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Study on the critical chip thickness in microcutting SiC single crystals

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Abstract.
In this paper fundamental research work is presented for diamond machining of single-crystal, hexagonal-structured silicon carbide (6H-SiC) on the (0001) plane, which was performed by plunge-cutting experiments on an ultra-precision machine tool. In relation to crystallographic orientations and cutting speeds ductile and brittle regime machining is examined by means of quantifying the critical uncut chip thickness. For a monocrystalline diamond tool a critical undeformed chip thickness between 108 nm and 321 nm was identified, depending on the crystallographic orientation. Here, cutting and feed speed did not show any influence within the examined range.

Keywords: Diamond machining, Single crystal silicon carbide, Critical undeformed chip thickness

1. Introduction

Single-crystal silicon carbide (SiC) is a corrosion and wear resistant high performance material with high hardness and low density. It is used as electronic material for high-power applications, quantum computing applications as well as for biomedical and optical devices and its applications [1]. As a result of its unique material properties, featuring a critical undeformed chip thickness of a few tens to hundred nanometers, compared to single-crystal silicon (Si) or germanium (Ge) with up to a few hundred nanometers, defect free machining of single-crystal SiC with geometric defined cutting edge for fabrication of complex optical geometries is still a major challenge [2]. These factors motivated the current study, wherein diamond machining experiments on 6H-SiC were carried out to investigate the transition from ductile to brittle regime cutting. When cutting into various crystal directions at different cutting and feed speeds, the resulting cutting forces and critical undeformed chip thickness were analyzed in detail.

2. Experimental details

In our experiments, hexagonal-structured, single-crystal silicon carbide (polytype 6H-SiC, micropipe density ≤ 100 cm^{-2}) samples of 10 x 10 mm^2 were prepared and applied on the (0001) plane. The sample surface was mechanically polished to a sub-nanometer roughness by the material supplier. The cutting experiments were conducted on a Nanotech 350FG ultraprecision machining centre, according to the experimental procedure described in [3, 4]. Cutting forces were acquired via a tool-side mounted piezo-electric 3-axis dynamometer (see Fig. 1) with high sensitivity (26 pC/N in X- and Z-direction, and 13 pC/N in Y-direction). The machined specimen's surface was analysed by 3D white light interferometry and high-resolution digital microscopy.

Within the plunge-cutting experiments a single-crystal, synthetic diamond tool with 1.037 mm tool nose radius, a uniform negative rake angle (-45°) with an included tool angle of 100°, and 10° clearance angle was used. The plunge-cutting itself was performed by programed inclined tool paths moving along specific crystal orientations with a cutting length of 3000 µm at a total depth of cut of 1 µm (inclination 0.019°, see Fig. 2).

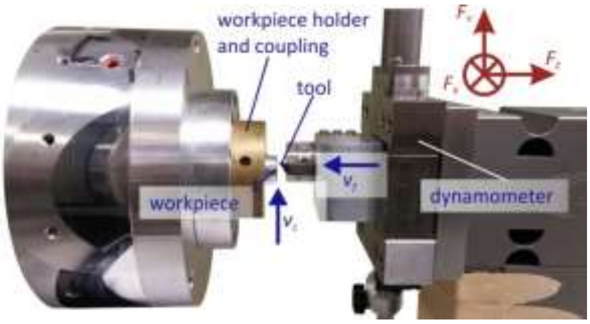

Figure 1. Experimental setup of the performed plunge-cutting process

To ensure precise alignment between the specimen surface and the cutting edge of the diamond tool, the specimen was precisely aligned by measuring the axial run-out of the surface by an electro-mechanical dial indicator. Measured deviations were compensated to a sub-micrometer level by precision screws within a mechanical three-point coupling holding the 6H-SiC specimen. Additionally, prior to each cut the specimen surface was determined by contacting it with the diamond tool while monitoring via the force measurement system.

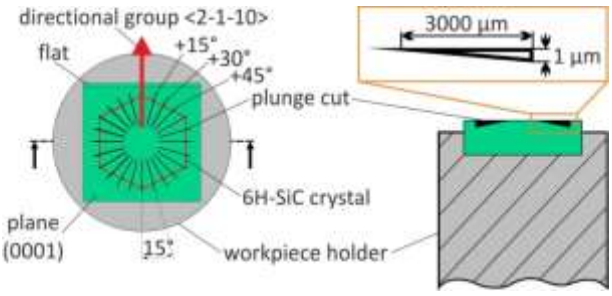

Figure 2. Plunge-cutting scheme of a 6H-SiC single crystal specimen

The specimen to be cut was than precisely aligned using the orientation flat, which is orthogonal to the <2-1-10> direction, applied by the material supplier. Here, deviations from the horizontal orientation of the flat were adjusted by the rotational C-axis of the machine tool, having the Y-axis of the machine tool parallel to the desired cutting direction. From the <2-1-10> starting direction (further used as 0°-direction), plunge-cuts were performed in 15° steps, resulting in six directional groups with identical crystal orientations (corresponding to the six transition regions of 6H-SiC), here cutting directions (shown in Fig. 2, left). To ensure reproducibility of the results, the plunge-cuts were repeated 3 times according to crystal orientation and cutting speed.

3. Experimental results and observations

In relation to crystallographic orientations and cutting speeds the transition from ductile to brittle regime machining is examined by evaluating the recorded process forces and quantifying the critical uncut chip thickness of 6H-SiC. Fig. 3 and 4 show a resulting plunge-cut and cutting force diagram by machining along the <2-1-10> +15°-orientation with a cutting speed of 10 mm/min. Both figures show clearly the different material removal regimes beginning with ductile mode (DM), the transition mode (TM) and finally the entirely brittle mode (BM) regime (from left to right).

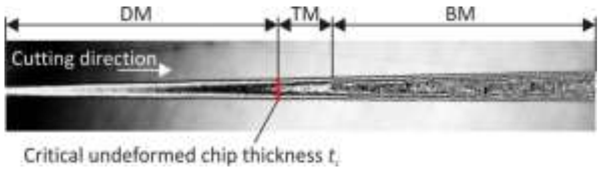

Figure 3. Machined plunge-cut along the <2-1-10> +15°-direction with a cutting speed of 10 mm/min

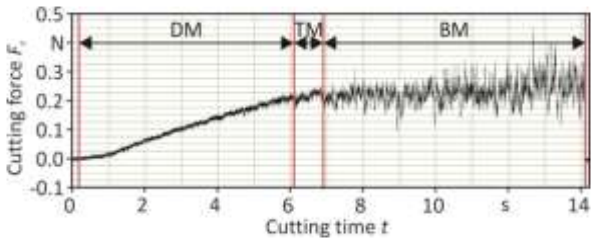

Figure 4. Cutting force along the <2-1-10> +15°-direction with a cutting speed of 10 mm/min

For the described diamond cutting tool and performed cutting speeds of v_c = 10 mm/min, 30 mm/min and 50 mm/min, a critical undeformed chip thickness between 110 nm and 320 nm was identified, depending on the crystallographic orientation (see Fig. 5). In detail, cutting along the 0°-direction (<2-1-10>-direction) shows highest values for the critical undeformed chip thickness, here between 220 nm (v_c = 10 mm/min) and 320 nm (v_c = 30 mm/min). Unlike the 30°-direction, which shows the lowest critical undeformed chip thickness with 110 nm (v_c = 10 mm/min) and 180 nm (v_c = 50 mm/min).

Figure 6 shows the measured process forces, here cutting forces (F_c) and thrust forces (F_p), depending on the crystallographic orientation and the used cutting speeds of v_c = 10 mm/min, 30 mm/min and 50 mm/min. These forces were determined within the transition mode (TM), corresponding to the captured critical undeformed chip thickness. It can be seen, that all thrust forces F_p show approx. two times higher values than the cutting forces F_c for all crystal orientations and cutting speeds. Regarding crystallographic dependency, highest forces were measured at the 0°-direction (<2-1-10>-direction, approx. 490 mN for F_p and approx. 270 mN for F_c), the lowest forces were measured at 30°-direction (approx. 300 mN for F_p and approx. 110 mN for F_c). A significant influence of the cutting speed on the cutting forces is not apparent.

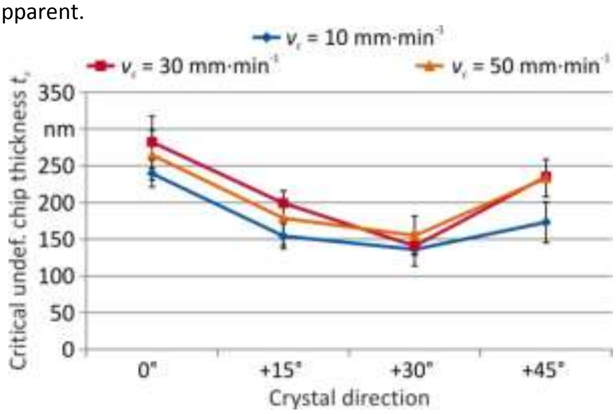

Figure 5. Critical undeformed chip thickness during plunge-cutting in different crystal directions

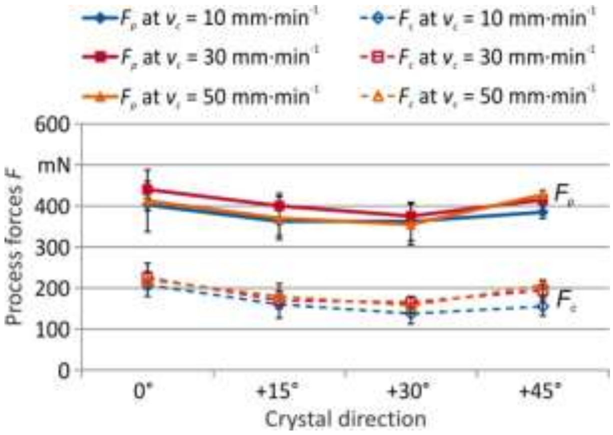

Figure 6. Process forces during cutting in different crystal directions within the transition mode (TM)

4. Conclusion and future work

We have performed ultra-precision diamond plunge-cutting of single-crystal, hexagonal-structured silicon carbide (6H-SiC). Here, the crystallographic orientation shows the major influence on the critical undeformed chip thickness and the monitored process forces, while the cutting speed shows an inconsistent influence on these parameters within the examined range. Ongoing work combines cutting parameters and forces to energy specific material loads to establish a sort of general valid mechanical process model for single-crystal materials.

Acknowledgement

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References

[1] Goel S 2014 The current understanding on the diamond machining of silicon carbide *J. Phys. D: Appl. Phys.* **47** 243001

[2] Patten J, Gao W, Yasuto K 2005 Ductile Regime Nanomachining of Single-Crystal Silicon Carbide *J. Manuf. Sci. Eng.* **127** 522-532

[3] Wang H, Riemer O, Rickens K, Brinksmeier E 2016 On the mechanism of asymmetric ductile-brittle transition in microcutting of (111) CaF_2 single crystals *Scripta Materialia* **114** 21-26

[4] Wang H, Riemer O, Brinksmeier E 2015 Theoretical study on the critical chip thickness in microcutting CaF_2 single crystals with crystal plasticity finite element method *Proc. of the 15th Int. euspen Conference* 337-338