Diamond Turning of CaF_2 for Nanometric Surface

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Abstract

Single crystal calcium fluoride is an excellent optical material for both ultraviolet and infrared wavelength ranges with important applications. Currently, calcium fluoride optical component is produced by polishing subsequent to grinding and/or lapping. In this paper, the authors investigated the possibility of machining calcium fluoride by single point diamond turning for fabricating high quality optical surface directly. It is found that due to the unique thermal property of calcium fluoride, a special type of crack occurs when the tool feed is smaller than a critical value during wet cutting. To solve this problem, two approaches are carried out: dry cutting and large feed wet cutting. Nanometric ductile surface is obtained with forming continuous chip.

Key words: calcium fluoride, fluorite, diamond turning, ductile regime machining, optical surface

1. Introduction

Single crystal calcium fluoride (CaF_2), usually known as fluorite, is a transparent colorless crystal having the fluorite crystal structure. The cleavage plane is (111) plane. Some of the main properties (optical, mechanical, thermal) of CaF_2 are listed in table 1. For comparison, the corresponding items of single crystal silicon are also listed in the same table. CaF_2 is an excellent optical material having extremely good permeability and refractive index from 0.125μm wavelength ultraviolet range to 12μm wavelength infrared range. It also has good water-resistance, thermal-resistance and chemical stability. Therefore, it has been widely used as lenses, prisms and windows for various advanced optical instrument. Moreover, CaF_2 is considered to be the most prospective lens substrate material for the lithography equipment (stepper) of the future semiconductor manufacturing industry. On the other hand, CaF_2 is a typical brittle material, having very low fracture toughness and low hardness. The thermal conductivity index of CaF_2 is also extremely low, approximately 1/17 of that of silicon. On the contrary, the thermal expansion coefficient of CaF_2 is very large, 5.8 times of that of silicon. Conventionally, CaF_2 is finished by polishing subsequent to grinding and lapping. However, it is difficult or even impossible for polishing to attain high form accuracy when fabricating complex components such as aspheric surface, free-form surface and diffractive optics. Therefore in this paper, the authors carried out the single point diamond turning experiments in order to examine the possibility of the direct fabrication of CaF_2 optical surface without polishing.

Table 1 Optical, mechanical and thermal property of CaF_2 and a comparison with silicon

Property	CaF_2	Silicon
Permeable wavelength (μm)	0.125~12	1.2~15
Reflection loss (%)	5.6 (4 μm)	46.1 (10 μm)
Crystal structure / Cleavage plane	Fluorite / (111)	Diamond / (111)
Knoop hardness (kg/mm^2)	158.3	1150
Young’s modulus (GPa)	75 (25°C)	170
Thermal conductivity index (cal/cmSec°C)	0.0232 (36°C)	0.39 (40°C)
Coefficient of thermal expansion (10^{-6}/°C)	24 (20~60°C)	4.15 (10~50°C)
Melting point (°C)	1360	1420
Specific heat (cal/g°C)	0.204 (0°C)	0.168 (25°C)

2. Experimental Procedure

In a previous report[1], the authors put forward a new method for ductile regime turning, where the straight-nosed diamond tool is used instead of the round-nosed tool[2] [3]. This method enables the thinning of undeformed chip thickness in the nanometric range over the entire cutting region, and at the same time provides significant cutting width ensuring the plain strain conditions. Compared to the traditional method, it has the consistency in chip thickness hence provides an effective means for studying brittle-ductile transition behavior[4]. This method is also proved to be capable of large feed ductile regime turning which improves both machining efficiency and tool life. Accordingly, the experiments in this paper are carried out using straight-nosed diamond tools.

The experiments are carried out on a commercially available ultra-precision lathe having a hydrostatic bearing spindle. The machine enables the cutting tool to move along X and Z-axis, and to rotate along the B-axis which is necessary for the adjustment of the cutting edge angle. Single crystal CaF_2 wafers with (111) orientation, 50mm in diameter, 5mm in thickness are machined. The tool rake angle is varied from 0 to -60°. The cutting edge radius is estimated to be ~40 nm before cutting. Undeformed chip thickness is varied from 0 to 1 micrometers by adjusting the cutting edge angle and the tool feed rate in the ranges of 0.1~1°, 0~60μm/rev respectively. Face turning is performed and cutting speed is varied in the range of 47~235 m/min. For wet cutting, kerosene, kerosene mist, water, dehydrated methanol and acetone are used as coolant respectively.

3. Results and Discussion

3.1 Thermal crack generation in wet cutting

In the cutting of single crystal silicon using the straight nosed diamond tool, as the tool feed rate is decreased at a constant cutting edge angle, the cutting mode transits from brittle to ductile[1]. This

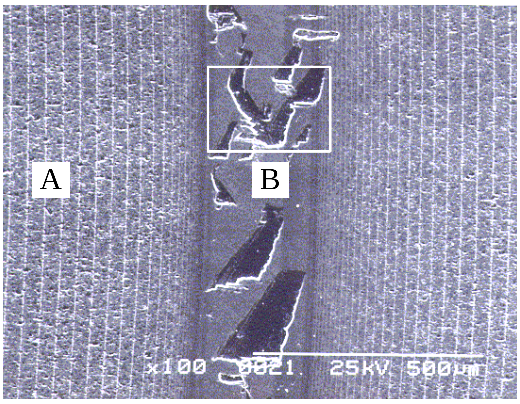

Fig.1 SEM photograph of CaF_2 surface machined under varied feed rate when using kerosene as the coolant, showing different micro-fractures occurred in large feed region (A) and small feed region (B) respectively.

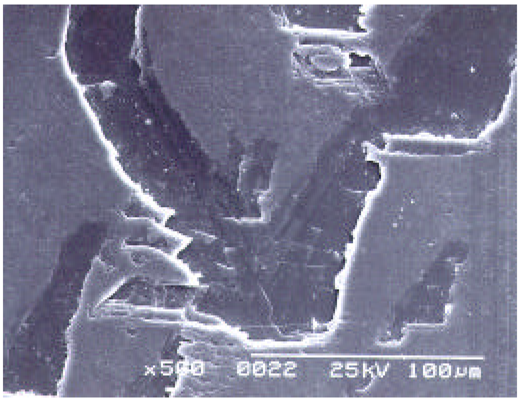

Fig.2 Detailed SEM photograph of the micro-fracture in the small feed region (B) of Fig.1, showing the flat crack surfaces and cleavage structure.

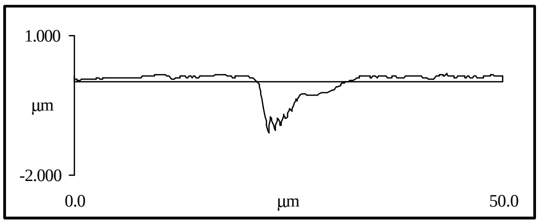

Fig.3 Sectional profile of a crack occurred in large feed region (A), cutting direction from right to left.

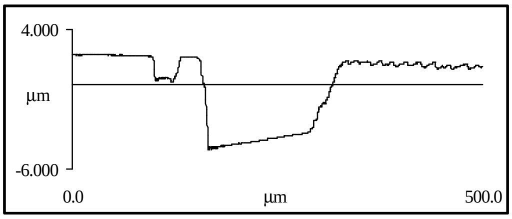

Fig.4 Sectional profile of a crack occurred in small feed region (B), cutting direction from left to right.

phenomenon is commonly observed for other hard brittle materials such as germanium and glass. However, in the cutting of CaF_2, when either kind of coolant is applied, extraordinarily large cracks occurred after the tool feed rate is decreased below a critical value. As an example, a scanning electron microscope (SEM) photograph of the CaF_2 surface machined under varied feed rate when kerosene is used as coolant is shown in Fig.1 (tool rake angle –30°, cutting edge angle 1.53°). In the large feed region (A), micro-fractures of size in the order of 10μm occurred densely, whereas in the small feed region (B), fractures as large as a few hundreds of micrometers occurred. Fig.2 shows the detailed SEM photograph of such a large crack in B region. The crack surfaces are generally smooth and the cleavage structure can be observed at the crack corner. Fig.3 shows the sectional profile of a micro crack in A region, measured by Form Talysurf along the cutting direction. The profile is curved as the V-shape, consisting of waviness on the bottom. This kind of crack is generated in front of the cutting edge during cutting, as discussed in cutting single crystal silicon5). Fig.4 shows the sectional profile of a crack in B region. The profile takes on the U-shape, consists flat bottom surface and steep wall surfaces. The depth of the crack reaches 6 μm, more than 3 time of that of Fig.3. Moreover, it is also found that the occurrence of the cracks in A region shows a strong crystallographic effect whereas those in B region do not.

Similar phenomenon is observed when either of the other types of coolant is used. Consequently, the crack generation of B region is considered to be due to the thermal aspects and resulted from the unique thermal property of CaF_2. As known from the cutting principles, the cutting heat generated from material deformation causes the temperature of the cutting point to rise significantly. Then after the tool pass, due to the rapid cooling effect of the coolant, the surface temperature drops suddenly. The above heating-cooling process yields tensile stress in the surface layer. As a result, cleavage fracture occurs. Here we term this kind of crack the "thermal crack". Unlike the cracks in region A, which are formed by the cutting force, the thermal crack is initiated due to the thermal stress. The thermal crack generation is especially significant for single crystal CaF_2 due to its extremely low thermal conductivity index and high thermal expansion coefficient. This kind of thermal property leads to great difference in both the temperature and the stress state between the outer surface layer and the internal region. Moreover, the thermal crack generation is particularly apt to occur when cutting at very low tool feed. Because the temperature rise in the cutting region depends on the heat quantity of per tool pass and the tool pass number on the constant area of machined surface, at an extremely low tool feed rate large quantity of cutting heat accumulates in the surface layer and the cutting temperature rises very high before being cooled.

3.2 Dry cutting

To avoid the thermal crack generation in wet cutting, one possible approach would be dry cutting. In dry cutting, there is no sudden cooling so the cutting heat in the surface layer can transmit to the internal region.

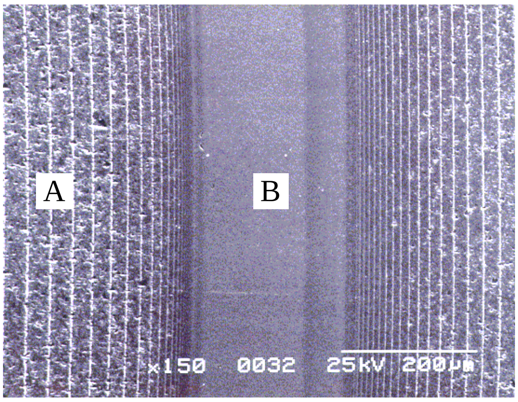

Fig.5 SEM photograph of CaF_2 surface machined under varied feed rate in dry cutting, showing micro-fractures occurred in large feed region (A) and no crack in small feed region (B).

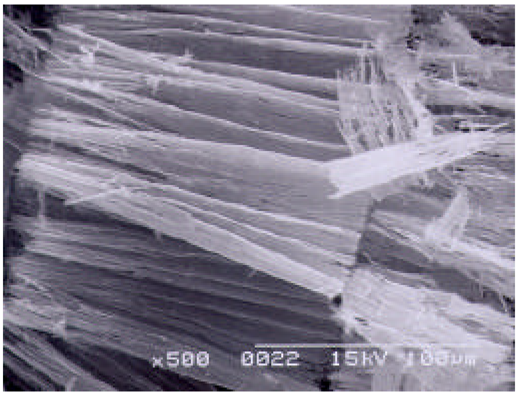

Fig.6 SEM photograph of CaF_2 ductile chips in dry cutting, indicating the material removal via plastic deformation.

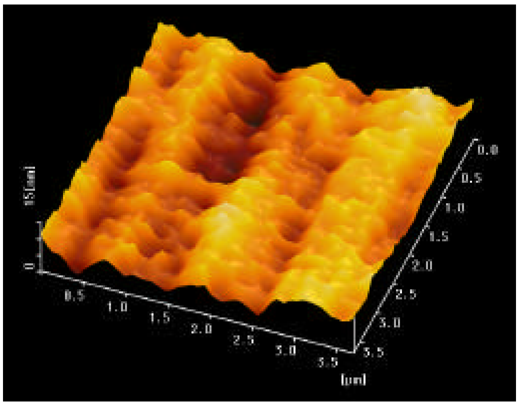

Fig.7 AFM image of CaF_2 surface machined under the feed rate of 1μm/rev in dry cutting, having the roughness of approximately 15nm Rmax.

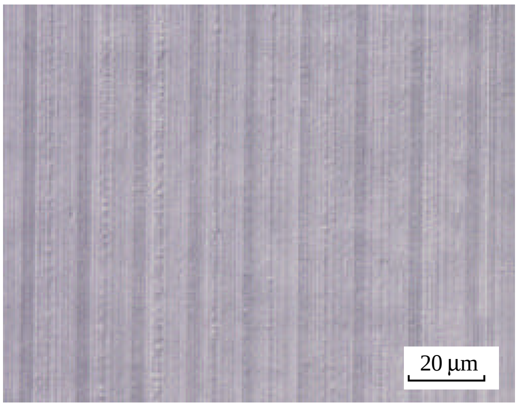

Fig.8 Nomarski photograph of CaF_2 surface machined under the feed rate of 15μm/rev in wet cutting, showing no thermal crack generation.

Thus the temperature difference and tensile stress decrease. Fig.5 shows the SEM photograph of the machined surface under varied feed rate of dry cutting. In region A, the same as Fig.1, micro-fractures occurred. However, in region B, good ductile surface is obtained without any visible crack. Fig.6 shows the SEM photograph of the CaF_2 ductile chips. The chips are continuous and similar to those of metal cutting, indicating the material is removed through plastic deformation. Fig.7 shows the AFM image of the CaF_2 surface, dry cut under the tool feed rate of 1μm/rev and the cutting edge angle of 0.57°. The surface is very smooth and has the surface roughness of approximately 15nm Rmax.

3.3. Large feed wet cutting

Another attempt for avoiding the thermal crack is large feed wet cutting. At large feed rate, the tool pass number and then the cutting heat on a constant surface area is decreased hence the surface temperature does not rise significantly. In this case, crack does not occur though the coolant is applied. In cutting with the straight-nosed diamond tool, by controlling the cutting edge angle to be small enough, undeformed chip thickness can be decreased to nanometer range even at a large tool feed up to a few tens of micrometers per revolution, thus ductile regime turning at large feed becomes possible.

Fig.8 shows the Nomarski photograph of the CaF_2 surface machined under the feed rate of 15μm/rev and the cutting edge angle of 0.12°, using kerosene as coolant. Although the coolant is applied during cutting, no thermal crack is generated. The surface is in good ductile mode with a surface roughness of 36nm Rmax.

4. Summary

Single crystal calcium fluoride is machined using single point diamond turning. It is found that coolant has significant effect on the machined surface quality. Due to the low thermal conductivity index and high thermal expansion coefficient of calcium fluoride, a special kind of crack, termed as thermal crack occurs when tool feed rate is smaller than a critical value during wet cutting. It is proved that dry cutting and wet cutting at large tool feed by using straight nosed tool are effective methods to solve this problem. Nanometric ductile surface is obtained with forming continuous chip on calcium fluoride.

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