Simulation of Orthogonal Cutting Process Using Arbitrary Lagrangian-Eulerian Approach

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Abstract: - This papers presents a FEM simulation model for the analysis of cutting mechanics in turning process. In the simulation, Arbitrary Lagrangian Eulerian (ALE) formulation is utilized, due to large deformation existing in the chip formation process. In this paper, advantages of ALE approach are considered regarding Eulerian and Lagrangian approaches. This FE model considers dynamic effects, thermo-mechanical coupling, constitutive material model and friction.

Key-Words: Arbitrary Lagrangian Eulerian (ALE), Orthogonal Metal Cutting, chip formation, Simulation

1 Introduction

Metal cutting is a common way of shaping metals. From a mechanical point of view it is a complex process, of which the details are poorly understood. Because of the complicated mechanics of chip formation process and a lot of effective parameters on metal cutting process, there isn't any general model that is able to predict effects of all cutting parameters on machining performance. Traditionally, machining parameters were selected by considering past experiences, experimentation and prototyping. But this approach has some disadvantages such as high costs and lack of useful information. Furthermore, there isn't any proof that this approach lead to the best solution. In recent years, with development in computational technology, use of numerical simulation of the processes has been replaced costly experiments. In addition, use of finite element modeling in chip formation process provides information about variables that are difficult to measure such as temperature, energy or stress. [1][2]

But lack of accurate constitutive material model and contact laws due to complex mechanics of chip formation and insufficient verification makes the finite element modeling of metal cutting processes as an uncommon tool in industry. Thus, the researchers have presented, in literatures, some formulations that can be used in FEM of metal cutting process. Most of the literatures have been presented in metal cutting simulation, can be divided into two major categories. First, Lagrangian formulation in which the grid is attached to the material, and second, Eulerian formulation in which the grid isn't attached to the material. These two formulations aren't sufficient and accurate, lonely, in simulation of metal cutting process. But, in recent years, arbitrary Lagrangian Eulerian (ALE) formulation have been presented that have advantages of both Lagrangian and Eulerian formulations. In ALE formulation the grid isn't attached to the material and it can move to avoid distortion and update the free chip geometry. In this paper, the ability of ALE formulation in 2D finite element simulation of orthogonal cutting process will be shown. [1-5]

2 Arbitrary Lagrangian Eulerian (ALE)

There are two types analysis in which a continuous medium can be described in FEM modeling of forming processes: Eulerian and Lagrangian.

In Lagrangian approach, elements are attached to the material and move with material during forming processes. Thus, this approach is a useful technique in solid mechanics analysis. For using Lagrangian approach in metal cutting process, we must define a criterion for chip separation from the work piece. These criteria can be divided into two main categories: geometrical and physical criteria.

A geometrical separation criterion is based on defining threshold value. When the distance between the tool tip and the nearest node, ahead of the tool tip, is greater than threshold value, element deletion or node separation in FE model will occur.
On the other hand, a physical separation criterion is based on defining threshold value of selected physical variables, such as stress, equivalent plastic strain or strain energy density in the elements which are closest to the tool tip.
The Eulerian approach is more suitable for large deformation solids and fluid-flow problems. In this approach the elements are fixed spatially and material can flow in Eulerian boundary region, independently. Since the mesh is fixed spatially, no mesh distortion and no chip separation criterion is required and a prior assumption should be made about the shape of the chip. In this approach metal cutting process is considered as a pure deformation process. Thus the final shape of the chip that is obtained from a Lagrangian approach can be used as a prior shape of the chip in Eulerian approach. This is the base idea to combine the Eulerian and Lagrangian approach in metal cutting simulation.[1][6-10]
This general approach named Arbitrary Lagrangian Eulerian (ALE) in which the mesh is neither attached to the material nor fixed in space. The formulation of ALE approach will be discussed in following section. Explicit dynamic ALE formulation is a useful way to simulate highly nonlinear problems that involves large localized deformations and changing contact condition as those experienced in machining. ALE is utilized in this paper, for 2D simulation of orthogonal cutting process.
The formulation of ALE is different from Lagrangian and Eulerian approach, and has its own motion governing equations. In figure 1, $\vec{X}$ is Lagrangian coordinate of material point and $\vec{x}$ is Eulerian coordinate of spatial point and $\vec{\xi}$ is arbitrary coordinate of reference point (grid) and we have:

$$\vec{X} = \psi(\vec{x}, t) \tag{1}$$

$$\vec{x} = \hat{\psi}(\vec{\xi}, t) \tag{2}$$

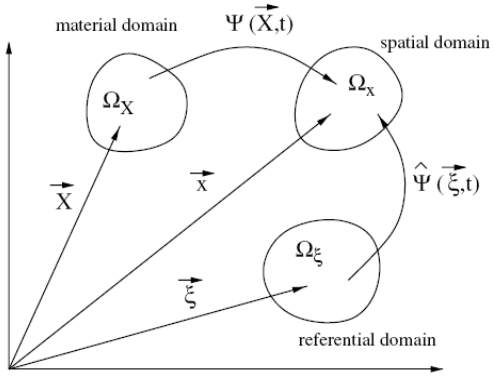

Figure 1: motion description in ALE approach.

Where (1) and (2) are material and grid motion equations, respectively. Pantale' et al. [11] represents the following equations:

$$\vec{v} = \dot{\vec{x}} = \frac{\partial \vec{x}}{\partial t}\Big|_{\vec{X}=cte} \tag{3}$$

$$\vec{\hat{v}} = \overset{\circ}{\vec{x}} = \frac{\partial \vec{x}}{\partial t}\Big|_{\vec{\xi}=cte} \tag{4}$$

Where $\vec{v}$ is material velocity that is obtained from a classical material $(\bullet)$ derivative, and $\vec{\hat{v}}$ is grid velocity that is obtained from a mixed $(\circ)$ derivative. The relationship between these two kinds of derivative is $(\bullet) = (\circ) + \vec{c}\nabla(\ )$, where $\vec{c} = \vec{v} - \vec{\hat{v}}$.
In ALE approach, conservation laws represented by equations (5)-(7):

$$\overset{o}{\rho} + \vec{c}\nabla\rho + \rho div\,\vec{v} = 0 \tag{5}$$

$$\rho\overset{o}{\vec{v}} + \rho\vec{c}\nabla\vec{v} = \vec{f} + div\sigma \tag{6}$$

$$\rho\overset{o}{e} + \rho\vec{c}\nabla e = \sigma : D - div\vec{q} + r \tag{7}$$

Where ρ is the mass density, $\vec{f}$ are body forces, σ is the Cauchy stress tensor, e is the specific internal energy, D is the strain rate tensor, r is the body heat generation and $\vec{q}$ is the heat flux vector. For spatial discrimination, we define all dependent variables as functions of element coordinates.
The ALE coordinates are given by $\xi = \xi_I N_I$, where N are the geometrical shape functions of element e.
We multiply equations (5)-(7) by a set of weighting functions ($\overset{\circ}{\rho}^*, \overset{\circ}{v}^*, \overset{\circ}{e}^*$) over the spatial domain R_x and then, by using divergence theorem and Galerkin approach, corresponding discredited equations are

obtained:

$$M^{\rho}\overset{o}{\rho}+L^{\rho}\rho+K^{\rho}\rho=0 \quad (8)$$

$$M^{v}\overset{o}{v}+L^{v}v+f^{\text{int}}=f^{ext} \quad (9)$$

$$M^{e}\overset{o}{e}+L^{e}e=r \quad (10)$$

Where M^{ρ}, M^{V}, M^{e} are generalized mass matrices, L^{ρ}, L^{v}, L^{e} are the generalized convective matrices, K^{ρ} is the stiffness matrix for density, f^{int} is the internal force vector, f^{ext} is the external force vector, r is the generalized energy source vector. [2][6].

The adaptive meshing technique In ABAQUS software utilized for ALE approach and makes it possible to maintain a high-quality mesh throughout an analysis, even when large deformation or loss of material occurs, by allowing the mesh to move independent of the material. Adaptive meshing consists of two fundamental tasks:

1- Creating a new mesh, and

2- Remapping solution variables from the old mesh to the new mesh with a process called advection.

A new mesh is created at a specified frequency for each adaptive domain and is found by sweeping iteratively over the adaptive mesh domain and moving nodes to smooth the mesh. The process of mapping solution variables from an old mesh to a new mesh is referred to as an advection sweep. At least one advection sweep is performed in every adaptive mesh increment. The determination of the new mesh in ABAQUS/Explicit is based on four aspects.

First, the calculation of the new mesh in ABAQUS/Explicit is based on some combination of three basic smoothing methods: volume smoothing, Laplacian smoothing, and equipotential smoothing. The smoothing methods are applied at each node in the adaptive mesh domain to determine the new location of the node based on the locations of surrounding nodes or elements. Although all the smoothing methods tend to smooth the mesh and reduce element distortion, the resulting meshes will differ depending on the methods used.

Second, initial element gradation can be maintained at the expense of element distortion if desired. Third, optimal positioning of the nodes before the basic smoothing methods are applied can improve mesh quality and minimize the frequency of adaptive meshing required.

Finally, solution-dependent meshing is used to concentrate mesh refinement near areas of evolving boundary curvature. This counteracts the tendency of the basic smoothing methods to reduce the mesh refinement near concave boundaries where solution accuracy is important.

Volume smoothing relocates a node by computing a volume-weighted average of the element centers in the elements surrounding the node. We use only volume smoothing for analysis in this paper.

Laplacian smoothing relocates a node by calculating the average of the positions of each of the adjacent nodes connected by an element edge to the node in question.

Equipotential smoothing is a higher-order method that relocates a node by calculating a higher-order, weighted average of the positions of the node's eight nearest neighbor nodes in two dimensions (or its eighteen nearest neighbor nodes in three dimensions).

When more than one smoothing method is used, a node is relocated by computing a weighted average of the locations predicted by each chosen method. All weights must be positive, and their sum should typically be 1.0. [12]

3 Finite element model

Because of complicated mechanics of chip formation process, we must use a suitable material model for simulation. Thus, the thermo-viscoplastic behavior of the work piece material is modeled by Johnson-Cook (JC) constitutive law. JC describe the flow stress of material $(\overline{\sigma})$ with the product of strain, strain rate and temperature.

$$\overline{\sigma}=\left[A+B\times(\overline{\varepsilon})^{n}\right]\times\left[1+C\times\ln\left(\dot{\overline{\varepsilon}}\Big/\dot{\overline{\varepsilon}}_{o}\right)\right]\times\left[1-\left(\frac{\theta_w-\theta_o}{\theta_m-\theta_o}\right)^{m}\right] \quad (11)$$

In JC constitutive model, $\overline{\varepsilon}$ is the plastic strain, $\dot{\overline{\varepsilon}}$ is the strain rate, $\dot{\overline{\varepsilon}}_{o}$ is the reference plastic strain rate, θ_w is the work piece material temperature, θ_m is the melting temperature of the work piece material and θ_o is the room temperature.

A, B, C, m, n are material parameters like as $T_o, T_{melt}, \dot{\overline{\varepsilon}}_{o}$. A is the yield strength, B is the hardening modulus, C is the strain rate sensivity coefficient, n is the hardening coefficient and m is the thermal softening coefficient. JC parameters used in figure 3 are given in table 1.

During cutting process, flow stress is dependent on temperature. Then we use an explicit coupled thermal-stress analysis.
Complicated mechanics of chip formation and chip separation processes and thermal effects of process make difficult simulation of metal cutting. In Many literatures have been presented different models of friction between work piece and tool. Coulomb Friction model utilized in this paper, with a friction coefficient μ=0.3.

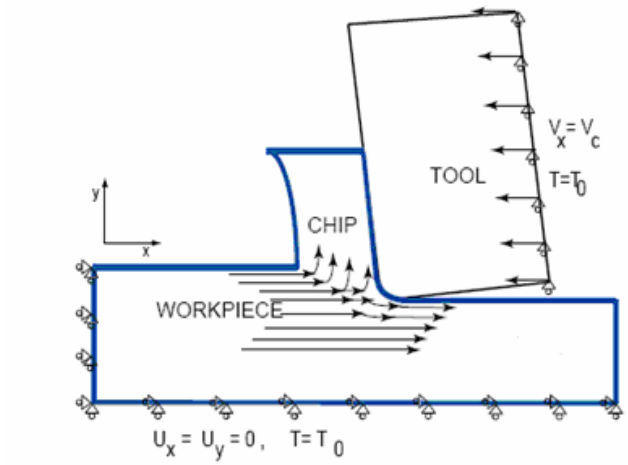

Figure 3: 2D Model of chip formation process

Plane strain with four nodes elements are used (CPE4RT).
Simulation of the chip formation process, as mentioned earlier, is divided into to adaptivity processes. In first step, work piece is fixed in space and tool is moved with the specified velocity. The first step is utilized for initial chip formation. Then, in the second step, tool is fixed in space and work piece is moved toward the tool.

Table 1: JC material model parameters

A	595 MPa	n	0.133
B	580 MPa	m	1.03
C	0.023	T_{melt}	1793 K

Other properties of the work piece material that have been used are:

Conductivity= 50 (W/mCo)
Thermal Expansion= 11E-6 (m/mCo)
Specific heat= 450 (J/kg/Co)
Cutting parameters for the turning process are given in table 2.

Table 2: machining parameters

Work piece material	42 Cr Mo 4
Cutting speed (Vc)	4 m/s
Depth of cut (S)	0.5 mm
Width of workpiece (W)	2 mm
Length of workpiece (Lw)	10 mm
Height of workpiece (hw)	5 mm
Thickness of workpiece (tw)	2 mm
Rake angle of tool	5.7o
Flank angle of tool	5.7o
Radius of cutting edge	0.1 mm
Initial temperature	300 k

4 Results

This FEM of orthogonal metal cutting process show the tool penetration in the work piece and the chip separation. In agreement with experimental result [13] the chip is a continuous one due to material model and cutting condition chosen.
Figures 4-6 show the maximum of Von Mises stress occur in the primary shear band.

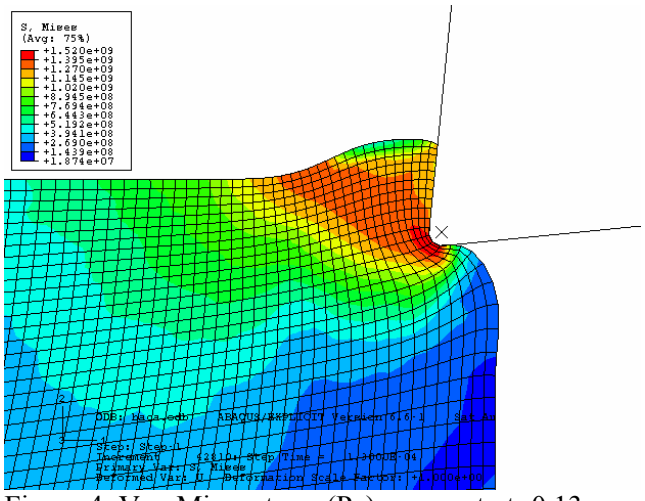

Figure 4: Von Mises stress (Pa) at t=0.13 ms

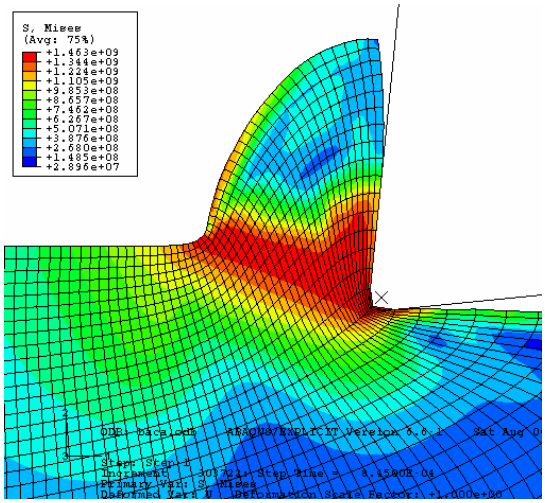

Figure 5: Von Mises stress (Pa) at t=.845 ms

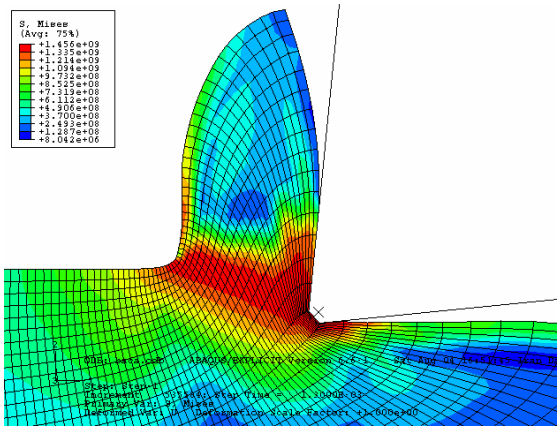

Figure 6: Von Mises stress (Pa) at t=1.3 ms

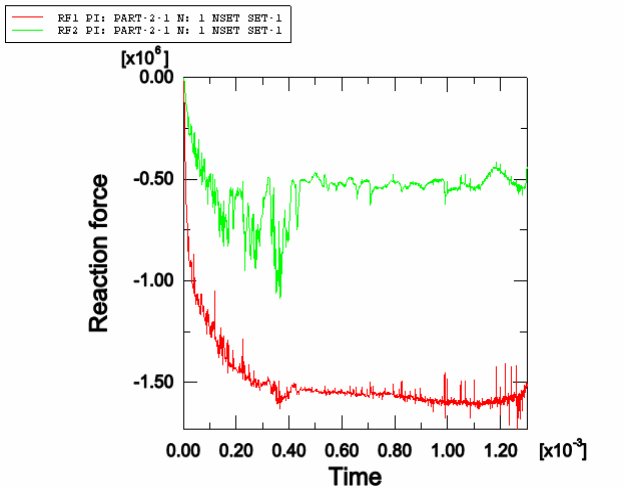

Figure 7: Cutting force changes in turning process

Cutting forces obtained from FEM of orthogonal metal cutting process are also in agreement with the result of experiment. [13][2]
As shown in figure 7, after formation of stable continuous chip, cutting force reach about 1700 kN, that is close to experimental result (1860 kN).

5 Conclusion

In this paper, we have used ALE formulation in the simulation of the orthogonal metal cutting process and cutting process. Johnson-Cook material model and Coulomb friction model are also used for the FEM of turning process. The simulation of the chip formation, stress field, cutting forces are successfully achieved. Small differences between numerical results and experimental results are due to complicated mechanics of process and unsuitable parameters for material model and friction model that have been used in the analysis. In summery, ALE formulation has good capability for FEM of metal cutting process with respect to Eulerian and Lagrangian formulation, lonely.

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