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Optimization of Surface Roughness in Micro-High Speed End Milling of Soda Lime Glass Using Uncoated Tungsten Carbide Tool with Compressed Air Blowing

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Abstract. Soda lime glass is a very important material in diverse manufacturing industries, including automotive, electronics, and aerospace. In these applications, the glass surface needs to be defect free and without impurities. However, the machining of glass is difficult due to its inherent brittleness which leads to brittle fracture and easy crack propagation. This research investigates the high speed micro-end milling of soda lime glass in order to attain ductile regime machining. It has been found by other researchers that ductile mode machining can avoid brittle fracture and sub-surface cracks. Also, in this study, a special air delivery nozzle is used to blow away the resultant chips and keep the machined surface clean. To accomplish this, Design Expert software and a commercial NC end mill were used to design and perform the machining runs, respectively. The surface roughness of the resultant surfaces was later analyzed with a surface profilometer. Microphotographs of the machined surfaces were also taken in order to see how effective the air blowing method is. The results of surface roughness measurements were then used to develop a quadratic empirical model for surface finish prediction. Finally, desirability function and genetic algorithms were used to predict the best combination of cutting parameters needed to obtain the lowest surface roughness. The predictions were later tested by experiments. The results demonstrate that this type of machining is viable and the roughness obtained is very low at 0.049 μm.

Introduction

Soda lime glass, a brittle material, plays an important role in modern industries, especially in aerospace, automotive, optical electronics, and semiconductor sectors [1]. This is due to its unique properties like chemical inertness, resistance to corrosion, high strength and stiffness at elevated temperatures, transparency to light and infrared etc. However, for these high-tech applications, the glass surface needs to be almost free of defects or impurities [1]. Such high surface finish and precise dimensions can be obtained through the selection of appropriate machining parameters so that ductile regime machining can be obtained [2].

Ductile mode machining is a special class of ultra-precision machining which is used to machine brittle materials. In this type of machining, material is removed predominantly by the chip formation process and leads to crack-free machined surfaces with surface roughness as small as a few nanometers [3]. Several approaches have been investigated in order to achieve ductile regime machining, including: low depths of cut (in micro-meter range), negative tool rake angle, and high static pressures. This research uses high speed micro-machining to attain ductile mode machining of soda lime glass. Micro-machining takes advantage of low depths of cuts, usually between 1 and 999μm. On the other hand, high speed machining (HSM), more specifically end milling, exploits the glass transition temperature in order to cut without brittle fracture [4].

Another challenge in glass machining has been the effective removal of chips from the machining site. Usually these chips adhere to the machined surface and thereby reduce surface integrity. Mahmud et al. [5] used a commercially available high pressure airline kit to blow away the resultant chips and obtained defect free surface in HSM of single crystal silicon. The current research built on the works of these researchers and successfully applied compressed air, delivered by a specially designed nozzle and fixture, in order to attain defect free machined surface in soda lime glass. Since a commercially available air delivery mechanism was used, the technique is very economical and cost effective.

Subsequently, the research investigated the effect of the three primary machining parameters (spindle speed, axial depth of cut, and feed rate) on the ductile regime machining and the attainment of fine surface finish. Finally, coupled response surface methodology (RSM) and genetic algorithm (GA) was used to model and optimize the resultant average surface roughness. The predictions were further validated using designed experiments.

Experimental Details

Machining runs were conducted on a 5-axis DMU 35M Deckel Maho NC mill. A NSK Planet 550 high speed attachment (65,000 rpm) was attached to the spindle and connected to the air supply via the Nakanishi AL-0201 Air Line Kit, which controlled the high speed attachment by regulating the compressed air flow. The set-up also consisted of another air supply for the air blower. Fig. 1 shows the experimental setup for the high speed micro-end milling of soda lime glass with uncoated tungsten carbide tool.

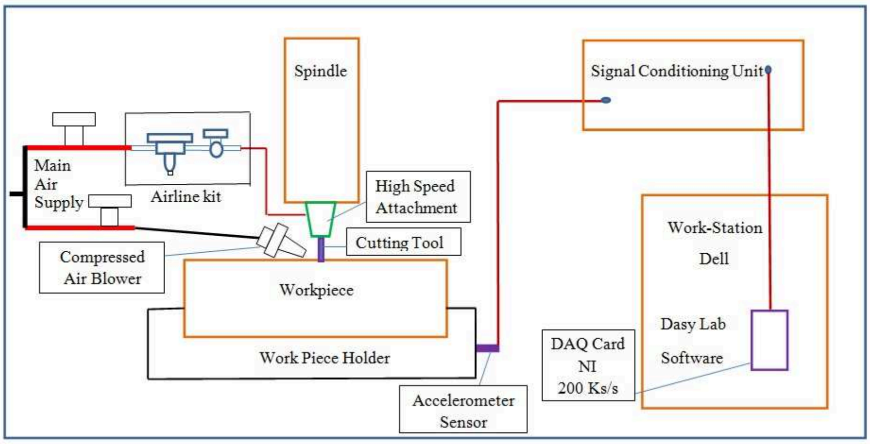


Fig. 1: Schematic representation of the experimental setup used for high speed micro-end milling of soda lime glass with compressed air delivery mechanism.

A micro-grain cemented carbide tool with plasma CVD coating (diameter = 2 mm, rake angle = 5º) was used to machine rectangular specimens of single crystal silicon (dimensions = 20 mm x 15 mm x 5 mm). The subsequent face of the work-piece was securely bonded with aluminum plates. At the beginning, the silicon workpiece was leveled by the abrasive diamond grinder wheel.

The input parameters were: spindle speed (30000-50000 rpm), depth of cut (10-20 μm), and feed rate (6-18 mm/min). Compressed air (0.35-0.40 MPa) was used to blow the chips from the machined surface.

Experimental runs were designed using the Design-Expert software (DOE version 8.0.7.1) based on a 3 factors 5 levels Face Centered Central Composite Design (FC-CCD) model of Response Surface Methodology (RSM) in order to model average surface roughness 'R_a'. The three input machining parameters were: spindle speed (rpm), axial depth of cut (μm), and feed rate (mm/min). These parameters were varied within fixed ranges taking into account the limits of the machine and the machining process: 30,000 to 50,000 rpm, 3 to 7 μm, and 5 to 15 mm/min, respectively. The air blowing pressure was kept constant at 0.35 MPa.

The soda lime glass was cut into small sizes from preparation of the experimental sample. The bottom face of the glass work-piece was securely bonded with aluminum plates. At the beginning, the soda lime workpiece was leveled by the abrasive diamond grinder wheel. Finally, after machining, the surface roughness was measured using SurfTest SV-500 surface profiler. The tool used was 0.5 mm uncoated tungsten carbide as shown in fig. 2. Table 1 lists the experimental runs.

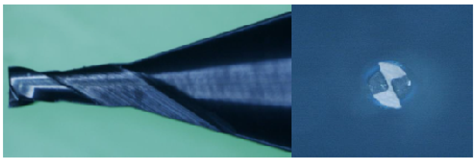


Fig. 2: Photo micrograph of tungsten carbide tool showing side view (left) and top view (right)

Table 1: Experimental sequence with response values

Runs	A: Spindle Speed (rpm)	B: Axial Depth of Cut (μm)	C: Feed Rate (mm/min)	Surface Roughness (μm)
1	40000	5	10	0.08
2	40000	5	10	0.11
3	50000	7	5	0.19
4	50000	3	15	0.11
5	40000	3	10	0.09
6	40000	5	10	0.1
7	30000	5	10	0.18
8	30000	3	5	0.2
9	40000	7	10	0.1
10	30000	7	15	0.12
11	40000	5	10	0.1
12	40000	5	5	0.2
13	40000	5	15	0.11
14	50000	5	10	0.1
15	40000	5	10	0.09

Results and Discussion

Model Generation. The Fit and summary test, table 2, indicates that the quadratic model had the least significant lack of fit (LOF). ANOVA analysis was then carried out to check the validity and confidence level of the developed empirical model, as displayed in table 3. The 'Model F-value' of 21.00461 shows that the quadratic model is significant and there is only a 0.02 % chance that a 'Model F-value' this large could occur due to random noise. Thus, the quadratic CCD model with a confidence level of more than 95% was selected for modeling the surface roughness (Eq. 1, below).

Table 2: Fit and summary test

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	Remarks
Linear	0.014447	7	0.002064	15.87546	0.009	
2FI	0.013113	4	0.003278	25.21795	0.0043	
Quadratic	0.000566	1	0.000566	4.355958	0.1052	Suggested
Cubic	0	0				Aliased
Pure Error	0.00052	4	0.00013			

$$Ra = 0.78699 - 2.49231E\text{-}005*\text{Spindle Speed} + 0.029167*\text{Axial Depth of Cut} - 0.026923*\text{Feed Rate} - 3.00000E\text{-}003*\text{Axial Depth of Cut}*\text{Feed Rate} + 2.61538E\text{-}010*\text{SpindleSpeed}^2 + 1.64615E\text{-}003*\text{Feed Rate}^2. \quad (1)$$

Table 3: ANOVA of the developed model

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	Remarks
Model	0.027771	6	0.004628	21.00461	0.0002	significant
A- Spindle Speed	0.0032	1	0.0032	14.52218	0.0052	
B-Axial Depth of Cut	1.67E-05	1	1.67E-05	0.075636	0.7903	
C-Feed Rate	0.01215	1	0.01215	55.13891	< 0.0001	
BC	0.0012	1	0.0012	5.445818	0.0479	
A^2	0.001976	1	0.001976	8.967758	0.0172	
C^2	0.004893	1	0.004893	22.20412	0.0015	
Residual	0.001763	8	0.00022			
Lack of Fit	0.001243	4	0.000311	2.390039	0.2097	not significant
Pure Error	0.00052	4	0.00013			
Cor Total	0.029533	14				

Optimization Using Desirability Function. In brittle machining, it is always desirable to have low surface roughness and good surface integrity. This target is obtainable if the cutting parameters are adjusted appropriately. Optimization of the minimum surface roughness attainable was obtained using the desirability function of RSM and the results are shown in table 4.

Table 4: Prediction of optimal cutting parameters for minimal roughness using desirability

Optimization Tool	Spindle Speed (rpm)	Axial Depth of Cut (µm)	Feed Rate (mm/min)	Surface Roughness (µm)	Desirability
RSM	44769	6.94	13.79	0.052	0.98

The contour plot for this optimum solution is shown in fig. 3 and the 3D plot of the desirability is shown in fig. 4. It was then verified by actually conducting machining operations on a sample of soda lime glass with the recommended machining parameters. The experimentally obtained Ra value was 0.066 µm and the error in prediction was 26.9%. Fig. 5a is a microphotograph of the surface obtained as per the cutting parameters suggested by RSM for obtaining minimum surface roughness. It is noticeable that there is very little surface contamination due to chips on account of the air blower.

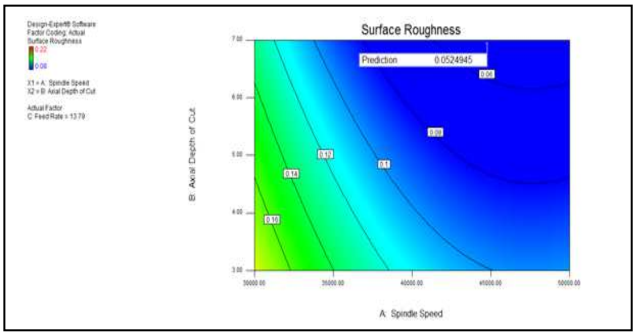


Fig. 3: Countour surface of optimal solution for surface roughness

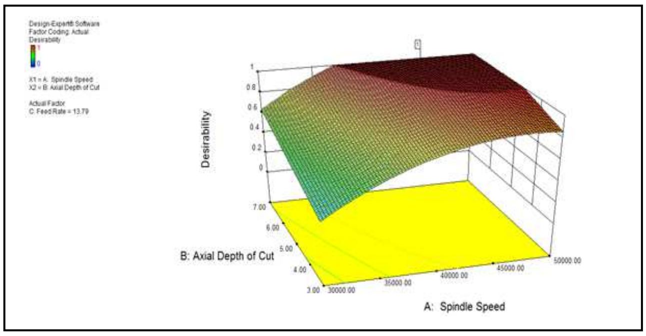
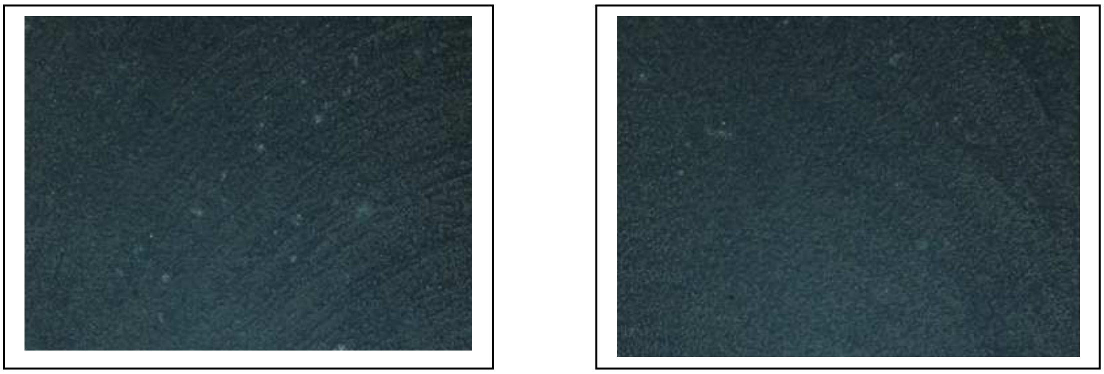


Fig. 4: 3D surface of desirability for optimal surface roughness

Optimization Using Genetic Algorithm. GA in Matlab 2010 was also used to predict the optimal surface roughness attainable. The same machining parameter ranges were used for this optimization. In order to find the fitness function, GA was coupled with the output of RSM modeling. Thus, the quadratic empirical equation developed for surface roughness was used as the fitness criteria function in GA. Fig. 5b is the microphotograph of the machined surface obtained by using the recommendations of GA. Fig. 6 is a graph showing the convergence of GA. The prediction of GA, along with its experimental validation is shown in table 5.



(a) (b)

Fig. 5: Photo micro-graphs of machined glass surface: (a) using RSM preditions and (b) using GA predictions

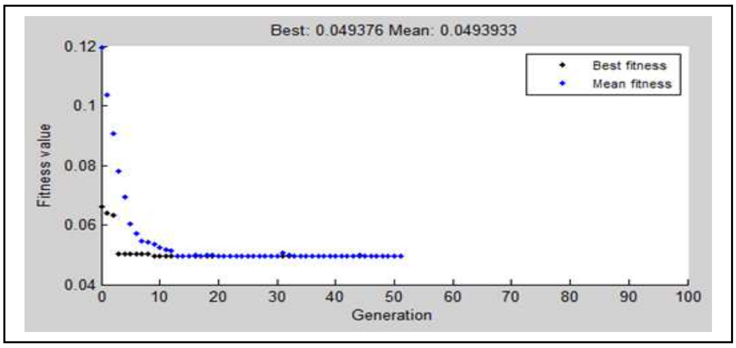


Fig. 6: Graph showing the convergence of the best and mean results with generation

Table 5: Output of GA and its experimental validation

Optimization Tool	Spindle Speed (rpm)	Axial Depth of Cut (µm)	Feed Rate (mm/min)	Surface Roughness Predicted (µm)	Surface Roughness Actual (µm)	Error %
GA	45942	7	14.558	0.049	0.052	6.12%

Conclusions

1. The results demonstrate that high speed micro-end milling of soda lime glass using 0.5 mm uncoated tungsten carbide tool and compressed air blowing is a viable machining approach.
2. The empirical model developed is effective in predicting average surface roughness.
3. Coupled RSM-GA optimization is better with minimum roughness prediction of 0.049 µm.

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