Application of single-grain scratch tests for analysing the removal mechanisms and surface properties of brittle materials

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Abstract
The research work presented here focuses on material removal mechanisms and resulting surface properties when abrasive processes are used for high precision machining of optical parts made from brittle materials. The high accuracy surface finish of these components is typically accomplished through complex process chains. Firstly, processes with high material removal rates are applied which imply the risk of subsurface damages affecting the performance and lifetime of the components. Therefore time and cost intensive process steps like lapping and polishing are used to generate surface integrity. Besides the final machining of these components, there is also a demand for improvement of fine and precision machining with large removal rates. Thus, enhanced surface integrity properties in grinding processes will lead to a more economic production. For a deeper understanding of grinding processes the presented work focuses on the characterization of surface damage and material removal in brittle materials by single grain scratch tests.

1. Introduction
Due to their specific mechanical properties, chemical stability and ultra-low thermal expansion optical glasses, glass-ceramics and sinter ceramics are attractive for high precision optical parts \cite{1}. Primary machining processes of high material removal rates are based on micro-fracture. The critical property of brittle materials therefore is the toughness \cite{2}. Nevertheless, grinding parameters are still selected on the basis of experience and preliminary investigations. Subject of this investigation is to establish correlation between material parameters and the machinability.

2. Material properties
The workpiece materials under investigation were commercially available fused silica (FS), two glass-ceramics (GC) and a sintered ceramic (SC). These materials differ in their rate of amorphous and crystalline structure and their material properties. Table 1 shows these properties: density $\rho$, Poisson’s ratio $\mu$, Knoop hardness $HK$, Young’s Modulus $E$ and fracture toughness $K_C$. Here, the hardness was measured with Knoop indentation at loads of 0.1 kp and 10 s dwell time. Fracture toughness was determined by the length of the cracks emanating from Vickers indentation corners with a load of 4.905 N \cite{4}. For each material five indents were performed. Surface roughness was measured with a white light interferometer (WLI).

Lawn and Marshall \cite{3} introduced in 1979 the ratio of hardness to fracture toughness as an index of brittleness which today is still relevant for the choice of process parameters.

To achieve similar cutting speeds like 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 behaviour - from ductile to cracking and chipping - were realised.

3. Experimental procedure

3.1. Experimental Setup

![Figure 1. Scratch kinematic (left) and geometry of a single cut (right).](image-url)

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.

<table>
<thead>
<tr>
<th>Table 1 Material properties</th>
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<tbody>
<tr>
<td>$\rho$ (g/cm$^3$)</td>
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<tr>
<td>2.19</td>
</tr>
<tr>
<td>$\mu$</td>
</tr>
<tr>
<td>HK (100p/10)</td>
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<tr>
<td>E (GPa)</td>
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<td>$K_C$ (MPa m$^{1/2}$)</td>
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3.2. Scratch Tests

The 25 x 20 x 5 mm³ specimens with polished surfaces (Sa 7-12 nm) were scratched with Vickers indenters. These diamond indenters have a pyramidal shape with 142.2° face-to-face angle and a tip and edge radius of 100 nm. All scratches were performed with the same indenter orientation – edge in scratch direction. With a spindle speed of 1000 RPM the resulting cutting speed was 8 m/s. In all experiments, the scratch depth was set to 10 µm, except for SC; here 7 µm were selected, due to the material properties. Indenter and samples were cleaned with acetone before each test.

4. Results

Fig. 2 shows the scratch patterns of the different materials. At low depth a uniform groove occurs corresponding to a micro-ductile regime. With increasing depth the so-called micro-cracking regime defined by radial and lateral cracks transfers to the micro-abrasive regime. The evaluation was purely optical, so sub surface median cracks cannot be excluded in all areas. To compare the scratch behaviour of the different materials two loci at the scratch pattern were defined (depths of transition - DOT).

Fig. 3 shows the transition-zone between ductile material behaviour (A) and radial cracking (B) and the beginning of the area of sub-surface lateral cracks (C). These cracks arise behind the indenter-tip and lead to an elevation of the surface way above the actual depth of cut. This elevation can be seen in Fig. 2 as iridescent areas. For each material ten scratches were evaluated.

Table 1 Depth of transition of the investigated materials

<table>
<thead>
<tr>
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<th>FS</th>
<th>GC1</th>
<th>GC2</th>
<th>SC</th>
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<tr>
<td>DOT 1 (nm)</td>
<td>136 ± 18</td>
<td>156 ± 22</td>
<td>100 ± 7</td>
<td>103 ± 9</td>
</tr>
<tr>
<td>DOT 2 (nm)</td>
<td>186 ± 25</td>
<td>328 ± 23</td>
<td>140 ± 11</td>
<td>346 ± 51</td>
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</tbody>
</table>

Even though the workpiece materials differ in their properties, the brittleness as the ratio of hardness and fracture toughness can be used for comparison. Figure 4 shows the DOT plotted versus the brittleness. With increasing brittleness the gap between DOT 1 and DOT 2 decreases.

5. Conclusion

Throughout the experiments different crack behaviour was observed, which cannot be attributed directly to the material parameters. The lateral crack propagation in amorphous materials (FS) seems to be undisturbed and leads to significant tension induced elevation of the surface. With an increasing rate of crystalline structures (GC1, GC2, SC), interaction between radial and lateral cracks leads to surface cracks and chipping which can be related to the gap between DOT 1 and DOT 2, here. The significance of the size of this gap for grinding operations, however, has to be clarified in further investigations.

References