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Establishing Relationship between Process Parameters and Temperature during High Speed End Milling of Soda Lime Glass

Mst. Nasima Bagum, Mohamed Konneh and Mohammad Yeakub Ali

Department of Manufacturing and Materials Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, Jalan Gombak, 53100 Kuala Lumpur, Malaysia

Email: nasimaanam@gmail.com

Abstract. In glass machining crack free surface is required in biomedical and optical industry. Ductile mode machining allows materials removal from brittle materials in a ductile manner rather than by brittle fracture. Although end milling is a versatile process, it has not been applied frequently for machining soda lime glass. Soda lime glass is a strain rate and temperature sensitive material; especially around glass transition temperature T_g, ductility increased and strength decreased. Hence, it is envisaged that the generated temperature by high-speed end milling (HSEM) could be brought close to the glass transition temperature, which promote ductile machining. In this research, the objective is to investigate the effect of high speed machining parameters on generated temperature. The cutting parameters were optimized to generate temperature around glass transition temperature of soda lime using response surface methodology (RSM). Result showed that the most influencing process parameter is feed rate followed by spindle speed and depth of cut to generate temperature. Confirmation test showed that combination of spindle speed 30,173 rpm, feed rate 13.2 mm/min and depth of cut 37.68 μm generate 635°C, hence ductile chip removal with machined surface R_a 0.358 μm was possible to achieve.

1. Introduction

Glass belongs to the hard and brittle ceramic materials. Under compression, glass exhibits softening of bulk modulus [1]. Glass appears to be strain rate sensitive, as loading rate increase tensile strength become high .Compression test at larger strain rate reported increase in its ultimate tensile strength UTS [2]. In addition, dynamic tensile is reported higher than static tensile strength [3]. At elevated temperature under indentation loading soda lime glass undergoes material softening, which showed effect on its mechanical properties such as fracture toughness, hardness and Young's modulus [4]. The fracture toughness of soda lime glass increased strongly with temperature starting at a temperature 300°C, which is around half of the glass softening temperature [4] and improved ductility was obtained near the range of T_g [5]. The fracture toughness increased around 600 °C, and a sharp decrease was detected above 620 °C [6]. Vicker's hardness decreased as temperature increased from 20°C to 500 °C [7]. Therefore, at elevated strain rate and temperature material's brittleness index decreases by reducing its hardness to toughness ratio.

High-speed cutting impose high amount of strain rate on materials and temperature generated at chip formation zone allows more plastic deformation than the low speed cutting. Reddy et al. [8] found that the increase of spindle speed caused the decrease of surface roughness. In the case of peripheral milling of BK-7 glass, Arif, et al. [9] identified that the critical chip thickness value could be increased by increasing cutting speed. Adiabatic melting and instant annealing of inorganic glass at higher cutting speed was stated [10] favorable to achieve stress free surface. Schinker et al. [11] stated that at high speed, the generated heat in the cutting zone owing to adiabatic micro shearing gives rise to continuous chip formation and produce smooth surfaces on optical glass. Conversely, it might also modify the properties of glass in the processing zone [11]. At high cutting speed and high depth of cut, adequate temperatures were generated within the work piece that make thermal softening as the prominent phase transformation phenomenon [12]. In case of material those glass transition temperature is low this thermal effects might be prominent [13]. However, quantitative research on thermal softening effect is not done yet. Hence, in this study investigation of the effect of high speed cutting parameters on tool-chip contact point temperature is carried out. Response surface model was generated using central composite design of RSM. The parameters were optimized at glass transition temperature range (520-600) °C to justify machinability of soda lime glass at T_g.

2. Experimental procedures

4 mm diameter tungsten carbide tool having 2 flutes was chosen to perform milling on soda lime glass work piece using the upgraded vertical axis CNC milling machine. The cutting conditions of spindle speed from 20,000 to 40,000 rpm, feed rate from 10 to 30 mm/min and depth of cut from 30 to 50 µm were employed in dry condition. The tool chip contact point temperatures were measured using IR thermal camera. The CCD of RSM was employed for designing and analyzing the experimental results.

3. Results and Discussion

The outcome of the experiment is represented in Table 1. Response model development followed the steps such as problem formulation; transformation checking and selection of the model that provides the finest relationship between dependent responses and independent input variables according to the instruction of fit summary tests; Analysis of variance (ANOVA); Model diagnostics.

Table 1 Central Composite Design using RSM along with the response value.

Run	Type	A: Spindle speed Rpm	B: Feed rate mm/min	C: Depth of Cut µm	Temp °C
1	Axial	40000	20	40	760
2	Axial	20000	20	40	748
3	Fact	40000	30	30	800
4	Center	30000	20	40	736
5	Fact	20000	10	30	342
6	Fact	40000	10	50	588
7	Fact	20000	30	30	654
8	Axial	30000	10	40	520
9	Fact	40000	30	50	790
10	Fact	40000	10	30	540
11	Center	30000	20	40	722
12	Fact	20000	10	50	422
13	Axial	30000	20	50	800
14	Center	30000	20	40	726
15	Center	30000	20	40	710
16	Axial	30000	20	30	756
17	Axial	30000	30	40	786
18	Fact	20000	30	50	650

In the fit summary statistics, the Sequential Model Sum of Square (SMSS) as well as Model Summary Statistics endorsed quadratic relationship between the independent variables such as spindle speed (A), feed rate (B) and depth of cut (C) and the response temperature (T). Lack of fit value showed insignificant. The analyses of variance (ANOVA) with all possible model terms implied that the model is significant with large F-value. The significant model terms are A, B and B^2. The "Lack of Fit F-value" of the model implies that it was not significant relative to the pure error. Also predicted R^2 was in reasonable agreement with the adjusted R^2 value as required by the design expert 7.0.0. Using back ward regression method, the non-significant terms that are not contributing to model's hierarchy were removed to improve model. The model equations are therefore obtained based on the reduced model ANOVA shown in Table 2 as in equation (3.1) in terms of coded factors and equation (3.2) in terms of actual factors.

$$\text{Temperature} = +753.50 + 66.20\,A + 126.80\,B + 15.80\,C - 144.30\,B^2 \quad (3.1)$$

$$\text{Temperature} = -339.10 + 6.62\times10^{-3}\,A + 70.40\,B + 1.58\,C - 1.44\,B^2 \quad (3.2)$$

Table 2 Analysis of variance and descriptive statistics of reduced model T.

	Sum of Squares	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	2.996E+005	4	74911.90	45.19	< 0.0001	significant
A-Spindle speed	43824.40	1	43824.40	26.43	0.0002	
B-feed rate	1.608E+005	1	1.608E+005	96.98	< 0.0001	
C-Depth of cut	2496.40	1	2496.40	1.51	0.2415	
B^2	92544.40	1	92544.40	55.82	< 0.0001	
Residual	21552.40	13	1657.88			
Lack of Fit	19420.40	10	1942.04	2.73	0.2208	not significant
Pure Error	2132.00	3	710.67			
Cor Total	3.212E+005	17				
R-Squared	0.9329					
Adj R-Squared = 0.91, Pred R-Squared =0.87, Adeq Precision=19.54, C.V. %=6.05						

In equation (3.1) the coefficients of each factor represents the effect of this particular factors on temperature. According to equation (3.1) as well as perturbation plot in Figure 1, it is clear that each of the factors showed positive influence on response and the most influencing process parameters are depicted as feed rate followed by spindle speed and depth of cut. Feed rate showed negative quadratic effect and hence, there is a continuous increase in T up to an optimal point, than decreased with further increase in this response. Depth of cut confirmed little contribution and its effect is insignificant in this model. The adequacy of each of the model was verified through the statistical features associated with it. Here R^2 was greater than 0.8, the difference of predicted R^2 with adjusted R^2 was less than 0.2; adequate precision was greater than 4. The residuals of the data were normally scattered (Figure 2), similarly constant variance assumption was satisfied, and residuals were not correlated.

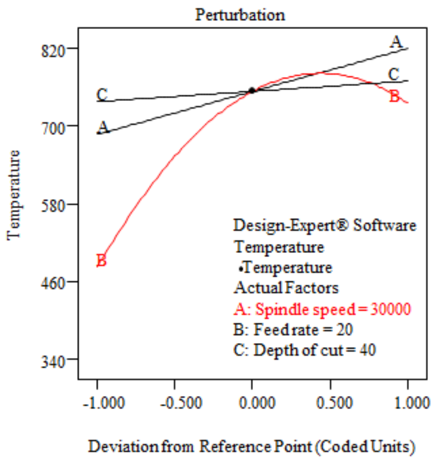

Figure 1. Perturbation plots.

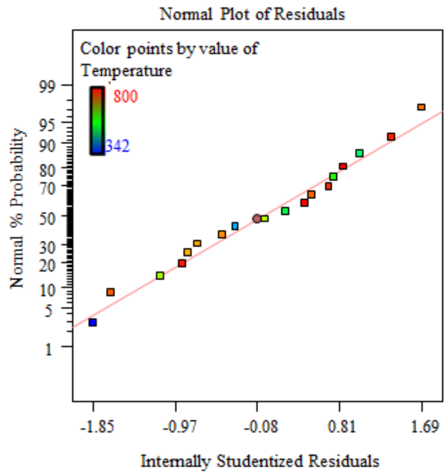

Figure 2. Normal plot of residuals.

The relationship between theoretical and experimental value of T is depicted in Figure 3 also suggests that predicted value is closer to experimental value. Hence, it was concluded that model equation (3.2) was adequate for application in navigating the design space within the experimental limit.

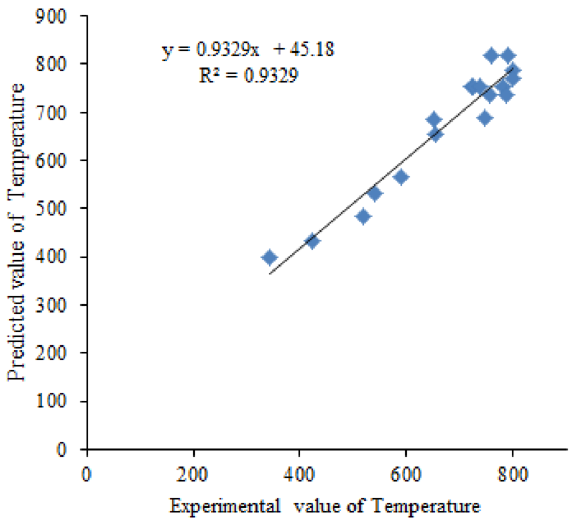

Figure 3. Relationship between predicted and experimental T.

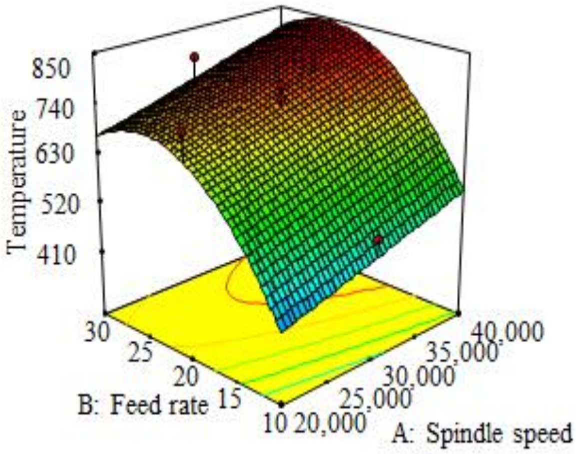

Figure 4. Spindle speed and feed rate interaction.

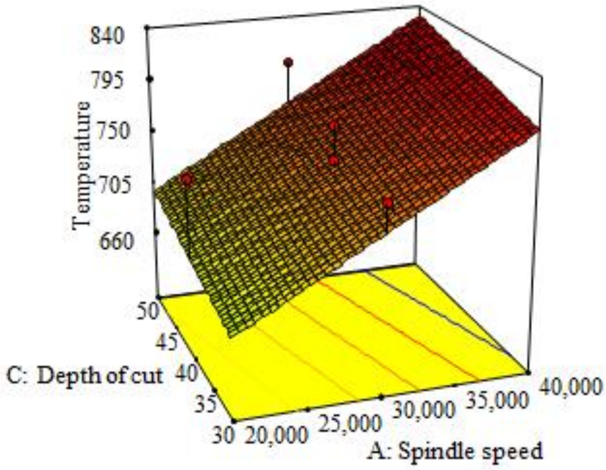

Figure 5. Spindle speed and depth of cut interaction.

The 3D plot of temperature for feed rate and spindle speed interaction demonstrated in Figure 4 shows that when both feed rate and spindle speed increased temperature rises sharply. On the other hand, the depth of cut and spindle speed interaction plot shown in Figure 5 illustrated that effect of depth of cut is almost constant. According to desirability function of RSM, the optimal combinations of parameters to achieve glass transition temperature (520- 600°C) provide 27 alternative solutions with 100% desirability. The optimal combination of parameters spindle speed 30,173 rpm, feed rate 13.2 mm/min and depth of cut 37.68 µm is predicted to achieve 597.94°C. Confirmation test showed that this optimal combination produced 635°C. Due to adiabatic heating ductile chip removal was possible, with surface R_a 0.358 µm shown in Figure 6.

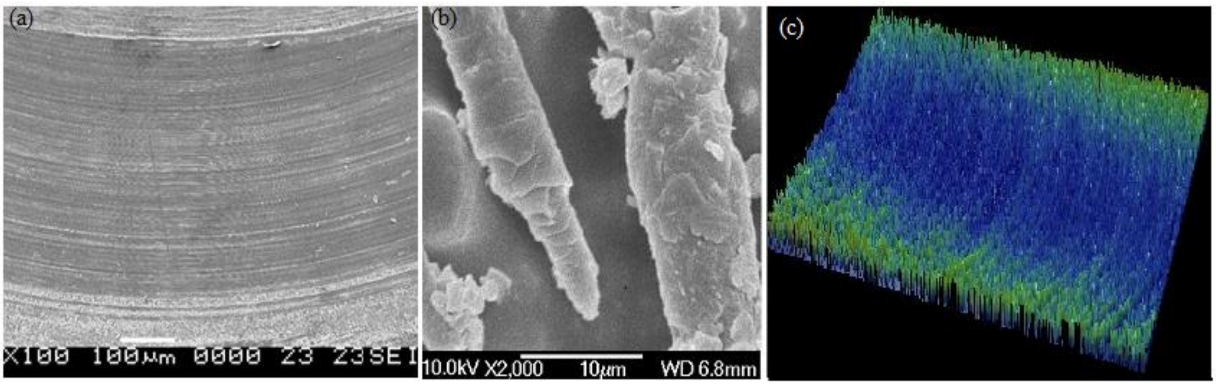

Figure 6. Optimal condition (a) Surface integrity, (b) Chip morphology (SEM view), (c) Surface roughness Wyko 3D display.

4. Conclusion

High speed end milling is capable to achieve ductile removal of soda lime glass around glass transition temperature. Feed rate is the most influencing parameter followed by spindle speed and depth of cut. The combination of 30173 rpm, 13.2 mm/min feed rate and 37.68 µm depth is predicted to achieve 597.94°C with 100% desirability. Confirmation test at optimal combination produced 635°C, where ductile chip removal along with machined surface R_a, 0.358 µm was achieved.

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