Modelling of Material Removal Rate and Hole Circularity Of Soda Lime Glass For Rotary Ultrasonic Drilling

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Abstract. Rotary Ultrasonic Drilling (RUD) is an efficient and accurate way to drill holes in hard and brittle materials. Material removal rate and hole circularity are the essential output performance characteristics of a drilled hole in these hard to cut materials. In the present article, experimental investigation has been performed for RUD in 3mm thick soda lime glass using response surface methodology. Mild steel tool of diameter 2mm was used. Effect of ultrasonic power, frequency, spindle speed and abrasive grit number on material removal rate and hole circularity has explored. It is observed that with increase in frequency both MRR and circularity decreases. Ultrasonic power significantly effect hole circularity but has less effect on MRR for different frequency. MRR increases with abrasive grit number but circularity is adversally affected. At higher value of abrasive grit number, increase in tool rotation increases hole circularity.

Keywords: Rotary Ultrasonic Drilling, Soda Lime Glass, Response Surface Methodology, Circularity.

1. Introduction

Soda lime glass presents an exclusive application in optical components because of its superior properties like high thermal coefficient of expansion, high wear resistance and low fracture toughness. Because of its high hardness and strength, it is very difficult to machine this material. Aerospace, automobile industries, dental, fluidics and optics are wide areas of application of soda lime glass. Surface cracks and subsurface cracks are major demerit of conventional drilling methods which reduces strength of material and also increases edge chipping and hence RUD was introduced [1]. Rotary ultrasonic machining was originated by Mr. Percy Legge (1964) at United Kingdom Atomic Energy Authority (UKAEA), however the idea of combining drilling and ultrasonic vibrations was carried out by Brown et al [2]. RUD is a hybrid non-conventional machining process that incorporates the mechanism of material removal of diamond grinding and ultrasonic machining.

Zhang,et al perfomed RUD on optical K9 glass and observed that there was significant increase in cutting power, decrease in thrust force and there was small effect on surface roughness. Further, the cutting power decreases with feed rate significantly and with spindle speed there is slight decreament. At higher speed and low feed, average surface roughness was reduced [3]. Ding et al. observed that cutting force, surface roughness and torque were reduced by 24%, 23%, 47% respectively in RUD of C/SiC as compared to conventional drilling [4]. During RUD of AI7075-T6 alloy, Amini et al. concluded that torque reduces with increase in spindle speed and decreases with reduction in ultrasonic vibrations [5]. Y.Ahmed et al concluded that RUD produces much smoother surface than conventional drilling in alumina [6]. B.Azarhoushang et al. concluded that for Inconel 738-LC, increase in vibration amplitude decreases surface roughness [7]. Y.Jiao et al. concluded that for C/SiC composites, feed rate was most significant factor which affect the surface roughness [8]. Wang et al establish a model for prediction of edge-chipping in case of brittle material considering brittle fracture and highest impact force of abrasives due to vibrations [9].

The literature review indicates that very few experimental investigation of RUD using RSM method has been performed. Therefore in this study an attempt has been made to study the effect of ultrasonic power, ultrasonic frequency, spindle speed and abrasive size on MRR and hole circularity at the entrance during RUD of 3 mm thick soda lime glass using mild steel tool.

2. Experimental Details

In the current investigation, a soda lime glass sheet with dimension 20×20×3 mm was chosen as work material. The chemical composition and mechanical properties of soda lime glass is shown in Table 1 & 2 respectively.

Table 1: Chemical Compositions of soda lime glass

Element	SiO_2	CaO	Na_2O	MgO	Al_2O_3
Percentage %	70-74	5-14	10-16	0-6	0-3

Table 2: Mechanical properties of soda lime glass

Property	Density	Modulus of Elasticity	Poisson Ratio	Shear Modulus	Knop Hardness
Amount	2500 Kg/m^3	72000 N/mm^2	0.23	29,166 N/mm^2	6GPa

All the experiments were carried using RUD setup as shown in figure 1. There is a mild steel cutting tool of diameter 2mm which is axially vibrated and a constant feed is given to work material towards the tool. Black silicon carbide was used an abrasive. Water has been used to make slurry of abrasive. A laser tachometer has been used to measure spindle speed and a digital multimeter to measure the frequency of vibration.

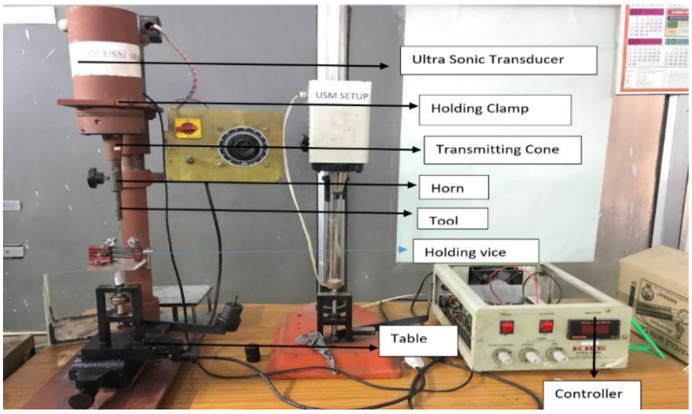


Fig. 1. Rotary Ultrasonic Drilling Setup

2.1 Selection of process parameters and their range

In the current investigation, the effect of several controllable input parameters i.e. ultrasonic power, frequency, spindle speed and abrasive grit number on the response namely material removal rate and hole circularity at entrance has been explored. The levels of input parameters has been selected on the basis of pilot experiments, machine capability and existing literature survey [Table 3].

Table 3: Input parameters and their values

Variables	Symbol	Level(-1)	Level(0)	Level(1)
Ultrasonic Power(%W)	A	70	80	90
Frequency(KHz)	B	21.5	22.5	25.5
Spindle Speed(rpm)	C	750	850	950
Abrasive Grit Number	D	30	46	60

2.2 RSM for parameter design

Experiments has been conducted according to the Box-behnken design of RSM. Box and Wilson (1951) utilized this method to develop a relationship between several machining parameters and response with the objective of obtaining optimum machining condition of the system [10]. RSM technique can be used to develop models from experimental or simulation data. It is the process of identifying and fitting an appropriate response surface model from experimental data. Compared to other RSM designs, Box–

Behnken design (BBD) can analyze the process more effectively with few experimental points.

In RSM a second order polynomial model is considered to explore the influence of parameters on the responses. In BBD, three levels of input parameters are required. Furthermore, it is confined when extreme responses are not required to be predicted. BBD is much cheaper and convenient to run than CCD with the same number of input factors. The RSM analysis was conducted using MINITAB software.

$$Y_i = \beta_0 + \sum^{k}_{i=1}\beta_i x_{iu} + \sum^{k}_{i=1}\beta_{ii} x^2_{iu} + \sum_{i<j}\beta_{ij} x_{iu} x_{ju} + e_u \qquad (1)$$

Where yi is the response, xiu is the coded value of the ith input variable for uth experiment, n is the total number of the input factors, β0 is a constant , βi, βii, and βij are the regression coefficents of second order and eu is the experimental error for uth observation [11]. A total of 27 experiment has been done as per as experimental design with four process variables, having three levels each. The BBD based experimental design matrix and corresponding responses are shown in table 4.

Table 4: BBD based experimental design matrix and result.

Exp. No.	Process parameters				Response	
	Ultrasonic power % W	**Frequency (KHz)**	**Spindle speed(rpm)**	**Abrasive Grit No.**	**MRR (g/min)**	**Hole circularity at entry**
1	70	21.5	850	46	0.0098	0.829
2	90	21.5	850	46	0.0156	0.881
3	70	25.5	850	46	0.0034	0.856
4	90	25.5	850	46	0.0026	0.831
5	80	22.5	750	30	0.0025	0.840
6	80	22.5	950	30	0.0048	0.899
7	80	22.5	750	60	0.0073	0.935
8	80	22.5	950	60	0.0076	0.809
9	70	22.5	850	30	0.0052	0.832
10	90	22.5	850	30	0.0040	0.868
11	70	22.5	850	60	0.0070	0.848
12	90	22.5	850	60	0.0154	0.856
13	80	21.5	750	46	0.0145	0.892
14	80	25.5	750	46	0.0026	0.827
15	80	21.5	950	46	0.0127	0.883
16	80	25.5	950	46	0.0036	0.874
17	70	22.5	750	46	0.0029	0.867
18	90	22.5	750	46	0.0026	0.898
19	70	22.5	950	46	0.0035	0.867
20	90	22.5	950	46	0.0024	0.866
21	80	21.5	850	30	0.0028	0.877
22	80	25.5	850	30	0.0028	0.865
23	80	21.5	850	60	0.0245	0.873
24	80	25.5	850	60	0.0051	0.879
25	80	22.5	850	46	0.0060	0.867
26	80	22.5	850	46	0.0054	0.876
27	80	22.5	850	46	0.0046	0.885

2.3 Process Variable

The weight of the work piece before and after the machining were measured using scientific weighing balance with minimum readability of 0.0001g and maximum weight capacity of 220g and MRR were calculated using Eq. (2)

$$MRR = \frac{initial\ \ weight - final\ \ weight}{time}\ gm/\min \qquad (2)$$

Hole circularity at entry (C_{entry}) was calculated as the ratio of minimum to maximum diameter of drilled hole at entry side. Since most of the geometrical variation occurs at the entrance, therefore circularity at the entry side will provide a good information about the effect of process parameters on geometrical accuracy. Dino lite's digital microscope was used to visualize the dimension of drilled hole. The geometrically circular hole will give the value of hole circularity as one.

$$C_{entry} = \frac{d_{\min}}{d_{\max}} \tag{3}$$

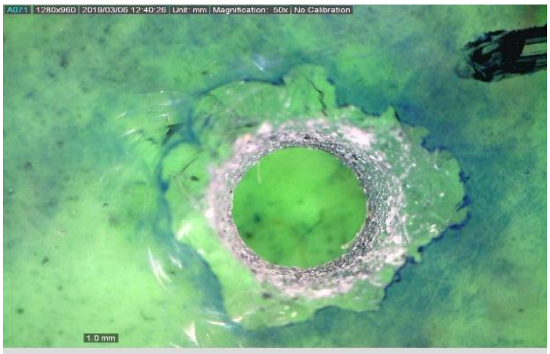


Fig.2. Drilled Hole sample

3. Result and Discussions

3.1 Mathematical Model

The mathematical model for correlating material removal rate and hole circularity at entry with various machining parameters as stated in experimental design are as follows:

MRR = 0.804 + 0.00139 A - 0.0797 B + 0.000181C+ 0.00097 D- 0.000002 A^2 + 0.001814 B^2 - 0.000000 C^2+ 0.000008 D^2- 0.000064 A×B- 0.000000 A×C+ 0.000016A×D + 0.000002 B×C - 0.000105 B×D - 0.000000 C×D

Hole circularity at entry = -1.74 + 0.0538 A + 0.019 B - 0.00091 C + 0.02889 D - 0.000153 A^2 - 0.00083 B^2 + 0.000000 C^2- 0.000022 D2 - 0.000857 A×B - 0.000008 A×C - 0.000046 A×D + 0.000093 B×C + 0.000119 B×D - 0.000030 C×D

To test whether model fits the data or not, S value for MRR and hole circularity are obtained as 0.0031888 and0.0155357, respectively which are low and value of R2 for both are 84.03% and 84.48%, respectively which are high. So the data are well fitted in developed model. ANOVA tests has been done to test the adequacy of the developed empirical model for MRR and hole circularity. Table 5 shows the ANOVA result for MRR and hole circularity. The p-value of the models are much smaller than 0.05 for both responses. Developed regression model for MRR is significant and linear, square terms are also significant. Regression model for hole circularity is significant and interaction of variables are also significant. Lack-of-fit for MRR and hole circularity have p value of 0.040 and 0.250 respectively represents that developed model are adequate at 95% confidence interval.

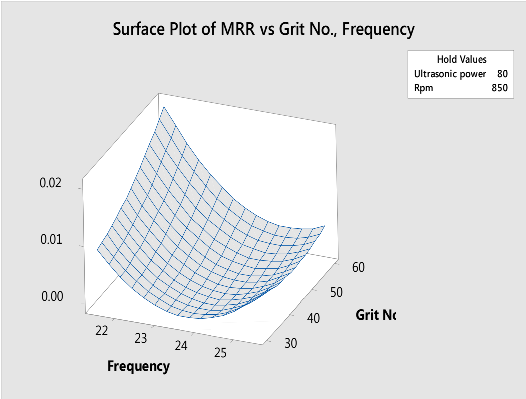
Table 5: ANOVA result for MRR and hole circularity at entry

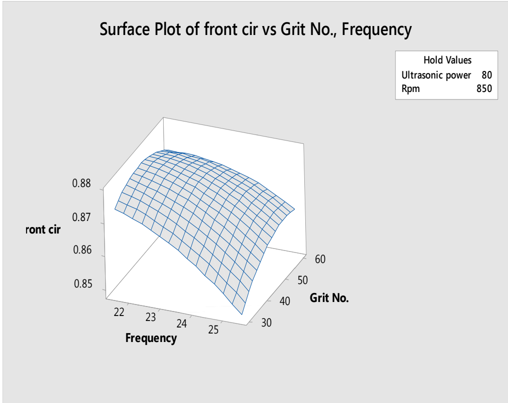
Source	MRR		Hole circularity	
	F-value	P- value	F-value	P- value
Regression	4.51	0.006	4.66	0.006
Linear	8.38	0.002	1.19	0.366
Square	5.05	0.013	1.90	0.176
Interaction	1.28	0.335	8.13	0.001
Lack-of-fit	24.53	0.040	3.38	0.250

3.2 Effect of process parameters on MRR and hole circularity

The MRR during RUD decreases with frequency 24 KHz but at higher values it begins to increase at constant abrasive grit number. Similarly the MRR increases with abrasive grit number for constant frequency. The increase of MRR with abrasive grit number is more rapid at lower frequency whereas at higher frequency the effect of abrasive grit number on MRR decreases as depicted in fig.3(a). Fig. 3 (b) indicates that the hole circularity continuously decreases with frequency for a particular abrasive grit number but the magnitude of effect decreases with increase of abrasive grit number. The increase of abarsive grit number increases the circularity [Fig. 3(b)]

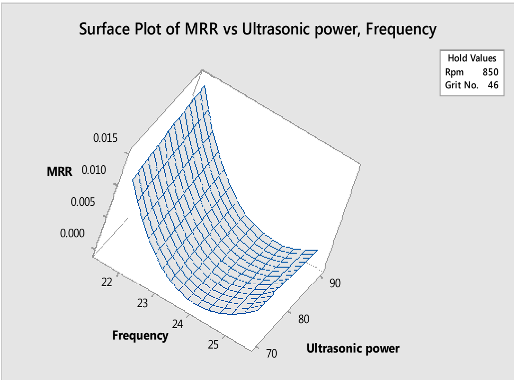
The corresponding effect of ultrasonic power and frequency on MRR and circularity has been shown in Fig. 4(a) and (b) respectively. The MRR decreases very rapidly with frequency for all values of ultrasonic power. The ultrasonic power increases the MRR very gradually at different frequencies. The rate of change of circularity with ultrasonic power is very high and it begin to decrease with ultrasonic power after initial increase

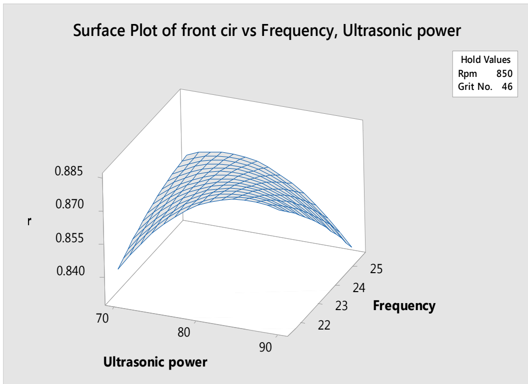




3(a) 3(b)

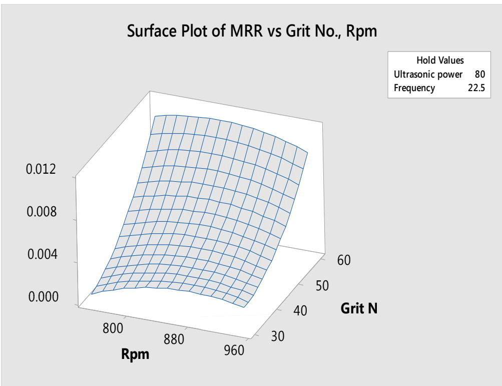
Fig. 3. Effect of frequency and grit number on (a) MRR (b) Circularity

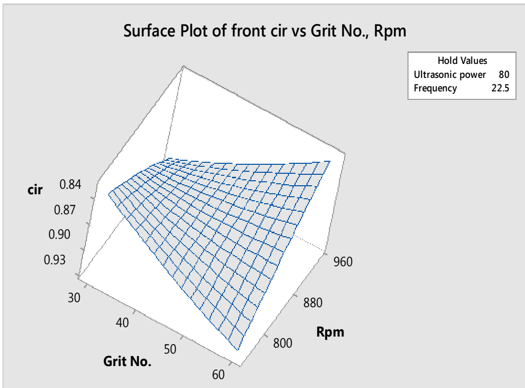




4(a) 4(b)

Fig. 4. Effect of frequency and ultrasonic power on (a) MRR (b) circularity





5(a) 5(b)

Fig. 5. Effect of grit number and spindle speed on (a) MRR (b) circularity

The effect of rotation of the tool and abrasive grit number has been shown in Fig. 5. The rotation of the tool has very minimal effect on the MRR for particular abrasive grit number but at certain rotation the MRR increases rapidly with grit number. The hole circularity shows a reverse trend with respect to these two parameters. The increase of grit number decreases the circularity but the rotation of the tool increase the circularity significantly at higher abrasive grit number.

4. Conclusions

Experimental investigation of Rotary Ultrasonic Drilling was performed with Box-Behnken approach of RSM for the creating hole of diameter 2 mm in soda lime glass sheet of thickness 3 mm. Second order regression model was developed for MRR and hole circularity considering the input process parameters of ultrasonic power, ultrasonic frequency, abrasive grit number. and rotation of the mid steel tool. The following conclusions can be drawn for MRR and hole circularity using the response surface plots for different combination of input process parameters.

(a) The increase of frequency decreases both the MRR and hole circularity. But at very higher values the MRR increases at particular abrasive grit number. The effect of increase of abrasive grit number is more significant on MRR compare to circularity.

(b) The effect of ultrasonic power on MRR for different frequency is very minimal on MRR but it influence the hole circularity very significantly.

(c) The MRR increase with grit number at a particular rotation of tool but the circularity is adversely effected due to increase of abrasive grit number. The increase of tool rotation at higher value of abrasive grit number increase the hole circularity.

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