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Cutting and ploughing forces for small clearance angles of hexa-octahedron shaped diamond grains

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ABSTRACT

Investigations on the cutting behaviour of hexa-octahedron diamonds outlined an enormous influence of the grains' clearance angle on the material removal process. Small negative clearance angles lead to increased specific cutting forces, decreased cutting force ratios and micro-structural changes. This is caused by additional ploughing of the material. This paper presents a kinematic-phenomenological model predicting the specific forces that are caused by the ploughed material. Therefore, the theoretical value of the specific ploughed volume is introduced as characteristic parameter. Results are subsequently compared for different grain cutting situations to experimental data allowing a validation of the proposed model.

1. Introduction

Cutting operations with geometrically non-defined cutting edges are essential to manufacture a huge variety of mechanical components with the desired surface quality. Therefore, a comprehensive knowledge about the material removal process in particularly the engagement of single grains with the workpiece material is required in order to synthesise the entire removal process of grinding tools. The inaccessibility of the contact zone as well as its stochastic character regarding grain size, grain morphologies and distribution on the tool body complicates the analysis of such processes. This emphasises the demand for meaningful models in order to predict resulting process forces, surface quality and surface integrity. However, it is widely known that the actual cutting process of single grains is also accompanied by elastic and plastic deformation, which makes it even more difficult to gain detailed information about the exact material removal mechanism at the cutting edge.

2. State of art in kinematic modelling of single grain cutting

The numerous research works about modelling and simulation techniques on grinding and single grain operations that were published in the past decades, were summarised by Brinksmeier et al. [1]. Early kinematic grinding models were presented by Kassen [2], Werner [3] and Lortz [4] focussing on the determination of statistical characteristic parameters of the abrasive layer of the grinding tool and the process. Inasaki [5] measured the topography of a grinding wheel with a profilometer and used such information for the kinematic interaction of the abrasive cutting edges and workpiece surface. Warnecke and Zitt [6] presented a software tool that is based on a 3D-model describing the kinematic engagement conditions of grinding tools and workpiece as well as a micro geometry of the abrasive grains. This kinematic model was enhanced and subsequently applied to the simulation of structured grinding tools by Aurich et al. [7].

Koshy et al. [8] simulated the surface roughness of the workpiece assuming the abrasive grains to be spherical bodies. Pinto et al. [9] presented a kinematic model for simulation of cylindrical external plunge grinding and modified three dimensional grain morphologies to a two dimensional projection area in cutting direction for simulating workpiece roughness and process forces. This modification enabled a reduction of computation time. Vargas [10] proved the applicability of this model for the linear kinematic of hone broaching operations and also introduced force models distinguishing between different grain orientation cases.

Most of the previously mentioned model approaches are only assuming the mere material removal mechanism and therefore using the cross-sectional area, cf. Fig. 1a, to determine the resulting specific cutting forces k_c as the ratio of the cutting force F_c and the cross-sectional area A_{cu} according to:

$$k_c = \frac{F_c}{A_{cu}} \quad (1)$$

Waldorf et al. [11,12] modelled ploughing in orthogonal machining processes in consideration of the cutting edge radii and negative rake angles by using the slip-line field theory. Park and Liang [13] presented a ploughing force model by estimating the plastic deformation of an indentation process. Malekian et al.

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[14] investigated and modelled the ploughing effect as the volume interference of the tool and the workpiece.

Recent investigations by Transchel et al. [15] have outlined an enormous impact of the clearance angle on the cutting efficiency of active-brazed diamonds. Negative clearance angles lead to contact between flank face and workpiece, causing a radially ploughing of the material. Hence, the ploughed material causes extremely high specific cutting forces k_c and decreased cutting force ratios μ (F_c/F_N) that are simultaneously accompanied by micro-structural changes of the workpiece material. This paper presents a kinematic-phenomenological model enabling the prediction of the specific cutting forces taking into account the influence of the ploughed material by the flank face, which is based on the novel definition of the specific ploughed volume.

3. Modelling of the specific ploughed volume

Artificial diamonds mostly consist of hexa-octahedron morphologies that are stochastically oriented on the tool body. This means that various grain orientations and thus stochastically distributed cutting edges in particular rake and flank face positions are possible. Subsequently, grains with excellent as well as insufficient cutting capabilities result, which leads to a drastic increase of forces in cutting as well as normal direction. The behaviour of the grinding wheel is the combination of all those individual interactions. Small negative clearance angles cause a prominence of the flank face. This requires an adjustment of the cross sectional area A_{cu} orthogonally to the cutting direction, as used in Eq. (1). This needs to be distinguished in positive (a) and negative clearance angles (b) as displayed in Fig. 1 using the example of a grain in Edge orientation.

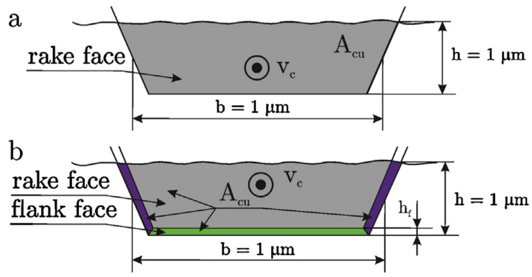

Fig. 1. Cross sectional area for (a) positive clearance angles and (b) negative clearance angles for the Edge orientation.

Accordingly, the specific cutting force k_c for both cases represents the incremental force per cross-sectional area of 1 μm^2 (b = 1 μm and h = 1 μm). The material radially and tangentially located in front of the flank face (green) is expected being heavily deformed, whereas the side planes (blue) rather increasingly cause the formation of lateral bulging. The elastic spring back of the material is not considered in this case. Assuming identical cross sectional area A_{cu} for grains with positive and negative clearance angles, both scratches are generally described with the cutting depth h and the average scratch width b, according to:

$$A_{cu} = bh \tag{2}$$

Commonly for cutting force equations and to compare the orientation dependency of forces, a standard flank face size of b = 1 μm (specific standard width) and l = 1 μm (specific standard length) was defined. Since the three dimensional grain needs to be considered because of the flank orientation, the functional influence of the third dimension l (length) needs to find entrance in the model by:

$$h_f = l \sin\alpha \tag{3}$$

This enables identical flank face cutting depth h_f over all investigated grain orientations in order to compare the analysed grain orientations. Fig. 2 shows the downscaled flank faces areas

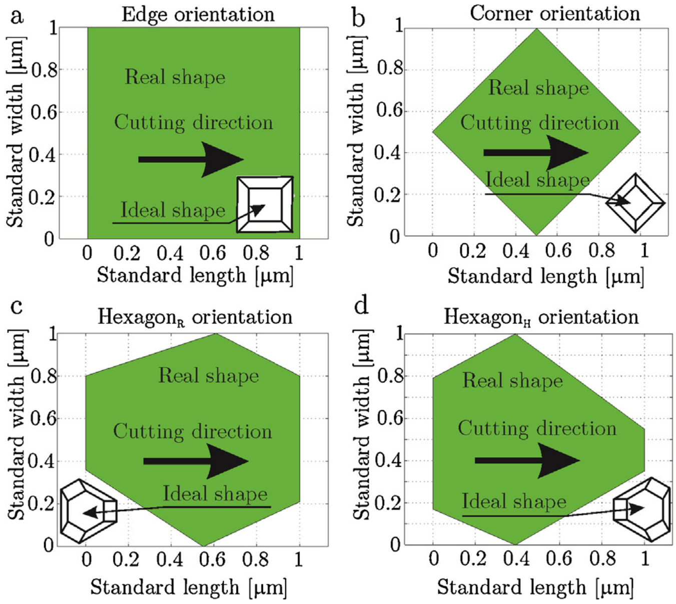

Fig. 2. Flank geometries for four different flank face orientations of blunt, octahedral-shaped diamond grain morphology with standard lengths of 1 μm: (a) Edge orientation; (b) Corner orientation; (c) Hexagon-R orientation; and (d) Hexagon-H orientation.

for typical orientations as: (a) Edge orientation, (b) Corner orientation, (c) Hexagon-R orientation and (d) Hexagon-H orientations. The microscopic analysis of the active-brazed diamond grains has shown significant differences between the ideal and real flank face shapes. Despite the fact that real grain shapes underlie irregularities and also all different orientations might occur in a grinding wheel, these four geometries and orientations are considered as being archetypical.

An inclination of these specific flank faces by a negative clearance angle α towards the cutting direction then enables the consequent determination of the specific ploughed volume V_{plough}. For small clearance angles, the material below the cutting edge, which must be removed to give path to the grain is assumed to be pushed aside and pressurised, normal to the surface and not removed by ordinary chip formation. Fig. 3 shows that the specific ploughed volumes significantly differ in dependence of the flank face geometry for constant clearance angles.

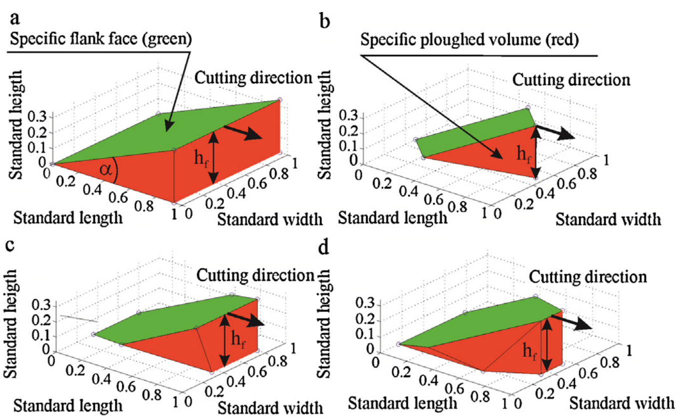

Fig. 3. Specific ploughed volume (red) for the (a) Edge orientation, (b) Corner orientation, (c) Hexagon-R orientation and (d) Hexagon-H orientation.

Fig. 4 shows a linear dependency of the specific ploughed volume of the clearance angle α. The mathematical slopes of the linear functions $t_{ploughj}$ of an orientation j represent the change of the specific ploughed volume per degree. Since it represents a value, which has been standardised to a standard volume, it is given the mathematical value of 1/°. The Edge orientation represents the grain orientation with the highest possible specific