Kerf Sidewall Groove Formation during Ductile Dicing of Ceramic Materials

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Abstract: Microgrinding using high precision outside diameter grinding machines ("dicing saws") and superabrasive grinding wheels has been successfully applied to create precision microstructures made of hard and brittle materials [1, 2]. To fabricate microstructures with lateral dimensions in the micrometer scale and high aspect ratio thin grinding blades can be used in a peripheral grinding process similar to wafer dicing. In this process, both cut-off grinding wheels ("dicing blades") and grinding wheels with a V-profile were used to generate complex structures [3, 4]. To achieve the desired accuracy and integrity of the machined microstructures, a precise control of the machining process needs to be maintained. Specifically, the transition from ductile to brittle mode cutting accompanied by a significant deterioration of the surface quality but also by a decrease of the specific grinding energy, significantly affects the grinding result. It is widely accepted that ductile mode machining can be achieved when the chip thickness decreases below a critical value $h_{cu,crit}$ as initially suggested by Bifano [5]. In this paper we are proposing a model describing the surface generation at the kerf sidewall. The model is based on a kinematic analysis of the dicing process and takes into consideration the stochastic nature of the interaction between the abrasive grains and workpiece [6].

1. Surface Generation during Dicing

Dicing is a peripheral grinding process applying thin grinding wheels ("dicing blades"). Typically, the functional surface generated by the dicing blade is the kerf sidewall. While the abrasive grains at the blade's circumference contribute mainly to the stock removal, only abrasive grains at the transition from the circumference to the blade's sidewall or grains protruding from the sidewall are involved in the machining of the kerf's sidewall. Figure 1 illustrates the dicing process with respect to the contribution of the blade's circumference and sidewall to kerf ground and kerf sidewall machining.

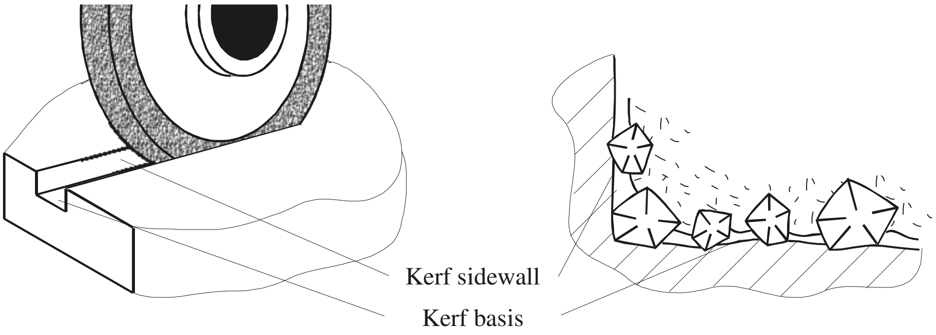


Figure 1: Dicing principle

The surface generation at the kerf ground is equal to a circumferential flat grinding process and shall not be considered in this paper. Furthermore, during dicing the cutting depth exceeds the workpiece thickness and the remaining surface at the workpiece is the kerf sidewall. To understand the cutting action of the abrasive grains during sidewall machining, the kinematics of a single grain at the edge between blade circumference and sidewall shall be analyzed as depicted in fig. 2. This cutting grain approaches with the cutting velocity v_c the workpiece and moves along a circular path during the cutting action (fig. 2 a and b).

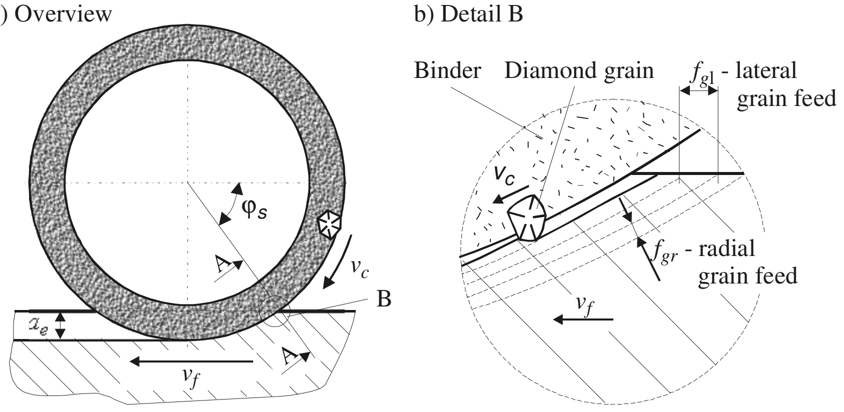
Considering two successive engagements of the grain, the following parameters characterize a single grain's kinematics: lateral grain feed $f_{g\ell}$ and radial grain feed f_{gr}, the first one parallel to the workpiece feed direction, the latter perpendicular to the grain's path. The lateral grain feed is given by the ratio of workpiece feed rate v_f and the blade's angular velocity:

$$f_{g\ell} = \frac{v_f \ \pi D}{v_c} \tag{1}$$

with the cut velocity v_c and the blade's diameter D.

a) Overview

b) Detail B



c) Trajectories of two consecutive active grains

d) Cross section A-A

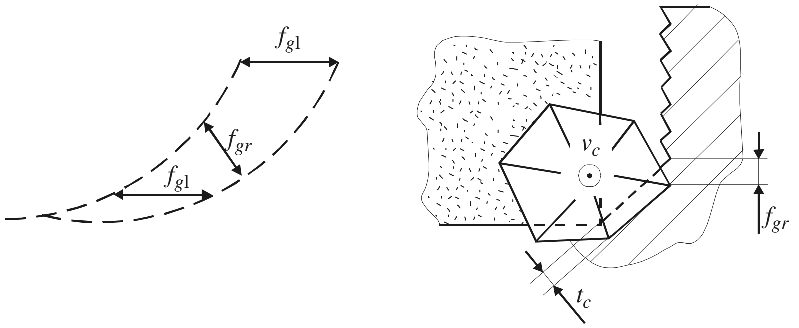


Figure 2: Kinematics of the abrasive grains during kerf sidewall generation

The lateral grain feed is the distance between two successive grain engagements in the moment the grain approaches the surface. The circular paths of the grain converge towards the end of the cutting action, i.e. as a first approximation, when the path reaches its lowest point. The radial grain feed f_{gr}, or the distance between two successive grain paths at a given point is therefore a function of the grain's angular position φ and the phase-shift between two blade revolutions.

$$f_{gr(\varphi)} = \frac{v_f \; \pi D}{v_c} \cos\left(\varphi - \arcsin \frac{v_f \; \pi D}{v_c} \right) \tag{2}$$

In this simplified model, which considers only one cutting grain on the blade, the distance between two adjacent grinding grooves can be calculated according to equation (2). The groove depth, which can be related to the surface roughness in this model, is basically a function of the grain geometry. Roughness considerations are not subject of this paper. The simplified model does not take into account that in a real process there are typically more than one grain active cutting grains. The number of active grains was investigated by several groups; as a for instance *Hou* and *Komanduri* estimated the fraction of active grains in surface grinding to be 1.5% to 2% [6]. As the number of grains in the transition region from blade circumference to sidewall is difficult to estimate, a precise number can not be given. Considering the circumference length and the grain concentration, a typical dicing blade features up to several hundred active grains. The overlapping cutting paths of this amount of active grains would yield in a typical dicing process a groove distance of few nanometers. But also the special case of only one active grain for the sidewall machining occurs as will be presented in the following chapter.

2. Experimental

In order to compare the sidewall generation model investigations of the kerf sidewall of diced samples were performed. The workpiece material for these investigations was Altic, a ceramic material consisting of 63% Al_2O_3 and 37% TiC. Dicing experiments were performed using a commercial dicing saw, model Disco DAC551 and annular dicing blades with diamond abrasives ranging from 5 µm to 45 µm grain size in resinoid and nickel binder. The blades were mounted on a precision flange. A white light interferometer (WLI) microscope model Wyko RST-

Plus was used to investigate the kerf sidewall. This method allows measuring the surface topography of a view field of 200 µm by 400 µm in highest magnification. Higher resolution analyses of specific samples were performed with atomic force microscopy (AFM) using a Topometrics Explorer TMX 2000 AFM.

The topography investigations of diced samples showed for a fraction of 10% to 15% of the sidewalls the occurrence of grooves. These grooves were only visible, when a predominantly ductile grinding mode prevailed. Typical parameters leading to ductile mode dicing were presented elsewhere [4, 7]. Figure 3 shows a WLI analysis of a sidewall ground in the transition between ductile and brittle cutting mode. The surface features high roughness values and grain pullouts in the upper region of the sidewall and low roughness and grooves in the lower region.

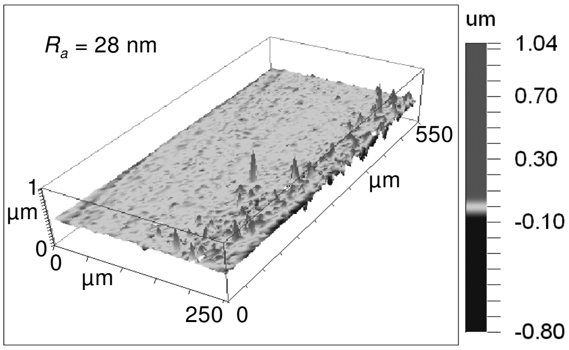


Figure 3: White light interferometer analysis of a kerf sidewall [7]

A closer look at the grooved surface of a sidewall shows the AFM analysis in fig. 4. Machining parameters are summarized in table I. The very regular groove pattern in fig.4 leads us to the conclusion that the same abrasive grain is responsible for the groove generation. This example shows the rather rare case that only one grain is actively forming the kerf sidewall.

Table I
Machining parameters for the sidewall presented in fig. 4

Wheel diameter:	55 mm
Wheel thickness:	0.2 mm
Binder:	Nickel
Diamond grain size:	15 µm
Cutting velocity v_c:	55m/s
Feed rate v_f:	0.5 mm/s
Cutting depth:	0.4 mm

From the machining parameters the theoretical grain feed for one active grain can be calculated according to equations 1 and 2. The feed during one blade revolution is 1.57 µm. For an engagement angle of the active grain at the position of the measurement of approx. 82° the theoretical value for the biggest possible groove distance considering one active grain that cuts at every blade revolution is 210 nm. As visible in fig. 4, the actual groove pitch is approx. 1.67 µm, thereby significantly higher then the theoretically calculated value. It means that only at every eighth revolution the grain really cuts.

3. Discussion

The observation that the active grains do not cut at every blade revolution correspond with the fact that the kerf is typically 20 µm wider than the blade thickness. This means that the blade performs an axial movement in the kerf. Due to the low stiffness in this direction (the blade is only 0.2 mm thick and consists of nickel) the blade is susceptible for axial deflection. Based on the equations to calculate the force of disk springs, the spring constant of the used blade can be estimated to be approx. 0.02 mN/µm [8]. Consequently, a force of 0.2 mN is sufficient to deflect the blade the observed 10 µm from the neutral position.

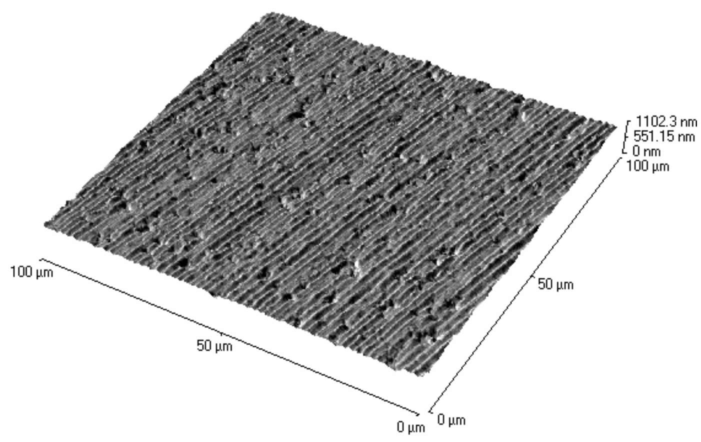


Figure 4: AFM analysis grooves in a kerf sidewall

On the other hand, during dicing the blade is subjected to counteracting axial forces between abrasive grains and workpiece material from both sides of the kerf. At the moment of maximal deflection, both static and dynamic forces are balanced. As a direct measurement of these forces is not possible, geometric considerations may lead to an explanation of the observed groove formation phenomenon. According to *Hou* and *Komanduri*, the minimal depth of indentation for cutting is 5% of the grain radius r_g. Below this indentation depth, the grain only glides over the surface [6]. In our example the grain size is 15 µm, therefore the critical indentation depth for cutting is 375 nm. This indentation depth or undeformed chip thickness t_c is a function of the abrasive grain's tip angle (see fig. 3). Considering a tip angle of typically 150°, the undeformed chip thickness during formation of the observed grooves with a pitch of 1.67 µm was 432 nm which corresponds well with the theoretical value of 375 µm.

4. Conclusion

Based on the analysis of grooves in the kerf sidewall generated during precision dicing and the fact, that the kerf sidewall is always bigger than the dicing blade thickness we draw the conclusion that cutting action at the blade's active grains does not occur during every blade revolution. Instead, the blade is deflected, while the abrasive grains slide over the surface or plough. This leads to a dynamic interaction between dicing blade and workpiece which is governed by the counterbalancing forces between abrasive grains and workpiece material on both sides of the kerf and the blade's elastic deformation. During abrasive grain and workpiece contact gliding, plastic deformation and cutting alternate. Only if a critical indentation depth is reached, determined by the counterbalancing forces between wheel and both sidewalls, cutting and material removal take place.

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