

# Chip morphology as a performance predictor during high speed end milling of soda lime glass

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**Abstract.** Soda lime glass has application in DNA arrays and lab on chip manufacturing. Although investigation revealed that machining of such brittle material is possible using ductile mode under controlled cutting parameters and tool geometry, it remains a challenging task. Furthermore, ability of ductile machining is usually assessed through machined surface texture examination. Soda lime glass is a strain rate and temperature sensitive material. Hence, influence on attainment of ductile surface due to adiabatic heat generated during high speed end milling using uncoated tungsten carbide tool is investigated in this research. Experimental runs were designed using central composite design (CCD), taking spindle speed, feed rate and depth of cut as input variable and tool-chip contact point temperature ( $T_{tc}$ ) and the surface roughness ( $R_t$ ) as responses. Along with machined surface texture,  $R_t$  and chip morphology was examined to assess machinability of soda lime glass. The relation between  $T_{tc}$  and chip morphology was examined. Investigation showed that around glass transition temperature ( $T_g$ ) ductile chip produced and subsequently clean and ductile final machined surface produced.

## 1. Introduction

Glass belongs to the hard and brittle ceramic materials. It is a challenging task to achieve ductile machining of brittle material, which is capable to attain fracture free surface. The difficulties in glass machining are mainly due to its low fracture toughness. Soda lime glass is a temperature sensitive material [1]. Researcher stated that with the increase of temperature starting at 300°C, which is around half of the glass softening temperature ( $T_g$ ), fracture toughness of soda lime glass increased [2]. Hence, improved ductility was obtained near the range of  $T_g$  [3]. Again, brittle ductile transition temperature increased with the increase of strain rate. Furthermore, fracture toughness increased around 600°C, and a sharp decrease was detected above 620°C [4]. Vicker's hardness decreased as temperature increased from 20°C to 500 °C [5]. Therefore, at elevated strain rate and temperature material's brittleness index is decreased by reducing its hardness to toughness ratio.

As of late, researcher focused on achievement of ductile mode material removal due to designated cutting condition and tool geometry, typically at low speed machining [6-8]. Also, identification of critical parameters for ductile brittle transition [9]. High speed machining was reported have positive influence on achievement of ductile machining. Reddy et al. [10] developed an analytical model for



the surface roughness of machinable glass ceramic under the condition of 10000 rpm to 20000 rpm, feed rate of 30 mm/min, and 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. [11] identified that by increasing cutting speed the critical chip thickness value could be increased. 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]. Schinker et al. [13] 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 [13]. In case of material those glass transition temperature is comparatively low, this thermal effects might be prominent [14]. However, quantitative research on thermal softening effect is not done yet. In order to assess machinability, along with ductile material removal confirmation from machined surface texture analysis, the extreme surface parameter,  $R_t$  which signpost the existence of a sharp spike or burr on the surface [15] is also important to justify process capability. Hence, in this study, along with machined surface texture,  $R_t$  was examined to assess machinability of soda lime glass during high speed end milling using uncoated carbide tool. In addition, the relation between the temperature generated due to high-speed end milling,  $T_{tc}$  and chip morphology was established.

## 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 varied from 20,000 to 40,000 rpm, cutting depth from 30 to 50  $\mu\text{m}$  and feed rate from 10 to 30 mm/min were employed in dry condition. The CCD of RSM was employed for designing the experimental run. The image analysis of surface texture and chip morphology was studied using Scanning Electron Microscope (SEM), JSM-5610 and JBM-6700F, respectively. The tool chip contact point temperatures were recorded using the thermal camera Thermo Pro TP8. The surface roughness  $R_t$ , was measured using Veeco Wyko Profiling system Microscope model NT110.

## 3. Results and Discussion

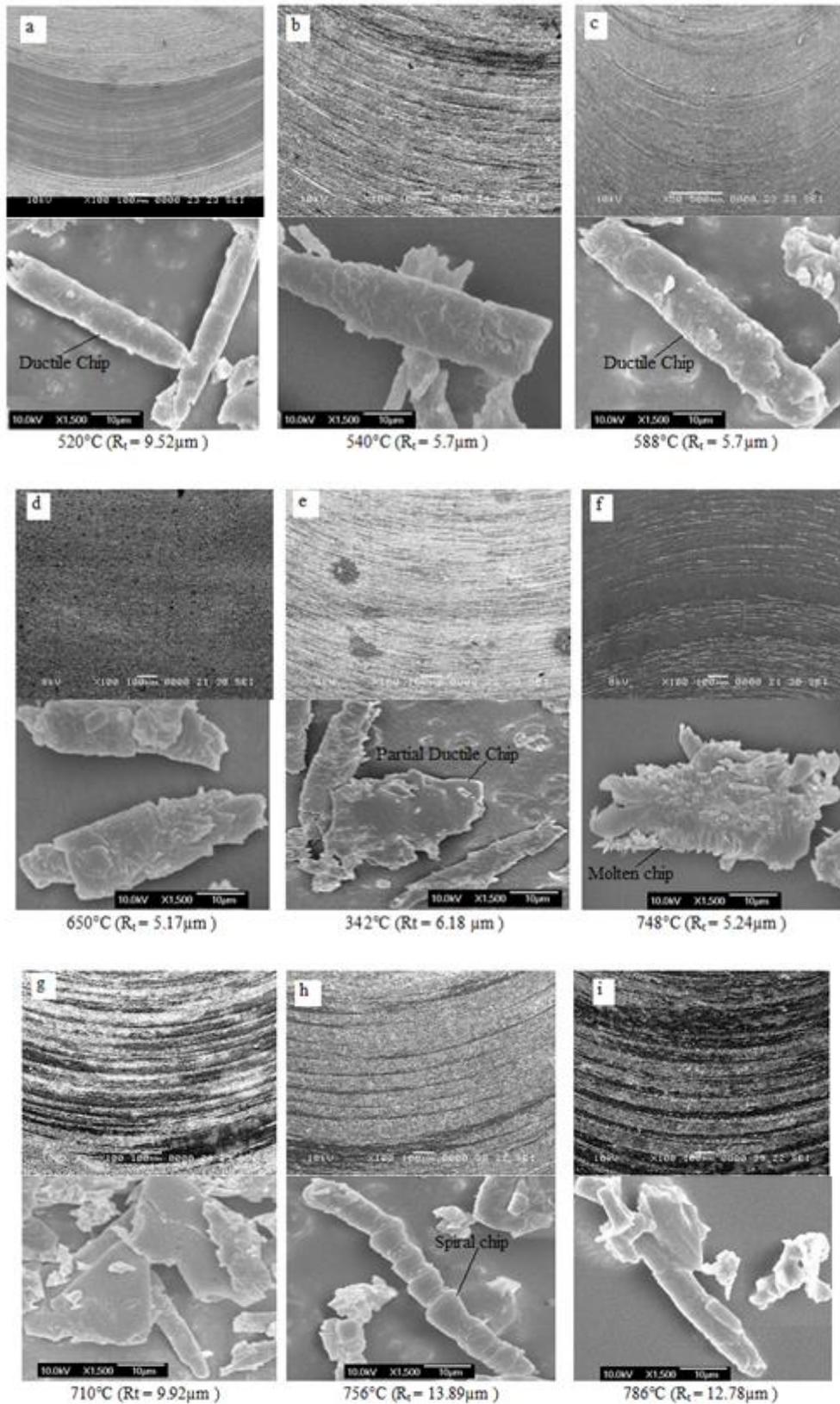
The experimental run along with roughness  $R_t$  and temperature  $T_{tc}$  are given in table 1. Figure 1 shows the corresponding SEM image of machined surface and chip in relation to  $T_{tc}$  and  $R_t$  values. The temperature recorded during experimental run, according to table 1 confirmed that high temperatures were generated in the tool-chip contact point. Subsequently, almost in all run, ductile chips produced, figure 1. The ductile chip formation and removal has significant effect on final machined surface. The extreme parameter,  $R_t$  signpost the existence of a sharp spike or burr on the surfaces, because of poor material processing. Considering only this parameter as an indicator of whether the ductile chips are removed from or contaminated with the machined surface, then,  $R_t$  value is equal at both 540°C and 588°C. In addition, surface textures and chip morphology shown in figure 1(b) and (c) are quite similar in these two cases. At 650°C,  $R_t$  is 5.17, also SEM image of surface and chip in figure 1(d), illustrated that ductile chip produced and removed. At 710°C, 756°C and 786°C SEM image of surface in figure 1 (g), (h) and (i), confirmed chip contamination and  $R_t$  value is high in these three case.

For clear understanding of chip removal process apart from SEM image and  $R_t$  value of machined surface, the chip morphology plays an important role. For instance, at 756°C and 786°C SEM image in figure 1 (h) and (i), are quite similar and  $R_t$  value is nearby. The chip morphology at these two conditions is different. Within the glass transition temperature  $T_g$ , (520-600°C) of soda lime glass and also up to 650°C the chip rolled uniformly and removed from the surface as cutting progress, hence clean final machined surface is produced as shown in figure 1 (a), (b), (c) and (d). Below the  $T_g$  (342°C), surface is not clean as both ductile and partial ductile chips are produced shown in figure 1 (e). As temperature increased beyond  $T_g$  chip started to molten.

**Table 1** Experimental run along with roughness and temperature.

Run	Type	Spindle speed rpm	Cutting speed m/sec	Feed rate mm/min	Feed/tooth $\mu\text{m}$	C: Depth of Cut $\mu\text{m}$	Rt $\mu\text{m}$	Temp $^{\circ}\text{C}$
1	Axial	40000	8.37	20	0.25	40	8.37	760
2	Axial	20000	4.19	20	0.50	40	5.24	748
3	Fact	40000	8.37	30	0.38	30	13.15	800
4	Center	30000	6.28	20	0.33	40	9.13	736
5	Fact	20000	4.19	10	0.25	30	6.18	342
6	Fact	40000	8.37	10	0.13	50	5.7	588
7	Fact	20000	4.19	30	0.75	30	7.16	654
8	Axial	30000	6.28	10	0.17	40	9.52	520
9	Fact	40000	8.37	30	0.38	50	8.28	790
10	Fact	40000	8.37	10	0.13	30	5.7	540
11	Center	30000	6.28	20	0.33	40	10.23	722
12	Fact	20000	4.19	10	0.25	50	8.65	422
13	Axial	30000	6.28	20	0.33	50	12.04	800
14	Center	30000	6.28	20	0.33	40	7.73	726
15	Center	30000	6.28	20	0.33	40	9.92	780
16	Axial	30000	6.28	20	0.33	30	13.89	756
17	Axial	30000	6.28	30	0.50	40	12.78	786
18	Fact	20000	4.19	30	0.75	50	5.17	650

In the temperature ranges from 710-800°C two types of surface - clean and chip contaminated are identified. Cutting speed 4.19 m/sec, feed/teeth 0.50 $\mu\text{m}$  and axial depth 40  $\mu\text{m}$  generated  $T_{tc}$  of 748°C. In this case soft chip are removed away before contaminated on the machined surface, hence almost clean surface is generated as shown in figure 1 (f). When the parameters speed and feed per tooth both are high such as at cutting speed 6.28 m/sec, feed/tooth 0.50  $\mu\text{m}$  and axial depth 40 $\mu\text{m}$  generated  $T_{tc}$  is 786 °C, in this case as ductile-molten chips are formed and surface is contaminated shown in figure 1 (i). At 6.28 m/sec, combination of moderate feed/tooth (0.33 $\mu\text{m}$ ) and depth of cut (30 $\mu\text{m}$ ) produced spiral helical ductile chip in figure 1 (h). Here, low and high strain regions formed in the chip. Hence, thermal softening is not homogeneous throughout the removable layers of material; therefore, molten chips contaminated on the machined surface.



**Figure 1.** Tool-Chip contact point temperature, surface roughness ( $R_t$ ) and chip image at different cutting condition.

#### 4. Conclusion

In summary, it can be concluded that High-speed end milling is capable of adiabatic heating of soda lime glass and ductile chip removal. The roughness parameter,  $R_t$  can predict existence of chip contamination on the surface. Chip morphology can indicate mode of material removal in ductile machining. Around glass transition temperature, clean, ductile surface with low  $R_t$  value is generated as ductile chip removed before contaminated on machined surface. Above  $T_g$ , both clean or chip contaminated surface produce depending on cutting parameters combinations.

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