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Numerical modelling of orthogonal cutting: Influence of cutting conditions and separation criterion

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Abstract. Chip formation is a high strain rate process studied with analytical and numerical models. Analytical models have the advantage of a small calculation time, however, they are often based on some assumptions which are difficult to verify. Finite element modelling (FEM) of chip formation process provides more details on the chip process formation, such as plastic strain, strain rate or stress fields. FEM can be used to improve the analytical models' assumptions. There is still a wide dispersion of formulations and numerical parameters adopted in order to obtain accurate results in numerical models. In the Lagrangian approach, it is of crucial importance to establish realistic criteria for element deletion, allowing chip separation from original workpiece. In the arbitrary Lagrangian Eulerian (ALE) formulation no element deletion is needed. This work is focused in modelization of orthogonal cutting. A comparison between both numerical approaches, Lagrangian and ALE is shown. The effects of geometrical parameters, erosion criterion and cutting speed are evaluated. Comparisons between numerical and theoretical results are performed, and the results obtained from the numerical approach are used as an input of analytical model, improving its accuracy.

1. INTRODUCTION

Cutting is a common way of shaping metals, being a complex process due to very large strains and strain-rates, which causes large increments of temperature. Although many authors have paid attention to the study of metal cutting processes, details are still poorly understood. Improvement of tool performance and quality surface imply good understanding of the process. Since most variables of the process are difficult to measure, analytical and numerical modelling of chip formation are versatile and reliable approaches to obtain information on some variables on the workpiece and the cutting tool. In the analytical model of Molinari et al. [1,2], the chip formation is supposed to occur mainly by shearing within a thin zone called the primary shear band. Thermomechanical coupling and the inertia effects (which are important at high cutting speeds) are accounted for. The primary shear zone is considered as a thin band of constant thickness h. The inclination of the primary shear zone with respect to the cutting direction is given by the normal shear angle ϕ, see Fig.1. The plastic deformation in the chip is supposed to be limited to this band. The complex material flow near the tool edge and the secondary shear zone, due to the friction at the tool-chip interface, are neglected. The analysis is limited to stationary flow (no time dependence). The material flow within the primary shear zone is modelled by using a one dimensional approach where all the variables in the band depend solely on the coordinate z along the normal to the band. On the other hand, at the tool-chip interface the friction condition can be affected by the important heating induced by the large values of pressure and sliding velocity. A Coulomb friction law with a friction coefficient dependent on the mean interface temperature is introduced [2].

Finite element modelling of chip formation process provides information on some difficult to measure variable like plastic strain, strain rate or stress, and thus it contributes to improve general

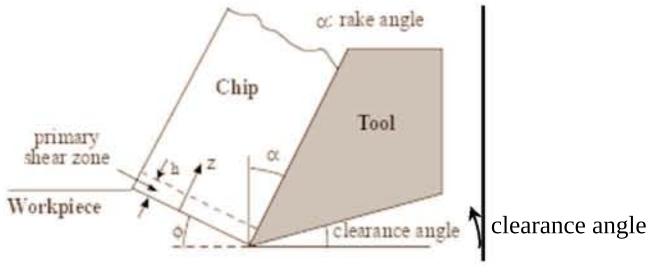

Figure 1. Scheme of primary shear zone for analytical model.

understanding of machining process. In Lagrangian approach, element deletion criterion should be established in order to avoid large distortion in the mesh and permit separation [3] or dynamic remeshing process should be used [4]. The arbitrary Lagrangian Eulerian (ALE) formulation has emerged in recent years as a technique that can alleviate many of the drawbacks of the traditional Lagrangian and Eulerian formulations [5]. Using ALE, the computational grid need not adhere to the material nor be fixed in space but can be moved arbitrarily. The grid is continuously moved to optimise element shapes independently from material deformation [6]. The aim of this paper is to show a comparison between analytical and numerical modelling, both Lagrangian and ALE formulation. An element deletion criterion is established in Lagrangian approach, and the influence of the tool geometry and the cutting speed is studied. The paper is focused in 2D simulation of orthogonal cutting process. Advantages of each formulation are showed.

2. FINITE ELEMENT MODELLING

The numerical simulations were performed with the commercial code ABAQUS/Explicit. The tool geometry and the cutting conditions are listed in table 1 and table 2, for Lagrangian and ALE approaches respectively. Figure 2 shows the initial geometry of Lagrangian and ALE models corresponding to a rake angle equal to 0°. Two minor differences are: element layer of 2 μm in the lagrangian mesh acting as an interface between the upper part of the workpiece (which will be cut forming the chip) and the lower part of the workpiece (wich will be the machined surface) to minimize the losses of material due to erosion and allow separation; small tool tip radius of 15 microns in the ALE mesh to avoid numerical problems. 4-node bilinear displacement and temperature element, with reduced integration and hourglass control (CPE4RT in ABAQUS notation) was chosen for both tool and workpiece solids, lagrangian and ALE meshes. The characteristic lengths of the element edge are 5 μm for the workpiece and 8 μm for the tool. Assuming a Mises type yield criterion and an isotropic strain hardening rule for the workpiece material, the yield stress σ_Y is given by the Johnson-Cook equation [7], which considers viscoplastic hardening and thermal softening.

Table 1. The cutting conditions and tool geometry used in Lagrangian approach.

rake angle α	clearance angle	cutting speed *V (m/min)*	Cutting depth t_1	Cutting environment
0°	7°	12, 30, 120, 240, 360, 480	0.1 mm	dry

Table 2. The cutting conditions and tool geometry used in ALE approach.

rake angle α	clearance angle	cutting speed *V(m/min)*	Cutting depth t_1	Cutting environment
−10°, 0°, 10°	7°	12, 30, 120, 240, 360, 480	0.1 mm	dry

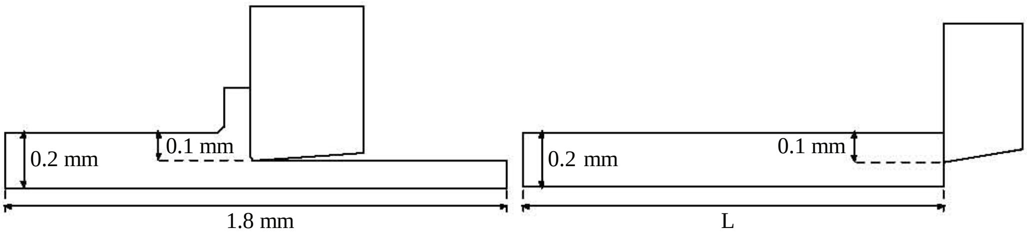

Figure 2. Left: initial geometry of the Lagrangian model for rake angle $\alpha = 0$, L depending on the cutting velocity. Right: initial geometry of the ALE model for rake angle $\alpha = 0$.

The tool was assumed to behave as an elastic solid. Table 3 shows the mechanical parameters and table 4 the thermal parameters of both material models.

An element deletion criterion based on a critical value of the equivalent plastic strain $\varepsilon_p = 3.5$ was considered in the lagrangian mesh for the workpiece material. This serves to erode the thin layer keeping the material at the chip. Previous work showed small influence of this criterion in cutting forces and temperature distribution, when critical value ranged from equivalent plastic strain 0.5 to 3.5. No distortion was observed in the mesh with this criterion.

An initial temperature of 293 K was fixed for both solids. Although friction phenomena produce an intense heating at the tool-chip interface, no friction was considered as a first approximation to the problem. The heat flux per unit area q crossing the tool-chip interface is assumed to follow the equation

$$q = k(\theta_{chip} - \theta_{tool}) \tag{1}$$

θ being temperature, and k the gap conductance defined through a linear function of the clearence between surfaces.

Lagrangian model resulted in high calculation time, close to 48 hours in a double Intel Xeon workstation. ALE formulation reduced significantly calculation time, less than 24 hours in the same computer. Mass Scaling option was used in order to fix a lower limit of integration time. Results obtained from both models were very similar in chip morphology (figure 3), shear angle and cutting forces (figure 4).

Both numerical models were used to analyse influence of several parameters in model results (cutting forces and shear angle mainly). The influence of the geometry is presented in figures 4a and 4b, showing a well known behaviour where the cutting force decreases and the shear angle increases with the rake angle. The shear angle from both ALE and Lagrangian approaches are much lower than shear angle predicted from Merchant theory [9], according to other works [4].

Table 3. Mechanical parameters of the workpiece [8] and tool [11] material models. β: Quinney-Taylor coefficient.

	ρ (kg/m^3)	E(GPa)	ν	A(MPa)	B(MPa)	n	$\dot{\varepsilon}_o$(s^{-1})	$\tilde{C}$	m	β
WP: steel 42CrMo4	7800	202	0.3	612	436	0.15	5.77E-4	0.008	1.46	0.9
Tool: carbide	12700	1000	0.3	-	-	-	-	-	-	

Table 4. Thermal parameters of workpiece [8] and tool [11] material models.

	specific heat (J/kg/K)	thermal conductivity (W/m/K)
WP: 42CrMo4 steel	500	54
Tool: carbide	234	33.5

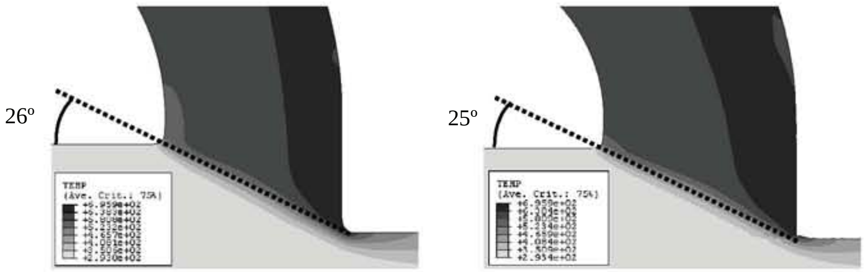

Figure 3. Picture showing chip shape, shear angle and temperature distribution for cutting velocity $= 240\,\text{m/min}$ and rake angle $= 0°$. Left: ALE mesh; right: Lagrangian mesh.

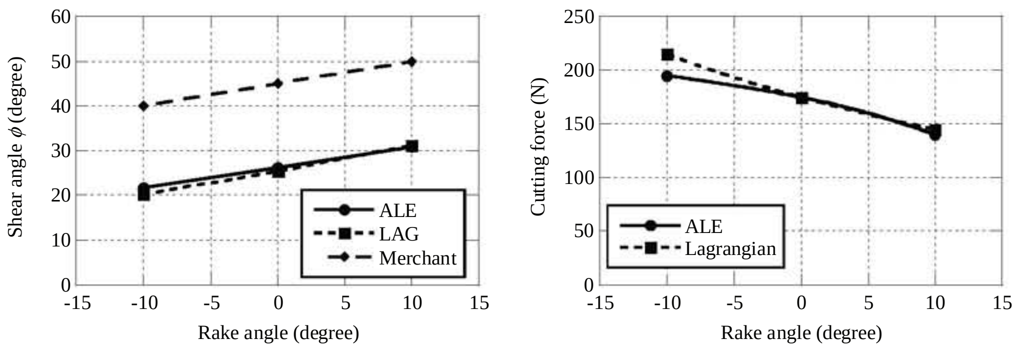

Figure 4. Left: shear angle versus rake angle; right: cutting force per mm of cutting width versus rake angle. Cutting velocity: 240 m/min.

3. ANALYTICAL MODEL

As it was indicated previously, the analytical model of Molinari et al. [1] is based on a one dimensional approach: all the variables in the band depend solely on the coordinate z along the normal to the band. In the primary shear band, the distributions of the shear stress τ, the shear strain rate $\dot{\gamma}$ and the absolute temperature θ, are obtained from the integration of the conservation equations of momentum, and of energy (assuming adiabatic conditions) by using the constitutive law. The plastic deformation is supposed to be limited to the primary shear zone. Then we have two boundary conditions: $\gamma(z = 0) = 0$ at the entrance and $\gamma(z = h) = \gamma_h$ at the outflow of the shear band with:

$$\gamma_h = \frac{cos\alpha}{sin\phi\, cos(\phi - \alpha)} \tag{2}$$

The integration of the differential equation corresponding to the material derivative of the shear strain γ leads to:

$$\int_0^{\gamma_h} \frac{V\, sin\phi}{\dot{\gamma}(\gamma, \tau_0)}\, d\gamma - h = 0 \tag{3}$$

If we suppose given the shear angle ϕ in this non linear equation, the only unknown parameter is the shear stress τ_0 at the entry of the primary shear band (for a given value of h). The quadrature in equation (3) is made by using the Gauss method, and τ_0 is calculated following a Newton-Raphson scheme. The cutting and feed forces F_P and F_Q are then calculated with the relations:

$$F_P = \frac{cos(\lambda - \alpha)}{sin\phi cos(\phi + \lambda - \alpha)} w t_1 \tau_h \quad and \quad F_Q = \frac{sin(\lambda - \alpha)}{sin\phi cos(\phi + \lambda - \alpha)} w t_1 \tau_h \tag{4}$$

where w, t_1 and λ represent respectively the with of cut, the undeformed chip thickness and the mean friction angle at the tool-chip interface. Note that the shear stress at the exit of the primary shear zone $\tau_h = \tau(z = h)$ is given by:

$$\tau_h = \rho V^2 \frac{sin\phi cos\alpha}{cos(\phi - \alpha)} + \tau_0 \tag{5}$$

ρ being the material density. The shear stress τ_0 is the solution of the non linear equation (3) for given values of ϕ and h. Note also that the thickness h can be estimated from experimental results or FE simulations. The shear angle ϕ can be determined from the minimisation of cutting energy such as in Merchant's model [9].

4. COMPARISON BETWEEN NUMERICAL APPROACH AND ANALYTICAL MODEL

In this paragraph, a comparison between analytical results using the model reported in [1] and FE simulation is presented. For the analytical approach, the thickness h of the primary shear zone is taken as $h = 0.025\,mm$ in agreement with [10]. The angle $\phi_{FE}(V)$ used in the analytical approach has been calculated from the numerical simulations performed for $V = 12, 30, 120, 240, 360, 480\,m/min$. Moreover, two cases have been considered: adiabatic condition ($\kappa = 0$) and with conductivity ($\kappa > 0$). In both FE and analytical approaches considering $\kappa > 0$ two regions are observed: a decrease of the cutting force below $V = 120\,m/min$ due to predominance of conduction (temperature map, Fig. 5) and a stagnation of the force for $V > 120\,m/min$. In this last case, the process doesn't allow conduction and the convection is predominant (temperature map, Fig. 5) inducing. a condition close to adiabaticity for which a stronger thermal softening in the material facilitates the chip formation. As can be seen in Fig. 5, the analytical and FE results obtained using adiabatic condition for $V > 120\,m/min$ are close to the numerical results obtained for $\kappa > 0$.

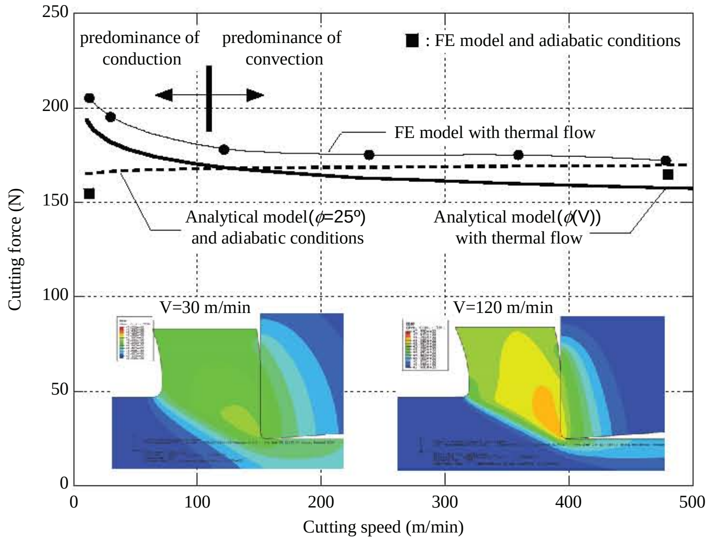

Figure 5. Cutting force per mm of cutting width versus cutting speed, numerical and analytical. Feed rate 0.1 mm and rake angle 0.

5. CONCLUSIONS AND FUTURE WORK

Analytical models present many advantages when simulating metal cutting, namely reduced calculation time and applications to the industrial process such as turning, milling and drilling. Numerical models could improve results obtained with analytical approach, using some numerical results as an input for analytical model: for instance the laws governing the variation of h and ϕ in terms of cutting conditions, material behaviour and friction conditions at the tool-chip interface. This approach combines advantages of both methods: accuracy and reduced calculation time. Future work should be done in order to complete this study. The work should include influence of feed rate, friction tool-chip and comparison with experimental test.

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References

[1] A. Molinari, D. Dudzinski, Stationary shear band in high-speed machining, C.R. Acad. Sci. Paris 315 (II) (1992) 399-405.
[2] A. Moufki, A. Molinari, D. Dudzinski, Modelling of orthogonal cutting with a temperature dependent friction law, J. Mech. Phys. Solids 46 (10) (1998) 2103-2138.
[3] M. Barge, H. Hamdi, J. Rech, J.M. Bergheau, Numerical modelling of orthogonal cutting: influence of numerical parameters, J. Mat. Process. Tech. 164-165 (2005) 1148-1153.
[4] M. Bäker, Does chip formation minimize the energy?, Comp. Mat. Sci. 33 (2005) 407-418.
[5] M.S. Gadala, Recent trends in ALE formulation and its applications in solid mechanics, Comput. Methods Appl. Mech. Engrg. 193 (2004) 4247-4275.
[6] A.H. Adibi-Sedeh, M. Vaziri, V. Pednekar, V. Madhavan, R. Ivester, Investigation of the effect of using different material models on finite element simulations of machining, Proc. 8^{th} CIRP Int. Workshop on Modeling of Machining Operations, Chemnitz, Germany (2005), 215-224.
[7] G.R. Johnson, W.H. Cook, A constitutive model and data for metals subjected to large strains, high strain rates, and temperatures. 7th International Symposium Ballistics. The Hague, The Netherlands (1983), pp. 1–7.
[8] A. Molinari, A. Moufki, D. Dudzinski, Etude du comportement du 42CD4, Final Technical Report, CREAS Ascometal, (1997).
[9] M.E. Merchant, (1945) Mechanics of the metal cutting process, I. Orthogonal cutting. *J. Appl. Phys*. 16, 267-275; II Plasticity conditions in orthogonal cutting. *J. Appl. Phys*. 16, 318-324.
[10] M. C. Shaw, Metal Cutting Principles, Oxford Science Publications, Oxford, 1984.
[11] Z.C. Lin, S.Y. Lin, A coupled finite element model of thermo-elastic-plastic large deformation for orthogonal cutting, ASME *Journal of Engineering Materials and Technology* 114 (1992) 218-226.