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Experimental investigation of material removal mechanisms of sintered ceramics by scratch tests

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Abstract
Technical ceramics are characterized by their low thermal expansion and high stiffness. With these properties they are nowadays used as high-temperature ceramics, for example as material for catalysts. Their high shape retention also makes them particularly suitable for auxiliary components for high precision optical devices like lens frames or wafer stages. However, sinter ceramics are brittle materials and hard to machine. Although it is possible to preshape the green body before sintering, a subsequent grinding is still necessary to provide the desired surface finish and dimensional accuracy. The machining of brittle materials always provoke the conflict between ductile machining with high surface quality and efficient machining with high material removal rates. Both are necessary for an economical process design. Aim of this work is the investigation of the material removal mechanisms of sintered ceramics in single grain scratch tests to build the foundation for the development of economic abrasive machining processes.

single grain scratch test, grinding, brittle materials, sinter ceramics, dynamic fracture toughness

1. Introduction

Due to increasing requirements in the field of lithography, there is a new field of application for sintered ceramics (SC). In order to generate structures in the nanometre range, the positioning of the wafer must be highly precise. In addition to the mechanical positioning the shape retention of the substrate also plays an important role. With high stiffness and extreme low coefficients of thermal expansion (CTE) sintered ceramics meet these requirements. A current topic of research is the ductile regime grinding of brittle materials, however for industrial production this is not yet significant. Even in precision grinding the brittle material behavior prevails. Usually, material properties are determined by static load test. Nevertheless, measured properties do not necessarily correlate with those observed during machining. E.g. for ceramics dynamic loading leads to a variation in fracture toughness [1]. Besides depth of cut and infeed rate, cutting speed is a critical process variable. Previous studies have shown that there is no influence of this parameter to the critical depth of cut [2]. In order to investigate the influence of the cutting speed on the grinding process the ratio of brittle fracture was analysed in the presented work.

2. Material Properties

Table 1. Material properties.

Properties	Symbol	Unit	SC 1	SC 2
Density	ρ	g/cm³	2.576	2.554
Young's modulus	E	GPa	146	145
Hardness	H	GPa	10.1	10.7
fracture toughness	K_c	MPa $m^{½}$	0.91	0.84
flexural strength	σ	MPa	203/15.4	323/15.5

The workpiece materials under investigation were sintered ceramics of two different suppliers. As a synthetic material the characteristics are generated by the manufacturing process. Typically, material properties such as hardness, fracture toughness, flexural strength and Young's modulus are used to classify brittle materials [3]. But it was shown that there is no correlation between these material properties and the machining characteristics for ceramics [4]. In a comprehensive analysis these properties were determined for both workpiece materials as shown in Table 1.

3. Experimental Procedure

3.1. Experimental Setup

To achieve similar cutting speeds for the scratch test as in grinding, an indenter was mounted radially on a face plate of an air bearing grinding spindle. Within a circular segment formed scratch different regimes of material behavior - from ductile to cracking and chipping - were realised.

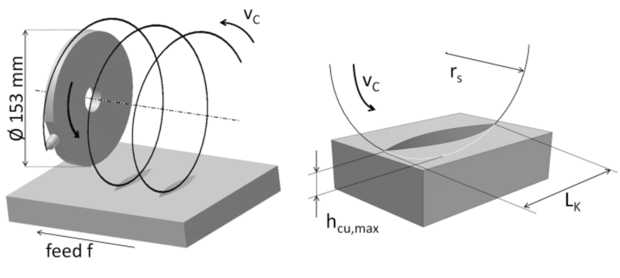

Figure 1. Scratch kinematic (left) and geometry of a single cut (right).

To generate several scratches under similar conditions the workpiece was moved with constant feed rate perpendicular to the scratch direction by a linear translation stage.

3.2. Scratch Tests

The 25 x 20 x 5 mm³ specimens with polished surfaces (Sa = 10-15 nm) were scratched with Berkovich indenters. These diamond indenters have a pyramidal shape with 142.3° face-to-face angle and a tip and edge radius of about 100 nm. All scratch experiments were performed with the same indenter orientation – pyramid flat in scratch direction. Within the experiments the cutting speed was varied between 10 m/s and 40 m/s. For each cutting speed two series with 25 scratches were performed. The achieved scratch depth lay between 6.2 µm and 7.0 µm, determined by compensating the sample tilt manually.

4. Metrology and Analysis

To determine the ratio of brittle fracture in relation to the initial surface the scratches on the specimen were investigated by white light interferometry (WLI). In addition, the length of the cracks was measured using a digital microscope. Plane correction and offset correction were performed to the raw data. Using a self-developed software the measured surface was subdivided into individual segments of 2.3 mm x 0.3 mm, each with a single scratch track.

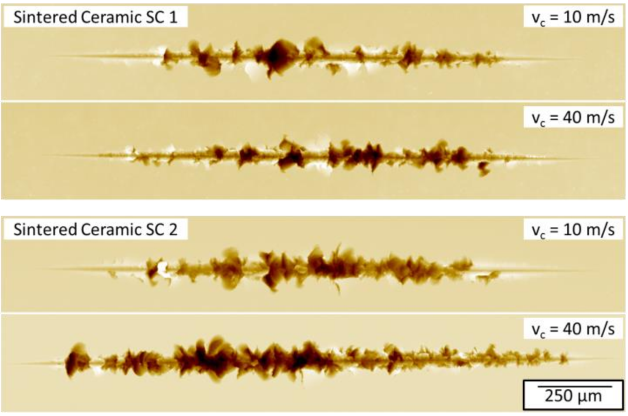

Figure 2. WLI Images of scratch patterns for different cutting speeds.

To evaluate the ratio of brittle fracture, the topography of the surface sections were partitioned into three areas. The initial surface, the elevated areas around the scratch pattern (brighter areas) and the area of brittle fracture (darker areas). To compensate the influence of different depths of cut due to the accuracy of the experimental setup the measured scratch length was used as correction factor.

5. Results

Figure 2 shows the scratch pattern of the machined samples SC 1 and SC 2 at 10 m/s and 40 m/s. It reveals that the pattern for SC 1 is very similar for the different speeds, whereas SC 2 shows significant differences. The scratch itself is longer and the amount of brittle fracture increases. In order to verify these observations and to meet the statistical variance in the material response, 50 scratches were evaluated for each cutting speed. First, the results in Figure 3 verify the expected distinct difference in the material behavior. The ratio of brittle fracture is up to 40 % higher for SC 2 compared to SC 1. As well, it is clear that the deviation is significantly larger in material SC 2 which indicates lower fracture toughness respectively a higher brittleness.

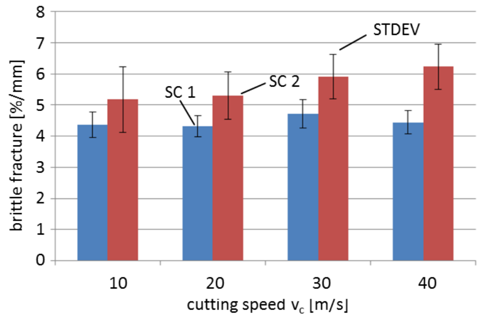

Figure 3. Amount of brittle fracture (mean and standard deviation) for different cutting speeds for both sintered ceramics.

Due to sub-surface lateral cracks the material rise above the initial surface level. The second criterion evaluated is this elevation of the surface along the scratch pattern. Figure 4 shows the different value of this feature for the different speeds.

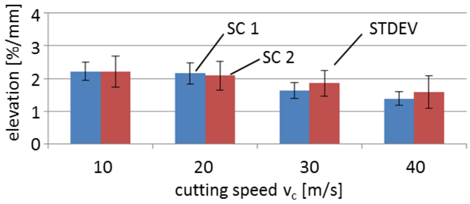

Figure 4. Amount of elevated surface (mean and standard deviation) for different cutting speeds for both sintered ceramics.

Here, the differences between the materials are much lower. At low cutting speeds, the material cutting characteristics are indifferent, only for cutting speeds larger than 30 m/s differences arise. Both materials show a decline in the raised surface what might indicate a lower residual stress in the material.

6. Conclusion

Considering the slightly distinctions between hardness and fracture toughness as main indicators of brittleness shown in Table 1, the results indicate clear differences for the two materials. Although a correlation between these properties and the material behavior was not expected there is a good compliance between flexural strength and ratio of brittle fracture. Clarifying the material response under dynamic conditions as in grinding, the scratch tests and the developed software offer an appropriate tool to evaluate the dynamic material response of ceramics.

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