euspen's 21st International Conference & Exhibition, Copenhagen, DK, June 2021
www.euspen.eu

Increasing the critical uncut chip thickness with coating-assisted microcutting on magnesium fluoride single-crystal

Yan Jin Lee

Department of Mechanical Engineering, Faculty of Engineering, National University of Singapore

lionel.lyj@u.nus.edu

Abstract
The machinability of brittle materials has long been limited by the ductile–brittle transition, defined as the critical uncut chip thickness in microcutting. However, the coating-assisted microcutting technique, which involves the microcutting of a pre-coated work material, has been proven successful to enhance the machinability of brittle materials. This method is investigated on the ductile–brittle transition of the (111) plane of magnesium fluoride (MgF_2) single-crystals by assessment of the critical uncut chip thickness during plunge-cutting. The application of solidified DYKEM High Purity marker ink coating increases the ductile–brittle transition by varying degrees along different cutting directions on the (111) plane with a significant improvement in the minimum critical cutting depth from 25 nm to 200 nm. This investigation also reveals that the coating affects the anisotropy in cutting.

Keywords: surface coating, ductile-mode cutting, magnesium fluoride, ultra-precision machining, critical uncut chip thickness

1. Introduction

Machining of brittle optical materials such as silicon, fused silica, and calcium fluoride (CaF_2) have often been discussed with the revolutionary advancement of ultra-precision technology. One central theme that commonly surfaces is that of the critical uncut chip thickness, sometimes called the critical depth of cut or the ductile-brittle transition. The critical value determines the machinability of the material during manufacturing of high-quality optical-grade surfaces, that is the production of defect-free surfaces. While there are various advanced methodologies to improve the machinability of these brittle materials, such as ultrasonic vibration-assisted machining [1], ion irradiation [2], and thermally-assisted machining [3], a recent finding on the use of a coating has been proven to enhance the machinability of brittle materials [4,5]. This technique employs a solid coating to be applied on the workpiece surface before machining, so as to induce compressive forces on the work material during cutting, which reduces the tendencies for brittle crack formation on the machined surfaces. To date, the coating-assisted technique, listed as a surface effect in microcutting, has only been tested on CaF_2 with the use of DYKEM High Purity marker ink and epoxy resin as the coating materials. Therefore, this work aims to investigate the coating-assisted microcutting on another optical material, magnesium fluoride (MgF_2), which has an excellent transmission range of 0.12–8.5 µm but has a higher hardness and lower fracture toughness when compared with CaF_2 [6,7].

2. Experiments

A ULG-100 ultra-precision machine center manufactured by Toshiba Machine Co. Ltd., Shizuoka, Japan, was used for microcutting experiments on the (111) plane of MgF_2 single-crystals procured from Latech Scientific Supply Pte. Ltd., Singapore. The single-crystal was first diamond turned to produce a flat surface with roughness of 1.06 nm Rq that was measured using a Bruker Dimension FastScan atomic force microscope (AFM). Figure 1 presents the experimental setup and surface profile of the diamond turned MgF_2 sample. Plunge-cutting was adopted to evaluate the critical uncut chip thickness, where the cutting tool orthogonally travels along the cutting direction at a speed of 50 mm/min and progressively moves deeper into the work material. At a particular depth, brittle cracks would form and be considered the ductile–brittle transition, otherwise defined as the critical uncut chip thickness (t_c). Optical imaging and measurement of the width of the groove using a Keyence VHX-200 optical microscope, together with the known geometrical information of the cutting tool, would sufficiently determine the actual depth of the groove. A single-crystal diamond cutting tool with a nose radius (r_n) of 0.8 mm, produced by A.L.M.T. Asia Pacific Pte. Ltd., was used for these cutting tests with the rake angle set at -10°.

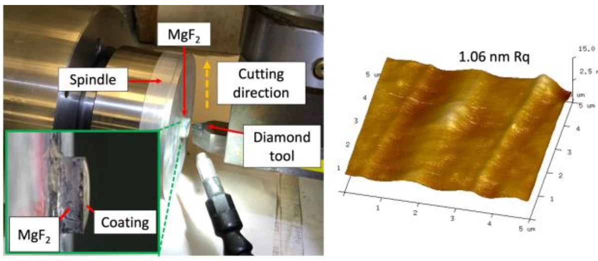

Figure 1. Experimental setup and the diamond turned surface profile of (111) MgF_2 measured by AFM

The anisotropic characteristics were also evaluated by repeating the plunge-cut tests along different orientations on the (111) crystal plane with a rotation of the sample at intervals of 15°, using the machine center spindle. The full set of experiments was performed without coating and with coating for comparison. Dykem High Purity Marker Ink (44404) was applied as the coating material (≈3 µm thick) on the diamond turned sample surface and left to dry and solidify for 30 minutes before plunge-cutting with reference to the workpiece surface. More details of this experimental procedure can be found in [5].

3. Results and discussion

Figure 2(a) presents a top view example of the grooves produced during plunge-cutting, which clearly exemplifies the significant improvement in machinability of the brittle material with the use of the coating. For a clearer observation of the groove, the coating was removed from the surface by dissolution with ethanol. The ductile–brittle transition for each groove is differentiated by the ductile- and brittle-regimes as shown in Figure 2(b). At these positions, the widths of the grooves measure to be 55.7 µm and 25.5 µm, with and without coating, respectively. Based on the geometrical relationship between the tool and the groove, the critical uncut chip thickness of these exemplary grooves are correspondingly calculated to be and 484.4 nm and 101.6 nm (i.e. a 376.8% improvement).

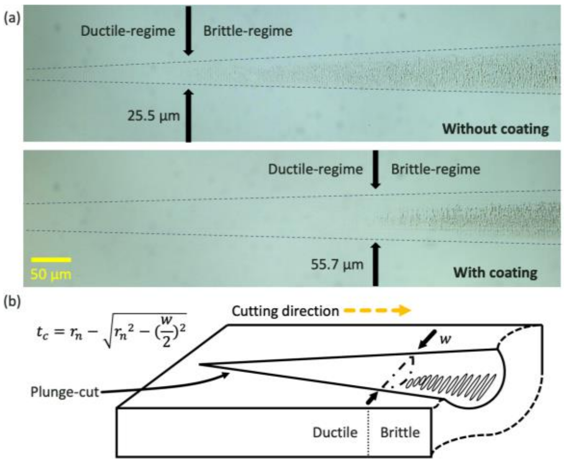

Figure 2. (a) Top view optical image comparison of the ductile- and brittle-regimes during orthogonal plunge-cutting of MgF_2 corresponding to the 150° cutting direction ; (b) illustration of the plunge-cut and the methodology to determine the critical uncut chip thickness (t_c)

The single-crystal anisotropy indicates that the critical uncut chip thickness will vary along different cutting directions. Min et al. [8] reported the anisotropy in the tetragonal-structured MgF_2 during micromachining on the (100) plane orientation. Likewise, the anisotropic properties for the (111) plane are shown in Figure 3, where certain cutting directions exhibit high critical depths as high as 553.4 nm. This is congruent with the observations in [8], which reported critical cutting depths of up to 500 nm for the (100) plane. While the critical cutting depth of 500 nm is considerably high in the ultra-precision level of machining, the fact that other directions have critical cutting depths as low as 25 nm creates a severe limiting factor for high throughput manufacturing. With the adoption of the coating-assisted technique, the lowest critical uncut chip thickness is raised to 200 nm as shown in Figure 3.

Although the lattice structure of MgF_2 differs from CaF_2, where the former has a cubic structure and the latter has a tetragonal structure, the concept of ductile-mode cutting as a result of slip activated plastic deformation can still be applied. During the course of material removal, a complex combination of shear stresses induced during chip formation and slip activity in the work material can also be resolved into tensile stresses that activate the primary cleavage planes of MgF_2 (i.e. {100}, {110}) to result in brittle-mode cutting. Therefore, the application of the coating to provide an additional compressive type of stress against the material removal process would provide the impetus to keep preexisting and new cracks closed, and achieve ductile-mode cutting.

The results in Figure 3, however, show conspicuously substantial increases by up to 412% in critical uncut chip thickness along easy-to-cut directions (i.e. directions that exhibits higher ductility), while others are only a mere 60%. This refutes the assumption made in [5] that the coating resistance to deformation does not induce additional anisotropic traits to the ductile–brittle transition. While the current understanding of the enhanced ductile-mode cutting is due to the decrease in stress intensity factor, it is critical to revisit the theory with vectorized stresses acting on the cleavage planes to evaluate the effectiveness of this technique. This concept can be applied to the machining of emerging single-crystals such as sapphire [9] as well as brittle polycrystalline materials, such as spinel [10]. Future works will also focus on the factors governing the anisotropic improvements in the ductile–brittle transition.

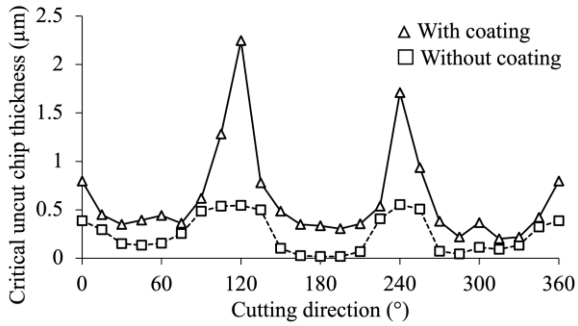

Figure 3. Anisotropic critical uncut chip thickness with and without coating on (111) MgF_2

4. Conclusions

This paper presents the applicability of the coating-assisted microcutting technique on a rarely discussed optical material, magnesium fluoride single-crystal, with the use of DYKEM marker ink as the coating material. Evaluations using the plunge-cutting method reveals the significant improvement in machinability of the brittle material with the increase in the lowest critical uncut chip thickness from 25 nm to 200 nm.

Acknowledgements

This work would not be possible without the financial support from the Singapore Ministry of Education Academic Research Fund (R-265-000-686-114 and MOE2018-T2-1-140). The author also expresses his gratitude to Dr Hao Wang for assistance rendered during the course of research and Mr Yeo Eng Huat Nelson (AML, NUS) for support in experimental work.

References

[1] Suzuki N, Nakamura A, Shamoto E, Harada K, Matsuo M and Osada M 2004 *Micro-Nanomechatronics Hum. Sci. 113-8*
[2] To S, Wang H, Jelenković E V 2013 *Int. J. Mach. Tools Manuf.* **74** 50-5
[3] Shahinian H, Navare J, Zaytsev D, Kode S and Azimi F 2018 in: *33rd Annu. Meet. Am. Soc. Precis. Eng. Las Vegas, Nevada* 1-5
[4] Lee Y J, Tan R T 2020 in: *20th Int. Conf. Eur. Soc. Precis. Eng. Nanotechnol. (Euspen), 2020*
[5] Lee Y J, Chong J Y, Chaudhari A and Wang H 2019 *Int. J. Precis. Eng. Manuf. Technol.* 1-11
[6] Tavernier H, Salzenstein P, Volyanskiy K, Chembo Y K, Larger L 2010 *IEEE Photonics Technol. Lett.* **22** 1629-31
[7] Zhang Q 2008 *University of Rochester*
[8] Min S et al. 2006 *CIRP Ann. Manuf. Technol.* **55** 103-6
[9] Gu X, Zhao Q, Wang H, Xue J, Guo B 2019 *Cer. Int.* **45** 20684-96
[10] Shi Z, Zhao Q, Guo B, Ji T, Wang H 2020 *Mater. Des.* **193** 108858