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FEM based modeling of cylindrical grinding process incorporating wheel topography measurement

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Abstract

In this research, the interaction of cBN cutting grains with a 100Cr6 bearing steel workpiece is simulated using Finite Element Method (FEM). Grinding conditions are associated with high temperatures and strain-rates. Therefore, a constitutive material model is used which accounts for the coupled temperature and strain-rate effects on the flow stress. Furthermore, as one of the main challenges in grinding analysis, the topography of the grinding wheel is modelled according to its actual confocal images. The parameters of a probability density function are extracted from the confocal microscopy data and the distribution of the cutting grains are accordingly defined. Through a transient kinematical approach, the single-grain model is extended to the aggregate action of cutting grains on the wheel surface in cylindrical grinding process of a 100Cr6 bearing steel. The simulation results are validated with experimental data.

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Keywords: single-grain scratch; finite element method; cylindrical grinding; cBN grinding wheel; wheel topography; Gamma distribution

1. Introduction

In recent years, the grinding research has been focused on the fundamental understanding of material removal mechanisms in the micro-scale (single grain-workpiece interaction) [1]. Thanks to the advances in numerical techniques and computational processing units, Finite Element Method (FEM) has been extensively used to model various aspects of the grinding process, especially the cutting behavior of the individual abrasive grains in micro-scale [2]. Though, the micro-scale numerical modeling approaches should be able to describe the plastic behavior of the workpiece material at high temperatures and strain-rates associated with grinding [3]. Many material models have been used for the numerical simulation of metal cutting processes, which treated the workpiece as an elastic [4,5], elastoplastic [6] or a thermoplastic [7,8] medium. The Johnson-cook model is a common model for machining at high temperatures, strains and strain-rates [9]. Though, in the case of grinding where high temperatures and strain-rates are common, the constitutive laws should consider the coupled effects of temperature and strain-rate in addition to their individual contribution to the material behavior [10,11]. Accordingly, the coupled effects of work-hardening and thermal softening can be addressed in the considered range of cutting parameters.

The random shape and orientation of the cutting grains along with the probabilistic nature of the grinding wheel surface topography are further limitations in the numerical modeling of grinding process. The distribution and shape of the cutting grains have been modelled based on different approaches. Most researchers have considered uniform distribution for the cutting grain over the grinding wheel surface [12,13]. Random and stochastic distribution of the cutting grains has been also considered in literature [14–16].

In this work a coupled empirical model was taken from the work of Hor et al. [17] for the single grain scratch simulation of 100Cr6 steel with cBN grains. DEFORM-3D commercial code was selected for the handling of the single-grain scratch simulation, whose performance was investigated and validated in comparison with the counterpart FEM software [18]. The

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single-grain scratch characteristics regarding the force values and the chipping mechanism are extended to the aggregate action of cutting grains in grinding process. The extension is performed through defining a suitable probability density function for the random distribution of cutting grains according to the measured topography of the grinding wheel surface by using confocal microscopy. The parameters of the considered Gamma probability density function are accordingly extracted.

2. Modeling of cylindrical grinding process

2.1. FEM simulation of single-grain scratch

The action of a single cBN grain on a 100Cr6 steel workpiece is simulated for two nominal grain sizes (d=76µm and 151µm) and under different cutting conditions (depth of cut and cutting velocity). The grain geometry is considered as lofted hexagonal volumes embedded in spheres with diameters equal to the nominal grain size (Figure 1). Five cutting velocity levels (v_c=10; 20; 30; 40; 50 m/s) and two grain depth of cut levels (a_g=3; 5 µm) are chosen for the FEM simulation. The material properties and the coefficients of the coupled constitutive relation are taken from the work of Hor et al [17]. The normal and tangential force components along with the material removal/ploughing behavior are extracted from the FEM results.

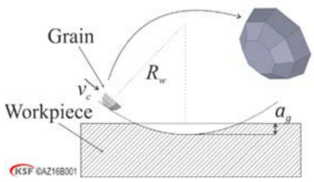

Figure 1. Single-grain scratch kinematics and the grain geometry

In order to quantify the chip formation and material removal characteristics a parameter is defined as the relative chip area η_c. The relative chip area is the ratio of the removed material cross section area $A_c - A_p$ to the ploughed material (pileup) cross section area A_p , and can be expressed as:

$$\eta_c = \frac{A_c - A_p}{A_c} = 1 - \frac{A_p}{A_c} \quad (1)$$

Figure 2 illustrates the geometrical parameters of a single grain scratch and the two areas A_p (dark-hatched) and A_c (light hatched) in the plane normal to the cutting direction. It is assumed that the pileup geometry can be defined by two parameters: pileup height h_p, and pileup angle β. In other words, the pileup volume is equally distributed on the both sides of the scratch, which forms equilateral triangles in the planes normal to the cutting direction.

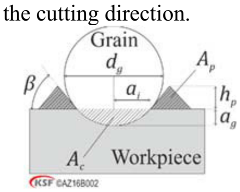

Figure 2. Single grain scratch cross-section areas and parameters

Larger values of relative chip area approaching 1 are favorable in terms of grinding efficiency. A view of the scratch simulated with v_c=20 m/s and d=151 µm grain size with maximum penetration depth of a_g=5 µm normal to the cutting direction and the effective stress distribution are presented in Figure 3. Figure 4 shows the corresponding force components.

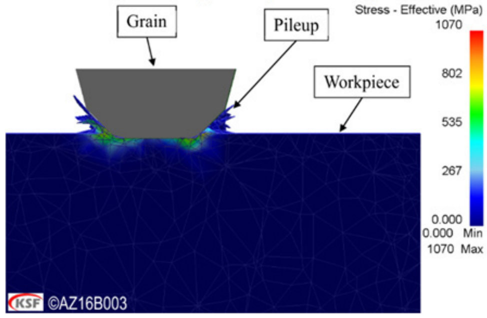

Figure 3. Scratch cross section and the effective stress distribution

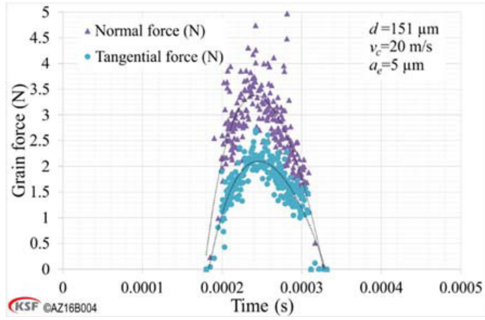

Figure 4. Simulated Normal and tangential force components of a scratch

The variations of the force components and the relative chip area with cutting velocity reflect the dependency of the material properties on the strain-rate. The tangential grinding force and relative chip area values are presented in Figure 5 and Figure 6 respectively.

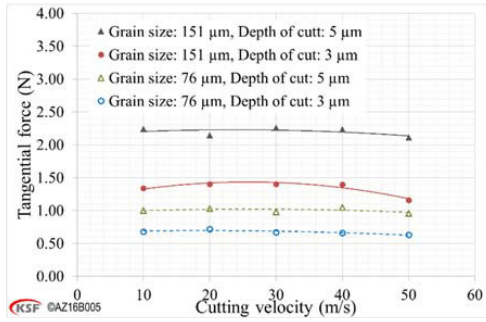

Figure 5. Variations of tangential force with cutting velocity and depth of cut

The increasing and decreasing behavior of the relative chip area with cutting velocity, which is also observed in the force diagram to a smaller degree, can be associated with the coupled material model. In small strain-rate values the work-hardening is the dominant phenomenon, where the chip removal is more