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Quality Evaluation on Rotary Ultrasonic Assisted Drilling for Chemically Strengthened Glass

R. Izamshah[1*], A. Lamat[2], M. Rafiq[2], M.Z. Kasman[2], M.S. Kasim[1], P.J. Liew[2] , M.S.A. Aziz[2] and R.S.A. Abdullah[3]

[1]Advanced Manufacturing Centre (AMC), Universiti Teknikal Malaysia Melaka,
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[2]Fakulti Kejuruteraan Pembuatan, Universiti Teknikal Malaysia Melaka,
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[3]School of Information Technology and Electrical Engineering, The University of Queensland,
Brisbane, Queensland 4072, Australia

ABSTRACT

Demand for Chemically Strengthened (CS) glass has steadily increased for the past decade predominantly by the electronic devices industry. One of the major reasons are due to its superior strength and crack resistance properties. However, due to its superior properties which resistant to compressive loads causing drawback to the subsequent secondary manufacturing process i.e. hole drilling. Conventional drilling process towards this glass tends to generate high tensile thrust that consequently affect the hole performances and accuracy. Considering these facts, in this paper a new drilling technique which assisted by the ultrasonic vibration frequency known as Rotary Ultrasonic Assisted Drilling (RUAD) is propose aim to increase the hole quality. A set of experimental work was conducted in order to assess the effects of the RUAD parameter namely cutting speed, feed rate, ultrasonic frequency and vibration amplitude towards hole quality. The analytical results demonstrated that the presence of the intermittent ultrasonic vibration amplitude was able to minimize the chipping area and enhance the hole quality with acceptable tolerance value.

Keywords: Precision drilling, rotary ultrasonic assisted drilling, chemically strengthened glass.

1. INTRODUCTION

Due to its superior properties i.e. high durability and high strength, the application of Chemically Strengthened (CS) glass has steadily increased. Compared to the thermal tempering glass properties, CS glass outperform the performances up to six times in terms of toughness and resistance to crack. For this reason, most of the CS glass application usage are predominantly by the electronic devices industry such as camera lens, optical component, mobile phone, tablet PCs screen, etc. [1-2]. In such aforementioned applications, micro holes drilling is required as to serve for the particular purposes such as camera lenses, speakers and proximity sensors as shown in Figure 1.

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[*]Corresponding author: izamshah@utem.edu.my

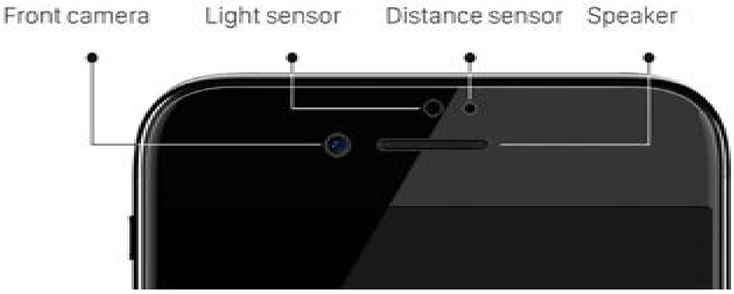


Figure 1. Micro holes' positions at mobile phone screen.

However, due to its superior properties which resistant to impact loads has cause problem to the subsequent secondary manufacturing process i.e. hole drilling. Conventional drilling process towards this glass tends to generate high tensile thrust that consequently affect the hole performances and accuracy. Therefore, significant development on techniques for processing CS glass has steadily increase for the past year. Recently, an ultrasonic application to improve the machining process has gained great attention with promising result especially for hard and brittle material known as Ultrasonic machining (USM). In USM process, the material are removes via micro chipping and hammering of abrasive slurry to the part surface with 20-40 kHz vibration [3-4]. By employing this technique, the thrust force that create crack initiation for brittle material such as glass and ceramic can be minimized. Although USM provide with promising result, its low in material removal rate limits its application. Based on this, with the aim to improve the hole quality for drilling CS glass this paper propose a new drilling technique which assisted by the ultrasonic vibration frequency known as Rotary Ultrasonic Assisted Drilling (RUAD).

Unlike USM process, for RUAD the material are removes through the combination between ultrasonic vibration frequency and rotating carbide drill bit. Theoretically, by incorporating between both actions causes the cutter to shear whilst periodically vibrate perpendicular to the work surface creating an intermittent cuts at a constant feed that substantially decrease the thrust force magnitudes and improve the material removal rate [5-6]. Rotary ultrasonic machining of borosilicate crown glass has been reported by Zeng et al. [7]. They claimed that by employing ultrasonic vibration capable to minimize the magnitudes of compressive loads and reduce the hole chipping size. In other feasibility attempt on ultrasonic machining of K9 glass, Zhang et al. showed that lateral cracks can be minimized through compressed air as coolant [8]. Figure 2 depicts the mechanics of RUAD material removal process.

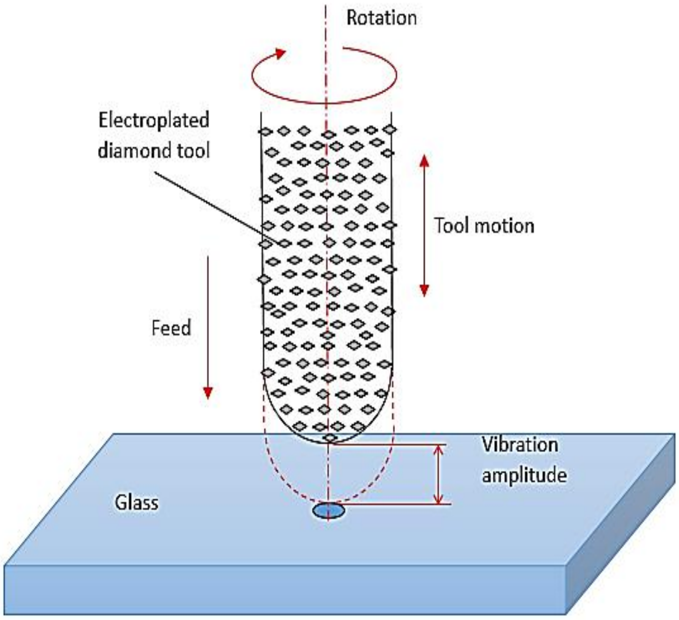


Figure 2. Mechanic of cutting for RUAD.

Although several researchers have claimed on the success of RUAD for glass material, one thing to be highlighted is the type of glass used in those experiment were made from heat strengthening method glass which are six times less tough than the chemically strengthening method. Hence, in this paper, a feasibility study of RUAD on chemically strengthening glass was performed to evaluate the occurrence of surface chipping at the hole entry and exit. The evaluation will include on the influences of RUAD parameter namely cutting speed, feed rate, ultrasonic frequency and vibration amplitude towards hole quality.

2. EXPERIMENTAL SETUP

A one mm thickness CS glass manufactured by Corning Inc. was employed as a specimen for the experimental work. The glass has a density of 2.39 g/cm3, Young Modulus of 69.3 GPa, Poisson's Ratio of 0.22 and Shear Modulus of 28.5 GPa. Table 1 depicted detailed properties of chemically strengthening (CS) glass used in the experiment.

Table 1 End mill specification

	CSG
Density [g/cm^3]	2.39
Young's Modulus [GPa]	69.3
Poisson's Ratio	0.22
Shear Modulus [GPa]	28.5
Vickers Hardness (200 g load) [kgf/mm^2] Unstrengthened Strengthened	 534 649
Fracture Toughness [MPam$^{0.5}$]	0.66
Critical Load [N]	150
Load to Failure (ring on ring) [N]	1225
Coefficient of Expansion (0 – 300 °C) [/°C]	75.8×10^{-7}

The drilling experiment was conducted using a cnc milling machine. A dedicated ultrasonic tooling system was designed and developed to suit with the machine spindle to perform the RUAD process. The ultrasonic tooling system capable to transmit ultrasonic frequency from the generator oscillating from 20 kHz to 27 kHz with maximum of 3 µm amplitude. An alumina oxide abrasive grit with the concentration ranging 5-15 % was used throughout the experiment. The developed RUAD system and CS glass arrangement are illustrate in Figure 3 below. In addition, special design jig and fixturing were fabricated to minimize the present of chatter. Since the CS glass has superior strength and crack resistance properties a dedicated jig design was fabricated to hold the sample. The design of the work holding device need to be rigid to cater the compressive stress occur during the RUAD process in both entry and exit surfaces.

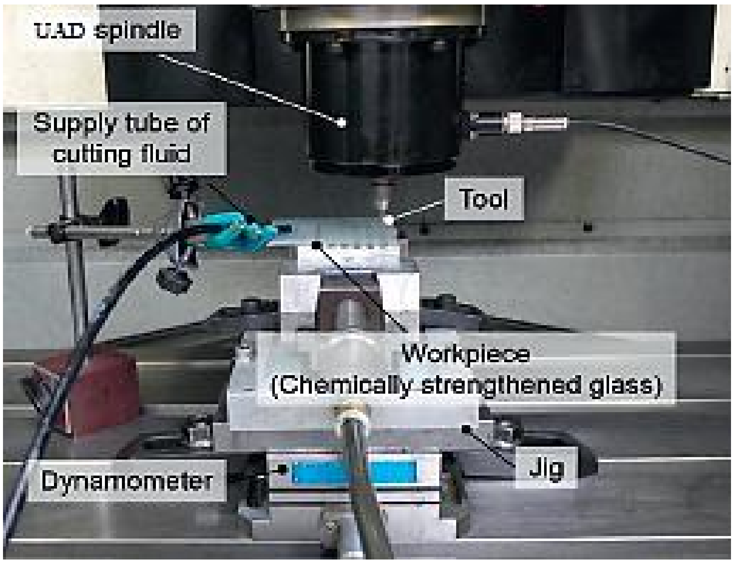


Figure 3. Rotary ultrasonic drilling setup and tool holder.

A special designed electroplated diamond tool dedicated for drilling CS glass consist of two chip discharge area was employed. Table 2 and Figure 4 depicted detailed specification for the electroplated diamond tool.

Table 2 Electroplated diamond tool specifications

Parameter	Value
Tool diameter	1.0 mm
Tool shank	3 mm
Diamond grit size	25-35 µm
Material	SK5

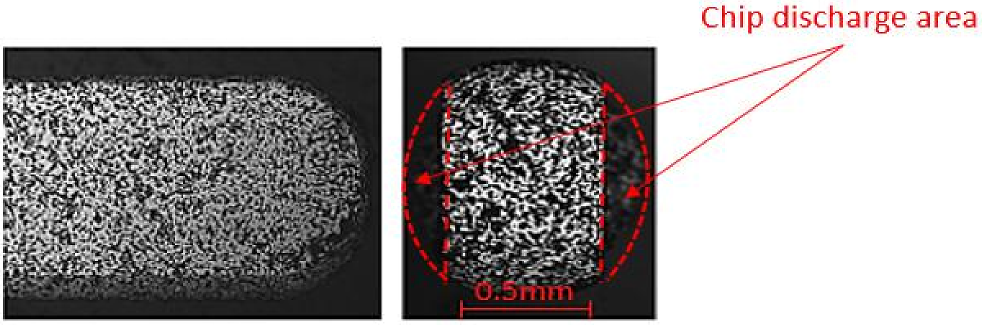


Figure 4. SEM images of the tool tip.

Historical Design matrix of Response Surface Methodology (RSM) technique was used as the Design of Experiment (DoE) to evaluate the RUAD parameters input to the output responses. The independent variables and levels namely; spindle speed (A), feed rate (B), ultrasonic frequency (C) and vibration amplitude(D) as explained in Table 3. The upper and lower limit value for the input variables were based from cutting tool's manufacturer recommendations and from the literature [2]. Optical microscope was used to captured the drilled holes images for the analysis. Subsequently, the image to be process by the ImageJ® software for measuring the chipping area at both entry and exit surface. To ensure the accuracy of the reading, the measurements were done five times.

Table 3 Factors and levels

Factor	Range	Unit
Cutting speed, N	6000-7000	(rpm)
Feed rate, f	0.25-0.75	(mm/min)
Frequency, f	20-27	(kHz)
Amplitude, a	1-3	(µm)

3. RESULTS AND DISCUSSION

Table 4 and Figure 5 tabulated the calculated chipping area for the entry and exit surface respectively. The observed chipping area value varied between 0.4976 mm^2 to 1.1706 mm^2 for entry surface and 0.2666 mm^2 to 0.9196 mm^2 for exit surface. The variations on the observed chipping area values indicate that the RUAD drilling parameters has significant effects on the hole's quality.

Table 4 Chipping area results for entry and exit surface

Run	Frequency (kHz)	Amplitude (µm)	Speed (rpm)	Feed rate (mm/min)	Entry chipping area (mm^2)	Exit chipping area (mm^2)
1	23.5	3	6500	0.75	0.957	0.479
2	27	1	6500	0.5	1.17	0.482
3	20	1	6500	0.5	1.11	0.919
4	27	3	6500	0.5	1.026	0.846
5	20	2	6500	0.25	1.017	0.545
6	23.5	2	6500	0.5	0.738	0.66
7	23.5	3	7000	0.5	1.013	0.887
8	23.5	2	7000	0.25	0.91	0.353
9	20	3	6500	0.5	1.014	0.881
10	23.5	2	6500	0.5	0.808	0.511
11	23.5	2	6000	0.25	0.775	0.44
12	20	2	7000	0.5	0.824	0.736

13	23.5	1	7000	0.5	0.998	0.898
14	27	2	6000	0.5	0.767	0.567
15	23.5	1	6500	0.75	0.83	0.712
16	23.5	2	7000	0.75	0.678	0.389
17	20	2	6000	0.5	0.684	0.541
18	23.5	2	6500	0.5	0.645	0.407
19	23.5	1	6000	0.5	0.921	0.868
20	23.5	3	6000	0.5	1.01	0.496
21	20	2	6500	0.75	0.583	0.36
22	23.5	1	6500	0.25	0.931	0.895
23	27	2	6500	0.25	1.013	0.377
24	23.5	3	6500	0.25	0.543	0.39
25	23.5	2	6500	0.5	0.566	0.469
26	23.5	2	6500	0.5	0.564	0.421
27	27	2	6500	0.75	0.497	0.266
28	23.5	2	6000	0.75	0.939	0.878
29	27	2	7000	0.5	0.892	0.623

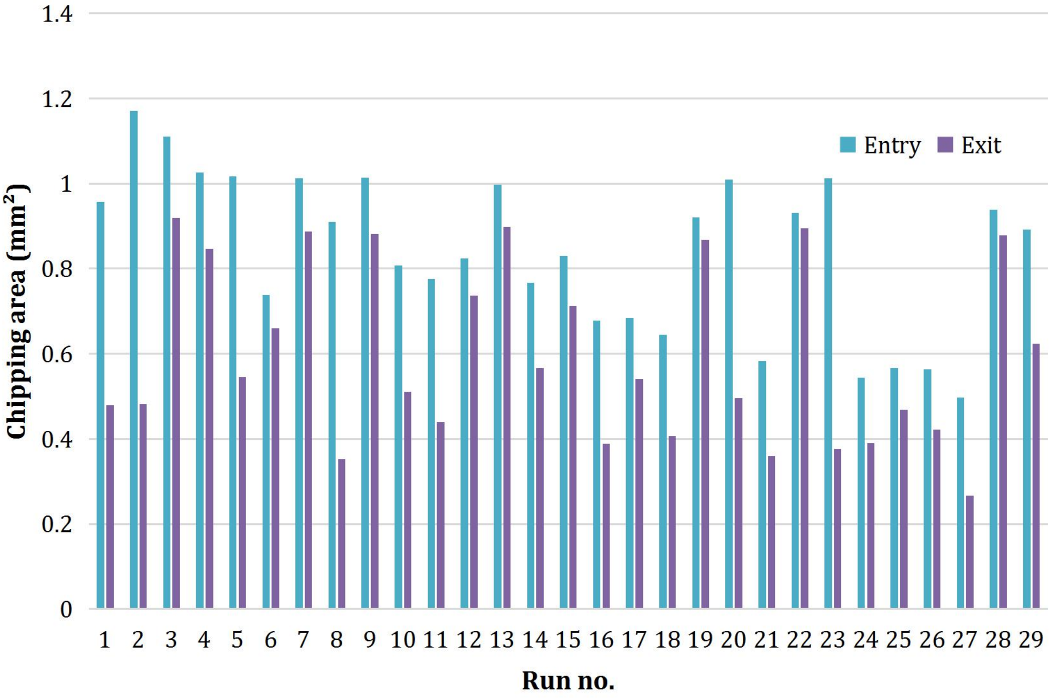
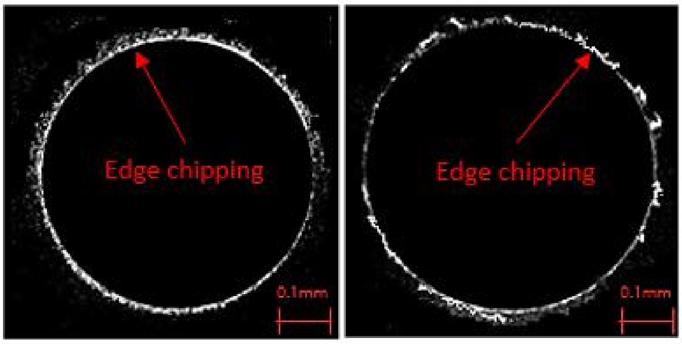


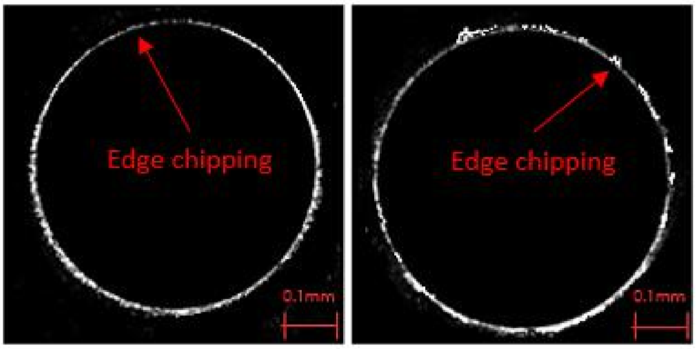
Figure 5. Comparison between chipping area at entry and exit surface.

Referring to the obtained results, it was found that for all the runs entry chipping area were larger than at the exit. One of the possible reason for this cause can be related to the knocking impact at the beginning stage of the drill process i.e. tool tip approaching the glass surface. At this stage, due to the compressive stress resulting from the diamond grits and alumina oxide particles chipping the glass surface. The magnitudes of the compressive stress will affect the cracks propagation rate. Figures 6 and 7 show the holes and chipping areas for the minimum and maximum at the entry and exit surface respectively.



(a) Minimum chipping area (b) Maximum chipping area

Figure 6. Entry holes' image.



(a) Minimum chipping area (b) Maximum chipping area

Figure 7. Exit holes' image.

Statistical ANOVA (Table 5) was performed to further investigated the relationship of RUAD parameters towards the chipping area for both entry and exit surfaces. Based on the ANOVA, a quadratic model was selected to exemplify the cutting parameters effects towards the chipping area for both entry and exit surfaces.

In addition, from the analysis if the obtained P-values of the cutting parameters smaller than 0.05 specify that it is statistically significant towards the outputs, in this case entry and exit chipping areas [9-10]. For both models (entry and exit), the lowest calculated P-value were found to be twice of vibration amplitude factor i.e. B2. The results revealed that, the hammering impact resulting from the vibration amplitude intensely has a direct effect towards the hole quality.

Although others parameters were not statistically significant, one thing to be highlighted are these parameters need to be considered i.e. spindle speed and feed rate as this experimental work employed a RUAD technique. Excluding these parameters will make the experimental become a normal USM process. Therefore, further analysis on the effect of RUAD on material removal rate need to be perform to access the feasibility on implementing RUAD technique for drilling CS glass material which are not covered in this paper.

Table 4 ANOVA results for entry and exit surface

Entry						Exit					
Source	**SS**	**DoF**	**MS**	**F-value**	**Prob>F**	**Source**	**SS**	**DoF**	**MS**	**F-value**	**Prob>F**
Model	0.5789	14	0.0414	1.4545	0.2462	Model	0.7753	14	0.0554	1.7541	0.1524
A	0.0019	1	0.0019	0.0668	0.7985	A	0.0566	1	0.0566	1.7928	0.202
B	0.0129	1	0.0129	0.4538	0.512	B	0.0529	1	0.0529	1.6756	0.2163
C	0.0039	1	0.0039	0.1372	0.7183	C	0.0008	1	0.0008	0.0253	0.977
D	0.434	1	0.4340	15.2661	0.2368	D	0.0006	1	0.0006	0.0190	0.8909
A^2	0.0856	1	0.0856	3.0110	0.1047	A^2	0.0054	1	0.0054	0.1710	0.6853
B^2	0.3379	1	0.3379	11.8858	0.0039	B^2	0.3424	1	0.3424	10.8457	0.0053
C^2	0.0522	1	0.0522	1.8362	0.1968	C^2	0.0588	1	0.0588	1.8625	0.1937
D^2	0.0001	1	0.0001	0.0035	0.9865	D^2	0.0693	1	0.0693	2.1951	0.1605
AB	0.0006	1	0.0006	0.0211	0.8888	AB	0.0402	1	0.0402	1.2734	0.2781
AC	0.0001	1	0.0001	0.0035	0.9605	AC	0.0048	1	0.0048	0.1520	0.7016
AD	0.0025	1	0.0025	0.0879	0.7734	AD	0.0013	1	0.0013	0.0412	0.8424
BC	0.0014	1	0.0014	0.0492	0.825	BC	0.0328	1	0.0328	1.0390	0.3256
BD	0.0663	1	0.0663	2.3321	0.149	BD	0.0185	1	0.0185	0.5860	0.4567
CD	0.0392	1	0.0392	1.3789	0.2599	CD	0.0404	1	0.0404	1.2797	0.277
Residual	0.398	14	0.0284			Residual	0.442	14	0.0316		

Figure 8 and 9 illustrate a 3D response surface plot of the RUAD parameter and chipping areas for the entry and exit surface respectively. From the figures it shows that, the effects of RUAD can significantly affect the quality of the holes. Unsuitable combination of parameter will result in large edge chipping area due to the high knocking impact on the glass surface.

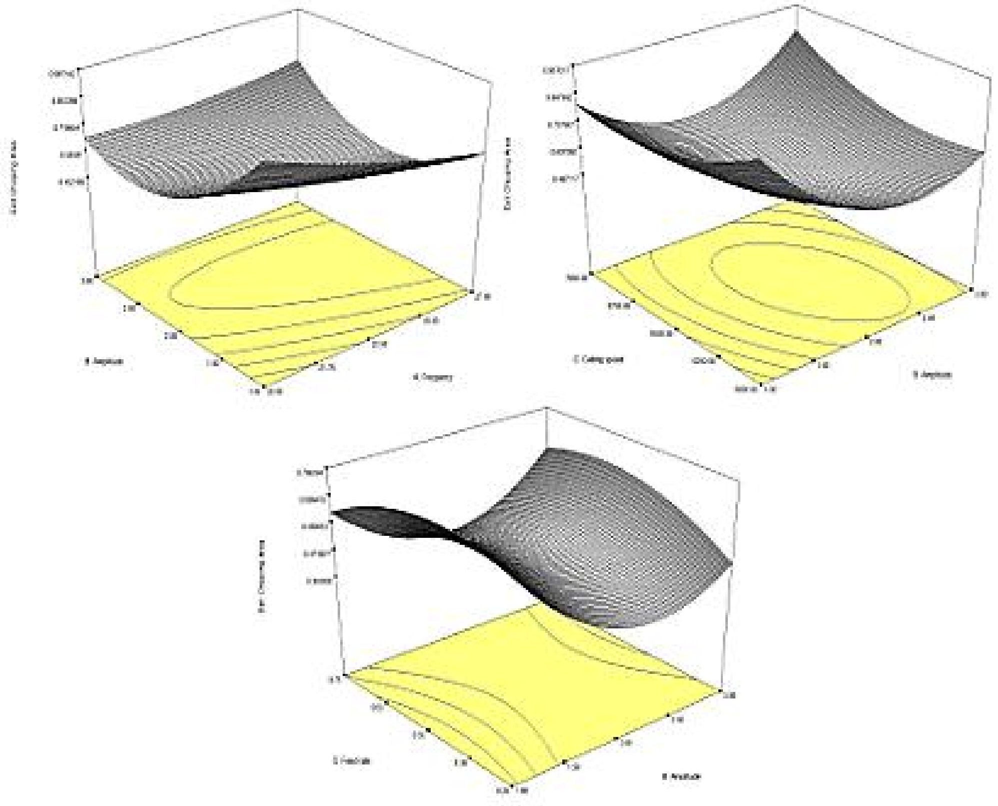


Figure 8. Surface plot of RUAD parameter and chipping areas for hole entry.

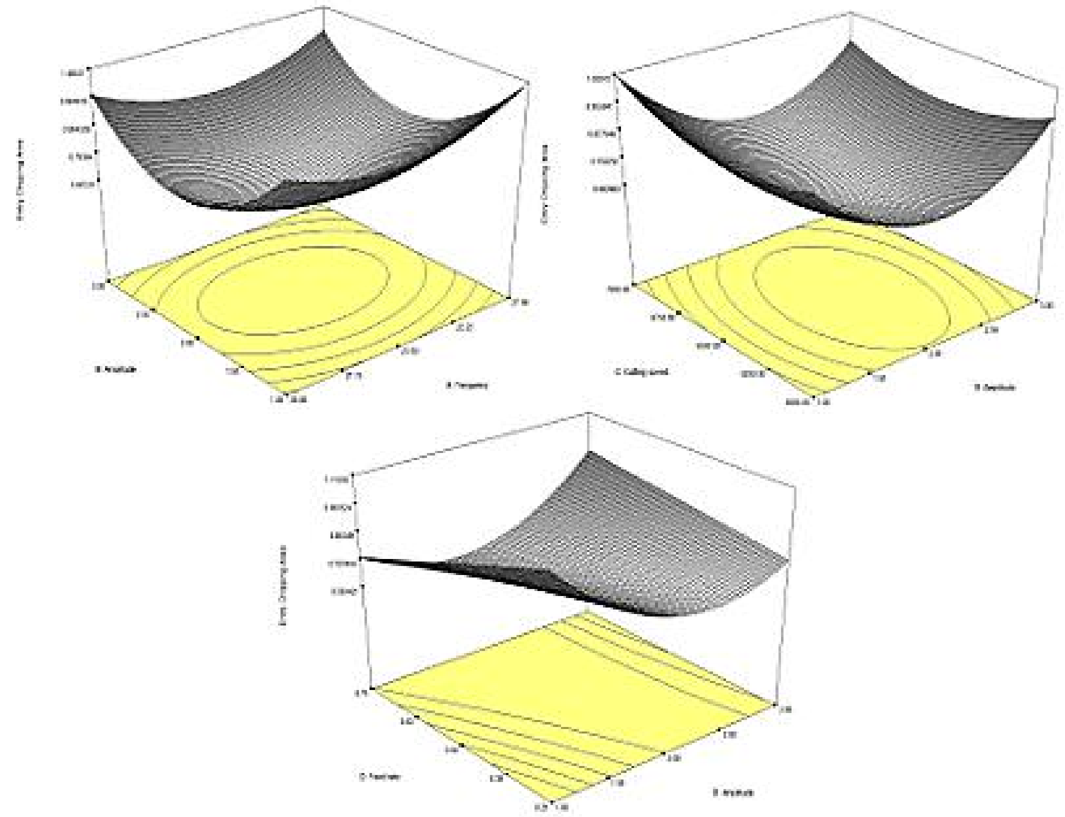


Figure 9. Surface plot of RUAD parameter and chipping areas for hole exit.

Figure 6 shows the SN ratios graph for cutting force. Lower cutting force values are required to produce good machining quality. This is because the cutting force is often closely related to the friction that leads to the cutting temperature. Therefore, 'smaller is better' is chosen to obtain good machining quality. This graph shows that the cutting force is influenced by helix angle and spindle speed followed by rake angle and number of flutes. Based on this graph, the low cutting force value can be obtained if the helix angle value (60°) clearance angle value (18°), feed rate value (500 mm/min) and depth of cut value (1.5 mm) is high and the spindle speed value (1000 rpm), rake angle value (5°) and number of flutes value (2) is low.

4. CONCLUSION

In this paper, experimental investigation of Rotary Ultrasonic Assisted Drilling (RUAD) of chemically strengthen glass was performed. A set of experimental work was conducted to assess on the effects of RUAD parameter namely cutting speed, feed rate, ultrasonic frequency and vibration amplitude towards chipping areas for the entry and exit surface. The experimental work proved that RUAD technique can be used to drill micro size hole at chemically strengthen glass surface with acceptable tolerance. However, further analysis on the effect of RUAD on material removal rate need to be perform to consider on the feasibility of implementing RUAD technique for drilling chemically strengthen glass material.

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