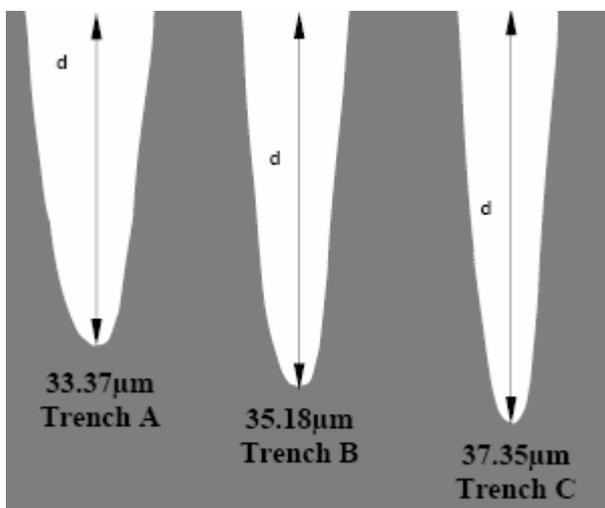


Fig. 9: Micrographs of fabricated channels in glass

During the micromachining of polymers, the laser beam of power density I , is made incident on the workpiece. The depth of the laser into the workpiece is taken as z . The power density after penetrating into the workpiece will become I_z . This can be given by Eq.1.

$$I_z = I_0 e^{-\mu z} \quad (1)$$

where μ is the absorption coefficient with units cm^{-1} . Its value ranges from 10^2 to 10^5 (cm^{-1}).

Furthermore, the used target material PMMA is such a fast burning plastic which remains in a glassy state below 115°C. The PMMA channels are approximately 4 times wider and deeper as compared to glass due to the unique properties of combustion and thermal decomposition. First, the temperature of the ablated material increases rapidly due to the high power density of the laser beam then it melts the material and decomposition occurs, with that result, edges of the channel simply deform, rather than resisting and being ablated. The larger deformation in the structure occurs when temperature exceeds the threshold deformation temperature which is 170°C to 210°C. CO₂ lasers are capable of generating very large pressure waves due to the fact that the energy deposition and heating occur rapidly in the focal volume at an optimized time scale.

The depth of grooves in the case of glass and PMMA is demonstrated and compared in the Fig. 10. Since PMMA is very sensitive to the CO₂ laser wavelength therefore the depth of the grooves has been extensively increased. From the Fig 7, when the power was raised from 1W to 2W the depth of micro-channel has been increased from 367 μm to 555 μm. By increasing the laser power the depth of grooves increases very rapidly.

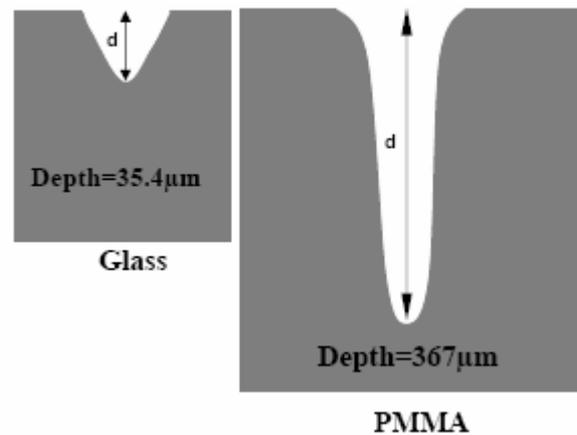


Fig. 10. Comparison of groove depth in glass and PMMA.

Fig. 8 (a) and (b) shows the accumulation of ablated material on the rims of channel. In order to reduce the bulges caused in microchanneling, the laser parameters such as scanning speed and power can be controlled. It is seen that the depth of groove is increased from 565 μm to 900 μm by decreasing the scanning speed from 4 mm/s to 2 mm/s. There is a slight decrease in the width of trenches from 300 μm to 280 μm as the scanning speed reduced to half. This suggests that the laser scanning speed is inversely proportional to the depth of grooves. Fig.8 shows the gradually decrease in the groove depth while laser scanning speed decreases. The formation of bulges is evident due to the resolidification of molten material inside the trench. When the irradiated beam is targeted on the PMMA, an instant energy is transferred to the material in a span of very short time. Due to the immediate transfer of the energy to the workpiece material vaporises and

quickly evaporates. When this evaporated material meets with the atmospheric cold air, it resolidifies and sticks to the trench resulting in bulge formation.

The cross sectional surface profile from Fig 8(a, b) of the channel shows a V- shape subjected to the gaussian distribution of laser energy in polymers. A large thermal stresses can be the cause of micro-cracks in the ablated region. From the obtained profile in Fig. 8, it is assumed that the laser beam has gaussian profile which is visible in more than one profile. The shape of profile is not only determined by laser power density but also from the thermal properties of polymer. In PMMA, the heat conduction is away from the melting zone in an uneven manner as it can be seen from the bottom of the channel. The amount of heat loss is always higher as the ablation rate decreases in this region. For the micromachining of PMMA the evaporation term is much larger than conductive term so for high incident laser power the irradiated area and heat capacity becomes shorter therefore the ablation temperature increases quickly before the material beside the laser interaction area gets affected. But in the case of low power and low scanning speed the energy balance shift occurs where the spot of laser beam gets warmed up quickly and more heat is lost in surrounding areas of trench. In the observation of Fig 7, the depth of grooves has a substantially increased at low scanning speed. So it has been found that low scanning speed cause the trenches depth to increase rapidly.

The width of channel depends on the spot size of the laser beam which is determined by diameter of beam. Since the incident laser beam has a gaussian distribution therefore the spot size defined in this way is time dependent as irradiance is greater than threshold value of ablation. This investigation shows that slow moving laser beams produces broader channels as compared to fast moving laser beams. The depth of trenches and further the cutting depth can also be reached by slightly increasing the laser power used in the above investigations. The thermal state of the workpiece is also dependent on the channel profile along with the binding energy of the polymer.

5. Conclusion

The 10 watt carbon dioxide laser can be efficiently used for the machining of glass and polymer. The optimum condition for inducing regular and tidy structures has been achieved. The laser power and scanning speed is controlled in such a way that both of them give a unique combination of the variance in over all depth and width of microchannels. Direct writing method for inducing microstructures has been remarkably tested and proves to be efficient in the formation of microgrooves. Periodic structures having period of 1 μm has been successfully

fabricated on glass. Microchannels on PMMA have also been fabricated using the same system configuration. Based on experimental results it has been found that scanning speed and laser power has great effect on the profile of formed structure. The threshold value for the laser power is very important for initial investigation from where it is increased for required results.

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