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# Development of a methodology for evaluating the process window of ductile machining for brittle-hard materials

Oliver Fähnle[1], Yannik Steimer[1],Henrik Surberg[1],
Niklas Sass[2], Marco Buhmann[2] and Thomas Liebrich[2]

[1]Eastern Switzerland University of Applied Sciences, Buchs, Switzerland,
[2] Rhysearch Institute, Buchs, Switzerland

This paper presents a standardized methodology for determining the process window for ductile machining of brittle materials. Its application for CaF2 is reported, identifying an optimized process window for single-point diamond turning on UPM machines by determining optimized process parameters.

**Introduction**
In contrary to the fabrication of mechanical elements, optical fabrication has been dealing with the generation of nanometer range accuracies for millenniums. Demand in industry is growing constantly for components made of brittle-hard materials like ceramics, glass or Silicon, e.g. for dental implants, optical lenses, WC-molds for PGM (precision glass molding) or sensors. Accordingly, it is characteristic that optical-functional surfaces must be produced which have shape deviations from the nominal shape of less than 100 nm and center roughness values of less than 5 nm rms. These features allow, among other things, the direct production of optical surfaces for applications in the infrared wavelength range without requiring subsequent polishing processes.
These are hard to machine materials, which usually results in high tool wear as well as in rough surfaces.
In general, only a greatly reduced process window is available compared to metals, which allows the required surface characteristics to be achieved. This is referred to as ductile machining with chip thicknesses below the critical chip thickness.

**Motivation**
Machining in ductile regime to improve surface qualities and to reduce subsequent processes like polishing. Therefore, using CaF2 as an example, a methodology for evaluating the machining of brittle-hard machining is developed and presented. For the characterization of the machining sub-surface-damages as well as surface roughness is measured

**Procedure**
One way of determining the critical chip thickness of brittle-hard materials is to carry out scratch tests with varying chip thickness, as described for example in [1] and [2]. The varying chip thickness makes it possible to identify the transition from ductile to brittle machining behavior with optical measurement methods and to determine the critical chip thickness at this point. That way and applying the three waggons method for optimization of optical fabrication processes [3], the impact of various process determining parameters onto the transition depth between brittle and ductile material removal regime can be studied. This enables the determination of optimized process windows for the ductile machining of materials to be tested following a standardized approach.

The approach implemented in RhySearch / OST is based on a circular indentation that is made in the surface of the material under investigation. The chip thickness is continuously varied along the angular coordinate of the groove. Figure 1 explains the tool path of this methodology. The marked points with the same scratch depth show an exemplary critical chip thickness, which can be identified four times on one tool revolution with the depicted tool path in view of a statistical evaluation.

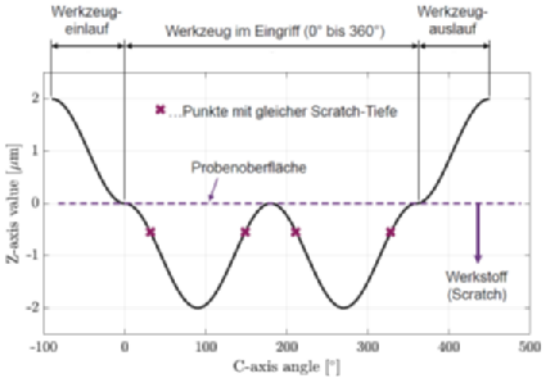


*Figure 1: Standardized procedure for determining the critical chip thickness by placing a rotary indentation with varying chip thickness into the specimen surface.*

**Results and interpretation**

Figure 2 shows the microscopy image as well as the photograph of a flat surface of a sample of calcium fluoride. The surface of a flat calcium fluoride sample has been machined with a turning process using a monocrystalline diamond cutting edge. The areas of brittle and ductile machining, which are characterized by different surface qualities, can be seen and are also marked. The area of brittle machining leads, as is also visually apparent, to a significant impairment of the optical transmission behavior.

Conducted analyses of this machining reveal that an unrecognized variation in the material thickness of the sample component on part of the surface has led to the critical chip thickness being exceeded and thus to brittle machining behavior. Therefore, in addition to the knowledge of the material behavior, a more elaborate assurance of the chip thickness with a tolerance in the range of one micrometer or even below is necessary for brittle-hard materials compared to ultra-precision machining of metals in order to keep within the limits of the specified process window. This can be made possible, for example, by tighter tolerances of the component pre-machining or the use of measuring technology integrated on the processing machine.

Repeating this methodology with different sets of process determining paramerets such as rake angle, ground velocity, pH value of the coolant applied and added ultrasound vibrations, the transition point rom brittle to ductile mode machining can be shifted higher values, optimizing the ductile machining process window for the given materia: in this case CaF2.

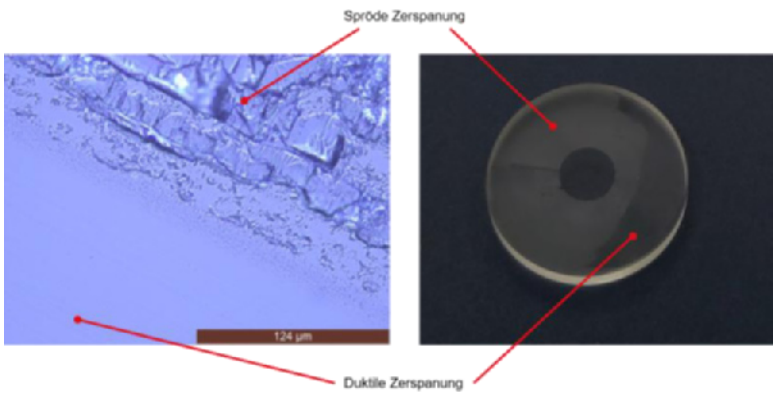


*Figure 2: Brittle and ductile machining behavior of calcium fluoride (CaF2) and associated visual appearance of the machined surface (visible impairment of transmission in the region of brittle machining behavior).*

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