Tool Wear Mechanisms during Cutting of Soda Lime Glass

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Abstract. Soda lime glass milling has high performance application. It is a challenging task to achieve fracture free surface on this material due to its brittle nature. High-speed end milling is capable to achieve ductile mode in an enhance flexibility. In this research, end milling of soda lime using uncoated carbide tool was performed where spindle speed varied from 20,000 to 40,000 rpm, cutting depth from 10 to 30 µm and feed rate from 5 to 20 mm/min in dry condition. The effects of cutting parameters (cutting speed, feed per tooth and depth of cut) on tool flank wear as well as wear mechanisms of tool flank investigated. Investigation showed that feed per edge has most influencing effect followed by cutting speed and depth of cut on flank wear and the main wear mechanism is abrasion wear. In some cases, oxidation, thermal diffusion and recast layer on tool flank also observed.

1. Introduction
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. Negative rake angle [1] and micro level radius of cutting edge [2] have proven favorable to achieve ductile mode. In soda lime glass milling, uncoated tungsten carbide tools were used by researcher to utilized adiabatic heating benefits [3], as the temperatures generated during machining using the uncoated tool are higher than those by the coated tools. However, one or more combinations of the criteria such as cutting tool wear, cutting tool life, power consumption, chip formation, machined surface integrity, geometrical accuracy, etc. [4] usually define machining performance of a work material. Tool wear is a complicated issue and still not clear even in case of metal machining and generally depends on the work piece, tool materials, tool geometry, machining parameters, lubricating condition, machine tools characteristics. For wear, monitoring flank wear is commonly used [5]. Contradictory illustrations are found regarding applicability of uncoated carbide tool, mostly in machining of brittle materials. It has proven better performance in terms of cutting force and surface roughness in milling of carbon fiber reinforced composite materials [6]. At high cutting speed, uncoated carbide tools fail mainly due to flank wear because of abrasion, notching, fracturing, cracking. Although coating believed to enhance the tool life, but once coating removed, the tool failure is similar to that of the uncoated tool. In milling process because of intermittent cutting action cyclic stress developed, hence once coating removed micro chipping of cutting edge also observed [7]. In case of turning of composites, wear morphologies of carbide was corner wear due to abrasion, adhesion and micro breakage in the cutting edge [5].
diamond cutting of soda lime glass main wear mechanism were mechanical, thermo-chemical and abrasion wear [8]. The mechanism of wear was abrasion dominant while TiAlN coated tool used for glass milling and diffusion of tool material was not present [9] because of low cutting speed.

In this research, end milling of soda lime glass performed using uncoated carbide tool at high speed. The purpose of the study is to investigate the effect of cutting parameters (cutting speed, feed per tooth and depth of cut) on uncoated carbide tool flank wear as well as wear (flank) mechanisms during high speed milling of soda lime glass.

2. Experimental procedures
The Box-Behnken Design was employed for designing the experimental run where the spindle speed varied from 20,000 to 40,000 rpm, cutting depth from 10 to 30 µm and feed rate from 5 to 20 mm/min in dry condition. The uncoated solid carbide flat end-milling tools having 4mm diameter, two flutes, edge radius 6 µm, rake angle -5° and grain size 0.6 µm were used to perform milling on soda lime glass work piece, in an upgraded vertical axis CNC milling machine. In each experimental run, tool flank wear after performing 75 mm milling length were measured using optical microscope. Tool wear mechanism were observed using Scanning Electron microscope (SEM) JSM-5610.

3. Results and Discussion
According to ISO-8688-2-1982, the milling time at which the tool flank wear \( V_b \) reached to 0.3mm is consider as tool life. In the cutting process of soda lime glass, lot of chips in powder form generated on the face of the tool and brittle break occurred at the tool corner. In real machining, surface integrity and dimensional accuracy are of primary concern. Therefore, in this research at the lowest value of cutting parameters i.e., spindle speed 20,000 rpm, feed rate 5 mm/min and depth of cut 10 µm, both of the tool flank wear and surface integrity of work piece were examined after certain milling path. The result showed that after 75 mm milling length, indentation marks were visible on the machined glass surface as shown in Figure 1, due to edge chipping of the cutting tool. Hence, instead of 0.3mm \( V_b \), considering the surface integrity, at each run the tool flank wear after 75 mm milling length was consider as the limiting value of tool wear. The shape of the wear area of the tool looks like an inverted triangle below the corner of the tool (Figure 2). Only maximum wear \( V_c \) was observed and recorded as flank wear.

![Figure 1](image1.png)

**Figure 1.** The machined surface integrity at different milling length.

![Figure 2](image2.png)

**Figure 2.** Shape of wear.

Table 1 shows the experimental results of the flank wear as designed by Box-Behnken design. In case of milling process, combination of spindle speed and feed rate along with no of cutting flute,
determine the value of feed per tooth. The interaction plot in Figure 3 (a) illustrates that feed rate has a much stronger effect on $V_b$ when spindle speed is at lower level. At lower level of spindle speed with the increase of feed rate tool wear increased sharply. This is because low cutting speed and high feed rate resulted in higher feed/tooth, which caused increased tool wear due to mechanical loading. At upper level of spindle speed, with the increase in feed rate tool wear increased up to an optimal point followed by little or no change in $V_b$ as this parameter further increased. This relation more clearly depicted in the contour plot shown in Figure 3 (b).

### Table 1 The Box-Behnken design matrix with response for flank wear.

| Run | Type | Factor 1  | Cutting speed (m/min) | Factor2  | Feed rate (mm/min) | Factor3  | Depth of Cut (µm) | Response 1 Flank wear ($V_b$) (µm) |
|-----|------|-----------|-----------------------|----------|--------------------|----------|-------------------|-------------------------------------|
| 1   | Center | 30000    | 376.8                | 12.5     | 0.21               | 20       | 189               |
| 2   | Center | 30000    | 376.8                | 12.5     | 0.21               | 20       | 200               |
| 3   | Ibfact | 40000    | 502.4                | 5        | 0.06               | 20       | 182               |
| 4   | Ibfact | 20000    | 251.2                | 20       | 0.50               | 20       | 228               |
| 5   | Ibfact | 40000    | 502.4                | 20       | 0.25               | 20       | 219               |
| 6   | Center | 30000    | 376.8                | 12.5     | 0.33               | 10       | 193               |
| 7   | Ibfact | 30000    | 376.8                | 20       | 0.33               | 10       | 193               |
| 8   | Ibfact | 20000    | 251.2                | 12.5     | 0.31               | 10       | 172               |
| 9   | Center | 30000    | 376.8                | 12.5     | 0.21               | 20       | 197               |
| 10  | Ibfact | 20000    | 251.2                | 12.5     | 0.31               | 30       | 200               |
| 11  | Ibfact | 30000    | 376.8                | 5        | 0.08               | 30       | 165               |
| 12  | Ibfact | 40000    | 502.4                | 12.5     | 0.16               | 30       | 210               |
| 13  | Center | 30000    | 376.8                | 12.5     | 0.21               | 20       | 191               |
| 14  | Ibfact | 30000    | 376.8                | 5        | 0.08               | 10       | 143               |
| 15  | Ibfact | 20000    | 251.2                | 5        | 0.13               | 20       | 161               |
| 16  | Ibfact | 30000    | 376.8                | 20       | 0.33               | 30       | 217               |
| 17  | Ibfact | 40000    | 502.4                | 12.5     | 0.16               | 10       | 202               |

**Figure 3.** Interaction plot and contour plot of $V_b$ with feed rate and spindle speed (a) Interaction plot and (b) contour plot.

In case of milling process, feed per tooth is reported as the most influencing parameter for ductile machining of brittle materials [2]. This is also true for tool flank wear. The effects of feed/tooth,
cutting speed and depth of cut on tool flank wear further illustrated in Figure 4. As depicted in Figure 4 (a), feed / tooth showed dominating influence on tool wear among the cutting parameters. Among the three identified zone, Zone-1 revealed that even though feed/tooth increased, there is a decrease in wear, explained by Figure 4 (b). At 5 mm/min feed rate, flank wear at 251 m/min cutting speed is lower than that of 502 m/min, because at faster cutting speed hard particle from work piece scraped the tool more violently. Zone-2, started at 0.13µm feed/tooth where tool wear is minimum, later as the feed / tooth and cutting speed increased wear increased up to 0.25 µm feed/tooth. Subsequently Zone-3 started, where the tool wear increased at 251 m/min cutting speed due high value of feed/tooth. Furthermore, Figure 4 (b) clarifies that at constant depth of cut, 20 µm and feed rate 20 mm/min, tool wear (high) is almost constant with respect to cutting speed. Also at high cutting speed, the depth of cut showed insignificant effect on tool wear (Figure 4 c).

Figure 4. Effect of cutting parameters on tool wear (a) Feed per tooth at constant depth of cut 20µm (b) Cutting speed at different feed rate at constant depth 20 µm (c) Depth of cut at different speed.

At the beginning of the milling process, a brittle break occurred at the corner of the carbide tool in all run. After that edge become round and gradual flank wear occurred. By means of microscopic examination, the major wear form of the tool found was abrasive wear. However, buildup edge also formed some time since there is aluminum exists in soda lime. At extreme combination of cutting parameters, (at cutting seed 502.4 m/min, feed per tooth 0.25µm and depth of cut 30 µm,) oxidation, recasting and thermal deformation occurred due to high temperature generated because of friction shown in Figure 5.
Figure 5. The tool wears mechanisms at high spindle speed, feed rate and depth of cut condition.

At high speed, moderate feed/tooth and low depth cut [502.5 m/min, feed/tooth 0.16 µm and depth of cut 10 µm] along with abrasion wear, thermal deformation and oxidation occurred at tool flank shown in Figure 6. At 20 µm depth of cut, low cutting speed (251.2 m/min) and high feed/tooth (0.5 µm) combination caused high tool wear due to mechanical loading, on the other hand high cutting speed (502.2 m/min) and high feed/tooth (0.25 µm) combination formed recast layer on tool flank, as shown in Figure 7. At this condition, the temperature generated was nearby dissolution temperature of carbide tool (1100°C) captured by thermal camera.

Figure 6. Thermal deformation at cutting speed 502.5 m/min, feed per tooth 0.16 µm and depth of cut 10 µm (run 17).

Figure 7. Recast layer at cutting speed 502.2 m/min, feed per tooth 0.25µm and depth of cut 20µm (run 5).

4. Conclusion
From the experimental results it is can be concluded that among the cutting parameters feed per tooth has the most dominant influence on tool flank wear followed by cutting speed and depth of cut. However, at high level of cutting speed (502 m/min), the depth of cut showed no significant effect on tool wear. From the perspective of the wear mechanism, the major wear form of the tool flank is abrasive wear. Furthermore, oxidation, recasting and thermal deformation of tool flank wear occurred due to high temperature generated at extreme cutting condition (at cutting speed 502.4 m/min, feed per tooth 0.25µm and depth of cut 30 µm).

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