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Process Parameter Optimization of Machining of Borosilicate Glass by Laser Assisted Abrasive Jet Machining

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Abstract: Borosilicate glass serves as the substrate of microdevices due to its good surface integrity and ability to withstand thermal shock. However, the brittleness and non-conductivity of glass makes it difficult to machine with high accuracy and precision using conventional and non-conventional machining processes. This Research focuses on machining of borosilicate glass using laser assisted abrasive jet machining. Laser assisted abrasive jet machining is a hybrid method of machining, which combines laser with abrasive jet in a sequential manner. Laser preheating is used to soften the workpiece, which in turn increases the machinability of material. The effect of process parameters like power, cutting speed and stand-off distance (SOD) on response parameters like material removal rate (MRR), kerf width (Kw) and heat affected zone (HAZ) are discussed. Experimentation was designed based on Taguchi's L9 orthogonal array. In addition, the Analysis of Variance is used to investigate the effect of cutting parameters on machining. The experimental results revealed that the developed hybrid machining process efficiently improves MRR and minimizes Kw and HAZ.

***Index Terms* – Borosilicate glass, Hybrid machining, Low power CO2 laser, Abrasive jet**

I. INTRODUCTION

Non-conventional machining plays a vital role in modern manufacturing industries, from abrasive jet machining researchers studied (Park et al., 2004b; k vijayakumar et al., 2020) Sand blasting and abrasive jet machining (AJM). Both methods for efficiently removing brittle and hard materials. AJM has been used for rough finishing and working, such as deburring. (Park DS et al., 2004a).The efficacy of the micro-AJM for glass micro-grooving was investigated. Regardless of the heating temperature, efficient masking results are still achievable. It is also possible to achieve excellent machining outcomes; output responses for grooves of the hole and line-type were investigated. Researchers also talked about how the length of the scanning time will impact the depth of the machined area. According to authors LCDs, electronics, and transistors could be productively machined at the nanoscale using micro-AJM. (Abhishek K et al., 2018 Saragih AS ., 2009) The nozzle feed system and sensing system were combined and built by researchers to make the m-AJM experimental setup. By using a cutting-edge method known as Micro-Abrasive Jet Machining (m-AJM), it is possible to drill holes with a high degree of cylindricality through delicate materials. Microfluidic applications, such as lab-on-a-chip and organ-on-a-chip devices, use circular micro holes as a fluid source. The circularity of the cross sections of the reservoir openings has significantly improved, according to the authors. (Abhishek K et al., 2016).The authors designed a technique for drilling holes in brittle quartz using a micro abrasive jet machine, where the nozzle is fed at a rate corresponding to the average rate of change of the workpiece thickness. Trials are conducted to determine the effects of this novel approach on the output properties of the machined hole design. (Nikhil Bharat, P.S.C. Bose., 2021)Through non-traditional methods such as laser assistance for machining applications, settings for laser assisted machining (LAM), input and output variables for the process, laser input parameters, and work substrate material characteristics, researchers investigated the thermal assistance process. It is therefore critical for optimization to comprehend and analyze these qualities and their effect on each process parameter in order to get a better output response. Authors recommended that it be necessary to look into how surfaces behave when heated at greater temperatures and increased strain rates. The obvious behaviour in the environment on the work area and the resistance at the tool-to-chip interface were investigated. The productivity of laser-assisted machining has improved in comparison to conventional machining techniques and the effectiveness of machining in challenging materials. In manufacturing sectors, the LAM are significant. (Sagar Hiwale, B. Rajiv .2021) Authors used ANOVA to analyze the responses and influencing factors of the laser process parameters. They found that, in addition to the power and feed of the laser process parameters, the working distance, or stand-off distance, will contribute to the highest kerf surface deviation because it has the highest F-value.(T. Kim et al.2020).According to Authors who looked into the process parameter for laser machining, the use of CO2 laser also decreased the workpiece's roughness. By heating the brittle materials of the workpiece, the CO2 laser beam can be used to enhance machining characteristics. In order to speed up the removal of fragile material like glass during milling to the micron level, it is essential to directly heat a desired area of the workpiece with a relatively low power laser. According to Authors, using a CO2 laser can enhance glass machining efficiency. (A Temmler et al., 2021)Researchers Studied the machining of quartz glass by CO2 laser, and compared with the Traditional machining techniques for spherical optics. The use of CO2 laser radiation, which utilizes the majority of the opposing laser's energy for matter ablation, to increase efficiency and accelerate typical machining processes like laser ablation represents one possible step forward. According to the experiment's findings, pulse stability had a significant impact on how quickly surface irregularity increased in the future. (A. Riveiro et al 2016). Materials with the same chemical composition were found to retain the same surface behaviour even after laser machining, according to the authors. Given that the crystal structure of the base materials remains crystalline and that of the laser-radiated surface is found to have an amorphous structure, continuous CO2 lasers and fibre lasers seem to be the most logical solutions for processing natural granite. The laser beam machining technique can create intricate geometric designs on natural stones without cracks.(D. Kumar and S. Gururaja ., 2020)Researchers studied a cutoff energy level called line energy for drilling laminates made of titanium, carbon fibre reinforced plastic, and titanium for higher CO2 laser frequency. They discovered that the heat impacted zone width and MCI damage factor were lowered at this level.(Jagannatha N et al 2012; Prakash ES etal ., 2012). The authors investigated the hybrid method known as "hot air assisted hybrid machining," which is being designed for soda-lime glass machining. It is a cutting-edge non traditional milling method that processes brittle materials by combining traditional machining with a jet of hot air. The experiment's findings demonstrated that the MRR and Ra will be impacted by the air temperature, and output characteristics were addressed. The process variable that most significantly affects both of the two reactions is air temperature.(Nagaraj Y etal. 2020). Hybrid machining is the technique of removing material that combines two unconventional machining processes or one unconventional machining process with traditional machining. By combining hot air with a conventional cutting tool, the authors of the present work developed a novel Hot Air Assisted Hybrid Machining (HAAHM) method for soda-lime-silica glass machining. Here, the output responses improved. (Ravindra I Badiger et al., 2018).Researchers conducted work hybrid technique of heating by micro wave on welding Inconel-625welded joints. Using design of experiments, it is determined how process factors affect the Inconel-625welded links' tensile strength after being heated with a microwave hybrid. The ideal processing conditions must be assessed in order to weld Inconel 625 using a microwave hybrid heating technique and guarantee that the formed joint has the desired tensile strength. Before the testing, many efforts were made to pinpoint the variables influencing the microwave welding process. (Nagaraj et al., 2019 Jerby E,et al., 2004). In-depth research has been conducted over the years to understand the mechanisms involved in the machining of brittle materials in an effort to get around the drawbacks of the different non-traditional machining techniques. According to authors, cutting brittle materials like ceramics, glass, and stone requires the hybrid non-traditional machining technique. (Taekyum Kim a et al., 2020) The authors looked at the process variables of milling with a laser in addition to conventional machining methods. By positioning the workpiece at the correct tool location, applying heat to a specific strain point, at a specified feed rate, and cutting to a specified depth, micro-channels with low power laser levels with limited surface roughness were created.(W.-S. Woo, C.-M. Lee ., 2018).Laser-aided milling (LAMill) edge grinding was enhanced when the preheating temperature was increased. The authors also looked into the workpiece's angular perspectives and the spindle's speed of rotation. Preheating temperature and cutting energy as well as preheating temperature and silicon nitride strength have inverse correlations. Cutting tools will last longer because of the enhanced surface roughness and minimal tool damage. (K. Rajesh ⥣, V.V. Murali Krishnam Raju…, 2019) By using laser cutting on SS-304 Stainless Steel, the entire analysis of the process parameters that affect it was performed. Authors stated that the Process parameters like cutting speed, assist gas pressure, and laser power had an influence on the quality of the laser kerf and cut edges (P). The L27 orthogonal array served as the foundation for the experiment's construction and execution. Through the use of ANOVA and numerous regression analysis, a predictive model was created. (A Parthibana, M Chandrasekaran., 2017) Authors studied the effect of kerf quality of AISI 304 stainless steel sheet by CO2 laser cutting. According to the RSM optimization technique, the main factors affecting the turning conditions of AISI 304 stainless steel sheet are the laser's power, the cutting speed, and the gas pressure. (Pathik Pate.., 2016)Researchers investigated the effect of laser cutting parameters for GFRP composite. They considered HAZ as response parameter. For the given range of input parameters. With greater than 97% accuracy, the ANN model demonstrated good agreement for predicting HAZ.

In the researchers' previous works, lasers were utilized to enhance surface deformation over the target region of tough and difficult-to-cut materials. But, many new combinations with conventional and non-traditional machining needs to be investigated to achieve better process parameters. In the current work, borosilicate glass is being machined with the assistance of a laser. Abrasive jet generated by compressed air is used as a second source to remove material mechanically. Both are oriented in place sequentially, hence it is a combination of two non conventional machining process which is non contact type of material removal mechanism, so it can be stated as non conventional hybrid machining process. The laser assisted abrasive jet machining (LAAJM) is a hybrid method of machining process for machining brittle materials where the low power CO_2 Laser is combined with the abrasive air jet. The principle of LAJM involves applying a CO2 laser to a localized portion of the machining area to lower the specimen's temperature below a predetermined level, which causes thermal deformation of the material's surface in addition to the impact of an abrasive air jet. The two methods are focused on the part that needs to be machined in order to achieve the same machining goal. There is a need to explore new combinations because earlier researchers have not focused on laser with abrasive jet machining.

II. MATERIALS AND METHODS

2.1 Materials and Experimental Setup

The abrasive jet machining conducted used silicon carbide (Sic) as abrasive particle, SiC of 220 mesh size was used as a tool assisted with compressed air media as abrasive jet. The continuous beam of CO_2 laser source which is of low power usually utilized for engraving purpose commercially available with computer controlled router (Power: 40W , AC220/ 50Hz , accuracy 0.02mm, beam and spot diameter less than 0.5mm) for machining the work material.

Silicon carbide (SiC) is a non-oxide ceramic engineering material that has generated a significant interest. The SiC particles exhibit high thermal conductivity, high hardness, and resilience to abrasion and corrosion. They also exhibit comparatively low thermal expansion. The borosilicate glass is used as Work material, composition as shown in Table. 1

Table 4.1: Borosilicate glass chemical composition and properties

Chemical Composition	wt.%	Formula	Melting point	Density (g/cm3)	Thermal conductivity (W/mK)
Silicon dioxide	80.6	SiO_2			
Sodium dioxide	13.0	Na_2O			
Calcium oxide	4.0	B_2O_3	500^0c	2.23	1.14
Aluminum dioxide	2.3	Al_2O_3			

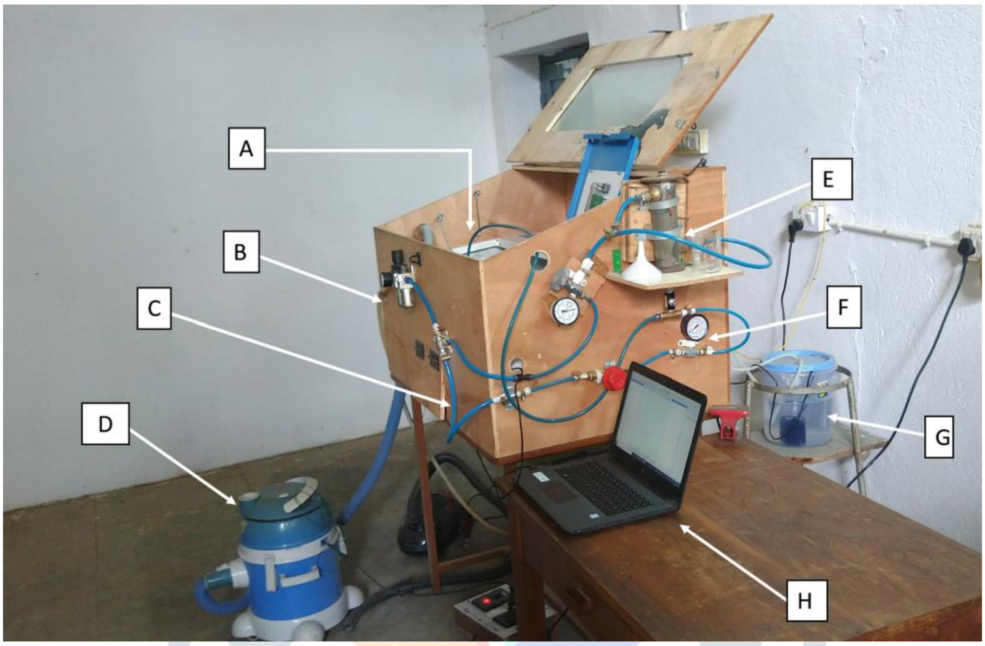

Fig. 1 – Experimental setup of CO2 laser assisted abrasive jet machining
A – Blasting chamber, B – Dehumidifier, C - Pneumatic pipe, D – Vacuum pump, E – Mixing chamber, F – Pressure gauge, G – Water cooling system, H – Computer

The compressor produces a jet of air that is circulated into a mixing chamber where abrasive mixture is present. Using an abrasive jet nozzle, SiC with an irregular form and a sharpness of 220 mesh size is directed at the surface of the target region. Fig 1 and Fig 2 shows the schematic diagram of a laser assisted abrasive jet machining system. The workpiece is positioned on the X-Y router table controlled by the CNC controller, as illustrated in Fig 2. The laser cutting speed is varied and controlled by the software (laserdraw 2013).

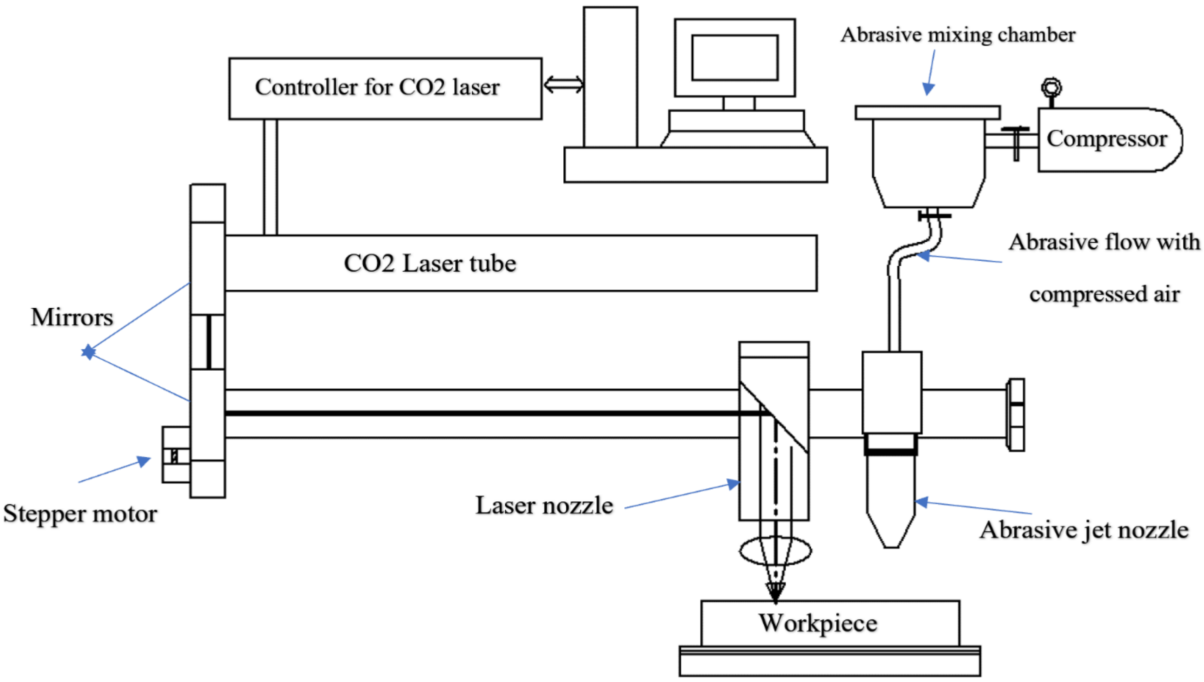

Fig 2. Setting up of laser assisted abrasive jet

2.2 Mechanism of Material Removal

The Material is removed as a result of the effect of abrasive particles, melting and evaporation caused by a low power continuous CO2 laser beam. The exterior of laser beam causes the temperature of the cutting area to increase. Due to the decreased flow stress and strain hardening rate brought on by the increased temperature, the material can be removed from the target more efficiently. Partially laser beam removes the material by ablation causing plastic deformation of the works piece thereby influencing in reducing the hardness of the workpiece. Additionally, the heating of the target region results in a decrease in the cutting forces. Hence more amount of material is removed by the combined laser beam and abrasive jet. The machining operation like drilling, grooving and etching are performed on borosilicate glass by the developed hybrid machining setup. A borosilicate glass of specified dimension is utilized as work material and for machining operations. The Fig.3 shows a grooving operation performed on borosilicate glass with a groove.

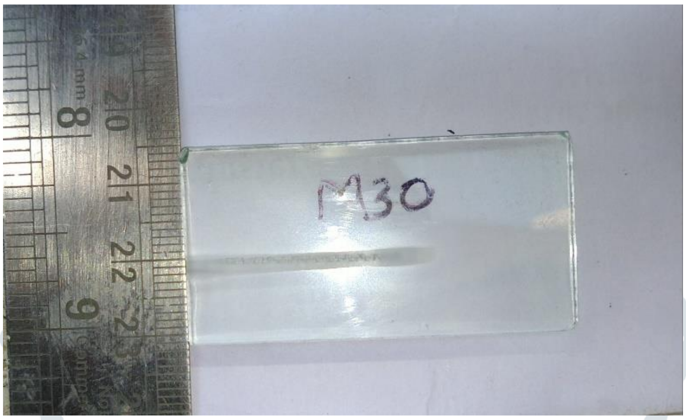

Fig 3: Borosilicate glass after grooving

III. EXPERIMENTATION

The experiments were conducted based on Taguchi orthogonal array L9 as it minimizes the number of experiments to be conducted for the study of response parameters such as Material removal rate (MRR), Kerf width (Kw) and Heat affected zone (HAZ) using LAAJM on brittle material like borosilicate glass.

The process parameters were selected based on the literature survey. In present work, the selected process parameters are Laser power, Laser cutting speed and Stand off Distance (SOD). The other parameters like size of the abrasive, diameter of nozzle, diameter of laser beam, nozzle to tip distance of laser beam is kept at a distance of 10mm constant, flow rate of abrasives, pressure of air etc., are kept constant during the process which is presented in Table 3. In the present work, the process parameters and their levels are selected as shown in Table 2. The response parameters like MRR, Kw and HAZ were determined to study the performance of hybrid machining.

The MRR was calculated by difference in initial and final weight per unit time (Patel and Tandon 2015) (Equation 1). The measurement of weight of the specimens were carried out using a digital electronic balance (ACZEL CY 224 with resolution of 0.0001g). The Machined Specimens were tested to measure the kerf width, HAZ using Tool Makers Microscope.

$$MRR = \frac{w1-w2}{tm} \qquad \text{Eq.1}$$

Where w_1 = Initial weight
w_2 = Final weight
t_m = Time taken for machining

Table 2: Levels of machining parameters

Sl no	Symbol	Process parameter	Unit	levels		
				1	2	3
1	A	Laser power	watt	10	20	30
2	B	Cutting speed	mm/s	2	4	6
3	C	Stand off Distance(nozzle to work distance in AJM)	mm	5	8	11

In the current work, larger the better S/N ratio for MRR and smaller the better S/N ratio for Kw and HAZ are considered for response parameters respectively. The experiments were conducted according to Taguchi Orthogonal Array L9 and the results were presented in Table 4.

[i] Larger the better: S/N ratio = $-\mathbf{10}\left[\frac{1}{n}\sum_{j=1}^{n}\frac{1}{a^2}\right]$ …. Eq.2

[ii] Smaller the better: S/N ratio = $-\mathbf{10}\left[\frac{1}{n}\sum_{j=1}^{n}\mathbf{a}^2\right]$ ……… Eq.3

Table 3: Process parameters and conditions

Sl no	Particular	Preliminary experiments
1	Dia of abrasive jet nozzle	3mm
2	Abrasive	SiC
3	Grain size	220 Mesh
5	Mixing Chamber	Cylindrical shape
6	Pressure	Between 0.4 to 0.6 MPa
7	Nozzle tip to work distance	1mm to 12mm
8	Work material	Borosilicate glass
9	Laser power	10W - 40 W capacity
10	Engraving speed	0-600 mm/sec
11	Laser type	CO_2 gas sealed
12	Control and drive	High speed M2 Cibtrik stepper motor high subdivision drive
13	Cooling system	Pure circulating water system
14	Frequency	50Hz

IV. RESULTS AND DISCUSSIONS

Table 4 represents experimental results of the laser assisted abrasive jet machining process as per the DOE and Taguchi orthogonal array L9. An Analysis of Variance (ANOVA) is a statistical technique commonly used to compute and compare differences between two or more sets of mean values. The statistical tool Minitab19 was used for ANOVA to identify the process parameter that significantly influences on the output response MRR, Kw and HAZ. (Nagaraj Y et al. 2021,Sathisha etal.2013).The obtained results from the ANOVA should be reliable so that it will lead to percentage contribution of all process parameters individually (Nagaraj Y et al. 2020,Agboola et al 2020, Badigeretal,2017) as shown in Table 5.

TABLE 4: Orthogonal array L9 experimental results

Sl no.	Laser Power(W)	Cutting Speed(mm/s)	SOD(AJM) (mm)	MRR (g/s)	Kw (mm)	HAZ (mm)
1	10	2	5	0.00088	1.64	0.65
2	10	4	8	0.00086	1.25	0.58
3	10	6	11	0.00083	0.81	0.56
4	20	2	8	0.00092	1.8	0.78
5	20	4	11	0.00091	1.73	0.72
6	20	6	5	0.0009	1.71	0.69
7	30	2	11	0.00094	1.91	0.95
8	30	4	5	0.00096	2.15	0.93
9	30	6	8	0.00093	1.67	0.89

Table 5: ANOVA for MRR, Kw and HAZ

Sl no	Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Kw	POWER	2	0.74807	0.74807	0.374033	56.39	0.017	**61.69**
	CUTTING SPEED	2	0.25307	0.25307	0.126533	19.08	0.05	20.87
	SOD	2	0.1982	0.1982	0.0991	14.94	0.063	16.34
	Residual Error	2	0.01327	0.01327	0.006633			
	Total	8	1.2126					
HAZ	POWER	2	0.161867	0.161867	0.080933	346.86	0.003	**93.89**
	CUTTING SPEED	2	0.0098	0.0098	0.0049	21	0.045	5.68
	SOD	2	0.000267	0.000267	0.000133	0.57	0.636	0.021
	Residual Error	2	0.000467	0.000467	0.000233			
	Total	8	0.1724					
MRR	POWER	2	1.07847	1.07847	0.539235	151.04	0.007	**85.11**
	CUTTING SPEED	2	0.12247	0.12247	0.061233	17.15	0.055	9.66
	SOD	2	0.05904	0.05904	0.029519	8.27	0.108	4.65
	Residual Error	2	0.00714	0.00714	0.00357			
	Total	8	1.26711					

Table 5 clearly shows that the laser power has highest contribution (85.11%), other two parameters cutting speed (9.66%) and sod (4.65%) having less contribution on output response MRR . It is clear that the power is the most influencing parameter on MRR.

It also found from Table 5 that laser power has highest contribution (61.69%), other two parameters cutting speed (20.87%) and sod (16.34%) having less contribution on output response kerf width. It is clear that the power is the most influence parameter on Kw.

It also found from Table 5 that laser power has highest contribution (93.89%), other two parameters cutting speed (5.68%) and sod (0.021%) having less contribution on output response kerf width. It is clear that the power is the most influence parameter on HAZ.

The Main Effect plots based on mean ratio for MRR, Kw and HAZ using ANOVA are presented as shown in Fig.4, Fig.5 and Fig.6. The mean response values of the estimated parameters at each set level are shown in the main effects plot. It is observed that the average MRR value increases as power increases and the MRR decreases by increasing cutting speed and SOD. As shown in Fig.4. The highest value of MRR is found at level 3 of Power(A), level 1 of Cutting speed (B) and level 1 of SOD(C) that is A3–B1–C1 (Power = 30watt, Cutting speed = 2mm/s and SOD = 3 mm). It is clear that the optimal combination of process parameters is A3–B1–C1 where the MRR is high. It is also seen from the main effect graphs, the mean value of Kw increases as power increases and Kw decreases with increasing Cutting speed and SOD as shown in Fig.5. The lowest value of Kw is found at level 1 of power(A), level 3 of cutting speed(B) and level 3 of SOD(C) that is A1-B3-C3.(Power = 10W, Cutting speed = 6mm/s and SOD = 11mm). It is also seen from the main effect graphs, the mean value of HAZ increases as power increases and decreases with increasing Cutting speed and SOD as shown in Fig.6. The lowest value of HAZ is found at level 1 of power(A), level 3 of cutting speed(B) and level 3 of SOD(C) that is A1-B3-C3.(Power = 10W, Cutting speed = 6mm/s and SOD = 11mm).

The external laser beam causes the cutting region's temperature to increase. Due to the reduced flow stress and strain hardening rate brought on by the increased temperature, the material was more easily removed off the target. By partially ablating the material, the laser beam causes a limited zone to deform plastically, reducing the hardness of the material. The heating of the target area also results in a decrease in chipping forces. As a result, the combined laser beam and abrasive jet removes more material.

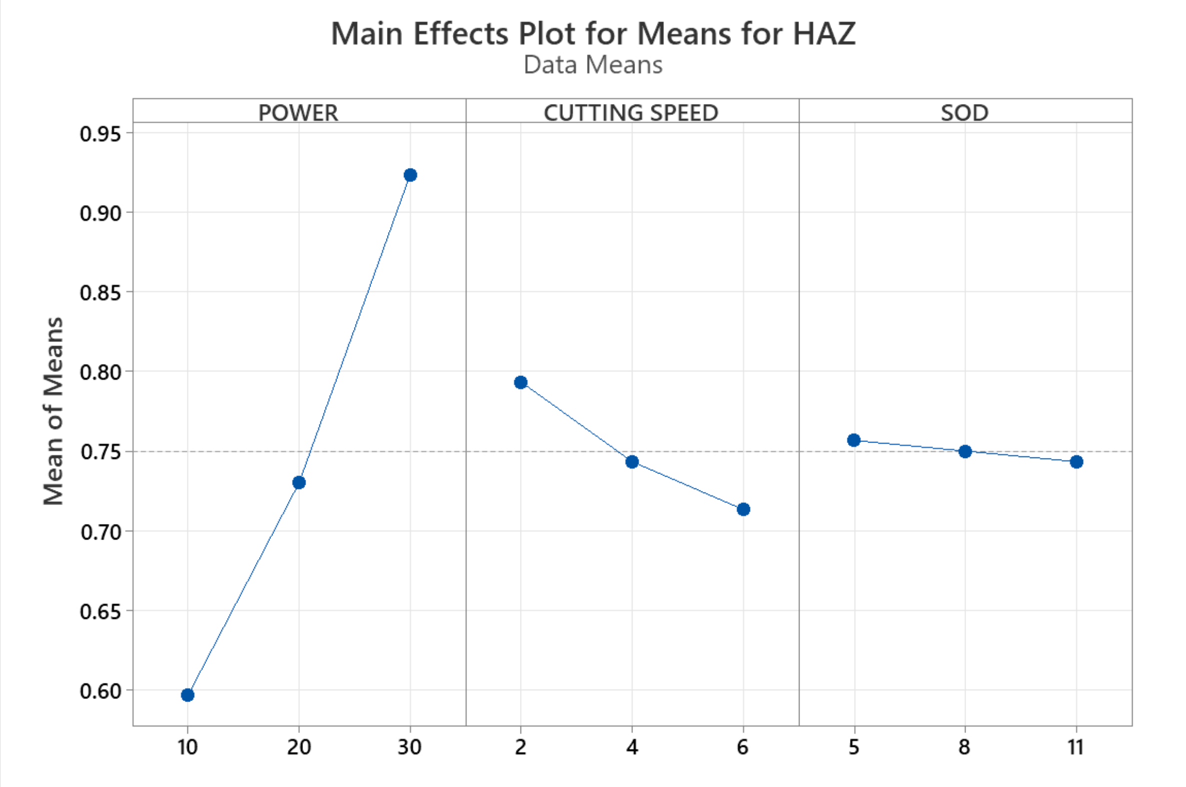

Fig 4: Main effects plot for HAZ

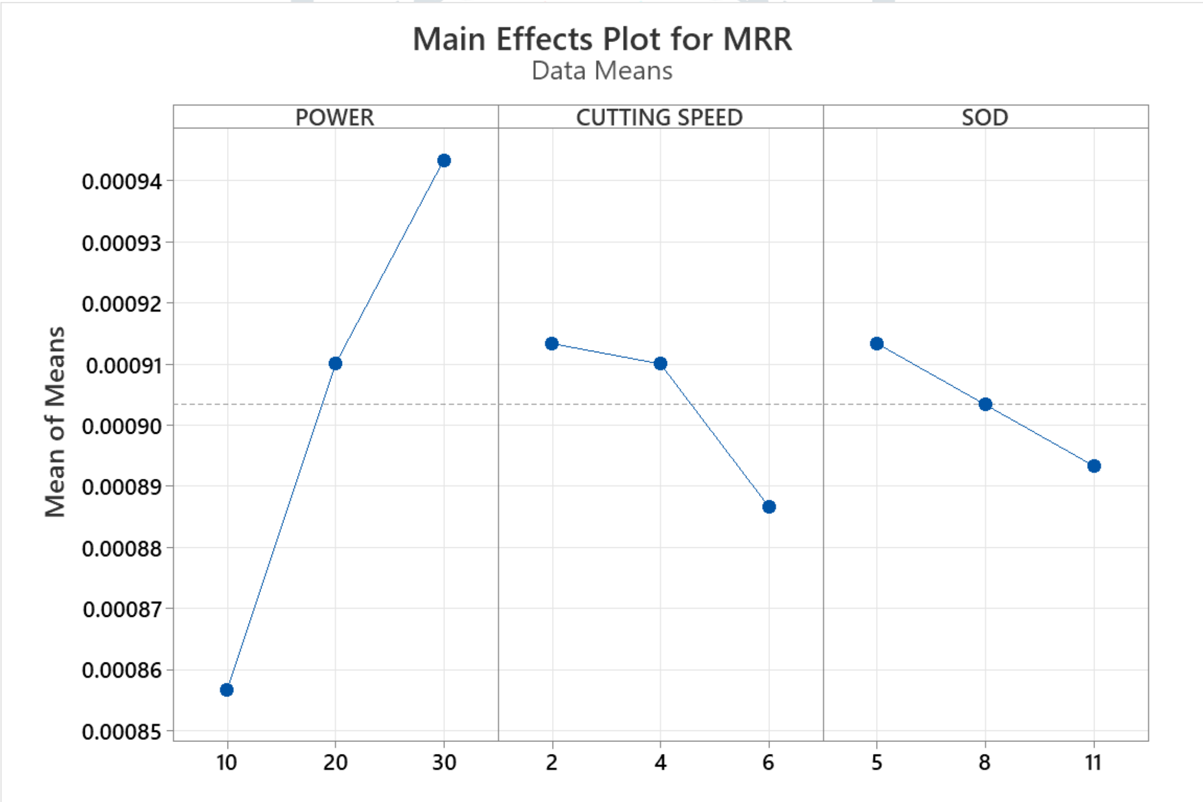

Fig 5: Main effect plot of MRR

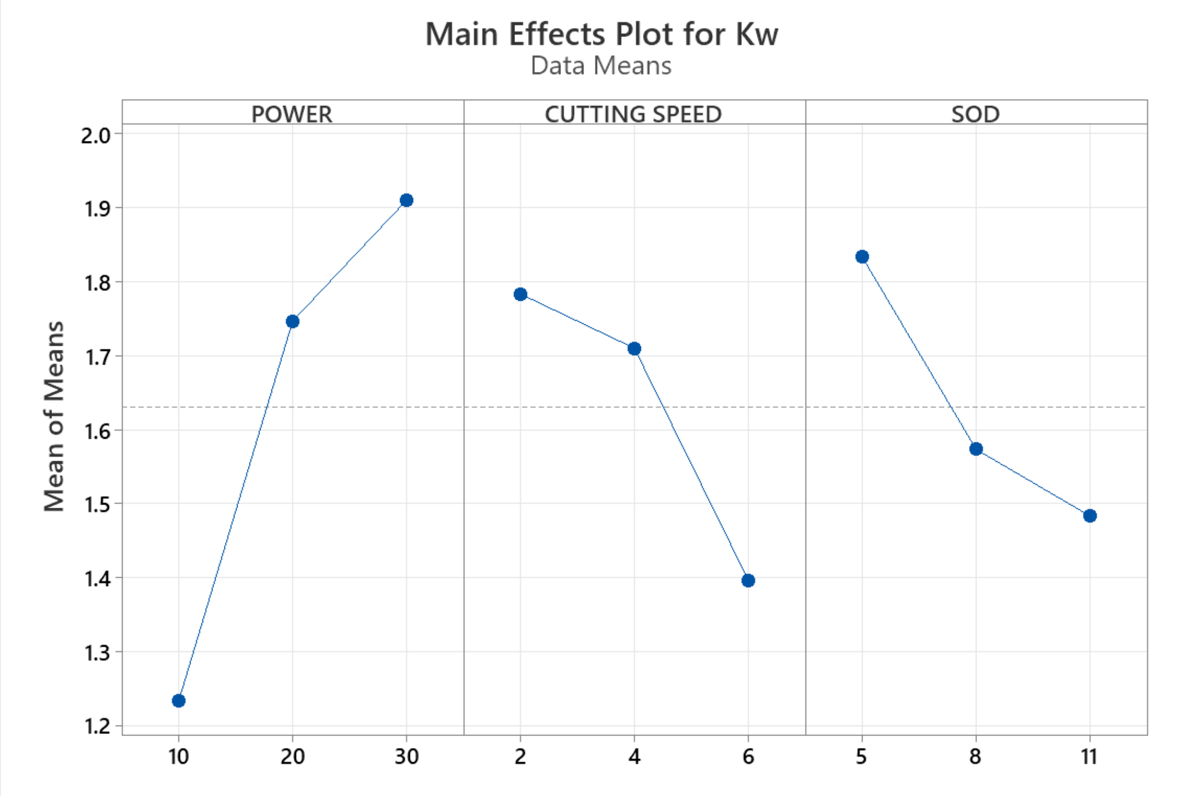

Fig 5: Main effect plot for kerf

V. CONCLUSIONS

In the current experimental study, Taguchi orthogonal array optimization of process parameters for laser abrasive jet machining is discussed. The experimental analysis and analytical investigation lead to the following result.

- It is observed that the mean value of MRR increases as the power increases and MRR decreases by increasing the cutting speed and SOD. The mean value of Kw and HAZ decreases as the cutting speed and SOD, & increases with the power.
- From the ANOVA table it is found that laser power is the most influencing parameter followed by cutting speed and sod.
- The main effect plots reveal that the laser power of 30w, the cutting speed of 2mm/s, and the sod of 5mm produces the highest MRR.
- The main effect plots reveal that the laser power of 10w, the cutting speed of 6mm/s, and the sod of 11mm yield the smallest kerf width.
- It can be seen from the major effect plots that the minimal HAZ is achieved at laser power of 10w, cutting speed of 6mm/s, and sod of 11mm.

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