SIMULATION OF CHIP FORMATION IN MACHINING

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ABSTRACT: An Arbitrary Lagrangian Eulerian (ALE) approach is used in this paper to model both continuous two-dimensional and three-dimensional orthogonal and oblique steady-state metal cutting. The thermo-mechanical coupled model includes the effects of elastoplasticity, high strain and strain rates, heat generation and friction between the chip and the tool. A thermal-viscoplastic constitutive equation associated to the Johnson-Cook flow law is adopted for the workpiece.

INTRODUCTION: Among earlier major works in modeling, Marushich et al. [1995] presented a numerical two-dimensional model of an orthogonal metal cutting process including crack propagation, suitable for modelling non continuous chip formation. In this paper, we present two and three-dimensional numerical models of orthogonal and oblique metal cutting processes. Both are based on an Arbitrary Lagrangian Eulerian (ALE) approach, generally dedicated to fluid simulations. Those models are ones of the first application of such an approach to cutting simulation. Briefly speaking, the use of this approach combines the advantages of both classic representations in a single description which can be considered as an automatic and continuous rezoning method.

PROCEDURE, RESULTS AND DISCUSSION: The Arbitrary Lagrangian Eulerian formulation is an extension of both classic Lagrangian and Eulerian ones where grid points may have an arbitrary motion (Joyot et al. [1998]). A constitutive equation used in cutting models must take into account plasticity or visco-plasticity, temperature, strain rate and damage, if we want to simulate discontinuous chip formation. In this paper the numerical model adopted is suitable for simulating continuous steady-state metal cutting as a thermo-elastoplastic constitutive equation associated with the Johnson Cook flow law has been adopted (Johnson et al. [1983]).

In a metal cutting process, because of high stresses, high strain rates and high temperatures, a high mechanical power is dissipated in the tool-chip interface this leading to many structural modifications of the contacting pieces. No universal contact law exists which can predict friction forces among a wide range of cutting conditions. Experience actually shows that stick and slip zones along the interfacial zone between the chip and the tool depend on cutting conditions, pressure, temperature, etc (Childs et al. [1990]).

In our model, a classic Coulomb friction law is assumed to model the tool-chip and the tool-workpiece contact zone. The contact algorithm also includes thermal capacities. Heat generation and heat transfer at the interface are taken into account. Generated heat flux is divided among pieces in contact in a ratio depending on the thermal features of both pieces, geometry and sliding conditions.

A finite element method (FEM) is adopted for the discretization of the momentum equation, while a finite volume method (FVM) is used for the discretization of the mass and the energy equations because of simplicity. An explicit integration scheme is adopted for time discretization. A total compatibility between FVM and FEM is ensured by setting identical control volumes and finite elements. Concerning time integration, a third-order explicit central difference scheme is used. Grid speed for one node at the end of an increment is given by the Giuliani relationship (Pantalé et al. [1998]).

Two-dimensional Orthogonal Cutting Simulations: Several numerical simulations are presented in this paper to illustrate steady state orthogonal and oblique metal cutting of a 42CD-4 steel with a tungsten carbide tool (SECO TPGN-160302 P10 tool). Neither geometry of the chip nor the contact length are known at the beginning of the calculation. Here the workpiece is modeled using an ALE formulation while the tool is rigid and Lagrangian . We used a Master/Slave algorithm for the tool-chip contact.
In addition to the ALE nodes of the workpiece, a typical finite element mesh contains purely Eulerian or purely Lagrangian nodes. By definition, an Eulerian node has a zero grid velocity while a Lagrangian node moves with the corresponding material node. The description of the free-surfaces of the model uses nodes which are simultaneously Lagrangian in the normal direction and Eulerian in tangential direction allowing a continuous update of the free surface location until the steady-state condition is reached. This means that the normal component of the material velocity reaches zero. In this sense the model is equivalent to an Eulerian one when the steady state solution is obtained (see Joyot et al. [1998] for futher details).
Concerning the thermal boundary condition, we assumed that all surfaces are adiabatic except for the contact surface where the heat flux created by the friction is prescribed.
The friction coefficient $C_f = 0.32$ has been obtained from an experimental apparatus by applying a normal force on a tool in contact with the rotating workpiece, and measuring the corresponding tangential forces (Joyot et al. [1998]). The thermal properties of the tool are supposed to be matched to those of the workpiece, giving an equal proportion of frictional heat allotted to the tool and the chip according to the Vernotte relationship linking the sharing coefficient α and the material effusivities of the two contacting bodies.
A sensivity analysis has been done on friction. Fig.1 shows chip geometry and temperature evolutions according to the following Coulomb friction coefficient values: $\mu = 0.10$; 0.32; 0.50; 0.70. Temperatures are in the range $300°K$ to $975°K$. In addition, Table 1 gives variations of cutting forces (F_c and F_a) and the tool-chip contact length (L_c) in function of the friction coefficient.

Fig.2 is associated with a simulation of the cutting process with a cratered tool showing the stabilized geometry with the Von-mises equivalent stresse. The influence of the crater on the numerical cutting force is significant: an increase of the order of 15 per cent was noted for simulated cases (for a crater of $0.35\mu m$ of depth).

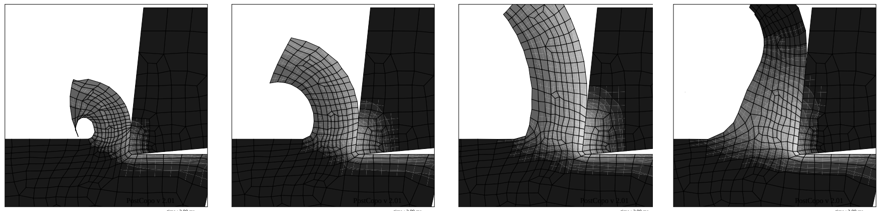

Figure 1: Friction Coefficient Sensivity Analysis

μ	0.10	0.32	0.50	0.70
F_c	$512N$	$579N$	$676N$	$695N$
F_a	$23N$	$145N$	$321N$	$472N$
L_c	$0.39mm$	$0.47mm$	$0.80mm$	$1.17mm$

Table 1: Numerical results of the friction sensivity analysis

Three-Dimensional Cutting Simulation: The use of a three-dimensional approach allows taking into account boundary effects in the transverse direction.
In our model we introduced an arbitrary initial geometry deduced from a two-dimensional simulation which is updated during the computation with a view to reduce simulation time.
The first application concerns a three-dimensional steady-state simulation of the orthogonal metal cutting process. The material properties of the tool and workpiece and the process characteristics are given in a previous publication (Pantalé et al. [1998]). The meshing used here is about 6400 nodes and 5200 elements. Time steps are of the order of $5.10^{-9}s$ which necessitates 8.10^5 steps (i.e. a total CPU time of 3or 4 days on a Silicon Graphics R4000). Comparisons (reported in Table 2) of experimental measurements of the cutting and advancing forces with numerical ones show a very good agreement. Table 2 also reports calculated temperatures in the secondary shear zone and comparison with an analytical result obtained using the Oxley model. The Oxley model gives direct the average temperature in the secondary shear zone, therefore an average temperature computation in the corresponding area has been done in the numerical model for comparison.

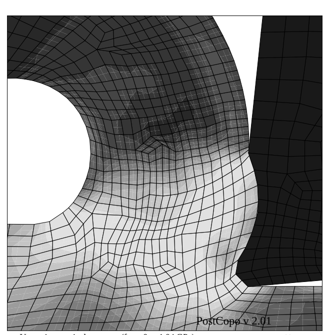

Figure 2: Von-mises stress using a craterized tool

F_c	$2209N$	F_c	$2150N$
F_a	$690N$	F_a	$720N$
$T_{chip_{max}}$	$910°C$	$T_{chip_{oxley}}$	$936°C$
$L_{T_{max}}$	$533\mu m$	$L_{d_{crater}}$	$530\mu m$
numerical results		experimental results	

Table 2: Numerical and Experimental Results

The second application concerns the numerical simulation of an oblique cutting process. In the presented model, we introduce an angle $\kappa = 75°$ as show on Fig.3. All the cutting parameters are the same as those used in the orthogonal model. Introducing $15°$ of oblicity in the model ($\kappa = 75°$) has an influence on all the results of the model. This causes the chip to flow in a lateral direction. Temperatures are quite the same as those obtained with the orthogonal model. Cutting and advancing forces F_c and F_a have been reduced, but the lateral force F_z increases in a wide range. Fig.3 shows four representations of the chip at the end of the calculus.

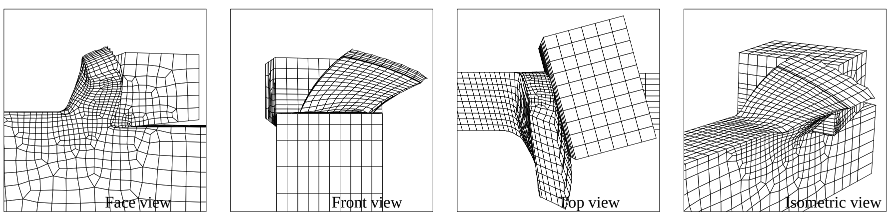

Figure 3: 3D Representations of the Oblique Cutting

CONCLUSIONS: An Arbitrary Lagrangian Eulerian cutting model was used to simulate the orthogonal and oblique cutting process. Different comparisons between numerical results and experimental measurements show a good level of agreement. Future works concern some investigations on constitutive and contact laws and shear band formation to simulate discontinuous chip.

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