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FINITE ELEMENT MODELING OF CHIP FORMATION PROCESS WITH ABAQUS/EXPLICIT™ 6.3

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Summary. *A 2D Finite Element Model (F.E.M.) of chip formation process, set up with an Arbitrary Lagrangian Eulerian (A.L.E.) formulation, proposed in the software Abaqus/Explicit™ v6.3, is shown. The experimental validation showed a good qualitative agreement. Thus, FEM of cutting process can be considered as a promising and reliable tool for machining development within the near future.*

1 INTRODUCTION

In machining process, quite often, process parameters selection is done considering past experience and experimental tests. This approach can lead to high costs and, even worse not necessarily to the best solution.

Despite some limitations: difficulties in identifying entry parameters, lack of robustness in quantitative results and so on, Finite Element Modeling of chip formation process can be considered as a promising approach to study the cutting process, allowing to reduce the experimental cost. It provides information on some difficult to measure variables like temperature, energy or stress and thus, it contributes to improve general understanding of chip formation process [1, 2, 3, 4, 5].

Three kinds of mechanical formulation can be used. Eulerian formulation [1], in which the grid is not attached to the material, is computationally efficient but needs to update the free chip geometry [2]. Lagrangian formulation, in which the grid is attached to the material, requires to update the mesh (remeshing algorithm) or to use a chip separation criterion to form a chip from the workpiece [3]. An alternative method is to use Arbitrary Lagrangian Eulerian (ALE) formulation [4, 6, 7]. In this case, the grid is not attached to the material and it can move to avoid distortion and update the free chip geometry.

The main objective of this paper is to show the possibilities of F.E.M. of chip formation process.

First, the numerical model set up in *Abaqus/Explicit™* (v6.3) is described briefly. Then, the experimental validation is detailed. Finally, overall conclusions are pointed out.

2 FINITE ELEMENT MODEL OF CHIP FORMATION PROCESS

The general-purpose FEA software *Abaqus/Explicit™* (v6.3) has been used to set up the finite element model in two dimensions (2D, orthogonal cutting), allowing easy modification of entry parameters. The model takes into account only the area closer to the cutting edge, where the chip is formed (see Figure 1A).

In Figure 1B, the mechanical and thermal boundary conditions of the 2D finite element model are briefly shown [5]. Workpiece is defined as a deformable body, while the tool is considered rigid. The workpiece is considered as a tube with one entrance and two exits, and the workpiece material flows from left to right (see Figure 1B). Coupled mechanical and thermal analysis is done using the A.L.E. formulation, which allows reaching steady state conditions after approximately 3 milliseconds of machining time at the cutting speed (v) of 300 m.min^{-1}.

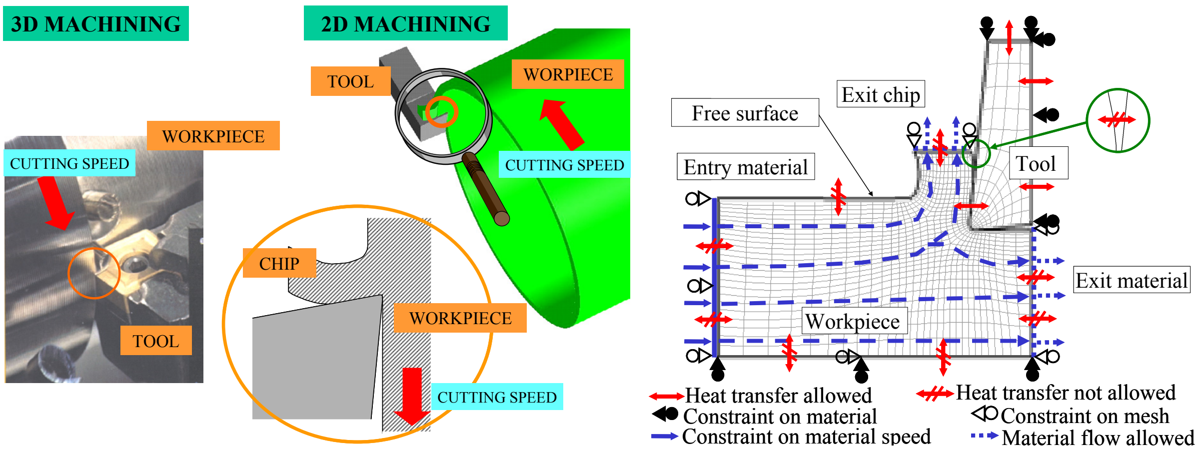

Figure 1: A) Studied area in 2D Finite Element modeling of chip formation process.
B) Mechanical and thermal boundary conditions.

2D analysis is a restrictive approach from an industrial point of view, but it is considered accurate enough to make a sensitivity analysis in order to validate numerical results. Furthermore, it reduces significantly the computational time.

Despite of the limitations reported in bibliography [8], the thermo-viscoplastic behaviour of the workpiece material is modelled by the Johnson-Cook (JC) [9] constitutive law. In this law the flow stress $\bar{\sigma}$ is given by:

$$\bar{\sigma} = \left[A + B \times (\bar{\varepsilon})^n\right] \times \left[1 + C \times \ln\left(\dot{\bar{\varepsilon}}/\dot{\bar{\varepsilon}}_0\right)\right] \times \left[1 - \left(\frac{\theta_w - \theta_0}{\theta_m - \theta_0}\right)^m\right] \quad (1)$$

In the above expression, $\bar{\varepsilon}$ is the plastic strain, $\dot{\bar{\varepsilon}}$ is the strain rate, $\dot{\bar{\varepsilon}}_0$ is the reference plastic strain rate (0.001s^{-1}), θ_w is the workpiece material temperature, θ_m (1793K) is the melting temperature of the workpiece material and θ_o (293K) is the room temperature. The coefficient A is the yield strength, B is the hardening modulus, C is the strain rate sensitivity coefficient, n is the hardening coefficient and m the thermal softening coefficient.

The Coulomb friction law governs tool-chip interface contact. Heat transfer is allowed at the tool chip contact area and at the backside of the tool.

Plane strain with four nodes elements are used (CPE4RT). The number of elements is 897 in the part and 97 in the tool, where their dimensions vary from 0.002 to 0.200 mm depending on the model zone considered.

A more detailed description of the numerical model can be found in reference [5].

3 MODEL VALIDATION

Figure 2A shows the temperature field when the reference values are employed in the finite element model (see column Reference value in Table 1).

In order to make a qualitative assessment rather than a quantitative one, validation has been done comparing experimental and numerical results, over a range of geometrical and cutting conditions, where effects and interactions of four process parameters: cutting speed (v), uncut chip thickness (h), cutting edge roundness (r_β) and rake angle (γ_o) were analyzed in a factorial design [10]. Parameter values for each level are shown in Table1 (see Level value column in Process rows). Finite element analyses are carried out with *Abaqus/Explicit*™ and the commercial software for machining purposes *AdvantEdge*™ (version 4.1).

Figure 2B shows the FEA and experimental effects of cutting process parameters over feed force (F_f). As can be observed, a good qualitative agreement is obtained for the three cases. For instance, it is observed that a variation of the uncut chip thickness (h) from 0.05mm to 0.3mm increases the feed force (F_f) by 93% in *Abaqus/Explicit*™, by 74% in *AdvantEdge*™ and by 75% in experimental tests.

In the case of other variables that are compared e.g., cutting force (F_v), temperature (θ_γ) (the latter with data from bibliography [11] and *AdvantEdge*™), quite good qualitative agreements were obtained as well.

Therefore, notwithstanding quantitative differences between the FEA and experimental results, as outlined in Figure 2B, the numerical model set up in *Abaqus/Explicit*™ can be considered to be reliable enough to make qualitative analysis of entry parameters related to cutting process and tool geometry.

Regarding the Von Mises stress in workpiece material, it is observed in Table 1, that there isn't any influence of all the process parameters analyzed.

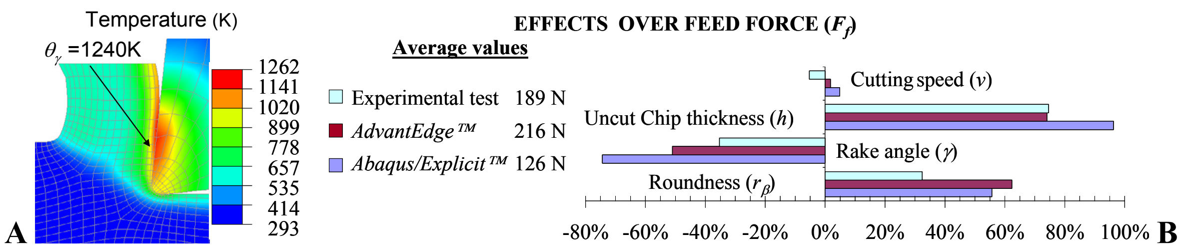

Figure 2: A) Temperature and stress fields (reference values: AISI-4140 steel and P10 insert grade). B) Experimental and FEA effects over feed force.

That is not the case for the total energy (*E)*, where all the parameters have a remarkable influence: the increase of the cutting speed (v), the undeformed chip thickness (h), and the cutting edge roundness and the decrease of the rake angle (γ_o) iincreases the total energy.

Regarding to some numerical parameters, it can be observed that moving from a minimum element dimension of 0.004 mm to 0.001 mm can make increase the maximum tool temperature (θ_γ) in 20% and the feed force (F_f) in 36% .Thus, a lack of robustness is observed with regards to this parameter.

Reference variable values (0.003s machining time; 1mm of d.o.c.)				*1240*	*1348*	*412*	*135*	*6,2*
PARAMETER		**Ref. value**	**Levels value**	θ_γ	σ_{vm}	F_v	F_f	E
PROCESS	Cutting speed (v) ($m \cdot min^{-1}$)	300	150-300	16	0	0	5	67
	Uncut chip thickness (h) (mm)	0.2	0.05–0.3	27	0	130	96	132
	Cutting edge roundness (r_β) (µm)	≈40	5-50	7	0	7	56	7
	Rake angle (γ_o) (º)	+6	-6/+6	-7	1	-17	-74	-18
NUMERI.	Number elements (Element dimension)	994	309-3976	20	1	-7	36	-2

θ_γ(K): Maximum Tool temperature over the rake surface. σ_{VM} (Mpa): Von Mises stress. F_v (N): Cutting force.
″ – "before effect values means a negative effect (decrease). E (J): Total energy. F_f (N): Feed force.

Table 1 : Process parameters effects over numerical results obtained after *Abaqus/Explicit* ™.

5 CONCLUSIONS

- Based on the results of the sensitivity study, Finite Element Modelling of chip formation process is qualitatively robust enough with regards to process parameters.
- However, the quantitative results need to be carefully assessed.

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