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Effect of Cutting Fluid on Machinability of Optical Glass SF6

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Abstract. For the technology of diamond cutting of optical glass, the machinability of glass is poor, which hindering the practical application of this technology. In order to investigate and ameliorate the machinability of glass, and achieve optical parts with the satisfied surface quality and dimensional accuracy, this paper first conducted SF6 indentation experiment by Vickers microhardness instrument, and then the scratching tests with increasing depths of cut were conducted on glass SF6 to evaluate the influence of the cutting fluid properties on the machinability of glass. Based on this, turning tests were carried out, and the surface quality of SF6 was assessed based on the detections of the machined surfaces roughness. Experimental results indicated that compared with the process of dry cutting, the machinability of glass SF6 can be improved by using the cutting fluid.

Introduction

To meet rapid developments of contemporary technology, brittle materials machining technique has also been keeping pace in the world. High efficiency mirror surface machining of brittle materials such as glass has become more important as these materials have become used more widely in optical and electronic devices [1]. Glass is brittle, although high hardness and high brittleness make the machining of glasses relatively difficult, the demand for precision parts made from them has risen at a very fast rate primarily because of other superior physical, mechanical, optical or electronic properties [2].

As high hardness and high brittleness render glasses very difficult to finish without causing substantial brittle fracture, the machinability of glass is poor, especially in cutting process. Consequently, machining of glasses to the required finish for intended applications often poses a serious challenge. For the sake of acquiring ultraprecision level quality surfaces and free of micro-fracture damages, the depth of cut or feed rate should be kept at an extremely low level over a wide range of cutting region, ensuring the material removed in ductile-regime. Due to this difficulty in practical manipulation, ductile cutting of glasses has been mainly tried with high-stiffness ultraprecision machine tools [3]. Therefore, technological measures for improving the machinability of glasses in diamond cutting are of great interest.

The objective of this research is to evaluate the effect of cutting fluid on the machinability of glass. This paper carried out the indentation and scratching tests of glass SF6, and the results of tests were detected by utilizing optical microscope (OM) and laser scanning confocal microscope (LSCM). And then, by comparing the results with and without cutting fluid (treatment fluid) function, the effect of cutting fluid on the machinability of glass SF6 was analyzed and interpreted.

Experimental Procedure

Indentation Experiments. In the present investigation, an indentation system was used to measure the strength and fracture toughness of glass. Although the deformation generated in hardness indentations differs geometrically and statically from chip formation in diamond turning, there are similarities in the two processes: the material removal mode changes from defined ductile to undefined brittle mode when the load in indentations or the feed rate and depth of cut in turning exceed a critical specific value. Accordingly, examination of the subsurface deformation under Vickers indentations can reveals the extent of ductile deformation that precedes the development of brittle fracture under a diamond tool [4].

In this work, indentation experiments were performed on a HXS-1000AK Vickers microhardness instrument. The apical angle of square-pyramid penetrator is 136°. The radius of SF6 glass specimen is 6mm. The roughness Ra of mechanical polishing sample surface is 12nm, and no cracks and fragments on the specimen surface were observed with optical microscope. Before indentation, the glass specimens were immersed in treatment solution for 15 minutes. After specimens wiped cleanlily, the indentation experiments were conducted immediately. The loads were increased gradually on the specimen surface by Vickers penetrator. The crack formation would be observed, when the load exceed the crucial value.

Considering the erosion effect of caustic liquid on glass, sodium carbonate solution (SCS) was chosen as the treatment solution. Because of the SCS will achieve saturation, when concentration reach 16% at room temperature, the concentration of the treatment solutions used in the test is 10.5%.

Scratching Experiments. Scratching and turning tests of tool wear were performed on 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. The schematic of the experimental setup is shown in Fig.1.

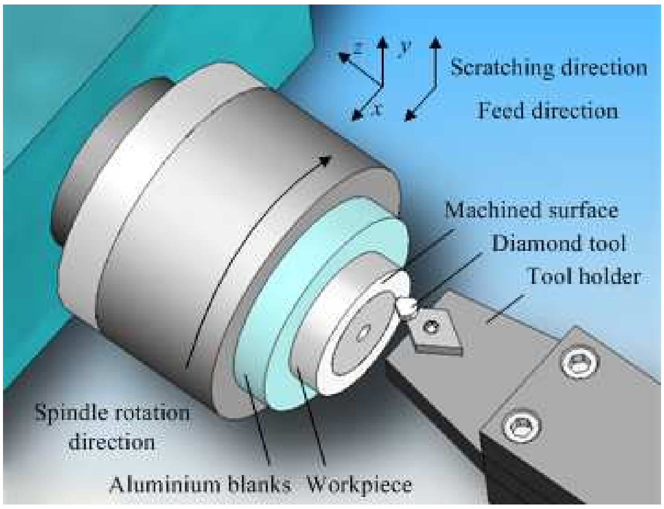


Fig. 1 Schematic of the experimental set up.

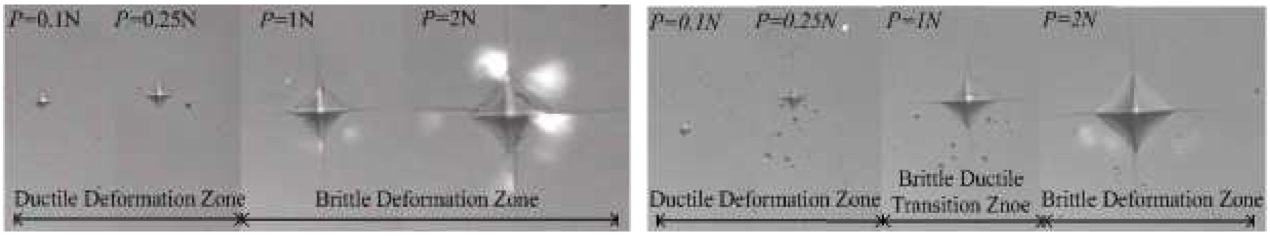
SF6 is a typical optical glass, with elastic modulus of 56 GPa and a Vickers hardness of 4.05GPa [5]. Workpiece used in this experiment was obtained from Schott optical industries. Each SF6 specimen, which was 12mm in external diameter and 5mm in thickness, was mounted on prefaced aluminum blanks using heat softening glue, fixed on the machine spindle. In addition, for the sake of centering conveniently, a central hole with a diameter of 4mm was processed on workpiece.

The round-nosed single crystal diamond cutting tool, manufactured by Contour Fine Tooling Co., was used in scratching and cutting experiments. The rake angle and the relief angle of diamond tool with 2.85mm nose radius were 0º and 11º respectively, and the orientations of rake face and flank face were both (100) plane. The main cutting edge of a diamond tool was smooth and sharp.

Results

Indentation Experiments. It is the purpose of this paper to research the machinability of SF6 glass. Comparative tests were conducted on glass SF6. One group indentation tests were performed on glass specimens directly; specimens of another group tests were immersed in SCS with the 10.5% concentration for 15 minutes preceding indentation, for simulating the chemical interaction of cutting fluids in cutting process. Fig.2 shows the topographic details of indentation pits examined by OM. Glass specimens in Fig.2 (a) were not immersed in the treatment fluid before indentation, and specimens in Fig.2(b) were immersed.

Duration loading time of this eight indentation tests are all 25 seconds. The results showed in Fig.2 demonstrate the fact that a limited amount of ductile deformation precedes the development of brittle fracture for localized-contact deformation under sharp indenter, in other words, ductile deformation can be achieved within a small control volume at the tool-workpiece interface in glasses before fracture occurs. The deformation mode changes from the ductile mode to the brittle mode as the applied loads increase to a critical value. The deformation features of glass specimens immersed in SCS or not are almost identical.



(a) (b)

Fig. 2 Indentation (350×) of specimens (a) without and (b) with immersing in the treatment fluid

When the loads (0.1N or 0.25N) are small, ductile deformation is dominant. While the load increased to 1N, the radial direction cracks were present to entire two group experiments, however, the fragments and side direction cracks were only observed in indentation of SF6 specimens without immersing in SCS, therefore, material deformation was placed in the brittle mode zone, and the deformation of specimens immersed was in brittle ductile transition zone. Fragments were all observed, when the load reached to 2N. Nevertheless, the degree of surface destruction of the specimens without immersing was severer than that of the specimens immersed in the treatment solution.

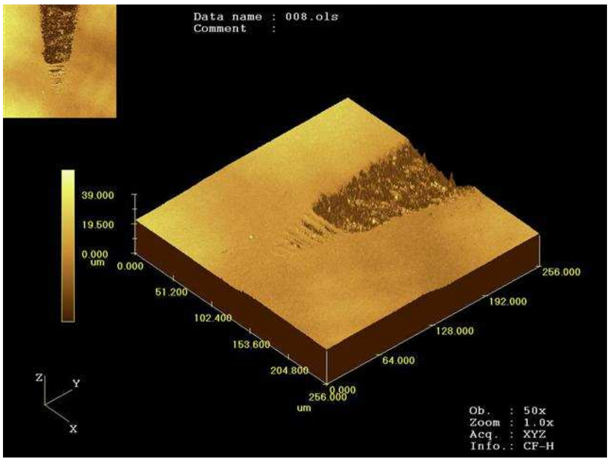
The results of contrast tests indicated that the hardness and the brittleness of glass SF6 decreased under the treating action of SCS, which could expect the machinability of SF6 would be improved in processing with SCS as cutting fluid.

Scratching Specimen. To investigate the effect of depth of cut on brittle-ductile transition in scratching process, scratching tests with increasing depths of cut were conducted on glass SF6. Fig. 3 show the photographs of the scratched grooves without and with applying cutting fluid, examined by LSCM.

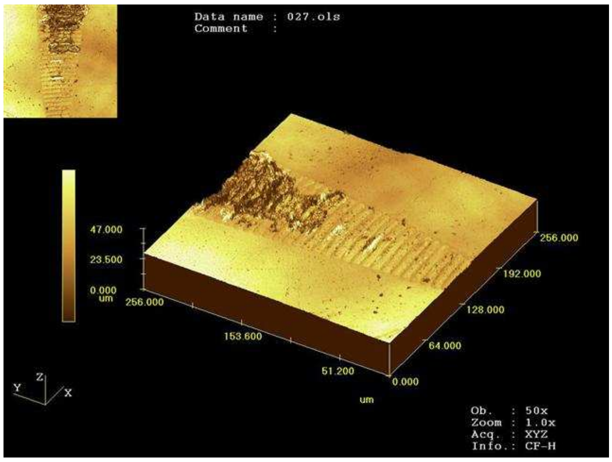
It can be seen from Fig.3 that according to the deformation features, the groove surface was smooth without sign of brittle damage when the depth of cut is small. Some brittle damage features such as pits can be observed with a large value of depth of cut. The removal of material changes from the ductile mode to the brittle mode as the depth of cut exceeds a critical value.

As shown in Fig.3 (a), the left section of scratching groove was the region of material removal in ductile mode, and then the glass material was removed in ductile mode at the right section of scratching groove in Fig.3 (b). With the function of 10.5% concentration SCS as cutting fluid, the region of material removal in ductile mode in Fig.3 (b) was larger than that in Fig.3 (a), which was without the function of cutting fluid.

The depth of scratching groove at the juncture of brittle removal region and ductile removal region can be regarded as the critical depth of brittle-ductile transition in cutting process. By measuring the depth of juncture utilizing LSCM, it can be found that the critical depth of cut in variable depth scoring SF6 specimen without cutting fluid function was 0.71μm. However, the critical depth of cut of SF6 in scratching with 10.5% concentration SCS function was 1.08μm. Compared with the value without cutting fluid function, the value of critical depth of cut was increased by 52.1%.



(a)



(b)

Fig. 3 Surface morphology of the scratched groove (a) without and (b) with 10.5% concentration SCS as cutting fluid.

The increase of the critical depth means that the material removal in ductile mode would be implemented easier in cutting with SCS as cutting liquid than that in dry cutting. The result of scratching tests were in accordance with that of indentation experiments, further confirming that the machinability of SF6 could be improved in machining with SCS as cutting fluid.

Discussion

In traditional cutting, the concerns with cutting fluids were mainly on the function of cooling and lubrication, however, the progressive experiments, scratching and turning in this work suggested that besides cooling and lubrication function, the primary reason for the improvement in the machinability of SF6 is that the chemical reactions take place between the SF6 workpiece and the SCS. The concrete analyses were given further:

SF6 belongs to lead silicate glass. The reaction of silicate glass with caustic liquid is shown in equation [6] as:

$$\equiv \text{Si-O-Si} \equiv + \text{OH}^- \rightarrow \equiv \text{Si-O-OH} + \equiv \text{Si-O}^- \quad (1)$$

The essence of this reaction is that, the hydroxyl in caustic liquid makes the silicon-oxygen bonds broken, and the number of non-bridging oxygen ion increase, then the main glass network structure is destroyed. This network structure is the principal reason for the high hardness and the low fracture toughness of glass. Consequently, the reaction of silicate glass with caustic liquid can cause the hardness decrease and the fracture toughness increase.

The critical depth t_c in glass diamond cutting can be predicted by the following equation [5]:

$$t_c = \Psi(E/H)(K_c/H)^2 \quad (2)$$

where E is the elastic modulus, H is the hardness, and K_c is the fracture toughness. Ψ is a dimensionless constant dependent on experimental condition.

According to Eq.2, the critical depth t_c is inversely proportional to the cube of the hardness H. The hardness decrease and the fracture toughness increase of SF6 specimens immersed in SCS, means that the critical depth t_c in glass diamond cutting increases. Therefore, it can be speculated that the lower hardness and the higher critical depth of cut would make it easier to remove material in ductile mode, which decreases the difficulty in cutting SF6 glass. Consequently, the machinability of glass can be improved in cutting machining for utilizing SCS as cutting liquid.

Summary

Indentation and scratching tests with and without cutting fluids were performed on glass SF6 to investigate the effect of cutting fluid on machinability of glass. Some conclusions can be drawn as follows:

(1) The formation of the indentation changes from the ductile mode to the brittle mode as the load increases to a critical value. The degree of surface destruction of the specimens with immersing in SCS was slighter than that of the specimens without immersed.

(2) The formation of the groove changes from the ductile mode to the brittle mode as the depth of cut exceeds a certain critical value in all two tests. Compared with the critical depth of cut in scratching without cutting fluid function, the value of the critical depth of cut increases by 52.1% with the 10.5% concentration of SCS.

(3) Experimental results indicate that selecting SCS as cutting fluid can improve the machinability of SF6 glass. Further investigation is needed to search the cutting fluid which possesses of excellent effect on glass machinability.

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