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A SENSITIVITY ANALYSIS OF THE FINITE ELEMENT SIMULATION OF THE HIGH SPEED MACHINING WITH THE MATERIAL RHEOLOGICAL BEHAVIOUR

Adinel Gavrus[1], Pascal Caestecker[2], Eric Ragneau[1]

[1]LGCGM, EA 3913, INSA de RENNES, Université Européenne de Bretagne, France
[2] ENSAM de PARIS, France
email: adinel.gavrus@insa-rennes.fr

ABSTRACT

This paper deals with the influence of the rheological behaviour on the morphology and geometry of the chip during a high speed machining. In order to describe the material rheology corresponding to high strain rates, large values of cumulated plastic strain and important temperature gradients, the Split Hopkinson Pressure Bars (SHPB) experimental test is used. A general parameter identification method based on an inverse finite element analysis is used to compute rheological parameters. The idea is to find a set of the constitutive coefficients which minimizes a least-squares cost function defining the difference between the global experimental measurements and the corresponding numerical data obtained from a finite element simulation of the test.
A finite element model of the high speed machining is employed to analysis the sensitivity of the numerical results in the cutting area with different rheological laws: a classical Johnson-Cook one and a proposed Arcsinushyperbolic one. This new law, proposed by the authors, shows the importance of the rheological formulation to a better description of the cutting results: distribution of equivalent strain rate, cumulated plastic strain, the equivalent Von-Mises stress, temperature and geometry of the cutting area.

KEYWORDS: high speed machining, finite element modelling, rheological sensitivity.

1. INTRODUCTION

The high speed machining requires important analysis of the chip shear process together with a better description of the chip morphology during the process. A first model of the cutting process has been proposed by Ernst and Merchant [1]. Or it’s model, describing especially the orthogonal cutting, ignores any effects of work hardening. It is the reason for each Oxley [2] proposes an improved analytical model taking into account the hardening effect and the thermo-mechanical coupling. This model permits to compute approximately the width of the principal shear band, but, more recently, Hamman [3] shows the difficulty to obtain a good estimation of this value. Moreover, using experimental measurements, the author evaluates the mean values of the strain rate about of 10^4-10^5 s^{-1} and about of 200% for the cumulated plastic strain. It is now evident that an analytical model cannot take into account the influence of all the chip shear process parameters: non-linear behaviour of the material and of the contact surface friction laws, localization phenomena, high values of deformation parameters, strong thermo-mechanical coupling and microstructure evolution. It is then necessary to use more sophisticated numerical models, as for example the Finite Element Modelling (FEM). The first finite element simulations of the machining have been developed in the 90’years [4-6]. Recently these numerical models were improved in order to simulate the high speed machining [7-8]. Important researches were focused to predict the three principal chip geometries: continuous, discontinuous and fragmented one. The last two ones can be obtained from a damage law coupled to the thermo-plastic deformation model [9].

For the simulation of high speed machining Huang [10] proposes the use of the Johnson-Cook law [11], introducing in a multiplicative form, effects of the hardening phenomenon, strain rate sensitivity and thermal influence. A similar mathematical form is generally used to introduce the damage model required to simulation of the cracks propagation. To improve the quality of the numerical results, accurate values of the physical parameters, describing all the material constitutive equations, are needed. The majority of the authors propose to use experimental results obtained from a Split Hopkinson Pressure Bars (SHPB) test in order to identify the constitutive parameters. Starting from previous researches of the authors, made in the laboratory GCGM of INSA de RENNES, an inverse analysis method is proposed to compute the rheological parameters [12]. It is based on a reduced finite element model of the SHPB, coupled to the optimisation software named OPTPAR. The constitutive parameter values can be then correctly identified and used in a finite element simulation of the high speed machining.

Some numerical analysis made by a research department of ENSAM Angers (France) [13] underlines the possibility to simulate fragmented chips starting from a rheological law based on a modified Johnson-Cook equation. A new formulation is then used for the stress-strain dependency, essentially based on the description of the competition between the hardening and the softening phenomena. Similar studies were made by the authors [8] in order to simulate a high speed machining of a stainless steel. Consequently, in order to obtain accurate numerical simulations of the chip shear process, firstly, an important scientific effort must be devoted to improve the material rheological behaviour analysis. This paper proposes a sensitivity analysis of the material behaviour formulation on the simulation of the high speed machining. It is based on numerical comparisons between the results obtained from a classical Johnson-Cook law and from an Arcsinushyperbolic equation (named Ash) proposed by the authors [8,14].

2. MATERIAL CONSTITUTIVE MODEL

To describe the material flow during high speed cutting process an elasto-viscoplastic description of the material behaviour must be written in the from:

$$\bar{\sigma} = f(\bar{\varepsilon}, \ \dot{\bar{\varepsilon}}, \ T) \qquad (1)$$

where $\bar{\sigma}$ is the Von-Mises stress, $\bar{\varepsilon}$ is the cumulated plastic strain, $\dot{\bar{\varepsilon}}$ is the generalised strain rate and T the temperature.

A general expression, taking into account competition between hardening and softening phenomena (recovery or recristalization of material), is proposed:

$$\bar{\sigma} = \left\{A + BH(\bar{\varepsilon})\exp(-R\bar{\varepsilon}^S) + C\left[1 - \exp(-R\bar{\varepsilon}^S)\right]\right\}G(\dot{\bar{\varepsilon}})F(T) \qquad (2)$$

In this paper only the hardening effect is used i.e. *R = S= 0*. The Table 1 synthesises the analytical form of the *H*, *G* and *F* functions. It is then presented the Johnson-Cook equation, used by the majority of authors, and the new proposed law. This last one, named Arcsinushyperbolic, was analysed in a more details by authors in [14]. It is based on physical mechanisms of dislocations motion and is defined from:

$$Arc\sinh(x) = Ash(x) = \ln\left(x + \sqrt{1 + x^2}\right) \qquad (3)$$

It is demonstrated that this expression degenerates mathematically in a classical Norton-Hoff law for small values of the plastic strain rate and in the Johnson-Cook one for increasing values.

Table 1. Material constitutive laws

Law		$G(\dot{\bar{\varepsilon}})$	$H(\bar{\varepsilon})$	$F(T)$
I	Johnson Cook	$1 + D.Ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)$	$B\bar{\varepsilon}^n$	$1 - \left[\frac{(T - T_0)}{(T_{fus} - T_0)}\right]^m$
II	Ash	$Arc\sinh\left[\frac{e}{2}\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)^D\right]$ $e = \exp(1) = 2{,}7182$		

3. PARAMETER IDENTIFICATION

Cylindrical specimens of a martensitic steel (35NCD16) were tested using the compression SHPB device developed in the laboratory [15]. To identify the parameters of the constitutive equations, two methods were used starting from a software developed by the authors and named OPTPAR. It is based on the optimisation of a cost function describing the differences between the experimental values (M^{exp}) and the computed ones (M^c) and written in the following form:

$$\Phi\left(P, M^c, M^{exp}\right) = \frac{\sum_{i=1}^{N\exp}\left[M^c - M^{exp}\right]^2}{\sum_{i=1}^{N\exp}\left[M^{exp}\right]^2} \qquad (4)$$

The parameter identification is formulated as a minimization of the cost function:

$$\begin{cases} \min\limits_{P \in D(P)} \Phi(P, M^c, M^{exp}) \\ D(P) = \left\{P / P_{\min} \le P \le P_{\max}\right\} \end{cases} \qquad (5)$$

A Gauss-Newton method is used to solve the optimisation problem starting from the computation of the first and second derivatives:

$$\frac{d\Phi}{dP_j}=\frac{2\sum_{i=1}^{N\exp}\left[\frac{dM_i^{\,c}}{dP_j}\right]\left[M_i^{\,c}-M_i^{\,\exp}\right]}{\sum_{i=1}^{N\exp}\left[M_i^{\,\exp}\right]^2} \qquad (6)$$

$$\frac{d^2\Phi}{dP_{jk}}\approx\frac{2\sum_{i=1}^{N\exp}\left[\frac{dM_i^{\,c}}{dP_j}\right]\left[\frac{dM_i^{\,c}}{dP_k}\right]}{\sum_{i=1}^{N\exp}\left[M_i^{\,\exp}\right]^2} \qquad (7)$$

The search of the parameters values minimizing the cost function is made from the parameter increment computed by:

$$[\Delta P]=-\left[\frac{d^2\Phi}{dP^2}\right]^{-1}\left[\frac{d\Phi}{dP}\right] \qquad (8)$$

The numerical iterations are stopped when the stagnation criteria of the parameters values is reached.

The first identification method is schematized in the Figure 1.

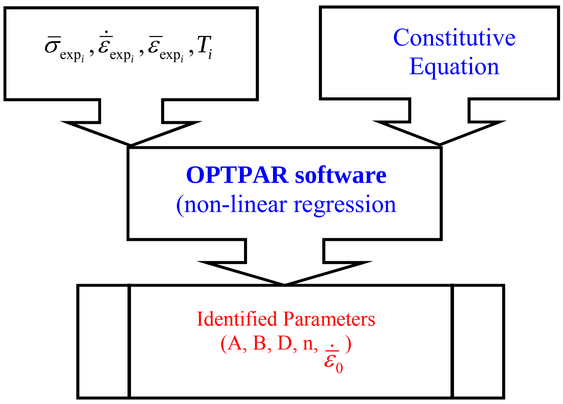


Fig.1. Scheme of parameter identification using a classical non-linear regression method

It is based on a non-linear regression method made in the space of the equivalent stress space ($M=\bar{\sigma}$). The experimental equivalent stress is computed analytically from the elastic strains measured by the gauges mounted on the bars and using the theory of elastic wave propagation. The identification results are presented in Table 2.

Table 2. Classical Identification Results (*m = 1*)

Laws	*A* [MPa]	*B* [MPa]	*n*	*D*	$\dot{\varepsilon}_0$	Error
I	1010.2	387.70	1.095	0.187	105.37	1.39%
II	980.40	376.30	1.098	0.208	137.80	1.39%

Or for large plastic deformations, all the assumptions used by the classical analysis (homogeneity of the specimen deformation, neglecting the friction on the material interfaces) are no valid. Then a new identification method, based on the inverse analysis, is proposed [16]. The main idea is to simulate the compression specimen with a finite element model. Friction on the contact specimen surfaces, heterogeneity of the plastic deformation and adiabatic heating are taking into account. All the boundary data: interface velocities and forces are computed from an analytical model of the elastic wave propagation in the SHPB bars [12]. It is regarded as input data for the inverse analysis procedure plotted in the Figure 2.

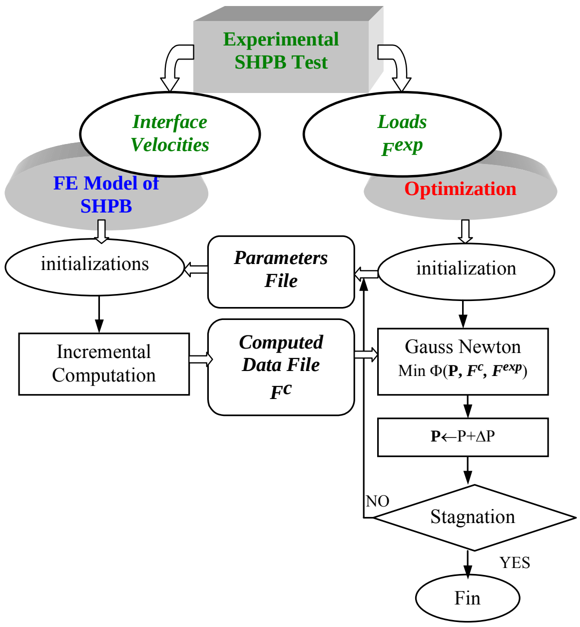


Fig. 2. Scheme of the OPTPAR software using the inverse analysis principle (*M*=*F*)

The results are presented in Table 3.

Table 3. Identification by Inverse Analysis (*m = 1*)

Law	*A* [MPa]	*B* [MPa]	*n*	*D*	$\dot{\varepsilon}_0$ [s^{-1}]	Error
I	1010.15	444.25	1.615	0.229	238.235	2.9%
II	980.40	373.08	1.102	0.206	205.277	3 %

The comparison between the parameters values obtained by the two methods shows that the errors could be important if a classical analysis of the material behaviour identification is used (Table 4).

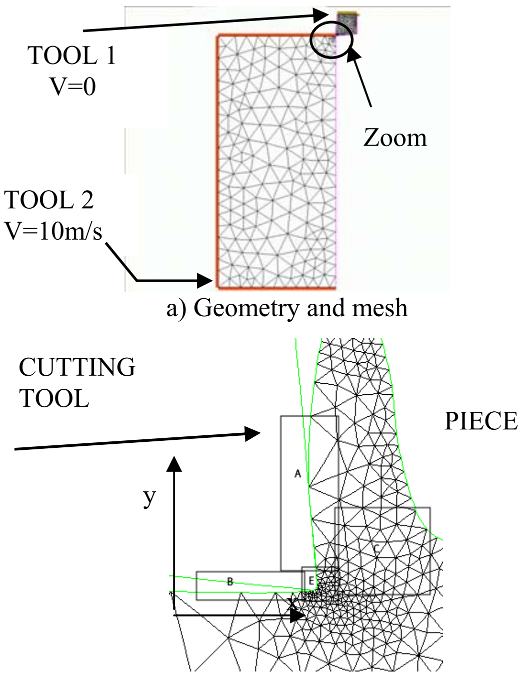
Table 4. Comparison between the parameters values obtained by classical method and inverse analysis one

Law	*B* [MPa]	*n*	*D*	$\dot{\varepsilon}_0$ [s^{-1}]
I	14.59%	47.49%	22.46%	126.09%
II	-0.06%	0.36%	-0.96%	48.97%

All these results show the capability of the two laws to describe the material behavior, especially because we have approximately the same least squares errors (approximately 1.4-3%). Obviously the identification results obtained by inverse analysis are more precisely. Or the principal property of a constitutive equation is it's capacity to give correct results for extrapolated values of all the flow variables: plastic cumulated strain, equivalent strain rate and temperature. On this point of view, only a sensitivity analysis of the constitutive equation on the numerical simulation results can indicates which is the more adequate.

4. FINITE ELEMENT MODEL

For this study we propose a finite element model of a high-speed orthogonal cutting process.



a) Geometry and mesh

b): Zoom

Fig. 3. The finite element model: Rigid Tools (Tool 1 and Tool 2), Cutting Tool and the Piece.

In the Figure 3 are pictured all the geometry defining the two rigid tools and the cutting one together with the finite element discretization of this last one and of the piece.

The initial mesh of the work piece is rather coarse, but during the simulation, automatic remeshing leads to more refined mesh, especially for the shear and cutting zones, using specific boxes (A, B, …E) which define small local element sizes. The cutting tool has only a thermo-elastic deformation, and inertia effects are taking into account according to the cutting speed of 10 m/s. The most important boundary conditions are the friction and the conduction between the chip and the tool. The heat transfer due to the friction on the contacting bodies (edge area, rake face) is also computed. A realistic characterisation of the friction on the chip-tool contact is then at least as important as the constitutive equation of the piece material.

The cutting speed is equal to 10 m/s, the depth of the cut is 0.2 mm, the rake angle is 5 degrees, the relief angle is 6 degrees and the radius of the cutting edge is 0.06 mm. All the principal material properties of the tool and piece are indicated in Table 5.

Table 5. General material data for the piece and tool

	Elastic Properties and Thermal Data (SI)								Friction
	E GPa	ν	ρ	C	k	h_{cd}	h_{cv}	ε	Coulomb μ
Tool	$8x10^5$	0.3	11400	376	35	6000	8.	0.7	0.23
Piece	210	0.3	7690	677	26	6000	8.	0.7	0.23

The thermal data are defined here by the specific heat C, conductivity k and coefficients of the heat transfer by conduction h_{cd}, convection h_{cv} and emissivity ε. The material of the tool is a martensitic 35NCD16 steel. All the simulations were running for the Law I:

$$\bar{\sigma} = \left(1010.2 + 444.3\bar{\varepsilon}^{1.6}\right)\left(1 + 0.23\ln\left(\frac{\dot{\bar{\varepsilon}}}{238.2} + 1\right)\right)F(T) \quad (9)$$

and for the Law II :

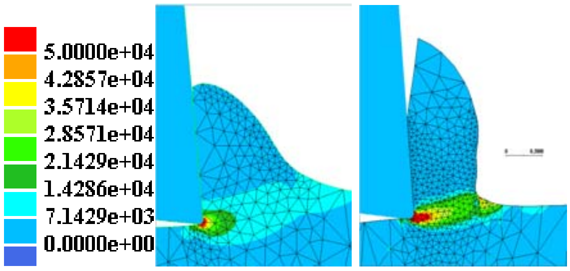
$$\bar{\sigma} = \left(980.4 + 373.1\bar{\varepsilon}^{1.1}\right)\left(Ash\left(\frac{e}{2}\right)\left(\frac{\dot{\bar{\varepsilon}}}{205.3}\right)^{0.2}\right)F(T) \quad (10)$$

where *F(T)* is defined in Table 1 (*m = 1*).

The mathematical expression of the Johnson-Cook equation (4) was regularized in order to avoid any numerical problems for negative values of the logarithm. Using the previous data, the non-steady cutting process is simulated using the implicit FORGE2® software. It is based on an updated Lagrangian numerical resolution. Concerning the incremental resolution of the finite element problem, a time step of around 10^{-7} s is used. The convergence of the Newton-Raphson algorithm, used to solve the non-linear thermo-mechanical equilibrium, is reached after 15-25 iterations.

5. NUMERICAL RESULTS

Regarding the chip geometry and the chip generation after 0.27 ms of the cut time (Figure 4), a big difference can be observed.

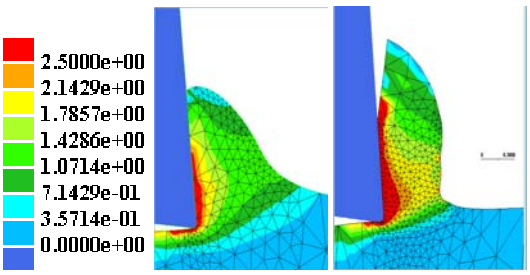


a) Law I b) Law II

Fig. 4. Iso-values of the generalized plastic strain rate at t=0.27 ms

The influence of the yield stress and of the strain rate gradients is here very important. In the first case, the material is more robust due to the strong hardening model, caused essentially by the extrapolation of the Johnson-Cook law for smallest values of the strain rate. In the second one, the chip has a little rigidity, caused by a softening effect of the stress values on the chip outside the shear band. More details of the shear zones, show that, for the first constitutive law, the principal shear band is not still completely close (average values of the strain rate of $10^4 s^{-1}$), on the contrary to the second one where this is more localised and recovers all the principal shear area (average values of the strain rate of $3x10^4 s^{-1}$).

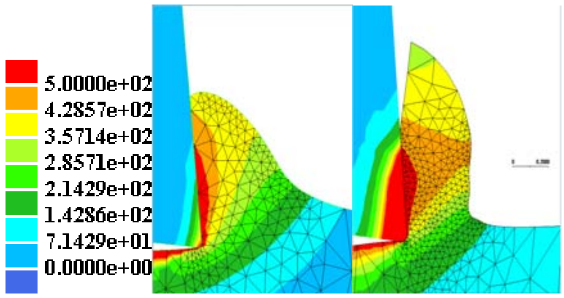
The Figure 5 illustrated differences on the second shear band formed on the contact area between the chip and the cutting tool. This one is more pronounced for the law II. The great values of the cumulated plastic strain (average values of 150%-200%) show the importance of the strong coupling between the hardening term and the strain rate one.



a) Law I b) Law II

Fig. 5. Iso-values of the cumulated plastic strain at t=0.27 ms

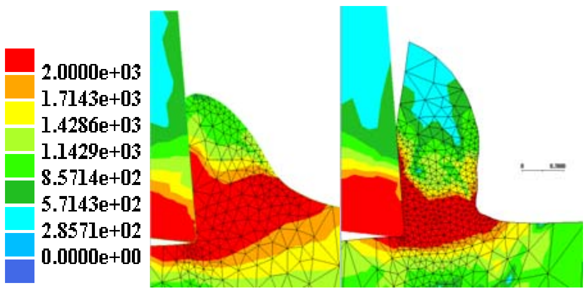
Concerning the temperatures evolution (Figure 6) it is important to see, that using the proposed law (law II), the most important thermal energy, generated by the dissipation of the plastic work and of the friction, leads to increase the temperature of the tool (until 500°C). Other principal part of the heat is evacuated on the chip. These results are confirmed by experiences.



a) Law I b) Law II

Fig. 6. Iso-values of the temperature for the piece and the cutting tool at t=0.27 ms

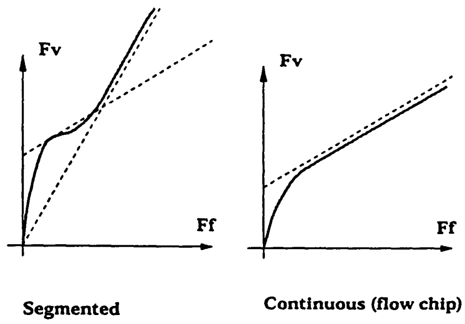
For the equivalent Von-Mises stress the results are plotted in the Figure 7. The stress is more concentred on the principal shear band in the case of the law II compared as the case of the law I. Moreover a different distribution of the stress is obtained inside the cutting tool. The high rigidity of the chip for the Johson-Cook law is also confirmed here by the more important values of the stress obtained in a more large area of the chip (see Figure 7a).



a) Law I b) Law II

Fig. 7. Iso-values of equivalent Von-Mises stress for the piece and the deformed tool at t=0.27 ms

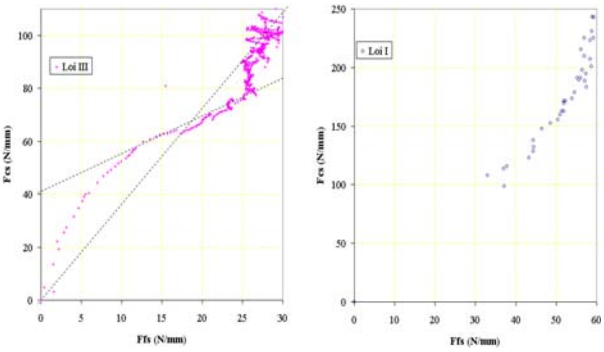
A zoom of the chip geometry obtained from the law II (Figure 7) shows that small instabilities occurs on the right free surface of the chip. These ones can be regarded as the origin of small cracks, which can occurs in this chip surface. It is the possible to talk about the possibility to simulated fragmented chips.



a) b)

Fig. 8. Evolution of the cutting force versus thrust force [MESL_00]: a) for the segmented chips, b) for the continuous chips

Some experimental analyses have been proved that a differentiation between segmented and continuous chips can be made from the variation of the cutting force (F_v) with the thrust force (F_f) (see Figure 8). F_v acting in the direction of cutting and F_f thrust force needed to keep the tool in the workpiece (direction perpendicular to the workpiece surface). In figure 9 are plotted these variations for the two constitutive models.



a) Law II b) Law I

Fig. 9. Numerical variation of the specific cutting force (F_{cs}) versus specific thrust force (F_{fs})

It is easy to see that the proposed Arcsinushyperbolic law gives similar results that the curve predicting fragmented chips (Fig. 8a).

6. CONCLUSIONS

Particularly, if a large plastic strain (100%÷300%) occurs during the machining process, an extrapolation of stress curves obtained from SHPB test (where the strain is limited to 20-25 %), using a continuous hardening model, can be wrong. Moreover the important gradient of the strain and of the strain rate require a constitutive law which allows to describe the material behaviour simultaneously at small and high strain rates. It is the main reason for why the formulation of the constitutive law is very important to simulate correctly high speed machining. A new constitutive model has been examined to describe more accurately the influence of the strain-rate and temperature on the metal behaviour in large deformations and high strain rate ranges. A robust inverse analysis technique has been used in order to determine the constitutive coefficient values, starting from experimental data obtained by SHPB tests.

To improve the rheological sensitivity on the high speed cutting simulations, in a future work we propose to analyse the influence of a more complex law. It is then necessary to take into account the competition between the hardening and the softening phenomena.

These ones are important for the machining simulation, where high strain localisation and adiabatic heat phenomena occur during the flow process. In this case the large values of the cumulated plastic strain (up to 50-100%) can leads to a microstructure change, as for example the recovery or the recristalization.

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