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AN INVESTIGATION OF THE RUBBING AND PLOUGHING IN SINGLE GRAIN GRINDING USING FINITE ELEMENT METHOD

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ABSTRACT

In this research, a simulation of single grain grinding is conducted by using ABAQUS/Standard™. The aim of this finite element method (FEM) simulation is to demonstrate the removal mechanism of single grain grinding and to predict the machining-induced stresses and forces in single grain grinding. A grinding process principally includes three phases which are rubbing (elastic deformation zone), ploughing (with elastic and plastic deformation) and cutting (chip formation). This paper mainly focuses on the grinding actions in rubbing and ploughing phases. The stress distribution over the workpiece is demonstrated and interpreted. Consequently, grinding-induced forces and their variations over the sliding path are illustrated. The generation of ground surface is illustrated by using multiple passes of a single grain in the simulation.

Key words: Finite element method, grinding, simulation

1 INTRODUCTION

The modelling and simulation of a grinding process are generally based on the relationship between the process parameters and results in grinding. Finite Element Method (FEM) is the most frequently used numerical methods in metal cutting processes (Wu et al. 2005). With the increasing capability of computer system, using FEM, geometrical kinematics models and Molecular Dynamics (MD) for grinding simulation become feasible (Brinksmeier et al. 2006).

To date, grinding and other abrasive processes have been modelled mostly using kinematic models and some physical models using FEM also exist (Klocke 2003). Generally grinding process has been modelled using heat transfer modelling technique in which case grinding wheel has been modelled as moving heat source and using elasto-mechanical material characteristic where the grinding wheel has been modelled as mechanical surface pressure (Brinksmeier et al. 2006; Mamalis et al. 2003; Moulik, Yang, and Chandrasekar 2001). This type of model is called as macro-scale model which deal with the interaction between grinding wheel and workpiece (Brinksmeier et al. 2006; Doman, Warkentin, and Bauer 2009). The other approach is the modelling of single grain action during machining process, which is called as micro-scale model dealing with individual grain interaction with workpiece (Brinksmeier et al. 2006; Doman, Warkentin, and Bauer 2009). Micro-scale modelling of grinding is still in a developing stage. Micro-scale FEM model of grinding process is difficult because it requires high computational power. However, recently researchers have begun to investigate micro-scale modelling and simulation of grinding process. Recent studies in both macro-scale and micro-scale finite element analysis (FEA) of grinding process were reviewed in some literatures (Brinksmeier et al. 2006; Klocke 2003; Doman, Warkentin, and Bauer 2009).

The grinding action of a single grain including rubbing, ploughing and cutting three phases was first put forth by Hahn (1962) and was called as a prevailing rubbing hypothesis (Doman, Bauer, and Warkentin 2009). Some single grain scratch tests have been conducted experimentally as physical processes. One of the earliest researches was performed by Takenaka (1966) using single grit action over the workpiece. He verified the Hahn's rubbing hypothesis at the depth of cut about 0.5µm or less. All three grinding action described by Hahn, namely cutting, rubbing and ploughing processes were observed. He concluded that the rate of cutting process is relatively small and decreases with decrease of depth of cut, however, the rate of the ploughing process increase with decrease depth of cut.

Ram et al. (2003) developed a 2D simulation of an abrasive grain using elasticity theory. They mainly investigated the wear-induced elastic stresses due to impact and sliding of abrasive particle in tribological contact situation. They used Hertzian contact theory and LS-Dyna implicit finite element analysis to implement their model and their FE model was close agreement to the theoretical results. Yao et al. (2004) investigated the elastic contact of two dimensional rough surfaces by using multiscale finite element method. They concluded that Hertz theory is not fully capable to explain when approaching finer scale geometry. On the fine scale, the real contact traction at the peak of an asperity would be many times higher than the results of Hertz theory. Lambropoulos et al. (1996) developed a finite element model for axisymetric indentation of glass surfaces. It was developed to study in plastic zones created by abrasive grain contact. Ohbuchi and Obikawa (2006) proposed a new model of grain cutting in grinding process. It was proposed that upheaval or residual stock removal caused by the effect of grain shape and cutting speed, and effect of elastic deformation of grain. Doman et al. (2009) developed a three dimensional FE model of rubbing and ploughing phases in single-grain grinding considering elastoplastic material characteristic. Scratch tests were used to validate the model and a very good agreement was obtained with simulation. Klocke et al. (2002) simulated the finite element analysis for the single-grit abrasive process on the workpiece. Single-grit scratch was modelled in a 2D model considering thermostructural material properties under the DEFORM simulation environment.

In this research, micro-scale modelling approach in grinding process will be addressed and investigated by using FEM in Abaqus/standard™. The aim of this research is to illustrate the material removal mechanism of single grain grinding and to predict the machining-induced stresses and forces in single grain grinding. Furthermore, the formation of ground geometrical surface is investigated.

2 SINGLE GRAIN SIMULATION

In the FEA model, remeshing technique is used to increase solution accuracy and control distortion of element in subsequent steps due to dramatically increasing strain rate at large deformation state such as grinding. Fine meshes over the cutting area also provide better conformity of contact between grain and workpiece. Material properties of grain and workpiece used in simulation are shown in Table 1. Grain is modelled as a half solid sphere section with a diameter of 100 µm. Dimensions of the workpiece (*length (l),width (w), and depth (d)*) are 2 mm, 1 mm and 0.5 mm, respectively. Simulation path for single grain FEM model is illustrated in Figure 1. Frictionless surface to surface contact with finite sliding formulation is used as interaction properties.

Table 1: Material properties of grain and workpiece.

Elastic properties	Grain	Workpiece		
Mass density (kg/ m^3)	4000	7800	Yield stress (MPa)	Plastic strain rate
Young's modulus (E) (GPa)	530	200	180	0
			200	0.1
Poisson's ratio (ν)	0.2	0.3	250	0.25
			300	0.3

A typical mesh of the grain and workpiece is C3D4 element which is a four node linear tetrahedron elements are used to mesh both single grain and workpiece part. Both parts are meshed by using free-mesh technique. Coarse meshing may results in poor conformity of simulation due to the relatively large stress gradients in the grinding contact zone. Iterative remeshing rules are applied to improve conformity.

Encastre (all translational and rotational degree of freedom are fixed) boundary conditions is applied to workpiece bottom plane nodes. A two directional, -Y and –X, displacement boundary condition is applied to the nodes on grain top flat surface to simulate indentation and sliding respectively. Boundary conditions are created in the first step and propagated through all steps. Displacement boundary conditions are modified according to the grain path in the simulation.

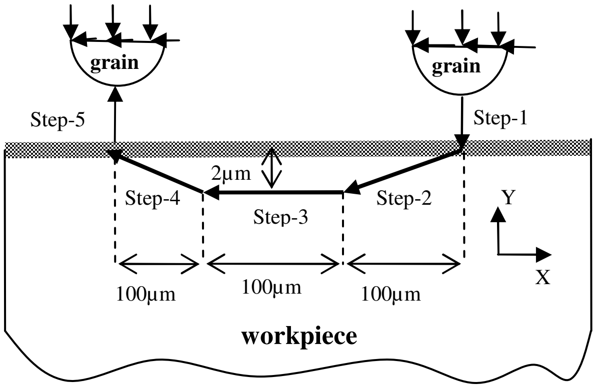


Figure 1: A single grain simulation path.

3 FINITE ELEMENT SIMULATION RESULTS

Stress distribution through the simulation path is illustrated with contour lines in Figure 2. It is very obvious to detect stress and deformation change during process. The deeper point indicated with 'PE' in Figure 2 represents where the grain engaged with the workpiece during simulation and includes elastic and plastic deformation together, while the unengaged section exampled as 'E' only includes plastic deformation. Workpiece material in front of grain indicated with 'pile-up' would be attributed to the beginning stage of chip formation. When the stresses reach the breaking point, chips may form. Stresses due to elastic deformation would disappear from workpiece after the grain passed and only residual stresses due to plastic deformation remain on the workpiece.

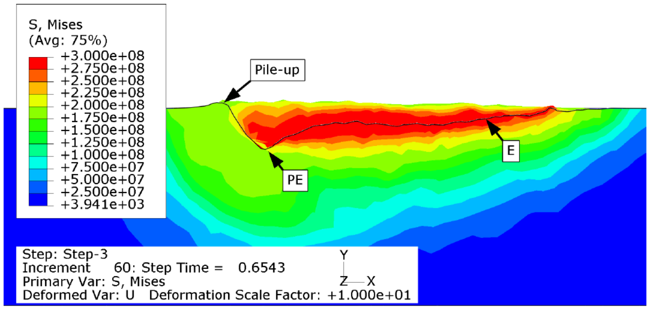


Figure 2: Stress distribution during simulation.

Rubbing, ploughing and chip formation are the three phases taken place during grinding process. Rubbing phase only include elastic deformation while ploughing phase include elastic and plastic deformation together. Transformation from rubbing to ploughing phase is demonstrated in Figure 3. At the beginning of simulation, plastic-strain free section can be attributed to rubbing phase. The rubbing length is measured as a 5.825 µm as shown in Figure 3 (a). The undeformed depth of cut at the transition point is evaluated as 0.1165 µm without considering mesh asperity. In ploughing phase plastic-strain exists due to plastic deformation. There is indention with a depth of 0.205 µm at the intitial contact point (Figure 3(b)) due to mesh asperity of grain. The asperity over the grain is caused by the coarse meshing of grain element where grain acts as a master part and workpiece is slaver, although it has designed geometrically perfect sphere shape.

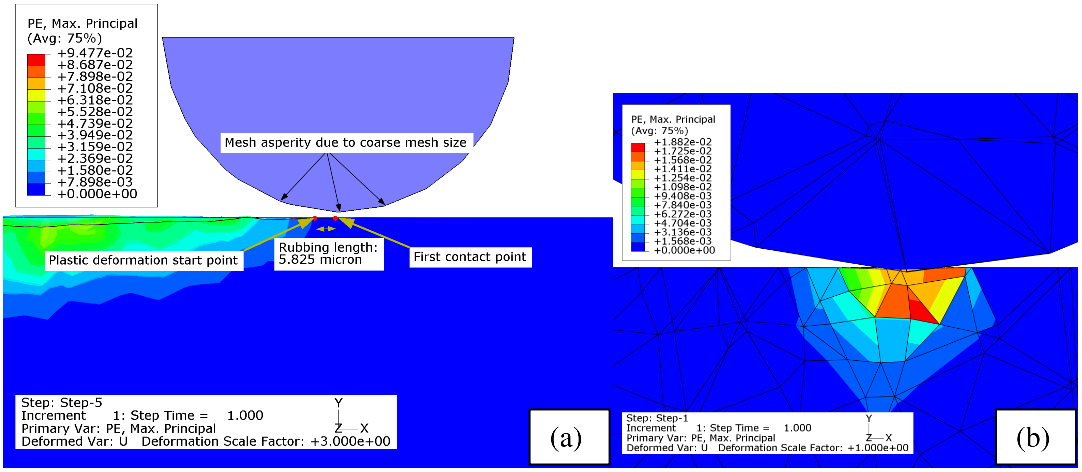
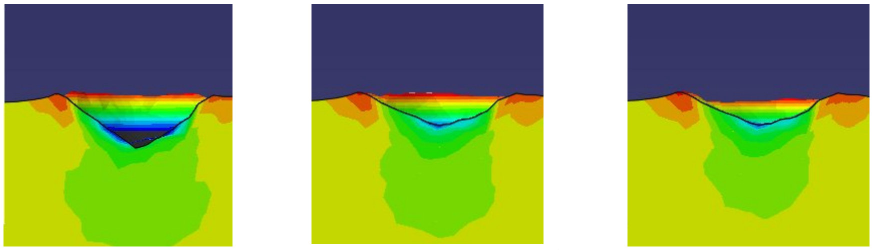


Figure 3: Transformation from rubbing and ploughing phase (a) rubbing section, (b) first contact point.

The remarkable point is that the shape of groove and ridge are changed while grain is moving away from the point. The phenomenon can be described by using a few snapshot from the same cut-view section while the grain diverges from cut-view section and illustrated in Figure 4. When the grain is settled at very closing to view section, the shape of groove is deeper as shown in Figure 4(a). However, when the grain is moving away from the section, the shape of groove gradually become smoother and shallower as shown through in Figure 4(a) to (c), which present elastical recovery. Each picture is named according to the grain position along the simulation path.



(a) Step-3, frame-30 (b) Step-3, frame-52 (c) Step-4, frame-23

Figure 4: Section-view of single grain simulation.

A simulation is designed to demonstrate how ploughing could affect the generation of ground surface in grinding. Single grain scratchs three times with 10 µm apart in transverse direction. Figure 5 shows subsequent grit passes push material aside forming ridges which alter the ground surface. The subsequent scratches give larger depths of cut and the grove shape becomes unsymmetrical. Even so, the scratch force of each pass presents similar feature as shown in Figure 6.

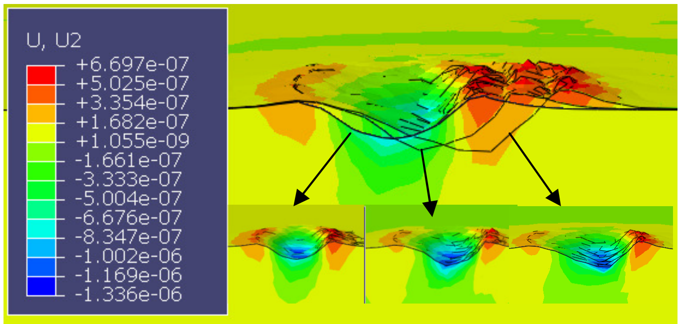


Figure 5: The deformation in the simulation of three parallel scratch passes with 10 µm apart.

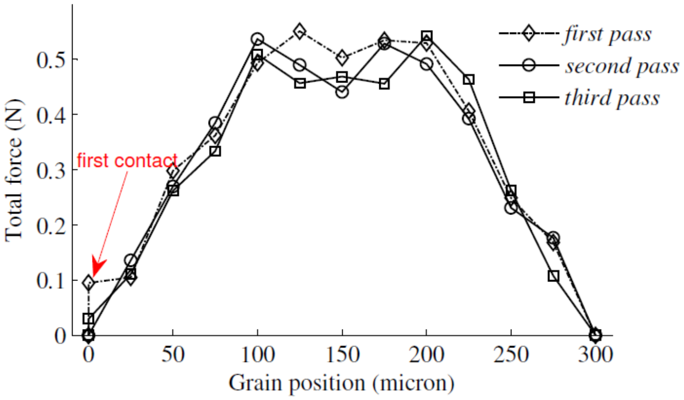
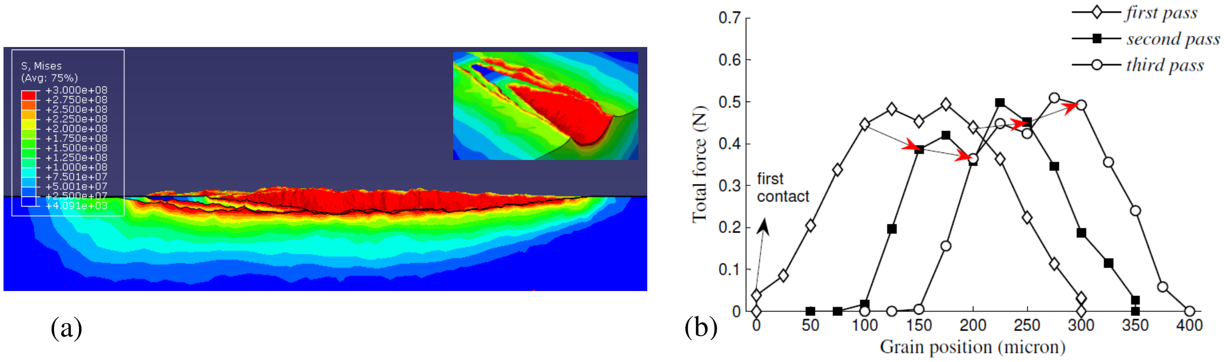


Figure 6: Force variation in the parallel scratching simulation.

Another simualtion is carried out with three grit scratchs along the scratching direction with 50 µm apart. The aim is to demonstrate the alteration of previously ground surface by subsequent single grain. According to the simulation, there is no significant change at the overlaid section as seen in Figure 7 (a). However, there is remarkable point in variation forces across each sliding. As illustrated in Figure 7 (b), the scratching forces at the beginning of step 3 is decrasing gradually for subsequent scratch passes while they are gradually increasing starting at the end of step 3. Although decreasing is due to preceding removed material, the increas in force can be attributed to the piling up of material in the leading edge of grain due to the preceding passes.



(a)

(b)

Figure 7: (a) Pictures illustrating the three grain sliding simulation over the same path subsequently with 50 µm apart, (b) force variation through in-line sliding.

4 CONCLUSIONS

The results of FEM simulation provide rich information about grinding process, including stress distribution and surface formation during grinding. Ploughing and rubbing phases in grinding can be observed clearly including ridge formation. Force variation in the grinding depends on grit cutting path. The material bulged due to previous ploughing action will increase cutting forces in subsequent cutting passes. As for a FEA model, remeshing strategy is very essential to obtain reliable results. It provides very fine size meshes through contact area to alleviate the element distortion due to large plastic deformation. With the aid of the simulations, some physical parameters, such as force, can be quantitatively analyzed. Moreover, ground surface roughness and material removal characteristics can also be studied by using properly designed FEA model.

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