Machining of Defect Free Holes Using Diamond Core Drilling by Optimization of Parameters

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Abstract**—Diamond core drilling is considered to be a cost effective method for making deep holes in advanced ceramics, composites, quartz, stone, glass etc. with superior surface finish. But its usage is limited in precise glass drilling operations because of the high edge chipping produced at the entrance and exit of holes which not only reduces geometric accuracy but also possibly cause an increase in post machining cost. This study investigated the effect of speed and feed on overcut, edge chipping thickness and cutting force. ANOVA has been adopted for finding the percentage contribution of parameters. Regression models are developed for predicting cutting force, edge chipping thickness and overcut. The designed experiment has revealed the main effects of process parameters on the response. The use of a back-up plate and adhesive as a support was found to be useful for producing crack free holes. Internal coolant flushing was found to be an effective method for enhancing tool life.**

Keywords—Diamond core drill; Edge chipping; Overcut; Cutting force.

I. INTRODUCTION

Glass is the most widely preffered material for window panes and containers for beverages, food, and some commodity items. Glass is relatively inexpensive, chemically stable and reasonably hard. Due to its optical transparency and biological compatability, glass is often considered a more desirable material for particular MEMS device. But the high brittle nature and its unique structure makes the glass one of the most difficult to machine materials as frequent occurance of fracture and edge chipping during machining has to be avoided. The available machining methods which includes abrassive jet machining, laser machining and ultrasonic machining have its own disadvantages like poor dimensional accuracy, hole taper and low material removal rate respectively. Moreover all the above mentioned process is expensive and may not be suitable for small scale industries. Diamond core drilling can provide an effective solution for drilling precise holes with high aspect ratios.

A Traditional CNC Controlled drilling or milling machine can be used easily for diamond core drilling (DCD). In this machining operation, a hollow cylindrical metal piece with diamond grits impregnated at its tip acts as the drill bit which is usually called diamond core drill. There are many variables that affect diamond drill performance. Understanding these variables will help the end user to select the right diamond drill specification for their application and optimize their drilling operation to ultimate level of efficiency. Several researchers have conducted studies on using diamond core drilling for making holes in ceramics, stones, composites etc. The results obtained revealed the potential of this method in the manufacturing industry.

Lei Zheng et al. [1] conducted a study on drilling kevlar fiber reinforced polymer (KFRP) sheets using diamond core drill and found that machining efficiency increases with increase in spindle speed and decrease in wall thickness of the drill. Tsao [2] made an attempt to study the variation of thrust force and surface roughness of core drill with drill parameters like grit size of diamond, thickness, feed rate and spindle speed in drilling carbon fiber reinforced plastic (CFRP) laminate. He suggested high speed and low drilling feed rate for the production of delamination-free and good surface finish holes in epoxy composites. Jun Wei Liu [3] studied the use of rotary ultrasonic machining (RUM) for drilling ceramics and found that the use of which will reduce the chipping at hole edges. But the complexity in construction and cost limits the use of RUM in small scale industries. Balykov [4] pointed out the importance of using internal coolant flushing to dissipate the heat developed and to remove the debris thereby preventing sudden tool failure. He developed a mathematical model for predicting the coolant pressure to be employed for a given tool diameter. Quan and Zhong [5] Compared the performance of cemented diamond core drills and plated diamond tools for drilling CFRP. The plated diamond tool was found to have better self-dressing capability and more chip pockets so that they are not easily clogged or smeared out. The effect of a plated diamond solid drill for drilling CFRP was not satisfactory.

Most of the studies conducted using diamond core drilling are on composites and ceramic materials. Only a few systematic studies have been reported on glass drilling using diamond core drills. This study is mainly focusing on formulating a practical method for reducing edge chipping during diamond core drilling of glass. In diamond core drilling, the tool contacts and cuts the workpiece and the liquid coolant usually water is forced through the core of the drill which washes away the swarf, prevents jamming of the drill and keeps it cool. The diamond core drilling (DCD) process is illustrated in Figure 1. A rotating core drill with metal bonded diamond abrasive is fed towards the workpiece. The material removal mechanism involves extraction due to grinding action of diamond grits and abrasion. The debris produced due to grinding mixed with the pressurized coolant are responsible for erosion at the walls of the hole during machining and contributes towards abrasion mechanism of material removal.

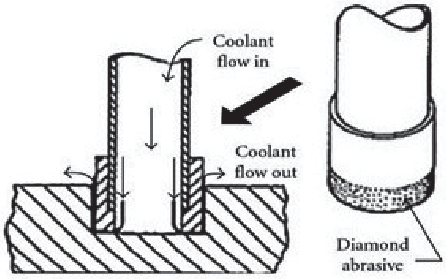


Fig. 1. Schematic diagram of diamond core drilling

One of the main remaining challenges of diamond core drilling is the edge chipping which happens at hole entrance and exit while drilling holes in ceramics. Figure 2. shows the edge chipping at the entrance of a hole drilled on soda lime glass using diamond core drills . Generally, edge chipping is not acceptable on finished products and has to be machined off by other processes after the drilling operation. The larger the edge chipping thickness, the higher is the total machining cost.

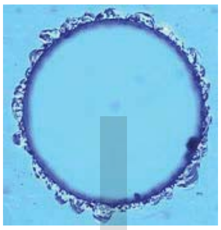


Fig. 2. Edge chipping produced on soda lime glass during drilling using DCD

The main influencing factor on edge chipping is the cutting force, which depends upon the machining variables such as spindle speed and feed rate. By proper optimization of these parameters we can reduce edge chipping at hole entrance and exit.

This paper reports the results of a systematic study on the parameters of diamond core drilling influencing the edge chipping and the dimensional accuracy of the drilled holes. Full factorial design (two- factors, three-levels) is used to investigate the effect of process parameters (spindle speed and feed rate) on cutting force, edge chipping thickness and overcut. Regression analysis has been used for developing mathematical models and ANOVA has been adopted for determining significant factors with percentage contribution.

II. EXPERIMENTAL CONDITIONS

In this section, the experimental setup and the design of experiment are described in detail. The effects of process parameters (spindle speed and feed rate) on cutting force, edge chipping thickness and overcut are investigated experimentally. Analysis of the experimental data were performed using statistical methods which is explained at the end of this session.

A. Experimental setup

A CNC vertical milling machine of BFW make (model-Agni BMV 45 TC24) available at National Institute of Technology Calicut is used for conducting experiments. A Kistler dynamometer 9257B is used for measuring the cutting force. The workpiece used is sodalime glass supplied by Saint-Gobain, which was glued on a back-up glass plate and the worpiece together with the back-up glass plate was glued on a stainless steel plate of dimension 100 x 170 mm using a silicon sealant. This plate is bolted on the dynamometer platform and the whole setup was clamped on the table of CNC machine. The coolant used in the process is a water-based coolant with 20:1 dilution of water soluble cutting oil. Fig. 3, shows the experimental setup. Table 1, provides a brief description of dynamometer, workpiece and diamond core drill.

(a) (b)

Fig. 3. (a) Vertical milling machine integrated with Kistler dynamometer amplifier and PC based dynamometer readout using Dynoware software (b) Dynamometer along with workpiece glued on a stainless steel plate.

TABLE 1. SPECIFICATIONS OF DYNAMOMETER, WORKPIECE AND TOOL

Dynamometer	
Make and model	Kistler, 9257B
Force range	F_X, F_Y, F_Z : (-5 to 5) kN
Sensitivity	F_X, $F_Y \approx -7.5$ pC/N $F_Z \approx -3.7$ pC/N
Workpiece	
Material	Sodalime glass
Dimension (LXBXT)	200 X 40 X 3 mm
Knoop hardness	418 kgf/mm^2
Tool	
Type	Diamond core drill bit
Material of shank	Steel
Length	50 mm
Outer Diameter	6 mm
Diamond coating length	3 mm

B. Design of experiment.

A full factorial 3^2 (three level-two factor) design was employed, which results in 9 unique experiment conditions. Due to the limitations of the experimental set-up, the experiments focus on the study of the following two process parameters or machining parameters: 1) Spindle speed (rotational speed of cutting tool in revolutions per second) 2) Feed rate (vertical advance of cutting tool in millimeters per second). Table 2, shows the levels chosen for the parameters. Software called Mini-tab (Release 14.13, trial version) was used to generate the testing order as well as to assist in processing the experimental data. Replication, randomization and blocking were performed inorder to improve the precision of the experiment. The output variables are cutting force, edge chipping thickness and overcut.

TABLE 2. PARAMETERS AND LEVELS

Parameter	Unit	Level 1	Level2	Level 3
Speed	rps	16.67	33.33	50
Feed	mm/s	0.017	0.033	0.05

Table 3, shows the full factorial design for the experiment. Two replications were performed by treating each replicate as a separate block. Run order was randomized separately for each block.

TABLE 3. FULL FACTRORIAL DESIGN

Sl. No.	Standard Order	Runs	Block	Speed (rps)	Feed (mm/s)
1	9	7	Block 1	33.33	0.033
2	7	4	Block 1	16.67	0.033
3	3	2	Block 1	33.33	0.017
4	11	9	Block 1	50	0.033
5	17	1	Block 1	50	0.05
6	15	5	Block 1	33.33	0.05
7	5	3	Block 1	50	0.017
8	1	8	Block 1	16.67	0.017
9	13	6	Block 1	16.67	0.05
10	6	15	Block 2	50	0.017
11	2	16	Block 2	16.67	0.017
12	16	18	Block 2	33.33	0.05
13	12	12	Block 2	50	0.033
14	8	13	Block 2	16.67	0.033
15	18	17	Block 2	50	0.05
16	4	11	Block 2	33.33	0.017
17	10	14	Block 2	33.33	0.033
18	14	10	Block 2	16.67	0.05

Edge chipping usually happens at the entrance and exit of holes. At entrance, the chipping mainly happens because of the sudden rise in cutting force when the tool just comes into contact with the workpiece surface. At the hole exit, chipping happens mainly due to the lack of support when the tool just reaches the bottom layer[6]. Hole exit edge chipping can be quantified by measuring the edge chipping thickness from the rod obtained after machining as shown in Fig. 4. Overcut controls the dimensional accuracy of the drilled holes. It can be defined as the difference between the actual drilled hole diameter and the diameter of the drill bit.

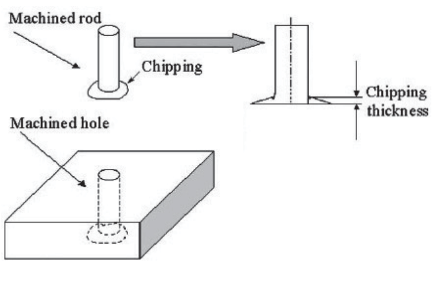


Fig. 4. Illustration of edge chipping thickness [7]

Edge chipping thickness was measured using an Olympus video measuring system and the overcut was determined using a universal microscope. The results obtained for the full factorial experiment with 9 sets and 2 replications are shown in the Table 4.

C. *Statistical tools for data analysis.*

For determining the optimum parameters, signal to noise ratio (S/N ratio) was calculated for the responses. The signal to noise ratio is a statistic that combines the mean and variance [8]. The objective in robust design is to minimize the sensitivity of a quality characteristic to noise factors. This is achieved by selecting the factor levels corresponding to the maximum S/N ratio. In this study the objective is to minimize the values of the responses like Edge chipping thickness, cutting force and overcut. Hence smaller-the better type of quality characteristic was used to compute S/N ratios of responses using (1)

$$\eta = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right] \qquad (1)$$

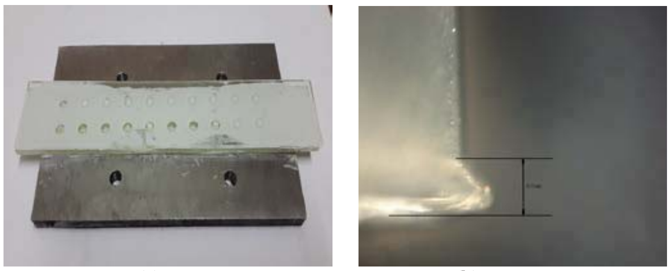
Where η is the S/N ratio, n is the number of replicates and Y_i is the ith response. The calculated S/N ratios of the three responses are included in the Table 4.

Analysis of Variance (ANOVA) was used to determine the significant factors and its contribution on response. ANOVA is a method of partitioning total variation into accountable sources of variation in an experiment and helps to interpret experimental data for taking decisions about the parameters under study[8]. The basic equation of ANOVA is given by (2)

Total sum of squares(SS_{Total}) = Sum of squares due to factors (SS_{Factor}) + Sum of squares error(SS_{Error}) (2)

III. RESULTS AND DISCUSSION

The combined effect of spindle speed and feed rate on edge chipping thickness(ECT), cutting force(CF) and overcut (OC) were determined using the designed experiment. Figure 5. shows the drilled hole and the glass rod obtained after drilling operation. The main effects plot which helps to predict the factor levels corresponding to highest S/N ratio was obtained using the MINITAB software. The main effects plot for edge chipping thickness is shown in Fig. 6.



(a) (b)

Fig. 5. (a) Drilled holes (b) Edge chipping thickness determined from machined rod using video measuring system.

TABLE 4. RESULTS OF FULL FACTORIAL EXPERIMENT

Exp. No.	Trial	Speed (rps)	Feed (mm/s)	Overcut [OC] (mm)		Cutting Force[CF] (N)		Edge chipping thickness[ECT] (mm)		Signal to Noise Ratio		
				1	2	1	2	1	2	OC	CF	ECT
1	8,16	33.33	0.033	0.2351	0.2398	310	333	0.18	0.2	12.5746	-50.1491	14.4129
2	2,11	16.67	0.033	0.2072	0.211	373	355	0.29	0.25	13.6712	-51.2246	11.3489
3	3,15	33.33	0.017	0.2348	0.2297	262	290	0.11	0.06	12.7272	-48.8293	21.0513
4	4,13	50	0.033	0.2987	0.2988	320	346	0.26	0.32	10.4948	-50.4554	10.7058
5	7,14	50	0.05	0.3201	0.2996	398	435	0.42	0.33	9.8919	-52.4008	8.4572
6	9,12	33.33	0.05	0.2122	0.2189	363	410	0.24	0.29	13.104	-51.759	11.4966
7	6,10	50	0.017	0.2973	0.3019	314	323	0.26	0.15	7.4518	-50.063	13.463
8	5,18	16.67	0.017	0.2034	0.2115	270	310	0.13	0.08	13.8324	-49.2685	19.3367
9	1,17	16.67	0.05	0.1997	0.2047	390	413	0.33	0.29	13.4935	-52.0772	10.1547

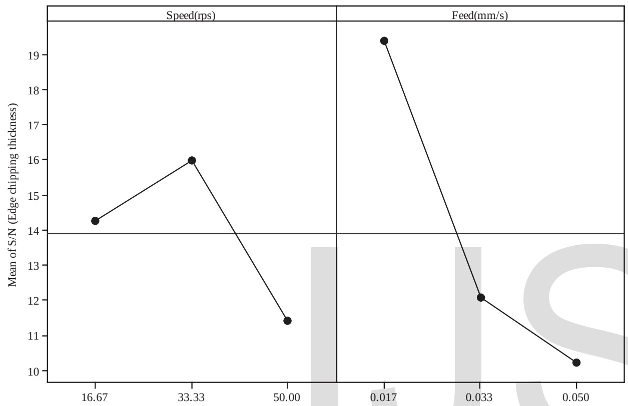


Fig. 6. Main effects plot for S/N ratio of edge chipping thickness

From the main effects plot it is evident that a medium speed of 33.33 rps (Level 2) and low feed of 0.017mm/s (Level 1) helps to reduce the edge chipping thickness at exit of holes. Figure 7. shows the main effects plot of cutting force.

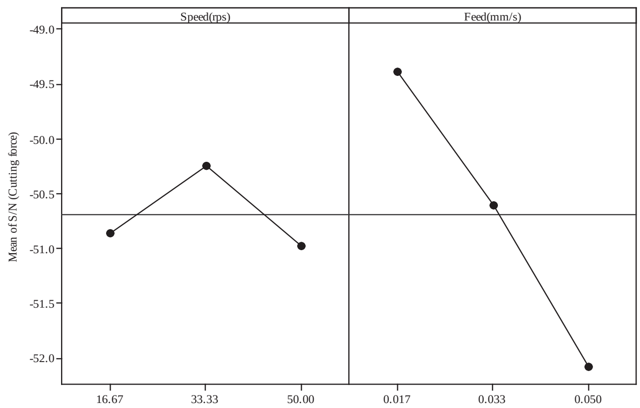


Fig. 7. Main effects plot for S/N ratio of cutting force.

The speed and feed corresponding to the highest value of S/N ratio are 33.33rps (Level 2) and 0.017mm/s (Level 1) respectively. These levels of parameters will reduce the cutting force to minimum value and helps to reduce edge chipping at the entrance of the hole. Cutting force plays a major role in producing edge chipping at the entrance of hole. Figure 8. shows the main effects plot for overcut.

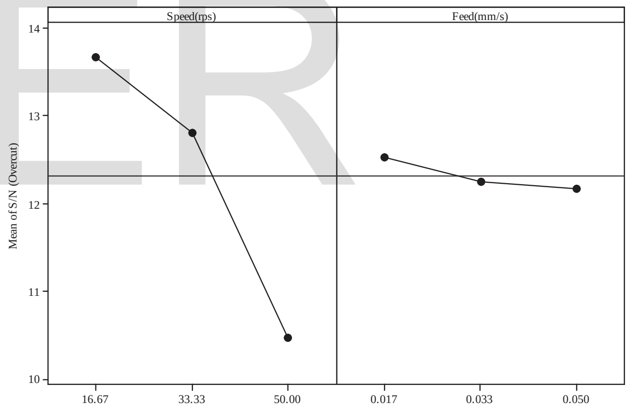


Fig. 8. Main effects plot for S/N ratio of overcut.

The main effects plot for overcut shows that a speed of 16.67 rps (Level 1) and feed of 0.017mm/s (Level 1) can produce holes with minimum overcut and helps in maintaining dimensional accuracy.

As an attempt for determining the significant factors and its contribution percentage on responses, ANOVA has been performed and the results are summarized in Table 5, Table 6, and Table 7 for edge chipping thickness cutting force and overcut respectively.

From the ANOVA conducted for edge chipping, it is evident that both speed and feed are significant with feed contributing a high percentage of 64 in producing edge chipping.

TABLE 5. ANOVA FOR EDGE CHIPPING THICKNESS

Source	Degrees of freedom	Sum of squares	Mean square	F_0	Percentage contribution
Speed	2	0.0365	0.0182	11.32*	22.42%
Feed	2	0.1053	0.0527	32.70*	64.68%
Error	13	0.0209	0.0016		
Total	17	0.1628			

$F_{0.05,2,13}$ = 3.81; *Significant at 5% level

TABLE 6. ANOVA FOR CUTTING FORCE

Source	Degrees of freedom	Sum of squares	Mean square	F_0	Percentage contribution
Speed	2	2738.8	1369	2.96	6.34%
Feed	2	34433.8	17216	37.17*	79.71
Error	13	6021.1	463		
Total	17	43193.6			

$F_{0.05,2,13}$ = 3.81; *Significant at 5% level

TABLE 7. ANOVA FOR OVERCUT

Source	Degrees of freedom	Sum of squares	Mean square	F_0	Percentage contribution
Speed	2	0.0292	0.0146	116.9*	92.99%
Feed	2	0.0006	0.0003	2.44	1.91%
Error	13	0.0016	0.0001		
Total	17	0.0314			

$F_{0.05,2,13}$ = 3.81; *Significant at 5% level

From the ANOVA table for cutting force, it can be observed that only feed rate is significant in developing thrust component of cutting force within the range of parameters under study. Thus a reduction in feed rate helps to reduce cutting force.

In the case of overcut, the only parameter which can be considered significant is spindle speed. To reduce the overcut, a low speed is preferred during diamond core drilling for a tool diameter of 6mm.

The results obtained from this study were used to formulate mathematical models of first order using regression analysis. Regression analysis is a statistical technique used to find relationships between variables for the purpose of predicting future values. Regression analysis is used to predict the result of an experiment before or to validate it after the experiment is done. When two or more independent variables are to be related in predicting a dependent variable a multiple regression mathematical model has to be used. In this study relations are framed for responses like cutting force, edge chipping thickness and overcut with the parameters speed and feed. Equation (5), (6) and (7) gives multiple linear- regression models for cutting force(CF), edge chipping thickness(ECT) and overcut (OC) respectively.

$$CF = 233 + 0.125 \times Speed + 3237 \times Feed \quad (5)$$

$$ECT = - 0.0152 + 0.00185 \times Speed + 5.59 \times Feed \quad (6)$$

$$OC = 0.136 + 0.00283 \times Speed - 0.429 \times Feed \quad (7)$$

Where speed and feed are in revolutions per second (rps) and millimeters per second(mm/s) respectively. The R^2 Values obtained for (5), (6) and (7) are 80%, 78.1% and 86.7% respectively. R^2 is a measure of the amount of variation explained by the model. The adequacy of model was checked using the statistical software MINITAB. The high R^2 values implies that the regression models obtained is adequate for predicting the responses.

IV. EFFECT OF COOLANT AND BACK-UP PLATE

The edge chipping at the exit of the hole happens mainly due to lack of support. When the tool reaches the bottom portion of the glass, cracking happens in the form of chipping due to the absence of support beneath the workpiece. This was confirmed with the help of experiments conducted on soda lime glass with and without support. One portion of the glass was provided bottom support by gluing it on a backup glass plate using silicon sealant and the other portion was left without any support. The schematic diagram of the experimental setup is shown in Fig. 9. Diamond core drilling was performed on both portions of same workpiece with the optimized parameters mentioned in the last session.

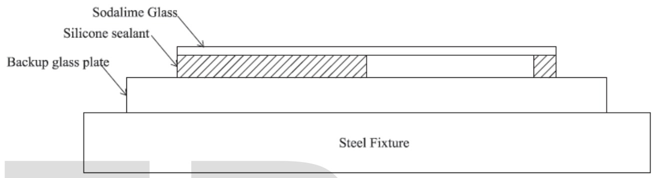


Fig. 9. Schematic diagram of experimental setup

It was observed that the portion of glass provided with silicon sealant and backup plate produced very less edge chipping at the hole exit. On the other hand the portion without support undergone severe cracking and chipping.

To study the effect of coolant on drilling performance, drilling on soda lime glass was performed with and without internal coolant flushing. It was observed that tool wear became significant while drilling without coolant flushing and also internal edge chipping occurred due to clogging of hole with debris. Drilling with internal coolant flushing produced clear holes with less chipping at entrance and low tool wear due to good heat dissipation and debris removal.

V. CONCLUSION

In this study a full factorial experiment was conducted to study the effect of process parameters like speed and feed on edge chipping thickness, cutting force and overcut produced during diamond core drilling. The optimum parameters were found to be a medium speed of 33.33 rps and a low feed of 0.033mm/s for minimizing edge chipping thickness and cutting force. For overcut, the optimum values are a low speed of 16.67rps and a low feed of 0.017mm/s. Further experiments to study the effect of coolant and support using back-up plate revealed some practical methods for reducing edge chipping.

At the entrance the edge chipping happens mainly due to the sudden high cutting force developed when the tool comes into contact with the workpiece. The cutting force can be minimized by delivering the tool at a low speed and feed. Optimized parameters can be used to achieve this. At the hole exit, chipping can be minimized by providing a back-up glass plate at the bottom. A full uniform support can be given by gluing the workpiece on the back-up plate using glass sealants or adhesives. This will reduce the tensile stress at the bottom corner of the hole and thereby producing crack free hole. This method of fixturing the brittle materials like glass to perform drilling can reduce the possibility of vibration and thereby prevents sudden cracking of the material when compared with any other mechanical clamping methods.

Internal coolant flushing helps to dissipate the heat generated and enhance tool life. It also helps to remove debris and prevents internal chipping on the walls of hole.

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