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FINITE ELEMENT SIMULATION OF CHIP FORMATION

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ABSTRACT

Grinding process is a derived form of cutting processes, in which the cutting tool is relatively small and has not well defined geometric shape as well as oriented with extremely high rake angle to workpiece. Considering single grit cutting process occurred in grinding, it can be associated with the orthogonal cutting process in some aspects. In metal cutting process, chip formation is a phenomenon needed to investigate in detail to explore the machining characteristic of materials. In this work, chip formation process has been performed in Abaqus/Explicit. Two different Mises plasticity model (with Johson-Cook and isotropic hardening) are applied in conjunction with the suitable damage laws. Therefore, continuous chip formation is simulated. Stress and force variation has been analyzed. A few different simulations have been performed as to find the suitable model and technique considering remeshing, material constitutive model, elasticity and plasticity, damage initiation criterion, contact properties.
Keywords finite element method, simulation, chip formation, orthogonal cutting, ALE adaptive meshing

1 INTRODUCTION

As commonly known, grinding process include three phenomena which are rubbing, ploughing and chip formation. Finite element method simulation of this process can be separately achieved due to complexity of process in one model. Rubbing and ploughing phenomenon have been simulated and published in (Chen and Öpöz (2010)). For the chip formation process recently researchers have used orthogonal cutting model with negative rake angle to simulate chip separation by single grit cutting (Obhuchi and Obikawa (2003)). Chip formation process was generally investigated experimentally in early work due to insufficient computer power and undeveloped simulation algorithm. Computer simulation by using finite element method in machining has been performed for last two decades but more realistically finite element modelling of machining process has been simulated by using integrated remeshing and fracture model for last decade. Finite element simulation of abrasive grit by using real shape of grit is impossible due to numerical difficulty but by using simplified model of single grit that shows the grinding cutting phenomenon characteristic such as high negative rake angle and/or changing tool tip shape or orientation with respect to work material. The simplified model of single grit with negative rake angle can be considered as derived form of orthogonal cutting simulation. Thus, we take the orthogonal cutting simulation as a reference to simulate single grit simulation. Here we give some previous works about simulation of single grit and orthogonal cutting process. Ohbuchi and Obikawa (2003) developed a thermo-elastic-plastic finite element modeling of orthogonal cutting with a large negative rake angle to reveal the mechanism and thermal aspects of grinding. Serrated chips that observed in single grit grinding were formed with a rake angle of minus forty five or minus sixty degrees. Chip formation and chip shapes are dependent to several parameters and criterions taken place during machining. Ohbuchi and Obikawa (2006) introduced a critical undeformed chip thickness, under which chip may not form or form with great difficulty. Majority of finite element simulation of metal cutting process are performed using explicit method which is guaranteed to converge. Shet and Deng (2000) modelled the orthogonal cutting process with finite element method under plane strain conditions. Critical stress based chip separation criterion and nodal release procedure were used for chip formation process. An over-stress, rate-dependent, elastic-viscoplastic constitutive law was employed along with temperature dependent material properties. Large deformation was prevented by an updated Lagrangian formulation. Mesh refinement or remeshing during chip formation process is very important to assure convergence problem when mesh elements highly distorted and also to increase accuracy of stress and strain distribution along the cutting path. Bäker et al (2002) developed a finite element model of orthogonal cutting process by using special mesh generator that that is able to mesh the chip completely with regular quadrilateral element and a strong mesh refinement in the shear zone for continuous and segmented chip formation. Recently to make the cutting simulation more realistic, failure model with chip separation criteria (Huang and Black (1996)) and adaptive remeshing (Movahhedy et al (2000)) (like Arbitrary Lagrangian Eulerian adaptive meshing) are integrated to the finite element model of cutting simulation. Johson-Cook plasticity and damage model with element deletion technique are often applied to finite element simulation of cutting (Belhadi et al (2005), Pantalé et al (2004)).

In this paper, Chip formation process is performed by using Arbitrary Lagrangian Eulerian (ALE) adaptive remeshing and some plasticity model combined with damage laws in Abaqus/Explict. An example of ploughing process simulation is also given to show in simulation condition and feasibility.

2 FINITE ELEMENT MODEL OF CUTTING PROCESS

2.1 Material Constitutive Model and Damage Law

An accurate and reliable flow stress models are considered highly necessary to represent work material constitutive behaviour under high-speed cutting conditions. Von-Misses yield criteria combined with rate dependent Johson-Cook (J-C) and isotropic hardening method are employed to finite element model separately. Rate dependent yield is required to model materials yield behaviour accurately when the yield strength depends on the strain rate (Abaqus user's manual). The J-C hardening method (1985) describes the flow stress of a material with the product of strain, strain rate and temperature effects that are individually determined as given equation (1). It is suitable for problems where the strain rates varies over large range ($10^2 s^{-1}$ to $10^6 s^{-1}$) and the temperatures changes due to plastic deformation caused by thermal softening (Duan et al (2009)). The equivalent flow stress model of J-C model is defined by

$$\bar{\sigma} = [A + B(\bar{\varepsilon})^n]\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right] \quad (1)$$

Where $\bar{\sigma}$ is the equivalent stress, A is in fact the initial yield strength (MPa) of the material at room temperature, B is the hardening modulus, n is the work-hardening exponent, C is the coefficient dependent on the strain rate, m is the thermal softening coefficient and a strain rate of 1/s and $\bar{\varepsilon}$ represents the equivalent plastic strain. The strain rate $\dot{\bar{\varepsilon}}$ is normalized with a reference strain rate $\dot{\bar{\varepsilon}}_0 = 1.0s^{-1}$. T_{room} and T_{melt} represent the room temperature and melting temperature, respectively. Johson-Cook plasticity parameters used in this paper are given in table 1.

Table 1 Johson-Cook parameters

A (MPa)	B (MPa)	n	C	m
490	600	0.21	0.015	0.6

Damage model proposed by Johnson and Cook is used in conjunction with J-C yield model. According to classical damage law, damage (fracture) of an element is defined by

$$D = \sum \frac{\Delta\bar{\varepsilon}}{\bar{\varepsilon}^f} \quad (2)$$

Where $\Delta\bar{\varepsilon}$ is the increment of equivalent plastic strain during an integration step, and $\bar{\varepsilon}^f$ is the equivalent strain to fracture, under current conditions. Fracture is then allowed to occur when *D=1.0* and the concerned element are removed from computation. According to J-C damage law, the general expression for the fracture strain is given by

$$\bar{\varepsilon}^f = \left(D_1 + D_2 exp D_3 \frac{\sigma_m}{\bar{\sigma}}\right)\left(1 + D_4 \ln\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\left[1 - D_5\left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right] \quad (3)$$

Where σ_m is the average of the three normal stresses and $\bar{\sigma}$ is the von Mises equivalent stress. The J-C damage model is suitable for high strain rate deformation, such as high speed machining, therefore, it is most applicable to truly dynamic simulations. In this paper, the J-C damage model was used in conjunction with the J-C plasticity model. The J-C damage parameters used in this paper are given in table 2. Example of chip formation simulation results solved with J-C model are shown in figure 2-a for 2D and figure 2-c for 3D model.

Table 2 J-C damage law parameters

D_1	D_2	D_3	D_4	D_5
0.05	3.44	-2.12	0.002	0.61

The overstress power law dependent isotropic hardening plastic yield model is also employed to finite element model in conjunction with ductile and shear damage law. Tabular yield strength data corresponding with plastic strain is given in table 3 to be employed to model (Shet and Deng (2000)). Plastic strain rate governed by rate dependent power law can be defined by

$$\dot{\varepsilon_p} = D\left(\frac{\sigma}{\sigma_0} - 1\right)^p \text{ for } \sigma \geq \sigma_0 \qquad (4)$$

where $\dot{\varepsilon_p}$ is the effective plastic strain rate, σ the current yield stress, σ_0 the initial yield stress, and D and p are the material parameters (D=2.21x10^{5}s^{-1}, p=2.87).

Table 3 Plastic yield parameters

Yield stress(MPa)	Plastic strain
414	0
517	0.01
759	0.09
1100	0.9

A chip formation simulation (figure 2-c) governed by power law rate dependent plastic yield is combined with ductile and shear fracture (damage) model. Ductile fracture and shear fracture are the two main fracture model in a ductile metal. Ductile fracture due to the nucleation, growth, and coalescence of voids assumes that the equivalent plastic strain at the onset of damage, $\bar{\varepsilon}_D^{pl}$, is a function of stress triaxiality and strain rate. Shear fracture due to shear band localization assumes that the equivalent plastic strain at the onset of damage, $\bar{\varepsilon}_S^{pl}$, is a function of the shear stress ratio and strain rate (Abaqus/CAE user's manual).

2.2 Remeshing

Two different remeshing technique has been applied to FEM model, which are Arbitrary Lagrangian Eulerian (ALE) adaptive remeshing (applicable both in Abaqus/Standard and Abaqus/Explicit) and adaptive remeshing (applicable only in Abaqus/Standard). Both of them have peculiar advantageous. ALE adaptive remeshing technique combines the features of pure Lagrangian analysis in which the mesh follows the material, and Eulerian analysis in which the mesh is fixed spatially and material flows through the mesh. ALE formulation is utilized in simulating machining to avoid frequent remeshing for chip separation. Explicit dynamic ALE formulation is very efficient for simulating highly non-linear problems involving large localized deformations and changing contact conditions as those experienced in machining (Özel and Eren (2005)). However, it is critical to use ALE adaptive remeshing with fined tuned parameters (for example; remeshing sweep, frequency, smoothing method, curvature refinement etc.) to simulate chip formation successfully. ALE adaptive remeshing is applied to chip formation process in this paper both for 2D and 3D simulation.

The other remeshing technique, adaptive remeshing, involved in FEM simulation is typically used for accuracy control, although it can also be used for distortion control in some simulations. The adaptive remeshing process involves the iterative generation of multiple dissimilar meshes to determine a single, optimized mesh that is used throughout an analysis (Abaqus user's manual). We used this technique to simulate ploughing and rubbing phenomena occurred in single grit grinding, example of a simulation is given in figure 1. This technique would not be suitable for chip separation due to remeshing sequences (iteratively) and limitation to use only in Abaqus/Standard. Therefore, ALE adaptive remeshing is used to simulate chip separation in Abaqus/Explicit and adaptive remeshing (iterative) is used to simulate ploughing and rubbing process in Abaqus/Standard.

2.3 Friction Model

A Coulomb's friction law is assumed to model the tool-chip and the tool-workpiece contact zones. According to the Coulomb's law, relative motion (slip) occurs at the contact point when chip shear stress τ is equal to or greater than the critical friction stress τ_c. When τ is smaller than τ_c there is no relative motion and the contact point is in a state of stick (Shet and Deng (2000)). The critical friction stress is determined by $\tau_c = min(\mu p, \tau_{th})$, where p is the normal pressure at the contact point where chip shear stress determined, μ is the friction coefficient and τ_{th} is the threshold value related to material failure. If the τ_{th} is set to a value rather than infinity, it is called as a modified Coulomb frictional law. In this paper, conventional Coulomb frictional law is used by setting τ_{th} to infinity. Penalty method is used as a friction formulation. Friction coefficient through all simulations are set to 0.1.

2.4 Material Model and Boundary Conditions

As described in the preceding section, finite element simulations of cutting have been performed by using J-C material constitutive model in conjunction with the J-C damage law but the simulation shown in figure 2-c which is modelled by using power-Law dependent von-Misses isotropic hardening plastic model in conjunction with shear and ductile damage criteria. Material properties of the workpiece including thermal properties due to temperature dependent constitutive law are given in table 3. Tool is modelled as a rigid by considering cutting tool is extremely harder comparing to workpiece material. The work material in 2D model is discredited by using CPE4R element (a 4-node bilinear plane strain quadrilateral reduced integration, hourglass control). The work material in 3D model is discredited by using C3D8RT element (an 8- node thermally coupled brick trilinear displacement and temperature, reduced integration, hourglass control). Workpiece material are constrained against any movement from bottom and left side edges (in 2D) or surfaces (in 3D) while tool is advancing with a speed of 5 m/s by penetrating into workpiece 100 µm as a undeformed chip thickness. Step time of 0.0005 second is applied to solve problem for all simulations. Surface to surface contact algorithm by using penalty mechanical constraint is employed to model. For the first surface, tool surface is chosen and for the second the workpiece surface with internal nodes by defining a set of nodes in which the tool would engage during simulation. Tool rake angle is set to zero for preliminary results.

Table 3 Thermal parameters of the workpiece

Thermal parameter	Workpiece
Density ρ (kg/m3)	7800
Elastic modulus E (GPa)	210
Poisson's ratio v	0.3
Specific heat C_p (J/kg °C)	475
Thermal conductivity λ (W/m C)	47.7
Expansion (µm/m°C)	11.5
T_{melt} (°C)	1520
T_{room} (°C)	25

2.5 Simulation Results

Finite element simulation of cutting process has been accomplished by using Abaqus/Explicit. 2D and 3D analysis have been performed as seen in figure 2. Mostly concerned phenomenon of shear band (figure 2-a) observed while chip separated from bulk material. Continuous chip observed depending of material parameters and simulation conditions which are decisive in the formation of chip type (such as serrated chip, break chip or continuous chip). The speed of cutting tool and depth of cut can be counted as most prominent parameters in chip formation. As seen in figure 2 chip formation occurred but machined surface and removed chip looks waving and not smooth due to ALE adaptive remeshing parameters, it must be optimized to get high quality mesh for future simulation. Finding the optimum parameters in ALE adaptive meshing is really difficult which is only possible by trial method. An example of cutting force and thrust force variation along cutting path are extracted as shown in figure 3. Oscillation along cutting is expected due to vibration caused by slip-stick behaviour of workpiece-tool interaction.

3 CONCLUSIONS

Chip formation has been simulated by using two different plastic model and damage criteria. J-C plastic model in conjunction with J-C damage is working good when regarding machining process which involves large deformation. Previous researcher have also noticed that the J-C model provide more realistic results consisting with experimental test. However, power law rate dependent isotropic plastic yielding in conjunction with ductile and shear damage is also working good if you manage to get accurate yielding strength for high strain rate. In addition, separate simulations from chip formation have been performed to simulate ploughing and rubbing action by using adaptive remeshing in Abaqus/Standard. We can conclude that three common phenomena of grinding which are rubbing, ploughing and chip formation can be suitably simulated in separate finite element model. Chip formation is more suitable to simulate in a dynamic model; ploughing and rubbing are more suitable to simulate in a static model. For more realistic results of metal cutting, a fracture mechanics of metal by element deletion technique has been applied, which gives more realistic result comparing to previously applied nodal separation technique. ALE adaptive mesh technique is also crucial to assure continuity of simulation without distorting element excessively.

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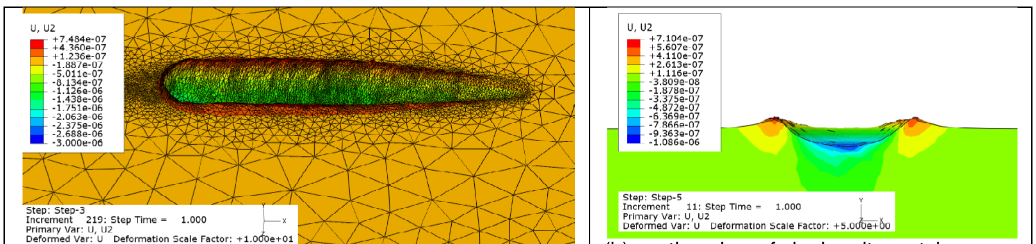
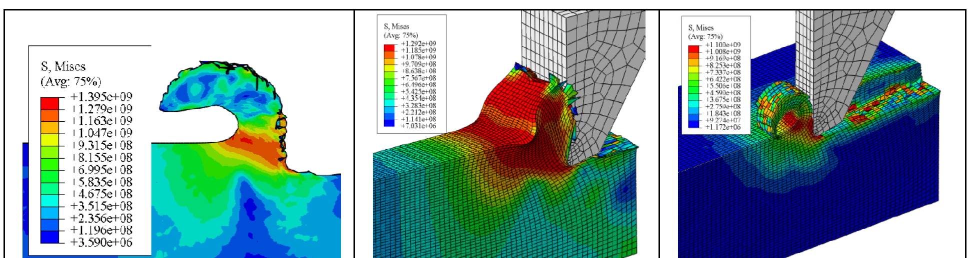


(a) 3d view of ploughing by single grit

(b) section view of single grit scratch

Figure 1 ploughing process without chip formation by using adaptive remeshing in Abaqus/Standard



a) example of 2D chip formatoin, depth of cut: 100 µm

b) workpiece width=200 µm, tool width=250 µm depth of cut=100 µm, # elements=76210 C3D8RT

c) workpiece width=1000 µm, tool width=200 µm depth of cut=60 µm, # elements=376210 C3D8R

Figure 2 Chip formation using (a) Johson-Cook Model and (b) Isotropic hardening model

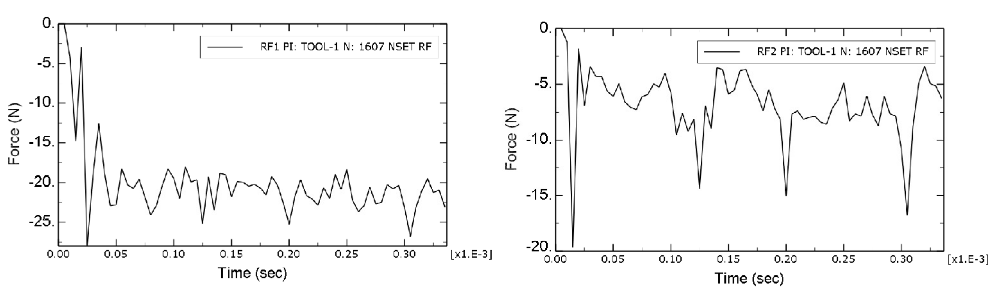


Figure 3 (a) cutting force and (b) thrust force variation for simulation in figure 2 -c