euspen's 19th International Conference & Exhibition, Bilbao, ES, June 2019

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Thermal expansion control in heat assisted machining of calcium fluoride single crystals

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Abstract

Single crystal calcium fluoride (CaF_2) is commonly used in the optical industry but has poor machinability due to low fracture toughness and brittleness. However, ductile-mode machining can be achieved through single point diamond turning process to fabricate high quality optical surfaces with nanoscale surface finishing. Localised laser assisted machining on brittle materials, such as silicon and silicon carbide, has successfully improved the material machinability and surface generation. In this work, the implementation of a globalised thermal assistance methodology incorporated in the ductile-mode machining process of CaF_2 is evaluated. The (111) plane orientation of CaF_2 was studied through orthogonal progressive grooving experiments under different temperature conditions. The decrease in hardness at elevated temperatures and activation of secondary slip systems result in the delay in ductile–brittle transition and a higher critical undeformed chip thickness with lower cutting forces. The concept of globalised thermal assisted machining with a low temperature gradient enables the precision control and machining of brittle materials where high thermal expansion rates are a major concern.

Keywords: calcium fluoride, thermal effect, micromachining, brittle–ductile transition

1. Introduction

Calcium fluoride (CaF_2) single crystals possess superior optical properties with high permeability and a wide transmission range from infrared to ultraviolet [1]. These properties create a demand in CaF_2 lens production to be used as optical windows for photolithography [2], micro resonators [3], etc. Advancements in the optics industry demand stringent requirements of optical lenses to have nanoscale surface finish with minimal subsurface damage to optimise the laser-induced damage threshold [4]. However, CaF_2 is relatively brittle with low fracture toughness and is conventionally fabricated by polishing or magnetorheological finishing (MRF) [1,5]. Single point diamond turning offers an advantageous solution to machining optical grade lenses at higher material removal rates and the capability to produce unconventional profiles such as aspherical surfaces [6]. Machining below the critical undeformed chip thickness, i.e. ductile-mode machining, produces the desirable outcome of crack-free surfaces [7]. On top of thermal softening effects, heat addition promotes the transition from an anisotropic material to become isotropic and enhances the material plasticity through the activation of secondary slip systems at elevated temperatures [8,9]. To date, thermal assisted machining has been proven to be an effective method to improve the machinability of brittle materials such as silicon by thermal softening [10] using a localised heating method called "micro-laser assisted machining (µ-LAM)" technology. In this work, an experimental study of the thermal effects on the machinability of CaF_2 single crystals is conducted through orthogonal grooving at elevated temperatures using a globalised heating method in consideration of the high thermal expansion rate of CaF_2 and avoids the inclination of thermal shock occurring at the tool–workpiece interface due to a temperature gradient.

2. Experiments

Orthogonal progressive scratches along the same crystallographic direction were conducted on a ULG-100 Toshiba ultraprecision machining centre shown in Figure 1. A 0.8 mm round–nosed single crystal diamond cutting tool with 0° rake and 5° clearance angle was used to perform progressive grooving tests on the (111) crystallographic plane of the CaF_2 sample at a cutting speed of 50 mm/min. The cutting forces were measured using a Kistler 9251B1 dynamometer and temperature measurements were recorded using the IR camera. The sample was preheated using a 100 W heat pad and held at (100 ± 5) °C to achieve globalised heating of the sample before performing the grooving experiments. The critical undeformed chip thickness value for each temperature was evaluated using a white light interferometer (WLI).

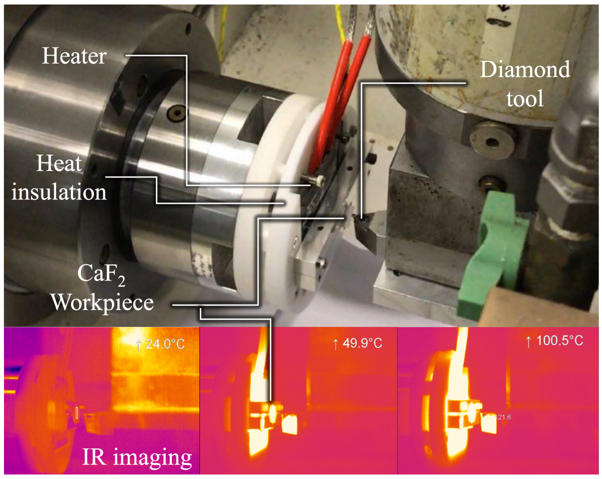

Figure 1 Globalised thermal assisted orthogonal grooving setup with thermal imaging

3. Results and discussions

As shown in Figure 2, the ductile regime can be observed by the relatively smooth depth profile and crack-free surfaces. Consequently, the brittle regime can be characterised by the severe fluctuations in the surface profile, which are caused by cleavage fracture of the machined surface. This characteristic can also be observed in the force measurements shown in Figure 3. The dutile–brittle transition (DBT) in the grooving tests at the room temperature occurs at ~0.4 µm, which is consistent with the experimental results from previous works [11,12].

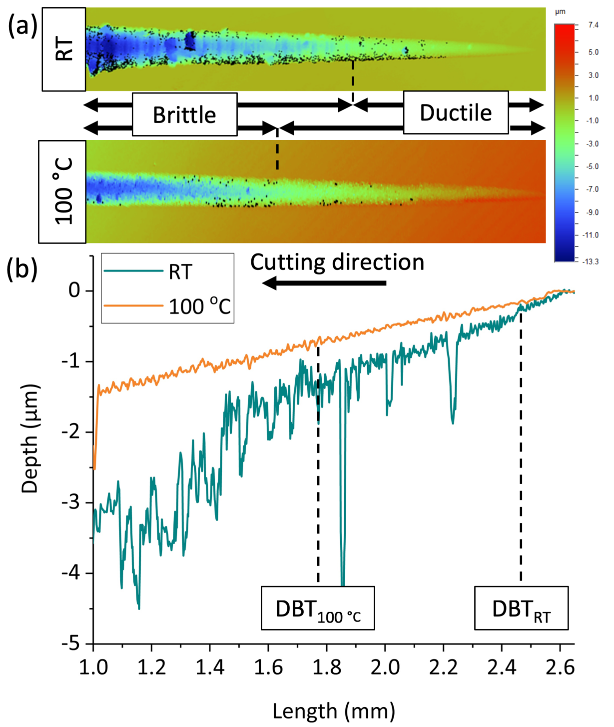

Figure 2 WLI profile measurements of grooves: (a) WLI image of each groove; (b) measured depth progression of each groove

The crack formations on the surface are indicated by the dark blue regions on the WLI images (Figure 2). Crack lines appear perpendicular to the cutting direction, which is also referred to as lamellar fracture [12]. Significant improvement in the critical undeformed chip thickness is recorded in the grooving tests at 100 °C (~0.7 µm). Cutting forces are observed to be reduced when machining at an elevated temperature by almost half. The improvement in machinability of CaF_2 can be attributed to thermal softening effects and activation of secondary slip systems. At room temperature, it was reported that the {100}<110> slip system is active for CaF_2 and secondary slip systems {111}<110> and {110}<110> can be activated at 90 °C and 400 °C, respectively [8]. The trend of the force reduction is consistent with the CPFEM simulation results observed by Wang et al. [13] in orthogonal cutting of CaF_2 with two activated slip systems. The globalised heating method reduces the influence of the high thermal expansion rate of CaF_2, such that the abrupt material expansion postulated in localised heating can be neglected. In contrast to localised heating, the temperature of the sample remains relatively constant and enables a stable material removal process at a constant defined undeformed chip thickness with negligible material expansion effects. This is a significant challenge to overcome for thermal assisted machining of brittle materials with precision control, particularly for CaF_2 with an extremely high thermal expansion rate of 18.85 x 10^{-6} /°C. The localised heating concept used in µ-LAM technology may be successful in machining other brittle materials, but those materials have a much lower expansion rate in comparison to CaF_2. For example, the thermal expansion rates of silicon and 6H-SiC were reported to be 2.6 x 10^{-6} and 4.4 x 10^{-6} /°C, respectively [14,15].

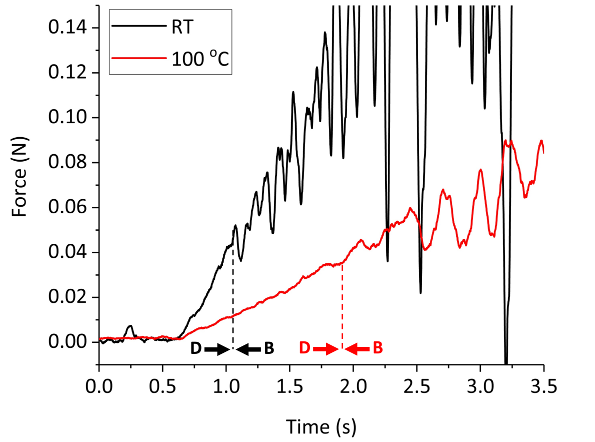

Figure 3 Orthogonal grooving cutting forces at room temperature (RT) and at 100 °C, where D and B represent the ductile and brittle regions

4. Summary

Micro-grooving tests at elevated temperatures successfully demonstrated the improved machinability of CaF_2 single crystals through thermal softening and activation of secondary slip systems. The globalised thermal assisted machining concept effectively reduces the influence of the high thermal expansion property and enhances the machining process to produce crack-free surfaces with a higher undeformed chip thickness. These experimental findings validate the new technique in thermal assisted machining to improve the machinability of brittle materials with a high thermal expansion rate.

Acknowledgements The author would like to thank Dr Hao Wang and Dr Akshay Chaudhari for their guidance in the research. The financial support from National University of Singapore Start-up Grant (Grant No.: R-265-000-564-133) and Singapore Ministry of Education Academic Research Fund Tier 1 (Grant No.: R-265-000-593-114) are gratefully acknowledged.

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