Modelling and numerical simulation of orthogonal metal cutting by chip formation and breaking using Thermo-elasto-visco-plastic constitutive equations fully coupled with ductile damage.

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ABSTRACT

Metal machining by chip formation is one of the mostly used industrial processes to obtain a final form of various mechanical components. Its numerical simulation (virtual machining) is today an increasing task studied by an increasing number of research teams in order to develop appropriated methodologies able to 'optimize' virtually the machining process under more and more severe conditions (High speed machining). This work proposes a complete numerical methodology combining 'advanced' elastoplastic constitutive equations coupling thermal effects, large elasto-viscoplasticity with mixed non linear hardening, ductile damage and contact with friction for 2D machining simulation. Fully coupled (strong coupling) thermo-elasto-visco-plastic-damage constitutive equations based on the state variables under large plastic deformation developed for metal forming simulation are presented. The relevant numerical aspects concerning the local integration scheme as well as the global resolution strategy and the adaptive remeshing facility are briefly discussed. This model is implemented into ABAQUS/EXPLICIT using the Vumat user subroutine. Applications are made to the orthogonal metal cutting by chip formation and segmentation. The interactions between hardening, plasticity, ductile damage and thermal effects are analysed.

1. INTRODUCTION

In today's world, many companies, concerned by the manufacturing of high level products, are interested in avoiding long and expensive experiments and in fulfilling the quality, the costs and the duration requirements within the very concurrent industrial environment. To do that, the numerical methods based on predictive constitutive equations are needed. Particularly, the use of numerical simulations in machining processes (or virtual metal machining) is necessary in order to determine the optimal process plan virtually before its physical realization. However, nowadays, the machining plan of various materials is still performed using the specific knowledge of engineers based either on analytical methodology or experimental procedure [1]. These analytical solutions seem helpful to predict some simple parameters as the cutting force needed to form the chip for various cutting conditions. However, they can not be helpful for predicting the effect of the cutting parameters on the distribution of the thermomechanical fields and their evolution during the process, nor to allow the accurate prediction of the chip formation and possible segmentation.

Nowadays, various Finite Elements (FE) software are proposed in order to simulate numerically different sheet or bulk metal forming processes by large plastic deformation as deep drawing, forging, stamping… However; much less FE softwares are available in order to simulate 2D and 3D metal cutting by chip formation processes (milling, drilling, cutting …) under various severe conditions (high strain rate, high temperature, strong friction, …). During the recent years, a great effort is done by the scientific community in order to enhance the numerical simulation of 2D and 3D cutting operations using rather simplified thermomechanical models. For example, the FE codes as Advantedge™, DEFORM3D® or FORGE2005®, LS-Dyna® oe ABAQUS® among others, allow the simulation of some simple machining operations using Norton-Hoff or Johnson-Cook type constitutive equations together with adaptative mesh facility. In these numerical approaches, the chip is formed thanks to the thermo-viscoplastic flow of the metal under the tool effect ([2], [3], [4], [22], [23]). Other works propose the use of local fracture criteria to propagate cracks which form the chips ([5], [24], [25], [26], [27]). These local fracture criteria are based either on equivalent stress, equivalent strain or a critical gap between the cutting edge of the tool and the nodes located ahead of the tool edge. The main crack propagates by using the nodes relaxation method ([5], [26]) or by the kill element method ([6], [7], [24], [25]). The chip formation can be also simulated using the ALE (Arbitrary Lagrangian Eulerien method) formulation in which the formed crack ([8], [9]). Finally some works ([20], [21]) use some kinds of mesh-less formulations (SPH method) in order to simulate the ship formation and breakage without dealing with remeshing techniques.

This work is devoted to the presentation of a novel numerical metal cutting methodology, based on the ductile damage at finite strain and its effect on the other thermo-mechanical fields. We focus on the ‘strong’ coupling between thermal aspects and the elasto-visco-plasticity fully coupled with the ductile damage including the mixed isotropic and kinematic non-linear hardening. Starting from an isotropic fully coupled finite strain elastoplastic model developed in previous works by Saanouni et al, ([10], [11], [12], [13]), isotropic thermal coupling is recalled from both theoretical and numerical points of view. The developed model has been implemented into ABAQUS/EXPLICIT using the Vumat subroutine. In this approach, the chip is formed due to the competing effects between the thermo-visco-plastic flow and the local ductile damage mechanisms ahead of the tool tip. Serrated chip and chip segmentation can be also naturally described depending on the process parameters as the material ductility, the cutting speed, the tool cutting angles, the chip thickness, etc…

2. THERMO-MECHANICAL-DAMAGE COUPLED MODEL AND NUMERICAL ASPECT

2.1 Fully coupled constitutive equations

The fully coupled thermo-elasto-visco-plastic behaviour is modelled in the framework of the thermodynamics of irreversible processes with state variables ([14], [15]) assuming the small strain hypothesis. Extension to the finite plasticity framework is done using the so called rotating frame formulation. According to the first gradient formulation, two ‘external’ state variables are introduced: ($\underline{\varepsilon}$, $\underline{\sigma}$) for total strain tensor and the Cauchy stress tensor; (T, s) for absolute temperature and specific entropy. The ‘internal’ state variables and their conjugate forces are : (ε^{e},σ) for small elastic strain tensor and the Cauchy stress tensor;

($\vec{q},\vec{g} = \overrightarrow{grad(T)}$) for thermal flux vector and its conjugate force; ($\underline{\alpha}$,$\underline{X}$) for back-strain and back-stress deviator tensors that describe the kinematic hardening (i.e. translation of the yield surface center); (r, R) equivalent plastic driving strain and stress representing the isotropic hardening (i.e. variation of the yielding surface size) and (D,Y) for isotropic damage and its conjugate force, which is also known as a damage strain energy release rate ([15]).

Following this approach thee complete set of fully coupled constitutive equations is obtained:

- State relations:

$(T - T_0)$

$\lambda(\varepsilon : 1)1 + 2 - 3$

$h()$

D

$()$

D

$\sigma \quad h_1^2$

$\mu\varepsilon$

ς

$e\, e$

(1)

1

$\underline{X} = \frac{2}{3} C.h_1^2()D\, \alpha$ (2)

$R = Q.h_2(D)r$ (3) $s = \frac{3}{2} k \varsigma h()^{e} : 1 + C \frac{(T - T_0)}{T_0} . D\, \varepsilon_v$ (4)

$\rho^{c\,1}$

$1\; e^2\, ee\; 3k_c \varsigma\; e\; 2\; 1\; 2$ (5)

$Y = \lambda(\varepsilon : 1) + \mu\varepsilon : \varepsilon - \frac{}{2 h_1 0 D}(T - T_0).\varepsilon : 1 + C\, \alpha : \alpha + Qr$

0

2 3 2

where: (λ , μ) – Lame's constants, T – temperature, T_0– reference temperature, ς – thermal expansion coefficient, k_c – bulk modulus, C – kinematic hardening modulus, Q – isotropic hardening modulus, C_v – specific heat coefficient, ρ – material density and h_i (D) – damage functions they chosen from:

k

=

c
1

√

1

1

$\sqrt{1-D^n}$

$- D \; i = 1$

h_i

()

D

=

(6)

$- D^n \; i = 2 \; n > 1$

• <u>Evolution equations:</u>

$\dot{\varepsilon}^{vp} = \dot{\delta}_{vp} n$ (7) $\dot{\alpha}^{vp} = \dot{\delta}_{vp} (n - a\alpha)$ (8) $\dot{r} = \dot{\delta} (\frac{1}{g()} - br)$ (9)

vp

$_2 D$

$\dot{\delta}_{vp} \, Y - Y_0 \; s$

$\dot{D} =$ β (10)

$(1 - D) \; S$

[13]):

$div\left(k\,\overrightarrow{gradT}\right.$

$q = -kgradT$ (11)

Eq.11 combined with the first law of thermodynamics (energy balance) leads to the generalised heat equation (Eq. 12) governing the temperature evolution ([10],

$: \dot{\varepsilon} +$

$\left.\right) + \varphi^{m} - \rho C\dot{T} + T \frac{\partial\sigma_e}{\partial T} \frac{\partial X}{\partial T} : \dot{\alpha} + \frac{\partial R}{\partial T} : \dot{r} - \frac{\partial Y}{\partial T} : \dot{D} = 0$ (12)

v

∂T

∂T where φ^{m} is the mechanical dissipation given by:

$\varphi^{m} = \sigma : \dot{\varepsilon}^{p} - \underline{X} : \dot{\alpha} - R\dot{r} + Y\dot{D} \geq 0$ (13)

$3\,1\;\sigma^{dev} - \underline{X}$

$n =$

$() J(\sigma - X)$ is the expression of the outward normal to the yield $2\,h_1 D_2$

surface which is here defined by: $J\left(\sigma - \underline{X}\right)_{-} R_{-\sigma}$ (14)

$f = {}^{2}$

$() \; Dh \; ()$

$h_{12} D$ Where $J_2(\sigma - \underline{X})$ is the equivalent stress defined in the isotropic case by:

$$J_2(\sigma - \underline{X}) = \sqrt{\frac{3}{2}(\underline{\sigma} - \underline{X})^{dev} : (\underline{\sigma} - \underline{X})^{dev}} \quad (15)$$

$\dot{\delta}_{vp}$ is the viscoplastic multiplier deduced from a viscoplastic potential written in hyperbolic cosine and it is given by:

$$\dot{\delta}_{vp} = K_1 Sinh \left\langle \frac{f}{K_2} \right\rangle \quad (16)$$

By using Eq. 7 the equivalent (or accumulated) viscoplastic deformation rate is given by:

$$\dot{p} = \sqrt{\frac{2}{3}\underline{\dot{\varepsilon}}^{vp} : \underline{\dot{\varepsilon}}^{vp}} = \frac{\dot{\delta}_{vp}}{h_1(D)} \quad (17)$$

Parameters figuring in constitutive equations (Eq. 7-Eq. 16) are:a and b the non linearity coefficients of the kinematic and isotropic hardeningrespectively.S, s ,$Y_0$and β define the evolution of isotropic ductile damage.
k is the heat conduction coefficient.
σ_y is the initial size of yield surface.

K_1 and K_2 define the material viscosity.

Each of material parameters figuring in the model equations are written as functions of the temperature; by naming P one of those parameters, its evolution according to temperature is chosen like the following:

$$P = P_0 \left(1 - \left(\frac{T - T_0}{T_f - T_0} \right)^n \right) \quad (18)$$

Where P is the value of the parameter at the temperature T , P_0its value at the reference temperature T_0, T_f is the melting temperature of the material and n is a temperature independent material parameter. Equation (Eq. 18) is applicable to all model parameters except Y_0 which depend either on the temperature as well as on the accumulated viscoplastic strain rate by the following equation:

$$Y_0(\dot{p},T) = Y_r \left\langle 1 - \left(\frac{T - T_r}{T_f - T_0} \right)^n \right\rangle Tanh\left(\frac{\varpi}{\dot{p}} \right) \quad (19)$$

2.2 Numerical aspects: adaptive methodology

Numerical aspect and implementation of the presented model in ABAQUS/EXPLICIT are detailed in ([6], [7], [10], [11], [12], [13], [17]). The resolution of global equilibrium equations is based on dynamic explicit algorithm scheme and the resolution of local equations to calculate constrains and internal variables at each time increment is based on iterative implicit algorithm scheme using the elastic prediction and viscoplastic correction with radial return mapping [7].

For 2D adaptive remesh we use the 2D mesher named DIAMESH2D and developed in [18]. This procedure adapts the mesh size and the loading path based on appropriate error estimates and used the 2D (linear and quadratic Quadrangular and Triangular element) [19]. Different steps of the 2D mesher are presented below:

<u>Step n°1</u>: Meshing the initial part with respect to a max size h_{max} and the tools local curvature. <u>Step n°2</u>: Call ABAQUS/EXPLICIT with the VUMAT to solve the problems for the first sequence of the total loading path <u>Step n°3</u>: Get the final solution (displacement and state variables) at the end of the loading sequence for the current mesh [Mi] <u>Step n°4</u>: If there are some damaged elements which not exceeds a known number of elements and all the fully damaged elements have the smallest size h_{min}^{endo}.

These fully damaged elements are then removed and new part boundaries are defined with a new mesh size generated to the error estimates. If the size of any fully couples damaged elements exceeds h_{min}^{endo} or the total damaged element exceeds the prescribed number, the analysis is cancelled and a new loading sequence is worked out with a smallest value. <u>Step n°5</u>: using the error estimates based either on the local curvature of the tools at the contact boundaries and/or the Hessian of the plastic strain and damage rate, the mesh size is calculated <u>Step n°6</u>: Knowing the distribution of the new mesh size, generate the new mesh [Mi+1] using DIAMESH2D software <u>Step n°7:</u> Transfer data from mesh M_i to the newly created mesh M_{i+1} by diffuse approximation and continue the analysis

3. APPLICATION TO THE ORTHOGONAL CUTTING

For the application to the orthogonal cutting we take the configuration used in [16] where the cutting angle is -6°, clearance angle is 5° with the initial mesh using quadrangular bilinear elements shown in Fig. 1. The part is clamped along the side of 12 mm. The material parameters of the part defining the thermoelasto-viscoplastic-damage are determined using the data given in [15] on the basis of the force displacement curves predicted by Jonson-Cook constitutive equations and concerning the AISI4340 stainless steel. They are given by: E=205000 MPa, ν =0.3, C_v = 457 J/kg°C, ς= 1.70 10^{-5} °C^{-1} for the thermo elasticity. σ_y =792 MPa, Q=1050 MPa, C= 18000 MPa, b=2.6, a=60, K_1=45, K_2 =50 MPa for the viscoplastisity and S= 40 MPa, s=2, β =5, Y_r=6 for the damage evolution equation. All these parameters are identified at the reference temperature T_0 = 20°C and their evolutions with respect to the temperature are governed by Eq. 18 and Eq. 19. In Eq 18 the parameter *n=0.3* for all parameters except for the parameter S were *n*=1.5, while in Eq. 19 the parameter ϖ =800. The material conductivity is taken equal to zero to fitful the adiabatic condition. Finally the melting temperature for this material is taken T_f= 1520°C .

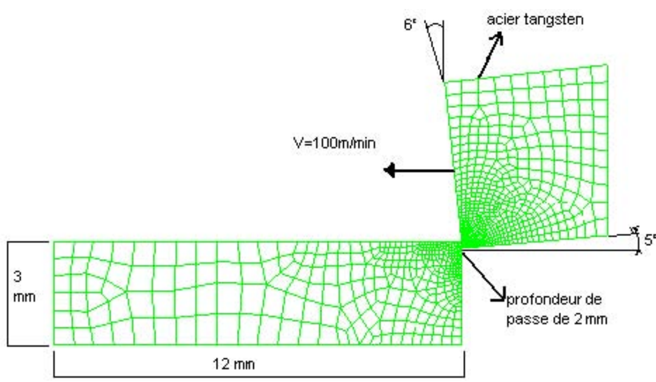
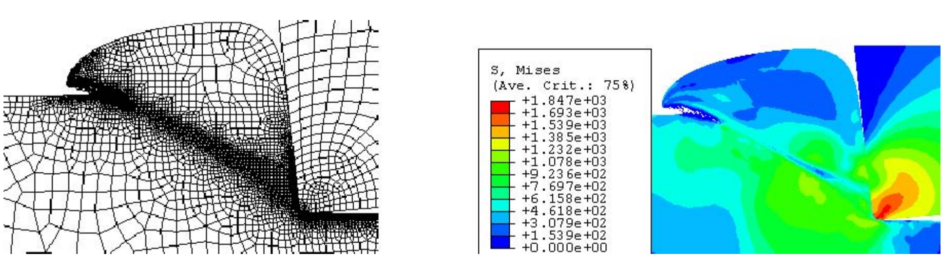


Fig. 1 Orthogonal cutting (initial mesh). The tool is meshed using the same element type and is supposed purely thermoelastic solid define by: E=450 000 MPa, ν =0.22, C_v = 400 J/kg°C, ς= 1.37 10^{-5} °C^{-1}.



(a) Adapted mesh (b) Mises equivalent stress
(c) Temperature (d) Equivalent viscoplastic strain
(e) Viscoplastic strain rate (f) Ductile damage

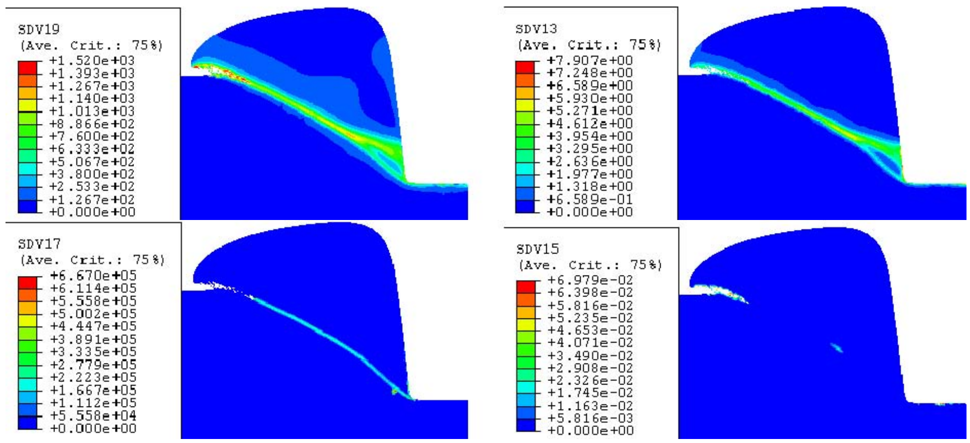


Fig.2: Distribution of some thermomechanical fields at 0.19 mm displacement of the tool.

Fig. 2 summarizes the distribution of the main thermomechanical fields inside the cutted part after u=0.19 mm of the tool displacement. The Fig. 2a shows the good working of the mesh adaptation procedure where the mesh is highly refined along the primary adiabatic shear band, along the secondary shear band and as well as at the contact interfaces. Inside the primary shear band we can observe the high localization of the temperature which reaches $T_{max} \approx 1400°C$ avery where inside the shear band except in some highly deformed and damaged elements where the it reaches the melting temperature. Also, we can observe the high localization of the accumulated viscoplastic strain of around $p_{max} \approx 400\%$ evry where inside the shear band except in some points where it reaches $p_{max} \approx 500\%$ (Fig. 2d). Similarly, the accumulated viscoplastic strain rate localization reaches $\dot{p}_{max} \approx 2.5\ 10^{+5}\ s^{-1}$. However in some points located at the beginning and the end of the primary shear band the maximum accumulated viscoplastic strain rate reaches $\dot{p}_{max} \approx 6.7\ 10^{+5}\ s^{-1}$.

As shown by Fig. 2f, the damage reaches its critical value at the external end of the primary shear band leading to the initiation of a macroscopic crack which propagates along the shear band down in the direction of the tool tip. However, a second crack initiation seems to take place at the middle of the primary shear band where the damage grows more rapidly than elsewhere. This is confirmed by the distribution of the equivalent stress showing a zero stress at the incipient of the macroscopic crack (Fig 2b). All these results seem very close to the experimental observation which can be found in [16].

4. CONCLUSION

An elasto-visco-plastic-damage model accounting for non linear isotropic and kinematic hardening, the temperature and the ductile damage effects is presented from both theoretical and numerical aspects. This model is shown to be efficient to predict the chip formation and segmentation including the high localization of the termomechanical fields inside the primary shear band. These encouraging results allow the prediction of the serrated chip shape as well as its fragmentation. This work is under progress in order to generalize this adaptive procedure to the 3D metal cutting simulations.

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