Plastic Deformability at Micro-Scale of Fiber-Reinforced Ceramics with Porous Matrix during Grinding

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Abstract

Fiber-reinforced ceramics (ceramic matrix composites (CMCs)) with uncoated alumina oxide fibers in a porous alumina oxide matrix represent a group of materials with high application potential and future importance. In most cases, a grinding process is necessary to fulfill surface and tolerance requirements. However, the machining characteristics of CMCs with a porous alumina oxide matrix and the underlying material removal mechanisms are not investigated yet. It has been shown that ductile grinding, requiring plastic deformation, of monolithic alumina oxide is possible. It is not known, if the existing knowledge regarding the grinding characteristics of monolithic alumina oxide can be transferred to CMCs with a porous alumina oxide matrix. Hence, the research question of this paper is whether a ductile grinding and thus plastic deformation of this CMC type is possible or only brittle material behavior is present.

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1. Introduction

In grinding, which can be considered as a forming process at micro-scale with high forming speeds, brittle and ductile material removal behavior can be differentiated. In case of brittle material removal behavior, the material is
removed by propagating cracks [1]. In contrast, the chip formation in ductile material behavior includes three phases. In the first phase, the material is only affected by elastic deformation. In the second phase, elastic and plastic deformations take place. Getting to a specific penetration depth, phase three starts and besides elastic and plastic deformation a chip is created. [2] In order to obtain undamaged and defect free workpieces, ductile material behavior is necessary. It has been shown in scientific works, that ductile grinding of ductile [3] as well as highly brittle materials [4], like aluminum oxide [5], is possible.

Due to the limited development potential regarding temperature strength of super alloys, Ceramic Matrix Composites (CMCs) evolved [6]. CMCs consist of ceramic fibers embedded in a ceramic matrix. Although both components are brittle, the composite materials show ductile fracture behavior on macro-scale, for example in bending tests. Due to their mechanical properties, CMCs are considered as a material with very high application potential in several industrial areas, like in gas and aero turbines [6] as well as in the heat treatment and aerospace industry [7]. CMCs consisting of uncoated fibers in a porous matrix represent a new design concept [8]. Although grinding is necessary in many cases to fulfill surface and tolerance requirements, the material removal mechanisms and hence the material removal behavior of this CMC type in grinding processes is unknown. In consequence it is not known, if a ductile grinding of CMCs with porous matrix is possible.

Hence, in this work the material removal mechanisms of fiber-reinforced ceramics with porous matrix are investigated by single grain cutting tests. Based on these tests, the material removal mechanisms are identified and correlated with the process forces and depth of cuts. The aim of this work is to analyze, whether a ductile grinding caused by plastic deformability of the two material components fiber and matrix is possible or only brittle material removal behavior is present during grinding CMCs with a porous alumina oxide matrix.

2. Fiber-Reinforced Ceramics with Porous Matrix

In general, two design concepts of CMCs to adjust the strength of the connection between fiber and matrix are distinguished. In the first design concept, the connection strength is determined by the coating of fibers, whereas in the second design concept, the connection strength is determined by the porosity of the matrix. In this case, alumina oxide crystals building the matrix are punctually connected to fibers due to sintering processes. Hence, coating of the fibers is not necessary. Fiber-reinforced ceramics with porous matrix represent a modern design concept, which can be produced at lower costs in comparison to conventional fiber-reinforced ceramics with coated fibers [8]. This concept is realized by the WPX Faserkeramik GmbH, Germany, in form of WHIPOX (Wound Highly Porous Oxide Matrix) ceramics, which were used for the tests presented in this work Fig. 1.

<table>
<thead>
<tr>
<th>Composite Material</th>
<th>Matrix</th>
<th>Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material: Al₂O₃/Al₂O₃ (Fiber/Matrix)</td>
<td>Material: Al₂O₃</td>
<td>Material: Al₂O₃</td>
</tr>
<tr>
<td>Density: ρ_CM = 1.5-3 g/cm³</td>
<td>Young’s modulus: E_M = 40 GPa</td>
<td>Young’s modulus: E_f = 390 GPa</td>
</tr>
<tr>
<td>Porosity: P~50 %</td>
<td>Density: ρ_M = 2.7 g/cm³</td>
<td>Density: ρ_f = 3.9 g/cm³</td>
</tr>
<tr>
<td>Young’s modulus: E_CM = 40-200 GPa</td>
<td>Structure: Porous</td>
<td>Structure: Dense</td>
</tr>
</tbody>
</table>

Fig. 1 Structure of the Ceramic Matrix Composite with highly porous matrix
Both, the fiber and the matrix, consist of alumina oxide, but they differ in their structure. The fibers have a dense structure, whereas the matrix is highly porous with a pore size smaller than \( 1 \leq \mu m \). According to the different structure of fibers and matrix, both components differ in their mechanical properties. Due to the different structure and properties, it has to be assumed, that fiber and matrix differ in their plastic deformability and in consequence in their chip formation behavior. Although both components, fiber and matrix, are made out of alumina oxide, which is known to be a highly brittle material, they act ductile considered as a composite material on macro-scale. As CMC-workpieces have to be ground in many cases in the final step of manufacturing, they experience mechanical and thermal loads at micro-scale, as the cutting depth of single grains and the chip thickness is in range of a few microns. The effects of these loads at micro-scale on the workpiece structure are not known yet.

3. Experimental Work

In order to analyze these effects, single grain cutting tests were performed on WHIPOX ceramics shown in Fig. 1 with a fiber diameter of \( d_f = 10 \mu m \) and a winding angle of \( \alpha_f = 15^\circ \). In single grain cuttings tests, only one diamond grain scratches the workpiece. Thus, the complexity of a grinding process is reduced to the interaction of one grain and the workpiece material. The methodical approach is shown in Fig. 2.

The first step was the preparation of samples for the single grain cutting tests (Fig. 2 a), in order to create a defect free surface. The preparation was done by polishing using a diamond slurry with a diamond grain size \( d_g \leq 1 \mu m \). Subsequently, single grain cutting tests were carried out on the prepared samples (Fig. 2 b). These single grain cutting tests were performed on pure matrix samples without fibers as well as on fiber reinforced samples on a ISOG S22P Turbo tool grinding machine with a cutting speed of \( v_c = 20 \) m/s. Diamond grains of the type MBG-640 60/70 with a mean grain size of \( d_g = 251 \mu m \) from Diamond Innovations were used as cutting tools. These diamond grains are characterized by a high impact and bending strength. As a result, the grains have a comparatively high wear resistance. A high wear resistance is necessary for a targeted depth of cut in the process as well as for constant engagement conditions with respect to the grain geometry. The cutting tests were carried out with flat grinding kinematics with axial feed and increasing depth of cut. Due to this kinematics, cones are formed, which are composed of non-overlapping cutting grooves with increasing depths and thus increasing grooves lengths. The depth of cut \( a_c \) corresponds to the maximum uniformed chip thickness \( h_{cu,max} \). The maximum depth of cut was \( a_c,max = 30 \mu m \). During the tests, the process force was recorded. The analysis of the cutting grooves was carried out by depth measurements of the grooves using the laser-scanning microscope VK X 150 from Keyence (Fig. 2 c) and by qualitative analyses, using SEM images (Fig. 2 d). Corresponding to Bifano, every material can be ground ductile, if a specific depth of cut is not exceeded [4]. By correlating the depth measurements with the SEM images and the cutting force, the cutting mechanisms can be described in a single grain engagement in dependence of the process forces. Thus, not only the influence of the depth of cut on the cutting mechanisms can be examined, but also the force components present in the process can be determined. The results of the single grain cutting tests are presented in the following subchapters.
3.1. Material Removal Behavior in Single Grain Cutting Tests

Grooves generated in the single grain cutting tests are shown exemplarily in Fig. 3. The two upper SEM images on the left side (Fig. 3 a,b) show a groove in the pure, highly porous matrix material at different depth of cuts in a range of \( a_c = 0 - 16 \mu m \). The two lower SEM images (Fig. 3 c,d) show sections of the cutting grooves of the fiber-reinforced samples with a fiber orientation parallel to the cutting direction for the same single grain engagement depths.

![Fig. 3 SEM images of scratch grooves](image)

In case of both samples, in general to areas of the single grain cutting groove can be differentiated. For small depth of cuts \( (a_c = 0 - 2 \mu m, \text{Fig. 3 a,c}) \), the surface of the groove appears smeared. At a specific depth of cut, the material behavior changes and large breakouts occur. Hence, the material removal mechanisms change at a specific depth of cut, respectively at specific mechanical load, as the normal and tangential forces increase with an increase of the depth of the cut. This behavior was observed in case of all fiber orientations tested. In case of the pure alumina matrix, the change of the material behavior took place at a depth of cut \( a_c = 14 \mu m \), a normal force \( F_n = 10 N \) and a tangential pressure (tangential force \( F_t \), divided by the groove cross section area) \( p_t = 0.0016 N/\mu m^2 \). Considering the fiber reinforced samples, the change of the material removal behavior was observed at smaller depth of cuts and lower forces. This can be explained by large pores, which arise randomly around fibers, especially on fiber crossing points, due to the manufacturing process weakening the fiber-matrix-interface. To analyze the material removal behavior, the matrix and the fibers were analyzed separately, as shown on the right side of Fig. 3. Examining the material removal behavior of single fibers (Fig. 3 f), a transition from ductile to brittle material behavior can be detected. At the area of the grain entrance, material bulging on the upper and lower contact area is visible (white stripe). This material bulging is caused by plastic deformation. With an increasing penetration of the grain into the fiber, cracks occur. Hence, a transition from ductile to brittle material behavior takes place. These findings correspond to existing knowledge regarding the grinding behavior of dense alumina oxide, which describe plastic deformation at very low depth of cuts. Considering the matrix (Fig. 3 e), also a transition from smearing to a clifffy surface can be identified. The clifffy surface is caused by matrix breakouts in consequence of cracks evolving under and around the contact area of the grain and the material surface. These cracks finally lead to breakouts revealing the sintered alumina oxide particles below a compressed area. This compressed area is located below the grain according to Marshall et al. [1]. In contrast to the material removal behavior of dense alumina oxide, no knowledge about the material behavior of the porous alumina oxide building the matrix exists. Hence, the effects leading to the surface characterized as smearing and marked with an g) in Fig. 3 e are
not known. In order to identify the effects and the material behavior, residual stress measurements, indenter tests and further structure analyzes were performed on the pure matrix material.

3.2. Effects of Single Grain Cutting on Residual Stresses

Residual stresses in tangential and axial direction were measured in three different spots by means of X-ray diffraction. The first spot was located in smeared areas, the second spot was positioned in areas with cliffy surface after breakouts and the third spot was in the polished area. Attributable to the measurement system used, the residual stresses were measured at a depth of 10 µm. As the matrix layers breaking out after the transition area have a thickness of 5 µm, the residual stresses below these smeared layers were recorded. The measurements showed tensile stresses below the polished surface (\( \sigma_{\text{ax,p}} = 65 \text{ MPa} \) and \( \sigma_{\text{tang,p}} = 13 \text{ MPa} \)). In the area of smeared groove surfaces lower tensile stresses were measured (\( \sigma_{\text{ax,p}} = 14 \text{ MPa} \) and \( \sigma_{\text{tang,p}} = 29 \text{ MPa} \)), whereas the cliffy area showed compression stresses (\( \sigma_{\text{ax,c}} = -7 \text{ MPa} \) and \( \sigma_{\text{tang,c}} = -6 \text{ MPa} \)). So, with increasing depth of cuts, which corresponds to higher process forces and hence mechanical loads, tensile residual stresses switch to compressive residual stresses. The change in residual stresses according to the mechanical load can be explained by plastic deformation. Furthermore, it is assumed that the smeared layers are created by compressive stresses below the grain contact area according to Lawn [9]. Below this area, tensile stresses appear which lead to plastic deformation and finally to residual compressive stresses.

3.3. Effects of Indenter Tests on Porous Matrix

Corresponding to existing models describing the fracture behavior of brittle materials in grinding processes on basis of indenter tests [9], indenter tests according to Vickers were made with an indentation force of \( F_1 = 50 \text{ N} \) on the porous matrix material in order to analyze the effects on the porous matrix material under mechanical load. As shown in Fig. 4 a, the shape of the diamond used for the indenter tests is reproduced in the surface of the sample. The depth measurement show material bulging on the side areas of the indentation field, which suggests plastic deformation (Fig. 4 c). The cracks show that the mechanical load of the indentation was transferred along the matrix material. Corresponding to the single grain cutting tests, smeared and cliffy areas exist. Taking a closer look at these areas (Fig. 4 b), the Al₂O₃ particles of the smeared areas are compressed what again suggests plastic deformation. In consequence of the mechanical load cracks below the compressed areas evolved and lead to breakouts exposing the cliffy surface.

![Indentation impression and depth](image)

3.4. Structure Analyses of Smeared Zone of the Groove

In order to analyze the material removal behavior of the matrix material, further structure analysis of the cutting grooves in the porous matrix material by means of SEM images was done. As shown in Fig. 5 (a,b), three spots were analyzed in detail (c,d,e). Spot c is located at the beginning of the cutting groove. In this section (c) of the cutting groove, many small grooves created by the surface micro topography of the diamond exist. The surface shows typical characteristics of ductile ground surfaces implying plastic deformation. Comparing the smeared area (e) with the cliffy area (d), the Al₂O₃ particles of the smeared area (e) build an almost closed surface, whereas in (d) the structure of the
initial matrix is apparent. Hence, it has to be assumed, that the plastic deformation leading to the grooves shown in (c) was supported by melting of the Al₂O₃ particles building the closed surface structure illustrated in (e).

Fig. 5: SEM pictures of cutting groove in the porous matrix material

4. Conclusion and Outlook

In this work, the material removal behavior of ceramic matrix composites with porous matrix in a grinding process was analyzed by means of single grain cutting tests focusing on plastic deformations. SEM images showed surface effects on the matrix as well as on the fibers corresponding to mechanisms caused by ductile material removal behavior in grinding. Ductile grinding behavior implies plastic deformation. Hence, plastic deformability at micro-scale of the two components fiber and matrix was detected. The appearance of plastic deformation was substantiated by residual stress measurements and indenter tests for the porous matrix. In further work, the material removal behavior of CMCs with porous matrix will be analyzed in flat grinding test. Hence, the transfer of the generated knowledge of single grain engagements to a real grinding process will be proofed. Also the effects of different matrix and fiber types on the material removal behavior will be analyzed.

References