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Tool Wear and Its Effect on Surface Roughness in Diamond Cutting of Glass Soda-lime

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Abstract: For the technology of diamond cutting of optical glass, the high tool wear rate is a main reason for hindering the practical application of this technology. Many researches on diamond tool wear in glass cutting rest on wear phenomenon describing simply without analyzing the genesis of wear phenomenon and interpreting the formation process of tool wear in mechanics. For in depth understanding of the tool wear and its effect on surface roughness in diamond cutting of glass, experiments of diamond turning with cutting distance increasing gradually are carried out on soda-lime glass. The wear morphology of rake face and flank face, the corresponding surface features of workpiece and the surface roughness, and the material compositions of flank wear area are detected. Experimental results indicate that the flank wear is predominant in diamond cutting glass and the flank wear land is characterized by micro-grooves, some smooth crater on the rake face is also seen. The surface roughness begins to increase rapidly, when the cutting mode changes from ductile to brittle for the aggravation of tool wear with the cutting distance over 150 m. The main mechanisms of inducing tool wear in diamond cutting of glass are diffusion, mechanical friction, thermo-chemical action and abrasive wear. The proposed research makes analysis and research from wear mechanism on the tool wear and its effect on surface roughness in diamond cutting of glass, and provides theoretical basis for minimizing the tool wear in diamond cutting brittle materials, such as optical glass.

Key words: diamond cutting, tool wear, surface roughness, soda-lime glass

1 Introduction

Manufacturing ultraprecision level quality glass parts is the significant research and application direction of single-point diamond turning technology[1–2]. However, diamond cutting of glass has not yet proven practical because of high tool wear rate. In practice, the high hardness and brittleness of glass render tool wear rapidly whilst machining glass, resulting in producing the glass part failure, which must be free of micro-fracture damages and possess ultraprecision level quality surface[3–4].

Many researchers have paid attention to diamond tool wear in the past. Uddin et al. investigated the effect of crystallographic orientation on wear of diamond tools[5]. Chemical aspects of diamond tool wear were researched by PAUL, et al[6]. The effect of oxygen atmosphere on tool wear was analyzed by TANAKA, et al[7] and SHIMADA, et al[8]. BORN, et al[9], surveyed empirically the influence of machining parameters on tool wear. YAN, et al[10], proposed that undeformed chip thickness has a dramatic influence on tool wear. SIKDAR, et al[11], studied the effect of cutting force on tool wear. The tool wear mechanisms in diamond cutting of various materials, such as silicon, germanium, aluminum, and ferrous metal, have also been discussed[12–13]. These works have made great contributions to a good understanding of diamond tool wear. However, there is little research that is directed to the tool wear in diamond cutting of optical glass. Glass is noncrystal and hard-brittle material; moreover, the cutting parameters of glass in diamond turning are less than those of materials mentioned above. Consequently, tool wear patterns and mechanisms may be different from those in diamond cutting other materials.

Therefore, research on tool wear characteristics in diamond cutting of glass is of significance to promote the practical application of diamond cutting of glass, and it would open up the possibility for producing glass optical elements in an economic and deterministic manner.

In this work, tests of tool wear in diamond cutting of glass soda-lime with cutting distance increasing gradually were carried out on an ultra-precision lathe. The experimental procedure, including the experimental set up, the workpiece material and specimen preparation, the cutting tool, the cutting conditions and the calculation of cutting distance are presented in section 2. The tool wear zone was examined by utilizing scanning electron microscopy(SEM), and Micro-Raman spectroscopy(MRS)

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was adopted for analyzing materials on tool tips. The corresponding surface features of workpiece were examined by laser scanning confocal microscope(LSCM), and the surface roughness were measured by atomic force microscopy(AFM). The detection results mentioned above are shown in section 3, followed by discussions (section 4) and conclusions (section 5).

2 Experimental Procedure

2.1 Experimental set up

Cutting tests of tool wear were performed in a home-made S1-255 ultra-precision lathe. The machine has a hydrostatic bearing spindle and two perpendicular slide tables along x-axis and z-axis. The long-range moving resolutions of guide x and z are both 100 nm. A precise optical tool-set station enabled the diamond tools to be accurately repositioned. Moreover, four air mounts were set under the machine base to isolate the environmental vibration.

2.2 Workpiece material and specimen preparation

Soda-lime is a typical optical glass, with elastic modulus of 70±1.5 GPa (measured with loads ranging from 20 mN to 500 mN) and a Vickers hardness of 5.2–5.9 GPa[14–15]. Workpiece used in this experiment was obtained from Schott optical industries. Each soda-lime specimen, which was 12 mm in external diameter and 5 mm in thickness, was mounted on prefaced aluminum blanks using heat softening glue, fixed on the machine spindle. The schematic of the experimental setup is shown in Fig. 1. In addition, for the sake of centering conveniently, a central hole with a diameter of 4mm was processed on workpiece.

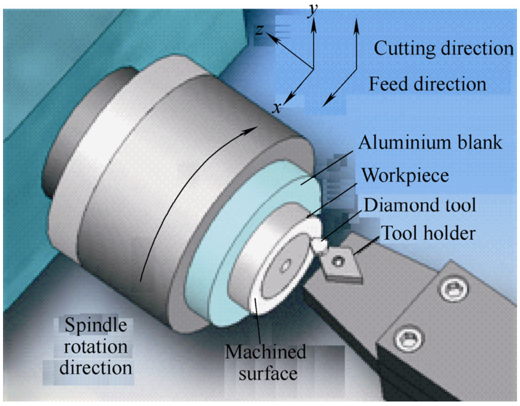


Fig. 1. Schematic diagram of the experimental set up

2.3 Cutting tool

The round-nosed single crystal diamond cutting tool, manufactured by Contour Fine Tooling Co., was used in the cutting experiments. The rake angle and the relief angle of diamond tool with 2.74 mm nose radius were −15º and 7º, respectively, and the orientations of rake face and flank face were both(100) plane. Before the tool wear experiments, the main cutting edge of a diamond tool appears to be smooth and sharp revealing no visible defects under higher magnification, as can be seen in Fig. 2.

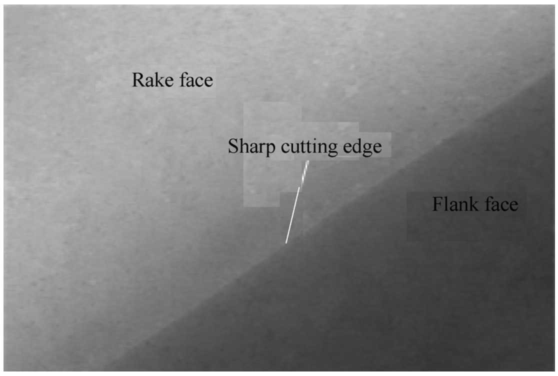


Fig. 2. SEM photograph of the main cutting edge of an diamond tool before cutting tests

2.4 Cutting conditions

As shown in Fig. 1, face-turning operations were performed and no coolant was used in the present work. Considering that the requirement of optical surface quality in practical processing, the selection of any cutting parameter should ensure that tool wear experiments of diamond cutting glass are carried out by means of workpiece material removal in ductile mode before the serious tool wear leads to the change of cutting mode from ductile to brittle. On the basis of the previous experiments of diamond cutting glass soda-lime in the ductile removal mode in Ref. [16], the finally designed configurations of cutting parameters are listed in Table 1.

Table 1. Principal cutting parameters in experiments

Parameter	Value
Spindle speed $n/(\mathrm{r \cdot min^{-1}})$	500
Depth of cut $a_p/\mu\mathrm{m}$	1
Feed rate $f/(\mu\mathrm{m \cdot r^{-1}})$	2

2.5 Cutting distance

The feed direction was from external to internal in the radial direction of workpiece, which was illustrated in Fig. 1. When the diamond cutting tool fulfills one-run facing operation, the individual cutting distance, L, is given by

$$L = \frac{\pi(r_o^2 - r_i^2)}{f}, \qquad (1)$$

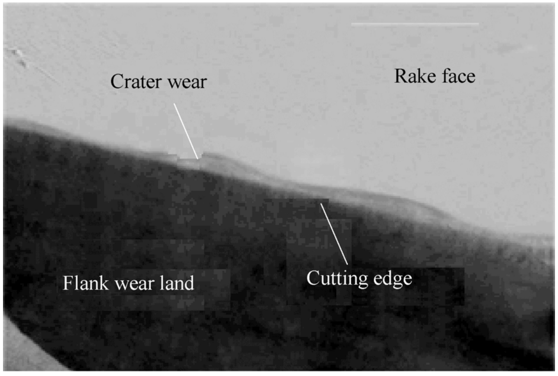
where r_o and r_i are the outer radius and inner radius of glass specimen, respectively, and f is the feed rate[17]. Substituting for all parameters in Eq. (1) gives L with a value of 50.3 m in one-run facing operation.

In addition, in order to retain the consistency of specimen surface state, workpiece was changed to a new one after every one-run facing operation. After the first pass of facing cut (with cutting distance 50.3 m), the tool wear was detected intermittently with an SEM, and then detected at intervals of every two facing cuts (with the increasing cutting distance of 100.5 m). Furthermore, other experimental data were taken, including LSCM observation of soda-lime glass finished surface and AFM inspection of surface roughness.

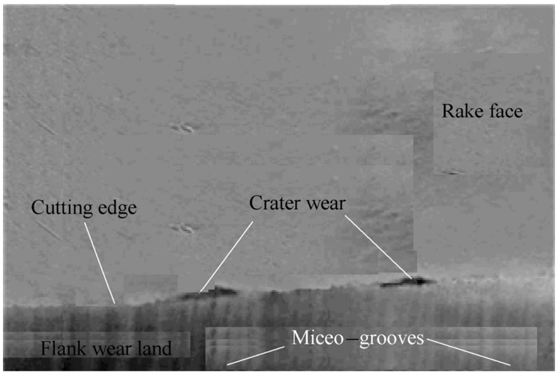
3 Detection Results of the Tool Wear and the Surface Quality of Workpiece

3.1 Tool wear patterns

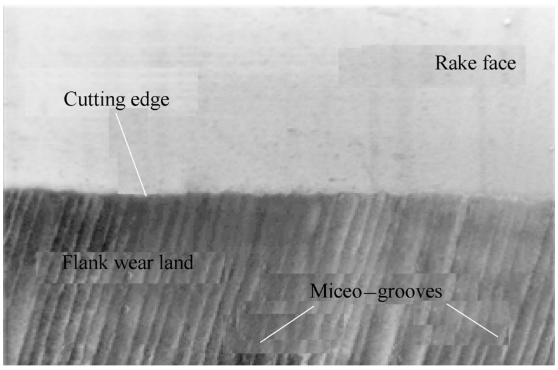
SEM photographs of the tool wear for cutting distance increasing gradually are shown in Fig. 3.



(a) Cutting for 50.3 m



(b) Cutting for 150.8 m



(c) Cutting for 251.3 m

Fig. 3. SEM photographs of the tool wear

It can be found from Fig. 3(a) that the crater wear near the cutting edge has been formed on the rake face after cutting for 50.3 m, and the maximum width is approximated as 600 nm. Meanwhile, a wear land of width exceeding 5 μm is formed on the flank face. Both the crater wear and the flank wear land are smooth and uniform, indicating that the tool wears have been a stable and gradual process.

The wear progression process can be seen in Fig. 3(b), when the cutting distance was increased to 150.8 m. Fig. 3(b) shows that the crater had no obvious increase in itself compared with that shown in Fig. 3(a), however, the width of crater narrowed due to edge recession. Different from that in Fig. 3(a), the flank wear land in Fig. 3(b) was covered with numerous micro-grooves oriented along the cutting direction, and the interspaces of micro-grooves were 250–400 nm. Moreover, the integrity and sharpness of cutting edge descended.

Fig. 3(c) shows the diamond tool wear after cutting for a distance of 251.3 m. In the SEM photograph, no obvious rake face wear can be observed anymore, in that the continuous proceeding of edge recession made the crater wear out gradually. The flank wear has been to dominate. The wear zone increased in length and width, furthermore, micro-grooves on the wear land increasing in amount and depth, nevertheless the interspaces of micro-grooves changed little, compared with that in Fig. 3(b). In addition, the edge recession induced further deterioration in the integrity and sharpness of cutting edge. These features indicate that the tool wear has been accelerated and has changed from a steady process to an unsteady process.

For identifying the changes of composition in the flank face of diamond tool with cutting distance increased, MRS (Horiba RH800) was adopted for analyzing materials on the flank face. The excitation wavelength is 547.8 nm and the analysis area is about 1 μm^2. Fig. 4 shows the detection results of MRS.

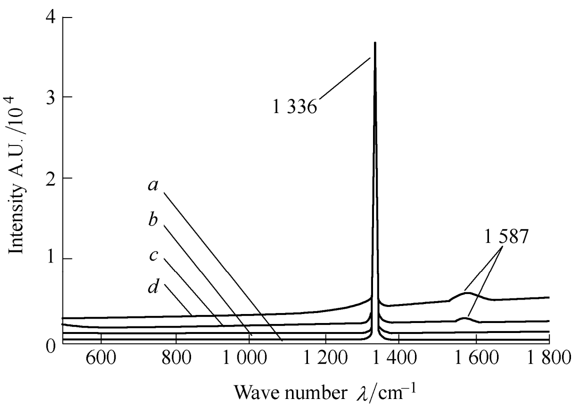
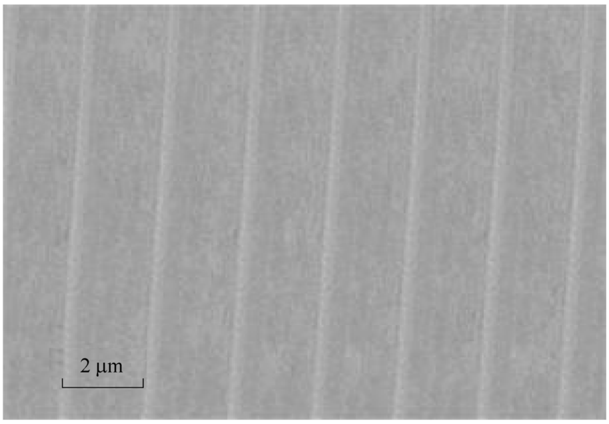


Fig. 4. Micro-Raman spectra from tool tips with increasing cutting distance (trace *a*, 0 m; trace *b*, 50.3 m; trace *c*, 150.8 m; trace *d*, 251.3 m)

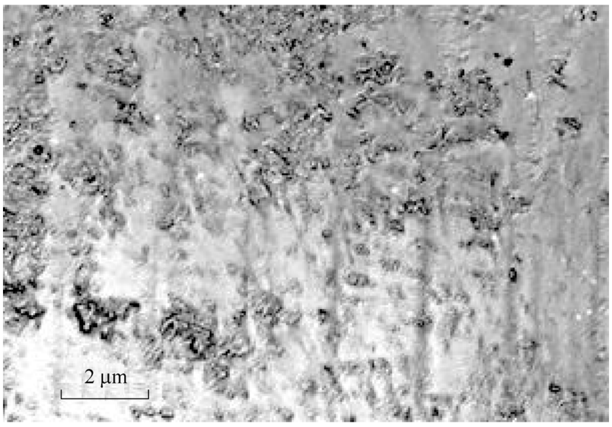
As shown in Fig. 4, trace *a* is the Raman response of a fresh and unused diamond tool tip. It is clear that the Raman band of diamond appears at 1 336 cm^{-1}. There was no band except that of diamond and no appearance of additional new bands on the trace *b*, which is the response of the diamond tool tip after cutting glass for 50.3 m. However, a weak Raman band response appeared at 1 587 cm^{-1}, which is the band of graphite, for diamond tool with the cutting distance increasing to 150.8 m and 251.3 m, respectively, shown as Fig. 4, traces *c* and *d*.

3.2 Effect of tool wear on the surface quality

The machined surface of workpiece was observed by utilizing LSCM. Fig. 5 displays the surface morphology.



(a) Cutting for 50.3 m

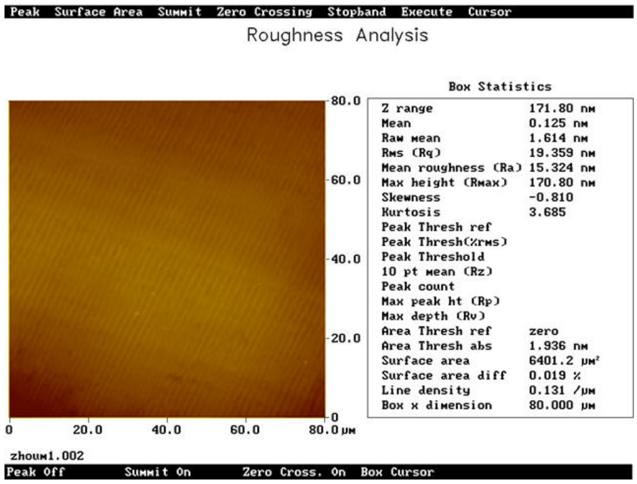


(b) Cutting for 251.3 m

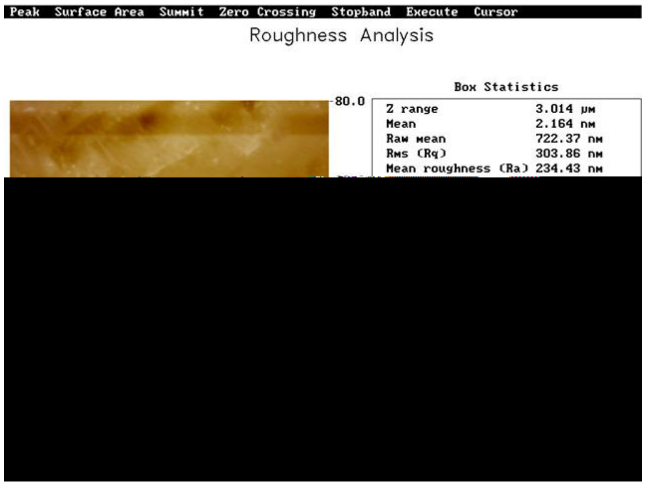
Fig. 5. LSCM photographs of machined surface

As shown in Fig. 5(a), when the cutting distance is approximately 50 m, the surface of specimen is very smooth with no apparent fractures, which demonstrates material removal was performed in ductile mode. The quality of machined surface shown in Fig. 5(b) was obviously poor, compared with that shown in Fig. 5(a). When the cutting distance is over 250 m, although tool marks remain visible on some part of the surface, most of the surface has been damaged by adjacent micro-fracture, which indicated the unsteadiness of the cutting process.

The measured results of machined surface roughness were shown at Fig. 6. The values of R_q (root mean square), R_a(average) and R_{max}(peak-valley) were 19.359 nm, 15.324 nm and 170.80 nm, respectively after cutting for 50.3 m. As shown in Fig. 6(b), the value of roughness increased substantially with R_q, R_a and R_{max} reaching 303.86 nm, 234.43 nm and 3.025 μm, when the cutting distance achieved 251.3 m. The surface morphology displayed in graphic box of Fig. 6(b) was consistent with the machined surface shown in Fig. 5(b), then mirror turning of soda-lime workpiece could not be implemented for serious tool wear.



(a) Cutting for 50.3 m



(b) Cutting for 251.3 m

Fig. 6. AFM roughness analysis of machined surface

Generally the surface roughness of machined workpiece depends on many factors such as tool wear, properties of the work material, and machining conditions. This section is concerned only with tool wear that is very much dependent on cutting distance assuming other factors constant.

The variation of surface roughness with cutting distance can be presented by Fig. 7. From the figures, it can be seen that until a cutting distance of 150 m, R_q, R_a and R_{max} were less than 25 nm, 32 nm and 300 nm, respectively, and the increasing extent of these three indexes did not exceed 70% from 50 m to 150 m, which indicated that the surface roughness kept almost constant at a low level.

However, when the distance exceeded 150 m the surface roughness began to increase rapidly. The value of R_{max} was over 3 μm, and R_a reached several hundreds nanometer with cutting for 251.3 m. The rapid increase in surface roughness indicates the cutting mode has change from ductile to brittle with the aggravation of tool wear. For acquiring ultraprecision level quality surface, the worn diamond tool has been unsuitable for cutting of glass before tool sharpening, when the cutting distance is approach to 200 m.

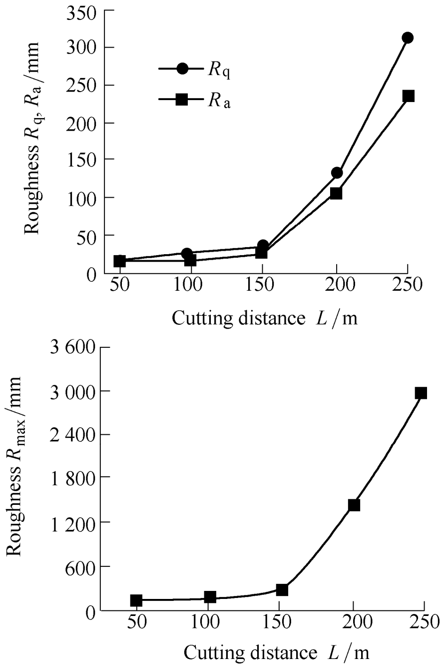


Fig. 7. Variation of surface roughness with cutting distance

4 Discussion

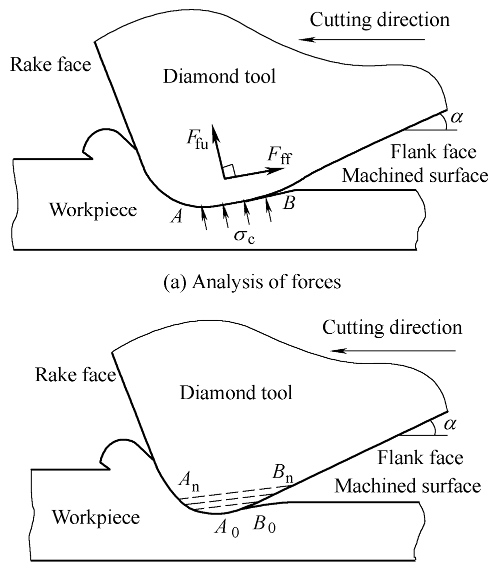
In ultra-precision machining, the wear of diamond tool has been the subject of controversial studies and is still not understood clearly[6, 18–20]. Even though several different mechanisms such as mechanical, thermal and chemical effects can contribute to diamond wear, some of which may be involved only under certain circumstances. However, the predominant wear mechanism will depend on machining conditions.

At the start of a cutting test, since the tool is new and sharp, the stresses on the tool cutting edge are very severe, moreover, the diamond tools with negative rake angle (−15° in this paper) are generally applied to brittle material processing for enhancing the ductile behavior of material[21–25]. Therefore, the rake face endures much higher pressure and temperature than the flank face, especially on the regions near the cutting edge. Under such conditions, diffusion wear would be predominant and the characteristic wear pattern is the crater on the areas close to the cutting edge.

Wear on the flank face of a diamond tool is caused by friction between the newly machined surface and the tool flank in contact, Fig. 8 presents a schematic illustration of flank wear analysis on the normal plane of cutting tool. As shown in Fig. 8(a), the flank face is subjected to positive pressure F_{fn} and friction force F_{ff}, as a result of the contact stress σ_c on flank face caused by minimal elastic recovery of the machined surface, and relative motion between cutting tool and glass workpiece. The relationships among F_{ff}, F_{fn} and σ_c are

$$F_{ff} \propto F_{fn} \propto AB \times \sigma_c,$$

where AB is the width of contact zone between the flank face and the machined surface. F_{ff} is comparatively small at the beginning stage of cutting, because σ_c is smaller and AB is shorter as shown in the Fig. 8(b). Consequently, the flank wear is in a stable process and characterized by smooth wear land during the initial phase of turning, which could be formed due to mechanical abrasion.



(b) Analysis of wear land broaden

Fig. 8. Analysis of flank wear

As cutting distance lengthening, the recession of cutting edge intensifies gradually, accompanied by the integrity and the sharpness of cutting edge decreasing, which could reduce stress concentration on the regions near the cutting edge in a certain degree. In addition, small cutting parameters, low material removal rate and high brittleness of glass cause chips in big size could not be produced in glass machining. The effect of chip flow on the rake face is considerably less than that in traditional cutting[26–28], therefore, the wear on the rake face results from the severe effect of chip flow characteristics would not appear in glass cutting. Base on both these reasons, crater wears on the rake face increase very slightly, even though the cutting distance rises continuously.

The flank wear land featured by micro-grooves becomes predominant with increasing cutting distance. Using analysis of Fig. 8(b), the width of flank wear land broadens (from A_0B_0 to A_nB_n) gradually. In addition, a loss of actual relief angle will lead to the increase of σ_c. According to the relationships between F_{ff} and σ_c, F_{ff} gets bigger with increasing AB and σ_c, and the incremental F_{ff} will result in the flank wear land further extending, consequently the flank wear land will keep broadening continuously with the cutting distance lengthening.

The increasing accumulation of thermal caused by frictional work induces the increase of temperature at contact zone between flank face and machined surface. When the temperature reaches the thermo-chemical deterioration point of diamond, the diamond material on the tool tips would transformed to graphite[6, 29]. As shown in Fig. 4, Raman spectra from tool tips presents that the graphite appeared when the cutting distance exceeds 150 m.

Furthermore, the ability of diamond tool to remove material is gradually weakened with the integrity and the sharpness of cutting edge decreasing continuously, which results in that the machined surface is not perfectly flat with residual material such as the uncut or low depth of cut portion on the workpiece.

Base on the both above analyses, it can be inferred that the graphitized diamond on flank would be scraped off, under the action of rubbing force between the flank face and the machined surface. This can lead to micro-grooves on the flank wear land along the cutting direction. With the graphitized diamond on flank face and the residual material on machined surface generated continuously, the micro-grooves increase in amount and depth for the residual material scraping off the graphitized diamond. This may be one of reasons why the intensity of bond for graphite didn't increase significantly with the cutting distance lengthening in Fig. 4.

This kind of wear, caused by a combination of thermo-chemical, mechanical friction and abrasive wear, is catastrophic and also causes unacceptable figure error in the part, and then the worn diamond tool has been unsuitable for cutting of glass before tool sharpening.

5 Conclusions

(1) The wear on rake face is characterized by the smooth and uniform crater near the cutting edge for diffusion effect. The crater enlarges very slightly in itself with cutting distance increasing, and the edge recession will narrow the width of crater. The wear land on rake face is much smaller than that on flank face.

(2) The wear land on flank face is initially flat and homogeneous, then the wear region extends and the wear land becomes roughened by micro grooves gradually. The micro-grooves on the flank wear land increase in amount and depth with further increasing cutting distance for the combined effect of thermo-chemical action, mechanical friction and abrasive wear.

(3) The recession of cutting edge intensifies continuously, accompanied by the integrity and the sharpness of cutting edge decreasing with cutting distance increasing, which weakens the ability of diamond tool to remove material.

(4) Tool wear significantly influences the machined surface roughness. When cutting distance exceeds 150m, the cutting mode begins to transit from ductile to brittle, leaving micro-fractures on the machined surface and the surface roughness(R_a, R_q and R_{max}) increasing rapidly.

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