Simulation of Grinding Surface Creation – A Single Grit Approach

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Abstract. The paper presents an investigation of grinding material removal mechanism using finite element method. Understanding of grinding removal mechanism relies on the investigation of material removal by each individual grain. Although some analytical formulations have been developed to predict and to quantify the machining events in grinding, they do not illustrate every stage of abrasive actions. Finite element analysis provides good facility to present details of physical behaviour in grinding. In this research, material removal mechanism of grinding, namely rubbing, ploughing and cutting, is discussed with the variation friction coefficient. The major emphasis here is on the ploughing. Total force variation exerted during indention and sliding of a grain is also presented along its path.

Introduction

Grinding is a material removal process where a large number of arbitrarily positioned abrasive grits pass across workpiece to remove material in forms of tiny chips. Creation of ground surface depends on not only grit shape and grinding kinematics, but also physical deformation during material removal. The grinding actions of a single abrasive grit classified as rubbing, ploughing and cutting three phases were first put forth by Hahn [1] and was called as a prevailing rubbing hypothesis [2]. The contribution of each of grinding action to ground surface creation depends on grinding conditions and associated physical phenomena. Most modelling and simulation grinding process are generally based on the relationship between system parameters, machining parameters, process parameters and results in grinding in a aggregated level [3]. To understand the creation of ground surface requires the knowledge of each individual grinding action. However, to define individual contribution of the grinding actions of each abrasive grit under different grinding conditions is almost impossible due to the random nature of grinding. By carefully design experiments, some of grinding action may be investigated physically to a certain level of accuracy with tremendous effort. One of the earliest researches was performed by Takenaka using single grit action over the workpiece [4]. 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.

Finite Element Analysis (FEA) is the most commonly used computing simulation technique in metal cutting processes [5, 6]. With the increasing capability of computer system, using finite element analysis for macro-scale and micro-scale grinding simulation become feasible. Recently investigations of grinding process using macro-scale and micro-scale FEA appear in some literatures [3, 7]. Ram et al [8] 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 presented close agreement to the theoretical results. Yao et al [9] 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. Under 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 [10] developed a finite element model for axisymmetric indentation of glass surfaces. It was developed to study in plastic zones created by abrasive grain contact. Ohbuchi and Obikawa [11] 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 [2] developed a three dimensional FE model of rubbing and ploughing phases in single-grain grinding considering elastoplastic material characteristic. A scratch test was used to validate the model and very good agreement was obtained with simulation. Klocke et al [12] simulated the finite element analysis for the single-grit abrasive process on the workpiece. Single-grit scratch was modelled as a 2D considering thermostructural material properties and the DEFORM was used as a simulation environment.

Friction between the abrasive grains and workpiece has a direct influence on grinding force, power, specific energy and wheel wear. Adhesion, plastic deformation, and ploughing also have their contributions to the friction coefficient, although both adhesion and ploughing mechanism are not yet fully understood. According to Fielding and Vickerstaff [13], the friction coefficient varies with the wheel speed, metal removal rate and dressing lead, and highly depends on the heat input to the process. Cai et al [14] investigated friction coefficient in single-grit grinding for different work materials. They found that the friction coefficients for most materials decrease with the increase of grinding speed. The friction coefficient for the same work material changes even at same grinding speed while using different types of wheel and abrasive. The work materials also substantially influence the friction depending on the properties such as the plasticity, hardness and also the tendency of adhesion to the abrasives. Subhash and Zhang [15] investigated that the influence of the interfacial friction coefficient μ and the apical angle α of the indenter on the induced maximum tangential force F_T and, normal forces F_N, and overall force ratio F_T/F_N were systematically studied. The tangential forces increases with μ, but the normal forces decreases with μ. The overall force ratio F_T/F_N was found to increase linearly with μ and tangent of the attack angle of the indenter. The maximum depth of cut for scratching simulation and experiment was 30 μm and scratch length of 2.2 mm. Albeit this is not in the range of normal grindings, it still give some clues for grinding tribology analysis. In metal cutting process, Shet and Deng [6] explored that the effect of friction coefficient and rake angle on cutting force. They used four rake angles and four friction coefficient, the cutting force is seen to approach a constant value as the cutting tool advances, indicating the achievements of a steady-state condition. For each rake angle, the cutting force is seen to increase as the value of friction coefficient increases. Matsuo et al [16] in their experiment with wet condition the CBN grain generated as large pile-up as diamond grain. They thought that the one of cause of large pile-up in diamond grinding is low frictional coefficient. From single-grit grinding test, it was found that grinding force increases linearly with increasing cross sectional area, and the slope of line is greater as apex angle becomes larger. As far as one grain is tested, the pile-up or the removal is largely dependent on the direction of grinding.

Simulation of Grinding Actions Using Finite Element Analysis

Simulation of single abrasive grain grinding actions in three dimensions is performed by using ABAQUS/CAE standard software package. Single abrasive grain is modelled as hemispherical solid section with a diameter of 100 μm. Work material is modelled with dimensions of length 2 mm, width 1 mm and height 0.5 mm. The material properties are listed in Table 1. The cutting path of single grain FEM simulation is illustrated in Fig. 1. The accuracy of the FE analyses requires a fine mesh in the contact region and the capability to deal with stick-slip behaviour in multiple three-dimensional contact surfaces [17]. In the FEM model, remeshing technique [17] is used to control distortion of element due to dramatically increasing strain rate at large plastic deformation state. During simulation of machining process severe mesh distortion take places and it is then necessary to remesh the part to carry out the finite element analysis. The remeshing technique is based on the refinement and coarsening techniques and avoids entirely remeshing the workpiece. The remeshing is governed by mesh element size and average plastic strain error indicator is used to make decision about satisfaction of element geometry and contact conformity at interaction area. Fine meshes over the cutting area provide better conformity of contact between grain and workpiece. 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 in first stage. Three iterations are applied to remesh the part as shown in Fig. 2. Coarse meshing may results in poor conformity of simulation due to the relatively large stress gradients in the grinding contact zone.

Table 1 Material properties used in FEA

Material Properties of Grain			**Workpiece**		
Mass density (kg/ m^3)		4000	7800		
Young's modulus (E)(GPa)		530	200		
Poisson's ratio (ν)		0.2	0.3		
Plastic properties			**Plastic properties**		
	Yield stress (GPa)	Plastic strain rate		Yield stress (MPa)	Plastic strain rate
1	15	0	1	180	0
2	15.4	0.03	2	200	0.1
3	16	0.2	3	250	0.25
4	16.5	0.5	4	300	0.3

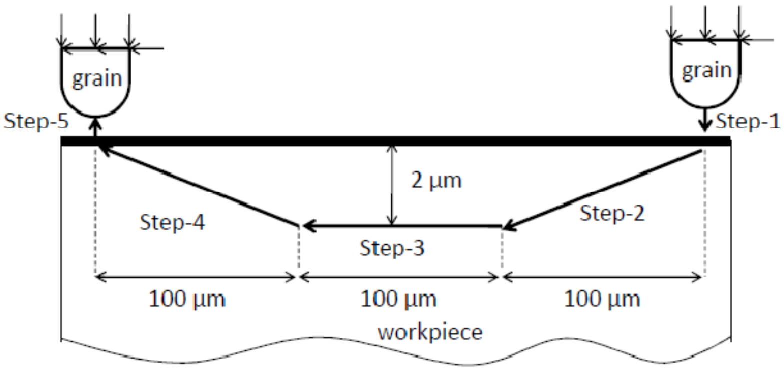
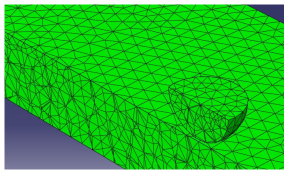
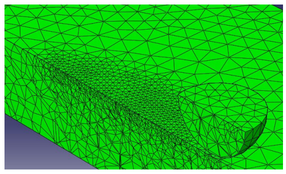


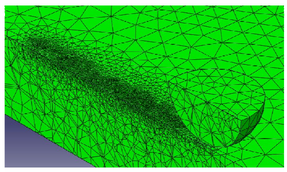
Figure 1 A single grain simulation path



(a) first iteration



(b) second iteration



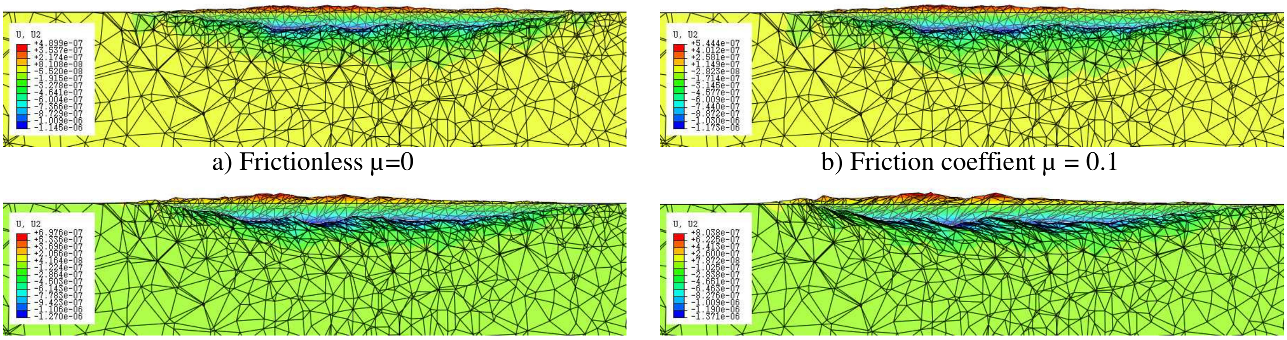
(c) third iteration

Figure 2 Iterative remeshing

Encastre (all translational and rotational degree of freedom are fixed) boundary conditions is applied to workpiece bottom surface nodes. A two directional, - Z 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 simulation path. Surface to surface contact method is applied to define contact mechanism between grain and workpiece. Simulation is run with friction coefficient of 0, 0.1, 0.3 and 0.5 by applying penalty friction formulation in Abaqus. Simulation comprises 5 steps for each scratch cutting pass. Geometric nonlinearity is activated.

Results and Discussions

Finite element simulation accomplished with a satisfactory results that illustrate the influence of friction coefficient in grinding. As it is commonly known, grinding action includes three dominant phases which are rubbing, ploughing and chip formation process. Rubbing phase is elastic deformation, which does not create new surface. Ploughing is plastic deformation which pushes materials away from their original positions forming a new surface. Chip formation removes materials from workpiece due to excessive plastic deformation. In grinding, larger proportion of grinding actions is ploughing. Therefore ploughing action is the major factor that determines final surface features. By using different coefficient between contact surfaces it has revealed that friction coefficient promote the ploughing rate in both vertical and horizontal dimension as shown in Fig. 3, where the ploughing ridge is the highest while μ = 0.5 and the lowest without friction. The other remarkable point is that the simulation shows the ploughing pushes materials forwards while the grain advances. This is clearly shown at cutting pass step-3 where cutting path is parallel to its original surface. The higher friction, the more materials been pushed forward.

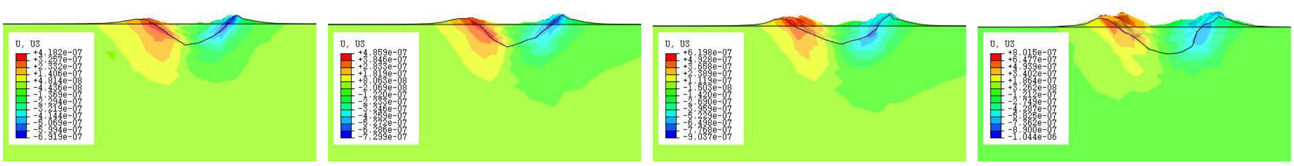


a) Frictionless μ=0 b) Friction coeffient μ = 0.1

c) Friction coefficient μ = 0.3 d) Friction coefficient μ = 0.5

Figure 3 Ploughing action across the sliding scratch with different friction coefficient between grain and workpiece surface, U2 represent displacement in vertical direction.

Displacement in transverse direction as shown in Fig. 4 is increasing with increase in frictional coefficient. Thus, ridge formed by frictionless scratch simulation produce narrower than ridge formed by frictional scratch simulation. These cross sections are taken from the end of step-3 of the cutting passes. The pictures are captured from Abaqus viewport and deformed part are magnified 10 times in displacement to give good illustrative shape otherwise it is not easy to see the ridge and deformation on figures since indention depth is already 2 μm and maximum plastic deformation in depth is around 1.2 μm. The elastic deformation may be up to 0.8 μm in depth. As it can be seen, the distortion on the ridge and ploughing profile in Figure 4 is obvious due to a high magnification (10 times). The accuracy of simulated geometrical profile may be improved by further remeshing contact area to even finer meshes.

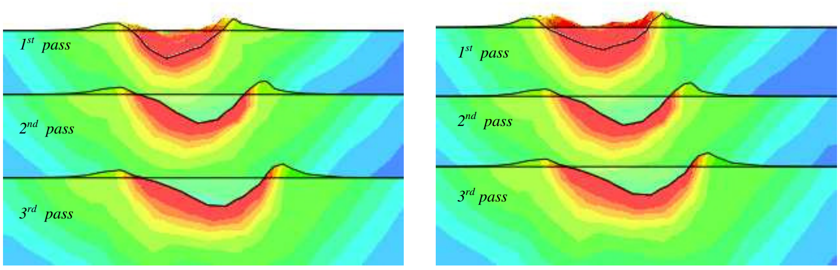


μ = 0 μ = 0.1 μ = 0.3 μ = 0.5

Figure 4 Ploughing action profile taken from the cross-section at the end of step-3.

The simulation also demonstrate how ploughing could affect the generation of ground surface in grinding. Fig. 5 shows a single grain scratches work surface three times cross over transverse direction with 10 μm apart. The 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. If the subsequent grit scratches are in line with the previous pass by advancing 50 μm forward, the surface created does not show much increase in ploughing ridge high (see Fig. 6), but the scratch slot depth increases slightly. A higher friction would increase such distortions.

Total force is estimated across the scratched groove for each of friction coefficient. Higher friction coefficient results in higher total forces as shown in Fig. 7. Each figure in Fig. 7 shows force variation through the three passes with 10 µm apart in transverse direction. When maximum total force exerted in frictionless scratch is around 0.55 N while maximum total force exerted with µ = 0.5 is around 0.9 N. It is gradually increasing with friction coefficient. The profile of force variation also depends on the friction coeeficient.



a) Friction coefficient µ = 0.1 b) Friction coefficient µ =0.3

Figure 5 Variation of cross section profile with subsequent three passes with 10 µm apart

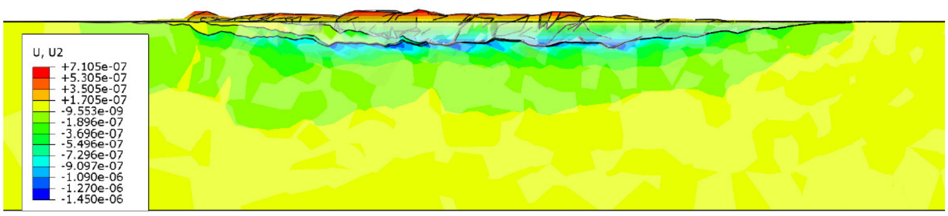


Figure 6 Subsequent three scratch passes in line with previous path with 50 µm advances (µ =0.3)

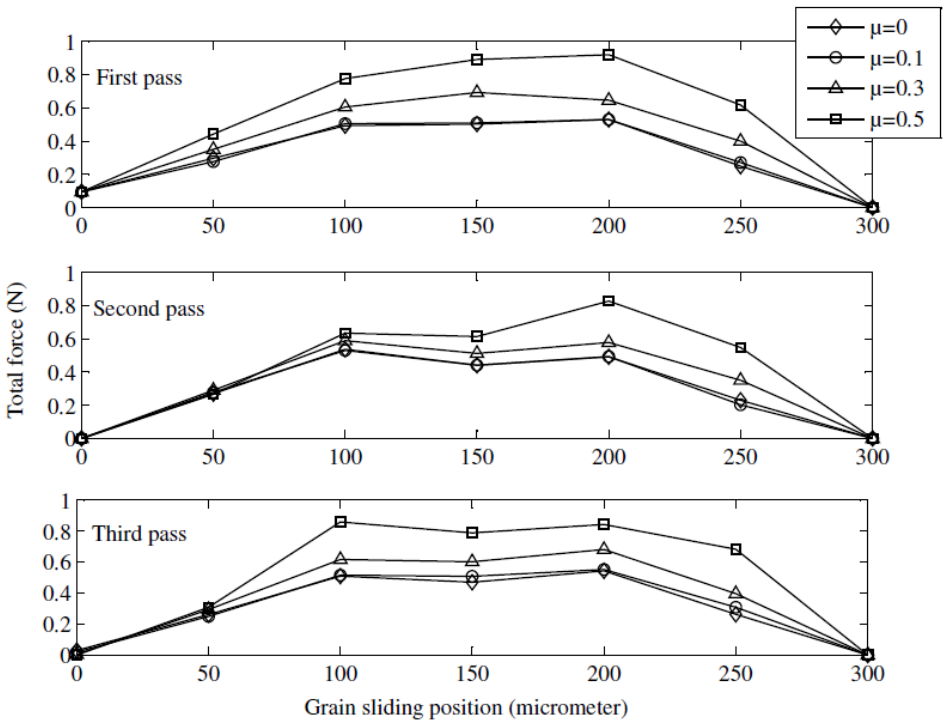


Figure 7 Total force variations with friction coefficient and cross-pass scratching

Conclusions

The results of FEM simulation provide essential information about grinding process, including stress distribution and surface formation during grinding. Ploughing and rubbing phase can be observed clearly as well as 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. Friction coefficient is an important factor that influences ground surface formation. Higher friction coefficient will lead to high ploughing ridges along the cutting path. Friction coefficient also affects total scratch force, which is increasing with increasing friction coefficient. The remeshing strategy in FEM is critical to obtain reliable results. It provides very fine size meshes through contact area to alleviate the element distortion due to large plastic deformation however it might be needed to increase the remeshing iteration size or smaller element size in contact area to obtain good geometrical convergence during ridge formation. With the aid of the simulations, some physical parameters, such as force, can be quantitatively analysed. Moreover, ground surface roughness and material removal characteristics can also be studied by using properly designed FEM model.

References

[1] Hahn RS, (1962) On the nature of the grinding process. In Proceeding of the 3rd International Conference On Machine tool design and research, Birmingham, UK, pp:129-154.

[2] Doman DA, Bauer R, Warkentin A, (2009) Experimentally validated finite element model of the rubbing and ploughing phases in scratch tests. Proc. IMechE Part B: J. Engineering Manufacture 223:1519-1527.

[3] Brinksmeier E, Aurich JC, Govekar E, Heinzel C, Hoffmeister H-W, Klocke F, Peters J, Rentsch R, Stephenson DJ, Uhlmann E, Weinert K, Wittmann M, (2006) Advances in Modeling and Simulation of Grinding Processes. Annals of the CIRP 55(2):667–696.

[4] Takenaka N, (1966) A study on the grinding action by single grit. Annals of the CIRP 13:183-190

[5] Wu HY, Lee WB, Cheung CF, To S, Chen YP, (2005) Computer simulation of single-point diamond turning using finite element method. Journal of Materials Processing Technology 167(2-3):549-554.

[6] Shet C., Deng X., (2000) Finite element analysis of the orthogonal metal cutting process. Journal of Materials Processing Technology 105:95-109.

[7] Doman DA, Warkentin A, Bauer R, (2009) Finite element modeling approaches in grinding. International Journal of Machine Tools & Manufacture 49:109-116.

[8] Ram A, Danckert J, Faurholdt T, (2003) Finite element analysis of stresses due to normal and sliding contact conditions on an elastic surface. In Proceeding of 4th European LS-DYNA User's Conference, Ulm, Germany, pp:21-34.

[9] Yao Y, Schlesinger M, Drake GWF, (2004) A multiscale finite-element method for solving rough-surface elastic-contact problems. Canadian Journal of Physics 82:679-699

[10] Lambropoulos JC, Xu S, Fang T, Golini D, (1996) Twyman effect mechanics in grinding and microgrinding. Applied Optics 35(28):5704-5713.

[11] Ohbuchi Y, Obikawa T, (2006) Suface generation model in grinding with effect of grain shape and cutting speed. JSME International Journal 49(1):114-120.

[12] Klocke F, Beck T, Hoppe S, Krieg T, Müller N, Nöthe T, Raedt H-W, Sweeney K, (2002) Examples of FEM application in manufacturing technology. Journal of Materials Processing Technology 120:450-457.

[13] Fielding E.R. and Vickerstaff T.J., (1986) On the relationship between the normal and tangential forces in cylindrical plunge-cut grinding. Int. J. Prod. Res. 24(2):259-268.

[14] Cai G.Q., Feng B.F., Jin T., Gong Y.D., (2002) Study on the friction coefficient in grinding. Journal of Materials Processing Technology 129:25-29.

[15] Subhash G., Zhang W., (2002) Investigation of the overall friction coefficient in single-pass scratch test. Wear 252: 123-134.

[16] Matsuo T., (1989) Effects of grain shape on cutting force in superabrasive single grit tests. Annals of the CIRP 38(1):323-326.

[17] Giraud-Moreau L., Borouchhaki H., Cherouat A., (2008) Adaptive remeshing for sheet metal forming in large plastic deformations with damage. Int. J Mater Form 1:129-132.