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Material Removal Mechanisms in Grinding of Mixed Oxide Ceramics

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Abstract

The technological basis for a cost-effective and reliable grinding process of mixed oxide ceramics requires a fundamental understanding of the prevailing grinding mechanisms to maintain surface quality and strength requirements. However, these material removal mechanisms are not yet fully understood. This paper presents an innovative quick stop device for the interruption of cut during grinding. This appropriate method allows a detailed analysis of the interactions of grains along the contact zone. The results reveal correlations between the prevailing grinding mechanisms, the tetragonal to monoclinic phase transformation of the zirconia based ceramics as well as the resulting bending strength.

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Keywords: oxide ceramic, material removal mechanism, active abrasive grains, grinding

1. Introduction

Mixed oxide ceramics have found a widespread utilization in a variety of biomedical applications due to their favorable material properties. Especially, zirconia doped oxide ceramics possess an unusual combination of high strength and high fracture toughness. These characteristics are largely associated with the volume-increasing effect of the tetragonal-to-monoclinic phase transformation and its release during crack propagation. This feature is attributed to the stabilization of the metastable tetragonal phase through alloying with aliovalent ions, thus the tetragonal phase can revert to the stable monoclinic form [1,2].

Because of the hardness and brittleness of ceramics, grinding is the only method to generate required shapes. Comparing all conventional machining processes in common use, grinding is the most expensive per unit volume of material removal. In manufacturing of precision sintered ceramic components, grinding is the most significant portion of the total cost and can comprise up to 80 %. To meet the increasing demand of high performance ceramics, cost-effective grinding processes are needed [3-5].

Besides the grinding cost, a reliable process is highly relevant to maintain the required surface integrity, especially for components in the field of medical technology like implants. Lowering of processing costs by grinding with higher material removal rates can cause surface damage, which applies particularly for sensitively reacting ceramic materials. During grinding, the abrasive grains of the grinding wheel generate intense local stress fields upon contacting and penetrating the ceramic surface. Thus, a thin layer of the workpiece surface is exposed to high stress combined with high temperatures that cause irreversible material deformation in the form of dislocations and cracks. This grinding induced surface damage can lead to strength degradation or even to a catastrophic failure of the ceramic implant. The stress caused by the process can also trigger the tetragonal-to-monoclinic phase transformation, which is not reversible without a further heat treatment. However, the processes in the contact zone of grinding wheel and workpiece are not fully understood yet. [3-8].

In the past, most research on grinding mechanisms for ceramics has followed either the “machining” approach or the “indentation fracture mechanics” approach. The “indentation fracture mechanics” approach simplifies the grinding process by using a single indenter. It assumes that the damage produced

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by numerous abrasive grains during grinding can be modeled by the idealized flaw system caused by a sharp indenter. The "machining" approach typically includes the measurement of process variables like grinding forces combined with the examination of the resulting surface morphology [3,4].

This paper aims to close the gap between the two main research approaches by using an innovative quick stop device for the interruption of cut during the real grinding process without any simplifications. With this method, it is possible for the first time for grinding of ceramic to investigate the interaction of the numerous active abrasive grains that are engaged within the contact zone at the same time, each under different conditions. Furthermore, it is possible to relate the process parameters, e.g. grinding forces, to the number of active abrasive grains and not only to the area of the contact zone. With respect to the grinding forces, this provides a more reliable information about the stresses upon the workpiece during grinding. For the investigation of the prevailing material removal mechanisms and their influence on the resulting surface damage and mechanical properties of the oxide ceramic two different bond systems, namely resin and metallic bond, were used. In addition, the results reveal correlations between the prevailing grinding mechanisms, the monoclinic phase content of the zirconia based ceramic as well as the resulting residual stresses and the measured bending strength.

Nomenclature

v_c	cutting speed
v_f	feed velocity
a_e	depth of cut
h_{cu}	uncut chip thickness
d_g	diamond grain size

2. Experimental setup

2.1. Quick stop device

For the investigation of material removal mechanisms, quick stop experiments have frequently been used in the past to describe the interaction of the tool and the workpiece by interruption of cut during the machining process. Due to the abrupt interruption, the contact zone can be seen as a snap-shot of the current material removal mechanisms. The high cutting speed is the critical factor for reliable results of quick stop experiments especially in grinding. This is the reason why the first experiments deal with the interruption of cutting processes [9]. Later publications contain the interruption of abrasive processes. Buda and Liptak for example obtained several chip roots in up-grinding by using a self-developed segment acceleration method [10].

Lately Denkena et al. developed two different quick stop devices for the investigation of chip roots while grinding metals [11-13]. However, these approaches had disadvantages regarding the maximum grinding speed of only v_c = 5 m/s and an unsatisfactory repeatability. Therefore, a new design of a quick stop device was developed combining the advantages of the two quick stop devices used so far. The main requirements were a very strong external acceleration unit, a universal setup that can be used on almost every machine tool and a secure brake device to decelerate the guided sliding carriage with the ground sample. This challenge has already been technically demonstrated with success for interruption of grinding processes with cutting speeds up to v_c = 35 m/s [14].

This quick stop device was improved once again. The major improvements were a stronger captive bolt pistol and a higher stiffness of the whole setup to achieve results that are even more reliable. For this, all components of the quick stop device were manufactured out of hardened tool steel to reduce any deflection or slight unintended movements to a minimum. The new and stronger captive bolt pistol produces a kinetic energy of 384 J when applying the most powerful available cartridges [15]. This means an increase of the kinetic energy of nearly 40 % in comparison to the old captive bolt pistol (275 J) [14]. To achieve the maximum acceleration, the masses of the sliding carriage and the sample must be as low as possible without breakage at the moment of impact. The mass of the sliding carriage together with the mounted sample is 122.2 g. Measurements with a high-speed camera show that the sliding carriage reaches a maximum speed of 66 m/s after impact of the bolt that has a mass of 233.4 g.

Fig. 1 depicts an overview of the experimental setup and five detailed images of the main process sequences of the quick stop experiment. The overview shows the entire quick stop device fastened on a single base plate that is mounted on the machine bench of a Röders RFM 600 machine tool. The main parts of the device are the captive bolt piston, the dovetail guidance, the sliding carriage with the sample and two brake devices. The first step of the process sequence is a pre-grinding process of the mounted sample to ensure the adjusted process conditions in the following quick stop experiment (Fig. 1a). A shear pin within the precision dovetail guidance fixes the sliding carriage. An additional screw produces a preload to avoid any movement. After pre-grinding, a metal cable is connected to the infeed axis to trigger the bolt in the upcoming quick stop experiment (Fig. 1b). The metal cable works like an automatic releaser that triggers the bolt in every experiment at identic time and position of the grinding wheel on the workpiece regardless of the feed velocity v_f. After triggering the bolt, it accelerates the sliding carriage due to the impact opposite to the feed rate direction into brake I (Fig. 1c). Brake I consists of a metal enclosure with an interior technical high-density foam absorbing the high kinetic energy of the sliding carriage. It may occur that the sliding carriage moves back to the grinding wheel because of expanding of the compressed foam. For this reason, a second break II moves out when the sliding carriage leaves its initial position to avoid a renewed contact with the grinding wheel after the interruption of cut (Fig. 1d). At the end of the experiment the sliding carriage stops between brake I and brake II (Fig. 1e).