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Experimental Study of Micromachining on Borosilicate Glass Using CO_2 Laser

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Laser beam machining (LBM) is a versatile process that can shape a wide range of engineering materials such as metals, ceramics, polymers, and composite materials. However, machining of glass materials by LBM is a challenge as most of the laser energy is not absorbed by the surface. In this study, an attempt has been made to increase the absorptivity of the glass material by using a coating on the surface of the material. Glass has been used in this study because of its extensive applications in the micro-opto-electro-mechanical systems. The optimal machining depends on both laser parameters and properties of the workpiece material. There are number of laser parameters that can be varied in the laser machining process. It is difficult to find optimal laser parameters due to the mutual interaction of laser parameters. A statistical study based on design of experiment (DoE) has been made to study the effect of coating and parameters like laser power, laser scanning speed, angle of inclination of the workpiece on depth of the slot, width of the slot, aspect ratio, and material removal rate (MRR) in the laser machining process using 2^k factorial design and analysis of variance (ANOVA). On an average, four times increase in depth of the slot, two times increase in width of the slot and seven times increase in the MRR were observed in the glass samples with coating when compared to uncoated glass work samples. [DOI: 10.1115/1.4048639]

Keywords: laser, micromachining, glass, absorptivity, coating, design of experiment (DoE), ANOVA, laser processes, machining processes, micro- and nano-machining and processing

1 Introduction

Glass is an excellent engineering material with unique properties such as transparency, chemical inertness, high hardness, and brittleness. Because of these properties, glass is one of the most popular materials used in scientific research and applications. Glass is used in the packaging of medicine and drugs. Some of the applications of the glass are making of glass cookware, flashlights, semiconductors, microwave, and ovens [1]. Micromachined glass has numerous applications in industries like electronics and communication, biomedical devices, aerospace, and optical devices. Due to the increase in demand for micro-opto-electro-mechanical systems (MOEMS), advanced techniques for precision machining of transparent materials, especially glass, have become necessary [2]. However, machining of glass using conventional methods is difficult because of low machinability, and also, glass is a hard and brittle material. Conventional machining of glass causes excessive tool wear and cracks on the glass surface. Attempts have been made to use non-conventional techniques such as water jet machining for machining of glass. In water jet machining, high-pressure water jet is used for machining of glass [3]. Laser beam machining of glass is another option wherein a beam of laser is used for thermal machining of glass. But both water jet machining and laser beam machining have their advantages and limitations. In general, the operating cost of laser beam machining process is lower than that of the water jet machining process.

During the process of machining of glass using laser machine, most of the energy is not absorbed when laser light is incident on the surface of the glass due to the transmissivity property of the glass. This is a major limitation in the glass machining using laser. Glasses typically reflect approximately 4% of the incident light at a glass-air interface. Experiments were conducted to show that spectral transmission can vary between 98% and 100% through glass with coating depending on the wavelength of the laser and type of the coating used [4]. Laser drilling has become the accepted, economical process for thousands of closely spaced holes in structures such as aircraft wings and engine components [5]. Silicon carbide composites are under investigation for high-temperature applications in the aerospace industry. The borosilicate glass matrix is almost transparent to the 1.06 μm emitted wavelength of the YAG laser. CO_2 laser would be more appropriate for machining the borosilicate glass as the far infrared (10.6 μm) emission of CO_2 laser is absorbed by the glass [6]. This was the main reason to select CO_2 laser to machine borosilicate glass in this study. Coating was applied to increase the absorptivity of the laser energy by the glass. For volume production, dip coating technique which is a cost-effective method can be used for coating on borosilicate glass. Coating on glass helps in the absorption of light (laser) by the glass surface. As a result, more energy is absorbed by the glass and the machining is expected to be more efficient than the machining on glass without coating. In this study, laser micromachining was performed on borosilicate glass. Coating was used to increase the absorptivity of the light emitted by the glass. The research mainly focuses on finding the effect of coating and other machining parameters like laser power, laser scanning speed, angle of inclination of the workpiece on depth of the slot, width of the slot, and material removal rate (MRR) in micromachining of glass by CO_2 laser. Experiments were conducted by changing the machining parameters with and without coating based on the 2^k factorial design. Width and depth of the slots machined on the glass samples were measured. ANOVA was used to study the individual and combined effect of parameters on the outcome of the experiments and to study the interaction plots.

2 Literature Review

Score and break cutting is a conventional method used for glass machining in which machining is performed with the help of a

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wheel cutter or diamond point tool. In this method, the glass surface is first marked and scribed using a diamond point tool and external force is applied with extreme skill or close control. A slight mistake in the position of cutting face of the diamond tool on the surface of the glass causes median crack to deviate from the vertical direction resulting in poor quality edges which decreases lateral bending strength [7]. Using this method resulted in irregular cut, poor surface finish and large material deformation. Grinding and polishing are necessary to make a smooth surface finish, which not only increased fabrication costs but also increased the processing time [8]. Inability to fabricate complex profiles in a single step is one of the limitations of the conventional technique. It has been reported that with the use of conventional technique to machine glass, the strength of the glass reduces to 60% on an average and there are greater risks of developing internal cracks which reduce the quality and life of the product [9].

Machining of small features in such materials represents a manufacturing challenge. In this regard, non-conventional manufacturing techniques came into practice as a possible alternative. Some of the non-conventional manufacturing processes used for machining of glass are ultrasonic machining (USM), abrasive jet machining (AJM), hot air jet machining, abrasive hot air jet Machining, electrochemical discharge machining (ECDM), and laser beam micromachining (LBM). Ultrasonic machining is a process that removes material from the surface of a part through high frequency, low amplitude vibrations of a tool against the material surface in the presence of fine abrasive particles. USM is one of the most advanced and effective means for machining of glass or ceramic [10]. The limitations of this process are as follows: material removal is very slow and difficult to understand, and process parameters cannot be optimized effectively [11]. Abrasive jet machining is also used for micromachining of glass. In this method, abrasives are driven with the high velocity glass to remove the material. From the workpiece, the major limitation of micro holes machined on the surface of brittle material through micro abrasive jet machining is tapered resulted in reduced cylindricity. It is possible to control the taper and cylindricity of the micro holes by giving the steady feed rate to the nozzle equal to the average rate of change of thickness of the workpiece [12]. Hot air jet machining is one of the novel methods for machining of glass. The jet of hot air was impinged on the glass sheet to generate stresses which generates crack along the axis of the jet. The thermal stresses developed in the glass may cause thermal damage to the manufactured product [13]. Electrochemical discharge machining is one of the most advanced and versatile hybrid non-conventional machining processes for both conducting and non-conducting materials [14]. It is the hybrid process of electrochemical machining (ECM) and electrical discharge machining (EDM) that can drill high aspect ratio holes [15]. Material removal takes place by spark erosion and electrochemical process. Micro holes were drilled on glass using the ECDM process. It was observed that the applied voltage and electrolyte concentration have considerable influence on the material removal rate (MRR), radial overcut (ROC), heat affected zone (HAZ) thickness, and roundness error (RE) of the micro holes [16]. Tool wear is one of the major limitations of the ECDM process.

Material removal in laser beam micromachining involves three steps—melting, vaporization, and chemical degradation. When laser beam is focused on the workpiece, due to the high heat flux generated, material is melted and vaporized [17]. Due to the various applications of glass, micromachining of glass has become important. Direct laser-assisted machining is a process in which a transparent tool is used, and the laser beam passes through the transparent tool and heats the workpiece which increases the machinability of metallic alloys with high strength and hardness like bulk metallic glass (BMG). The cutting forces can be reduced by around 30%, and surface roughness can be improved with the use of low laser power in direct laser-assisted machining (DLAM) process [18,19]. Hybrid machining processes like laser-assisted machining [20,21], liquid-assisted laser beam machining process [22], hybrid laser-waterjet machining [23], laser-induced plasma micromachining [24], laser beam micromachining aided by ultrasonics [25], and chemothermal micromachining are used in the micromachining of glass. For microfluid applications, there is a need for fabricating tapered microchannels with varied cross sections. Ultrafast laser machining process is used in micromachining of microchannels in glass. The laser parameters like pulse frequency and laser power are varied to fabricate tapered channels in glass [26]. By using laser-produced charge particles, ultrafine surface machining and crack-free microstructures are produced. To fabricate general complex and highly precise microstructures on glass, direct-write scanning motion by computer-aided design (CAD)-based integrated laser machining was used. Porous silica anti-reflective coating is used to increase the transmissivity and decrease the reflectivity of the glass. If porous silica anti-reflective coating is used, high laser damage thresholds and excellent optical performance are obtained [27]. It was reported that transmissivity was increased with the use of graded-index wide-spectrum anti-reflective coating. By controlling the irradiation conditions of a single-pulse femtosecond laser, it is possible to fabricate micro/nano-holes on the surface as well as inside boro-aluminosilicate glass [28]. Laser machining process, when performed in air, produces high thermal flux which causes thermal damage to the workpiece and poor surface finish on the surface of the workpiece. To avoid thermal damage to the workpiece and improve surface finish, liquid-assisted laser beam machining process has been attempted [29]. Using liquid as medium also helps in carrying of molten material away from the machining zone. Generally, water is used as medium in liquid-assisted machining process due to its high thermal conductivity and low cost [30]. However, using water as a medium in liquid-assisted laser machining of ferrous metals is not ideal. So, instead of liquid other liquids like soluble oil may be used as a medium in liquid-assisted laser machining of ferrous materials [31]. If a chemical solution is used instead of liquid, the process is called chemothermal micromachining. Experiments on chemothermal micromachining of glass using CO_2 laser were performed and 90% reduction in length of the cracks, and the number of cracks was reported [32].

The superior surface finish on the glass can be achieved by machining the glass in ductile mode. An experiment was conducted to machine the glass in the ductile mode with multipoint cutting tool using a four-flute milling tool with TiAlN-coated cemented carbide and observed that with relatively slow speed of the cutting tool, ductile mode cutting was achieved with crack-free surfaces [33]. By using an infrared fiber laser having the beam diameter of 100 μm, the soda lime glass can be thermally softened for achieving greater depth of cut without having transmission from ductile to brittle mode [34]. Preheating Yttria-stabilized tetragonal zirconia polycrystal using ultraviolet laser resulted in decrease in the mechanical strength and increase in the machinability. A new type of laser machining, namely selective laser-assisted milling was performed on glass. In this method, fiber laser whose wavelength (1070 nm) is out of absorption spectrum of glass. The precision machining cannot be achieved considering the wavelength of the laser and material cannot be heated sufficiently by considering ultrashort pulsed laser. The surface of the glass to be machined was coated with black body to absorb the laser beam. The absorbed heat is transferred to the glass. The heated area is removed by the cutting tool [35]. High power single-mode fiber lasers can be used practically in processing materials with high reflectivity and high thermal conductivity [36]. Micro holes with very thin or absent recast layers, without spatters and cracks were produced using Yb:KGW laser end-pumped by high power diode bars. Analysis of variance (ANOVA) analysis and artificial neural network (ANN) models were used to avoid defects, investigate and optimize the process of micro drilling of holes in this process [37]. Neural networks can be used to develop models that express the interrelationship between the input and the output of very complex systems. The ANN model was used to optimize the process parameters (welding speed and shielding gas) to increase the laser welding process quality [38]. Laser power bed fusion process (LPBF) is a

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metal-based additive manufacturing technology. A 3D thermofluid was developed to simulate the LPBF process, investigate keyhole behavior and pore formation, and find the effect of laser power and scanning speed in the laser powder bed fusion process (LPBF) [39].

Most of the recent studies are focused on laser machining of metals using ultrashort pulse lasers. The results with the use of ultrashort pulse lasers are effective, but expensive. The main objective of this study is to analyze the effect of coating on glass (workpiece) and laser parameters like laser scanning speed, laser power, and angle of inclination of workpiece on material removal rate in the laser beam micromachining process. A statistical study based on the design of experiment (DoE) was carried out to investigate the individual effect and combined effect of the above parameters on depth, width, aspect ratio, and MRR. In practice, 2^k factorial design and ANOVA were applied.

3 Materials and Methods

This study was carried out using a 40-W CO_2 laser system (Fig. 1) producing continuous wave laser of 10.6 μm wavelength in the infrared region.

The setup consists of a borosilicate glass slide on a stainless steel plate. The position of the bed of the laser machine was adjusted in such a way that the distance between the tip of the laser head and the top surface of the borosilicate glass is equal to the focal length of the lens used in the laser machine. The focal length of the lens used for this experiment was 50.8 mm. To study the effect of coating on laser micromachining of glass, chemical mixture of ethyl acetate, silica, camphor, and aluminum borosilicate was used as coating on glass. To study the effect of angle of incidence of the laser on glass, a wedge was used in this study as shown in Fig. 1. The wedge and workpiece were positioned in such a way that the distance from the tip of the laser head and the midpoint of slot machined is equal to the focal length of the lens used. It was made sure that the workpiece did not move during the machining process while it was placed on the wedge. The effect of other parameters like scanning speed of laser and laser power was also studied in this experiment.

In the experimental stage, 2^k factorial design was adopted with four process parameters as control factors. The adopted control factors are as follows: (A) laser power, (B) laser scanning speed, (C) angle of inclination of the workpiece, and (D) coating. Table 1 summarizes the level of control factors and their settings. Table 2 shows 24 design matrix, resulting in a total of 16 experimental runs. A slot of 50-mm length was machined on 16 samples to study the effect of the process parameters. To reduce the disturbance of any unnecessary noise factor, experiments were conducted randomly. The experiments were conducted three times. The data for width and depth of the slots considered for this study were randomly selected from one of the samples from the three experiments.

An optical microscope was used to measure the width of the cut, and a profilometer was used to measure the depth of the cut. To calculate the depth of the slot machined, readings of maximum depth at the start, middle, and end of the slot were recorded and the average of the three readings was considered as the maximum depth of the slot of the sample. In the same way, the width of the sample was calculated by taking the average of the width at the start, middle, and end of the slot. The same procedure was followed for 16 samples. Material removal rate (MRR) was calculated by using the Eq. 1

$$\text{MRR} = \frac{\text{Volume of the slot}}{\text{Time taken}} \tag{1}$$

where volume of the slot is given by the product of width, depth, and length of the slot. Time taken was recorded for every treatment. For the treatments with laser scanning speed 3 mm/s, the time taken was 16 s. For the treatments with laser scanning speed 6 mm/s, the time taken was 8 s. For the treatments with zero angle, length of the slot was taken as 50 mm, and for the treatments with 30-deg angle, length of the slot was considered as 36 mm as the effect of laser on the workpiece was negligible after 36 mm. Aspect ratio was calculated using Eq. 2

$$\text{Aspect ratio} = \frac{\text{depth of the slot}}{\text{width of the slot}} \tag{2}$$

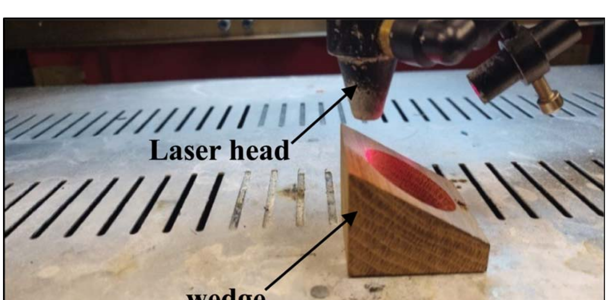

Fig. 1 Experimental setup with wedge

Table 1 Control factors and their levels

Control factors	Labels	Low(−)	High(+)	Unit
Power	A	24	30	W
Scanning speed	B	3	6	mm/s
Angle	C	0	30	deg.
Coating	D	N	Y	—

4 Results and Discussion

4.1 Effect of Coating

4.1.1 Depth of the Slot. Figure 2 shows examples of 2-D profile of the two slots machined in this study. The maximum depth of the slot machined in treatment XII (without coating) is found to be about 10 μm as shown in Fig. 2(*a*), whereas in treatment VIII (with coating) the maximum depth of the slot machined is as high as 80 μm as shown in Fig. 2(*b*). Similar observations were made in other cases too. In general, about four–eight times increase in the slot depth was observed when coating was used. This is because the amount of light absorbed was increased with the use of coating on the surface of the glass. Increase in light absorbed results in increase in heat absorbed by the workpiece. Standard deviation of depth of the slot calculated was 19.12 μm.

Table 2 2^4 Design matrix

Treatment	A	B	C	D
I	−	−	+	−
II	−	+	−	−
III	+	−	−	−
IV	+	+	+	−
V	−	−	−	+
VI	−	+	+	+
VII	+	−	+	+
VIII	+	+	−	+
IX	−	−	−	−
X	−	+	+	−
XI	+	−	+	−
XII	+	+	−	−
XIII	−	−	+	+
XIV	−	+	−	+
XV	+	−	−	+
XVI	+	+	+	+

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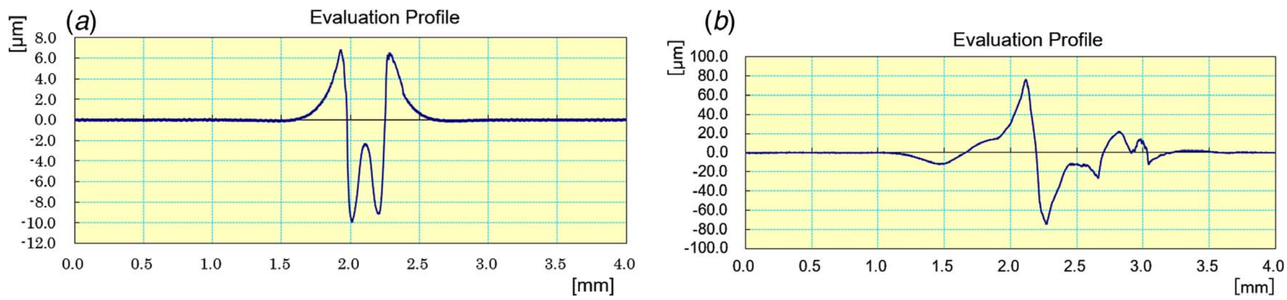

Fig. 2 2-D profile of the slots: (*a*) slot without coating and (*b*) slot with coating

4.1.2 Width of the Slot. From Fig. 2, the width of the slot machined in treatment XII (without coating) on the surface of the workpiece is found to be about 300 μm as shown in Fig. 2(*a*), whereas in treatment VIII (with coating) the width of the slot machined is about 800 μm as shown in Fig. 2(*b*). Similar observations were made in other cases too. On an average, about two times increase in the slot width was observed when coating was used. The surface of the workpieces with coating absorbs more light when compared to the surface of the workpieces without coating. In addition to this, flame was observed most of the time during the machining of the workpieces with coating. The flame resulted in the melting and vaporizing of the material on the surface of the workpieces with coating. Standard deviation of width of the slot calculated was 256.38 μm.

4.1.3 Edge Quality of the Slot. Figure 3 shows images of the slots machined with and without coating. As no medium was used in this experiment to carry away the molten particles during the machining process, some of the material got vaporized and the remaining was re-solidified in the slot and on either side of the slot. In the treatments with coating, along with the molten glass material, molten coating material was also re-solidified in the slots and on either side of the slot. So, the edge quality of the slot in the glass without coating is better than that of the glass with coating.

4.2 Effect of Inclination of the Workpiece. Figure 4 shows pictures of workpiece samples of treatment IV (with inclination) and treatment XII (without inclination). Due to the inclination of the workpiece, laser beam was not focused at the beginning of the slot and it was observed that the width at the beginning of the machining was more compared to the remaining part of the slot. Depth of the slot was maximum at the midpoint of the slot because the distance from the midpoint of the slot and laser head is equal to the focal length of the lens used. Also, just a light scratch was observed at the end of the slot as the distance between the workpiece and laser head is more and beyond the focal length of the lens used.

4.3 Main Effects and Interaction Plots. Analysis of variance (ANOVA) method was used to study the statistical effect of the control factors on width, depth, aspect ratio and MRR. With the help of the 2^4 factorial experiment, the data obtained was used to study the individual and combined effect of control factors on MRR in laser micromachining through main effects plots and interaction plots. The confidence level of the conclusions drawn using ANOVA was 95%. Figures 5(*a*)–5(*d*) shows main effects plots for maximum depth of the slot, width of the slot, aspect ratio and material removal rate (MRR) respectively. With the increase of power, increase in the maximum depth of the slot, width of the slot, aspect ratio and MRR can be observed. This is because increase in power results in increase in heat flux generated and more heat is absorbed by the workpiece. Increase in heat absorbed results in increase in material removal rate. The increase in aspect ratio is because the effect of power is more on the depth of the slot compared to width of the slot.

With the increase of laser scanning speed, decrease in depth of the slot, width of the slot, aspect ratio and slight increase in MRR can be observed. This is because the interaction time of laser with the workpiece will be decreased and less heat will be absorbed by the workpiece. The effect of laser scanning speed is more on width of the slot compared to depth of the slot. The increase in MRR is because of the decrease in time taken for machining of the slot and MRR is dependent on time. Even though MRR was increased, material removed is more at low speeds than at high speed. With the increase of inclination of the workpiece, increase in depth, width and aspect ratio and a slight decrease in MRR can be observed. When the workpiece is placed on the wedge, the

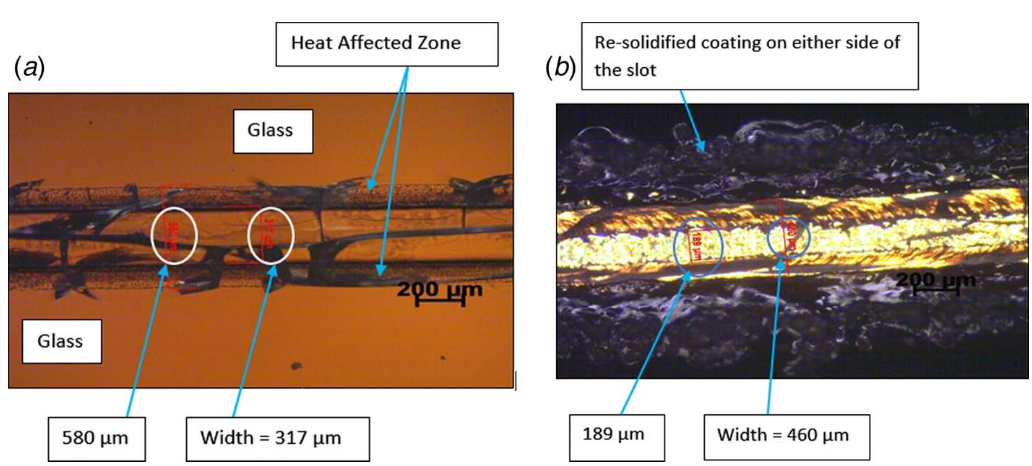

Fig. 3 Images of the slot: (*a*) without coating and (*b*) with coating

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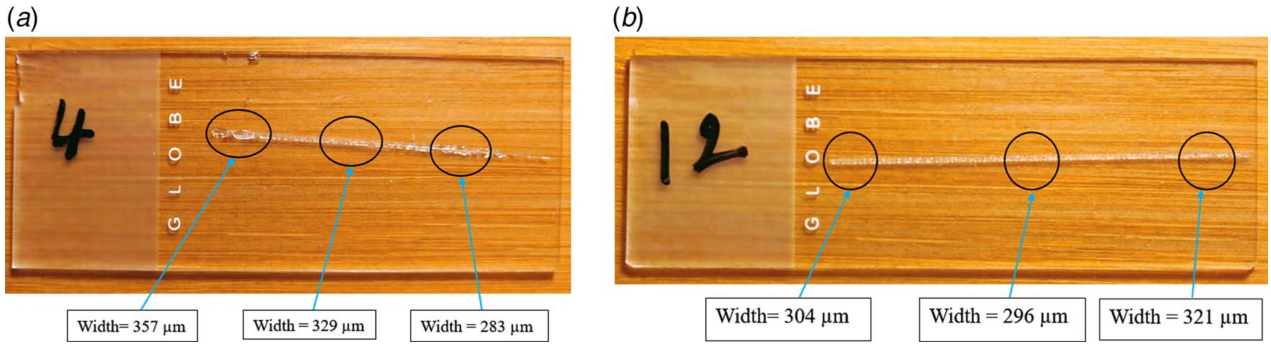

Fig. 4 Images of workpiece samples: (*a*) without inclination and (*b*) with inclination

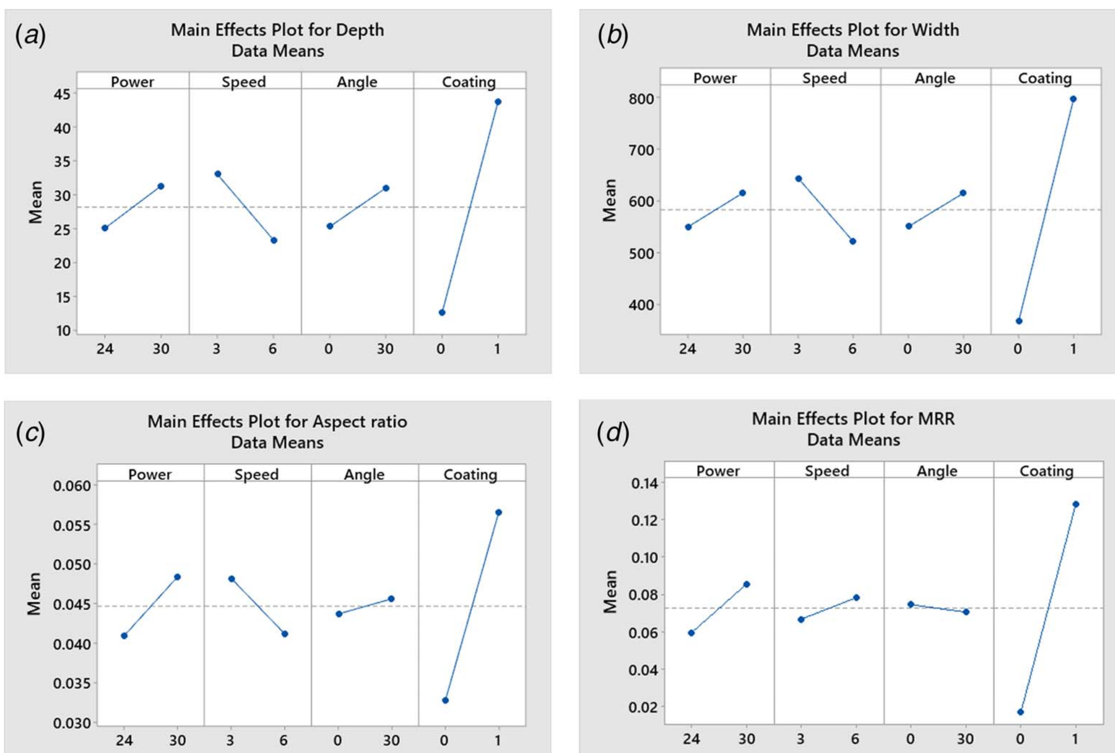

Fig. 5 Main effects plot: (*a*) depth (μm), (*b*) width (μm), (c) aspect ratio, and (*d*) MRR (mm^3/s)

distance between the laser head and workpiece at the beginning of the slot is less and laser beam is not focused on the workpiece which increases width. The decrease in MRR is because the length of the slot considered is 36 mm for the samples machined using wedge as the effect of laser after 36 mm is negligible.

Coating of the workpiece resulted in a significant increase in width, depth, MRR and decrease in the aspect ratio. Because of the coating, absorptivity of the workpiece is increased and more laser energy is absorbed by the workpiece. Most of the time, flame was observed during the machining of glass with coating. Due to the flame, material at the top surface of the workpiece was machined which resulted in an increase in width of the slot and decrease in aspect ratio. As regards the slot depth, its maximum values are obtained at a high level of laser power, with angle of inclination and at low speed. As regards the slot width, its maximum values are obtained when power is at a high level, speed is at a low level, angle is at a high level and coating is at a high level. As regards the aspect ratio, its maximum values are obtained at high values of power, angle, coating and at a low value of speed. As regards the MRR, its maximum values are obtained at high values of power, speed, coating and at a low value of angle.

Figure 6 shows the interaction plot for depth, width, aspect ratio and MRR.

From the Fig. 6(*a*), it can be observed that there is a combined effect of power and scanning speed; power and angle; scanning speed and angle; and power and coating on depth of the slot. There is a negligible combined effect of scanning speed and coating, angle and coating on depth of the slot. Figure 6(*b*) shows the interaction plot for width. It can be observed that there is a combined effect of power and scanning speed, power and angle, scanning speed and coating on width of the slot. There is no combined effect of scanning speed and angle; power and coating; and angle and coating on width of the slot. Figure 6(*c*) shows the interaction plot for aspect ratio. There is a combined effect of power and scanning speed; power and angle; scanning speed and angle; scanning speed and coating angle and coating; and power and coating on the aspect ratio of the slot. Figure 6(*d*) shows the interaction plot for MRR. There is a combined effect of power and scanning speed; power and angle; scanning speed and angle;

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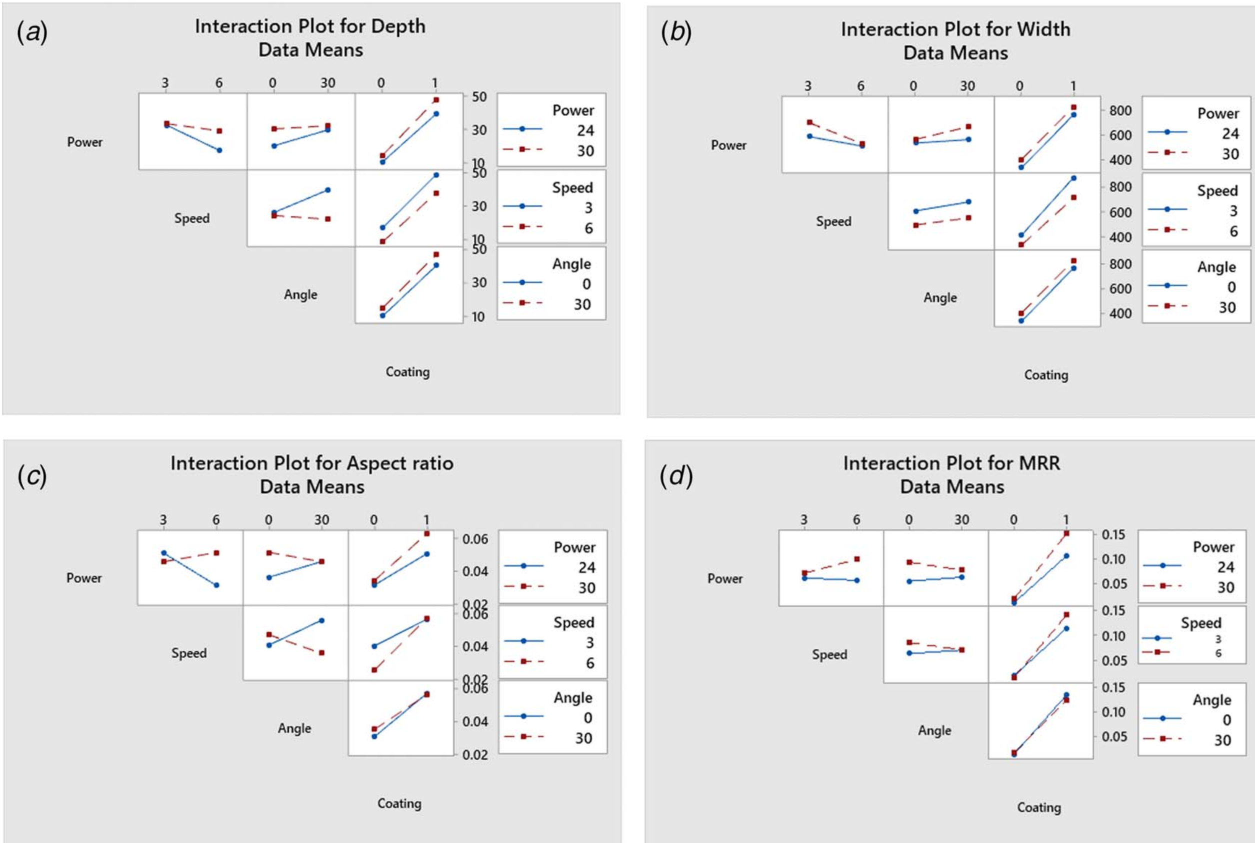

Fig. 6 Interaction plots: (*a*) depth (μm), (*b*) width (μm), (*c*) aspect ratio, and (*d*) MRR (mm^3/s)

power and coating; scanning speed and coating; and angle and coating on MRR.

5 Conclusions

Experimental and statistical analysis was performed to study the effect of laser parameters on micromachining of borosilicate glass with and without coating. Experiments were performed with the help of 2^k factorial design of experiment (DoE) and the individual effect and combined effect of laser parameters were studied using interaction plots and main effects plots. The study of the effect of laser parameters helps to find the best parameters to increase the MRR. In this experiment, use of coating on glass workpiece resulted in two times increase in width of the slot, four times increase in depth of the slot, and seven times increase in material removal rate (MRR) on an average. It was found that an increase in power resulted in around 1.5 times increase in MRR and a decrease in laser scanning speed also increased MRR. The effect of the inclination of the workpiece has a very low impact on MRR. Also, there is a combined effect of all the parameters on MRR. Since far infrared (10.6 μm) emission of the CO_2 laser is absorbed by glass and micromachined glass has number of applications in aerospace industry, CO_2 laser for glass micromachining could be a good option for applications in aerospace and aircraft industries. The study of effect of different coatings on borosilicate glass in laser micromachining can be done to extend this research.

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Data Availability Statement

The authors attest that all data for this study are included in the paper.

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