Ultrasonic Assisted Grinding of Advanced Ceramics

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INSTRUCTIONS

Among all manufacturing technologies cutting with geometrically undefined cutting edges is considered a serious challenge in terms of process understanding and optimization. The main reasons for this situation are the high complexity of interaction between setting parameters and work results, the stochastic nature of the cutting edges, the occurrence of the cutting action on a microscopic level and a permanent flushing of the active zone with cooling lubricant preventing a visual inspection.

Based on experiences in the field of turning and milling the use of simulation tools for grinding applications is a major research focus at the IWF Berlin and elsewhere for many years. The overall aim of the modeling activities is to generate a simulation tool which allows a comparative characterization of different grinding processes, a reduction in experimental work and an optimized selection of machine parameters and tool specifications. Due to the increased number of setting parameters, today's limited base of process understanding and its unique kinematical system Ultrasonic Assisted Grinding is particularly suited for a new simulation approach.

TECHNOLOGY OF ULTRASONIC ASSISTED GRINDING

Ultrasonic Assisted Grinding is a comparatively novel grinding technology which is characterized by the superposition of a conventional grinding operation with an ultrasonic vibration. This new hybrid manufacturing technology was developed from the idea of combining the impact-like material removal of ultrasonic assisted lapping and the high efficiency of grinding with bound abrasive grains. The vibration is usually generated with components based on the piezo-electric principle and can be introduced into the process through the workpiece or the tool. The most common form in today's industrial application is the face grinding operation for the manufacture of through-holes or grooves as depicted in Figure 1 where the grinding tool is excited with a frequency above 18 kHz [1, 2].

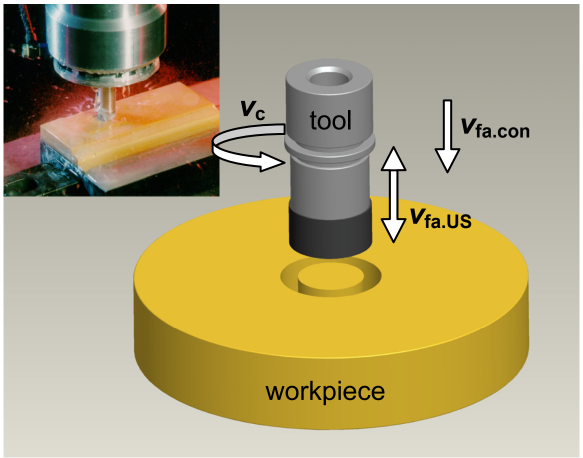


FIGURE 1. Schematic illustration of Ultrasonic Assisted Grinding.

In every form of Ultrasonic Assisted Grinding the cutting conditions of the abrasive grains change drastically. Depending on the setting of the ultrasonic parameters amplitude (A_{US}) and frequency (f_{us}) the scratching contact between grain and workpiece changes into a sinusoidal and impact-like penetration into the material. On the macroscopic level a considerable reduction in cutting forces is measured as shown in Figure 2.

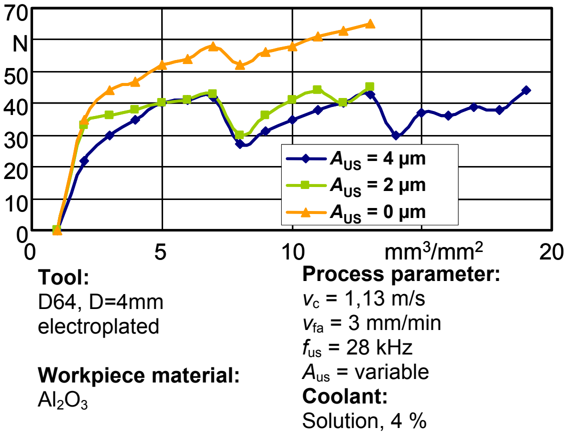
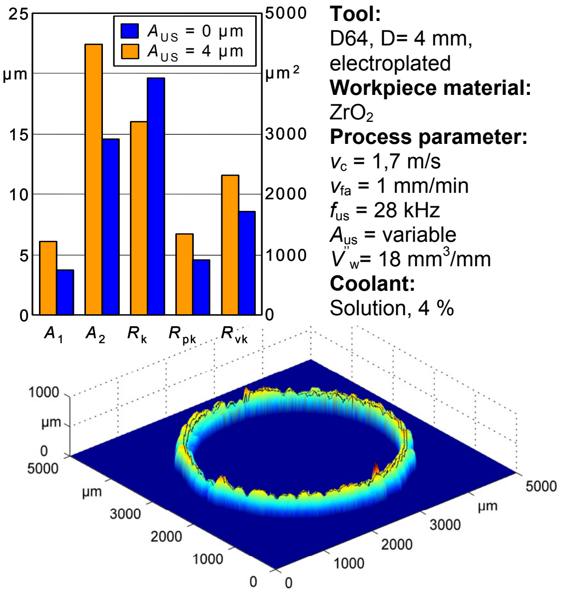


FIGURE 2. Process forces during face grinding with and without ultrasonic assistance.

The influence of the amplitude of the vibration with respect to the axial process force is depicted in Figure 2 proving the potential of this technology to increase the productivity of a grinding operation tremendously within a given allowable process force range.

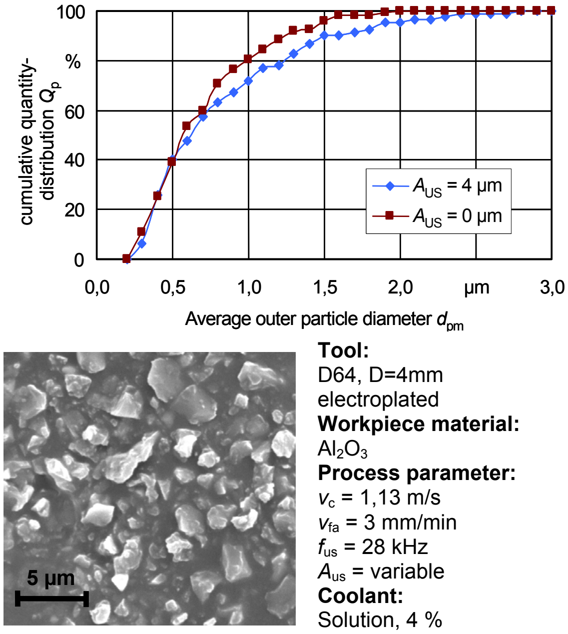
The extent of the reduction of process forces is directly linked to the brittle-hard behavior of the ground material, thus making the grinding of advanced ceramics and glass the predominant field of this manufacturing technology. Interestingly there is no deterioration in surface quality or subsurface integrity in comparison to conventional process observable [1, 2, 3]. The major reason for the benefits mentioned above is a shift in the wear behavior of the active grains away from the flattening and blunting of the grain tips toward an increased micro-splintering. The increased grain related normal forces and the highly dynamic process forces promote a self-sharpening of the active grain providing a permanent supply of sharp cutting edges. The change in the microscopic wear behavior can be proven through the analysis of the characteristic topography properties such as the reduced peak height R_{pk} or the peak area A_1 shown in Figure 3. After an identical initial state of the tool topography via dressing a significant reduction in the overall grain protrusion during the conventional process (A_{US} = 0 µm) can be observed in comparison with an ultrasonic assisted operation (A_{US} = 4 µm).



Tool:
D64, D= 4 mm,
electroplated
Workpiece material:
ZrO_2
Process parameter:
v_c = 1,7 m/s
v_{fa} = 1 mm/min
f_{us} = 28 kHz
A_{us} = variable
V'_w= 18 mm^3/mm
Coolant:
Solution, 4 %

FIGURE 3. Topography properties of grinding tools after machining with and without ultrasonic assistance.

Moreover the change in the cutting conditions due to the superposition of a high-frequency secondary movement in a face grinding operation can be retraced in terms of the produced cutting particles. Figure 4 illustrates the generation of slightly larger particles during Ultrasonic Assisted Grinding which corresponds well in its general trend with the simulation results presented below.



Tool:
D64, D=4mm
electroplated
Workpiece material:
Al_2O_3
Process parameter:
v_c = 1,13 m/s
v_{fa} = 3 mm/min
f_{us} = 28 kHz
A_{us} = variable
Coolant:
Solution, 4 %

FIGURE 4. Distribution of cutting particles after grinding with and without ultrasonic assistance.

VOXEL-BASED KINEMATICAL SIMULATION OF ULTRASONIC ASSISTED GRINDING

A profound knowledge of the cutting conditions in the active zone is a prerequisite for a general understanding of grinding processes [4, 5]. This includes the assessment of the mechanical and thermal load of the active cutting edges which determines the material removal mechanisms and the tool wear. Due to the problems of acquiring them on a microscopic level directly a number of approaches for the analytic description through characteristic chip parameters like undeformed chip thickness or engagement angle have been introduced. The basic goal for these efforts is the analysis of the microscopic cutting events under ideal boundary conditions with a selective variation of grinding parameters and tool specifications. This offers an opportunity to compare different settings within a certain operation or with other grinding operations [4, 5].

The macroscopic description of the movement of the abrasive grains in relation to the workpiece has been derived by several authors in detail and can be put into the following equation for the case of straight face grinding in z-direction (see Figure 1 [1, 2]:

$$\vec{l}_e(t) = \begin{Bmatrix} l_{ex}(t) \\ l_{ey}(t) \\ l_{ez}(t) \end{Bmatrix} = \begin{Bmatrix} r_s \cdot \sin(2 \cdot \pi \cdot n_s \cdot t) \\ r_s \cdot \cos(2 \cdot \pi \cdot n_s \cdot t) \\ v_{fa,con} \cdot t - A_{US} \cdot \sin(2 \cdot \pi \cdot f_{US} \cdot t) \end{Bmatrix},$$

wherein n_s the rotational speed of the tool and $v_{fa.con}$ the permanent feed rate are.

For the description of the micro-kinematical processes a new modeling concept was developed. Based on past research activities at the IWF Berlin a voxel-based approach was introduced which applies a 3-dimensional penetration of discrete volume elements, frequently called “voxel” [6]. This represents a major improvement with respect to the previous approaches which used exclusively a 2-D envelope of a virtual tool which sweeps through a workpiece surface. Due to the high engagement angles in Ultrasonic Assisted Grinding this concept is not feasible, hence a real penetration of 3-D bodies was necessary to be developed. A Boolean operation between the now 3-dimensional tool and workpiece generates a chip geometry, which is used to derive the characteristic chip parameters. Presently the simulation assumes ideal cutting meaning a total removal of volume elements of the workpiece which intersect with elements from the tool during the cutting process. Obviously this does not fully represent the interaction of the material removal mechanisms that have been observed in reality especially in the case of brittle-hard materials. But there is a broad knowledge about the correlation between characteristic chip parameters and the observable material removal behavior for conventional grinding operations which becomes now available for the new kinematical system of Ultrasonic Assisted Grinding [1, 2, 3].

The structure of the simulation tool was based on an approach being summarized as follows

- Generation of a statistical grain model,
- Generation of a statistical tool model,
- Calculation of the Boolean operation and
- Analysis of the chip geometry and surface topography.

Due to the statistical nature of the size and shape of the abrasive grains a large number of actual grains was analyzed using SEM-pictures from different view angles. In order to determine the distribution of grains on the surface of typical tools a SEM-based visual inspection as well as a laser topography measurement was conducted.

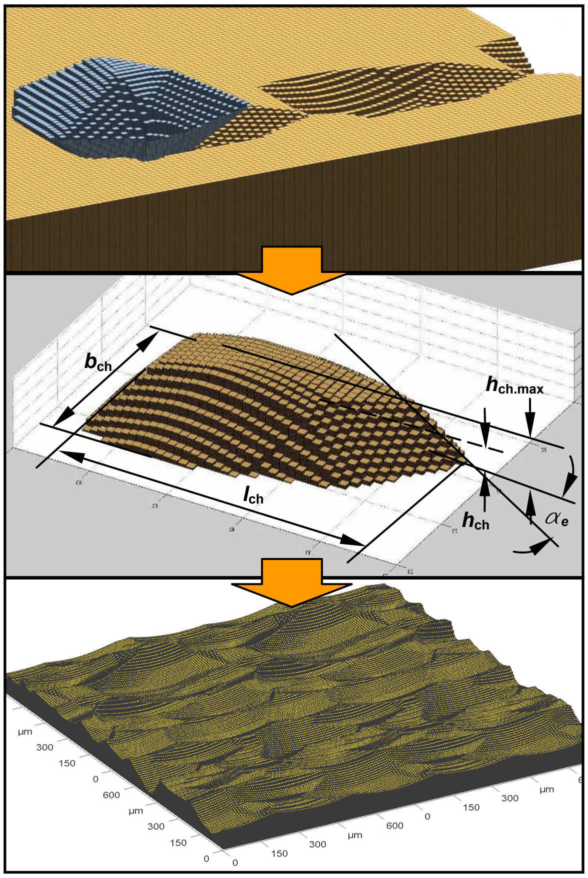
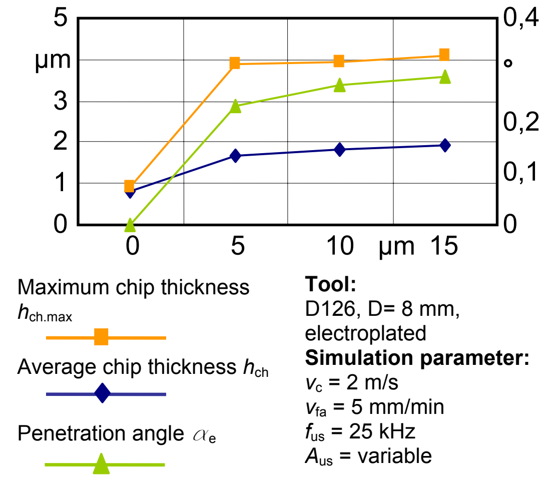


FIGURE 5. Schematic illustration the voxel-based simulation of Ultrasonic Assisted Grinding

The general procedure behind the newly developed simulation tool is depicted in Figure 5. Beside the opportunity of a visual inspection of the generated virtual surfaces the geometry of each virtual chip can be analyzed and statistically edited. The results of a set of simulated operation under the variation of the ultrasonic amplitude are presented in Figure 6. The introduction of the ultrasonic secondary movement of the grinding tool significantly alters the chip parameters. In contrast a further increase of the ultrasonic amplitude has only a minor effect on the shape of the virtual chips. Hence the observed process improvement of the grinding operation by increasing the ultrasonic amplitude, which is reported by several authors

[1, 2 ,3] must be connected with other phenomena such as the change in the fluid flow conditions through the active grinding zone. In order to acquire basic knowledge about this situation another numerical simulation method is presented below.



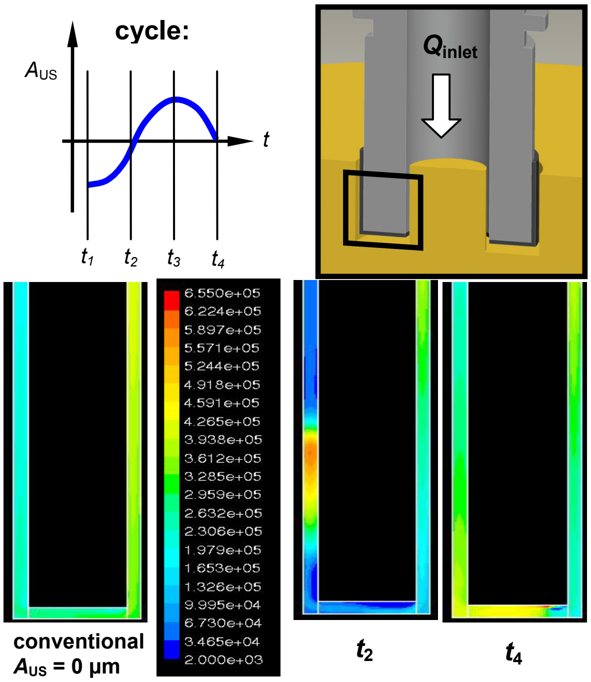
Tool:
D126, D= 8 mm,
electroplated
Simulation parameter:
v_c = 2 m/s
v_{fa} = 5 mm/min
f_{us} = 25 kHz
A_{us} = variable

FIGURE 6. Results of the simulation for different ultrasonic amplitudes A_{US}.

CFD-SIMULATION OF FLUID FLOW IN ULTRASONIC ASSITED GRINDING

A discontinuous contact between the tool and the workpiece with a frequency above 18 kHz is a distinct characteristic for Ultrasonic Assisted Grinding. As mentioned above it changes the contact conditions of the cutting edges but also the fluid flow conditions in the active zone. Many authors attributed at least to some extend the advantageous process behavior to the improved flushing of the active zone in particular at high aspect ratio of the ground holes. In contrast to peripheral grinding operations it is nearly impossible to analyze visually the fluid flow through the active zone during face grinding [1, 3].

The usage of Computational Fluid Dynamic (CFD) tools appears to be a promising method to reassess the flow conditions and develop strategies to improve the coolant supply system. The first step toward an optimized process control is the modeling of the actual state for a given set of representative parameters. At the IWF Berlin a simplified model was set up using the pre-processor GAMBIT of Fluent Inc. Subsequently a number of different simulations have been carried out applying the CFD-software FLUENT of Fluent Inc. First results of those calculations have been displayed in Figure 4 where the total pressure for the conventional process (A_{US} = 0 µm) as well as for different points in time within a vibration cycle can be seen.



Simulation parameter:

Rotational speed:	n = 1000 1/min
Ultrasonic frequency:	f_{US} = 11 kHz
Ultrasonic amplitude:	A_{US} = 15 µm
Inlet pressure:	$p_{KSS.zu}$ = 5 bar
Ambient pressure:	p_a = 1 bar
Width grinding gap:	b_{Spalt} = 90 µm
Depth of drill hole:	t_W = 5 mm
Tool diameter:	d_a = 8 mm

FIGURE 7. CFD-simulation results for the total pressure (Pa) of the coolant during conventional and Ultrasonic Assisted Grinding.

Apparent becomes a highly dynamic fluctuation of the simulated total pressure accompanied by a temporary increase in local pressure especially in the grinding gap which supports the assumption of an improved flushing of the active zone as mentioned above.

SUMMARY

Ultrasonic Assisted Grinding of brittle-hard materials like advanced ceramics proved in many applications its superior performance in comparison to conventional processes. Due to the new kinematical system and increased number of setting parameters to take into account the developed simulation is a valuable tool for the deepening of the process understanding. A 3-dimensional representation of the surface generation and chip characteristics within the limits of the modeled system can be obtained. An additional CFD-simulation in its present version provides another opportunity for qualitative analyses of flow conditions in the otherwise inaccessible contact zone.

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