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FLOW STRESS DETERMINATION IN ORTHOGONAL CUTTING PROCESS COMBINING THE PRIMARY AND THE SECONDARY SHEAR ZONES

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ABSTRACT: The rheological model of workpiece materials in the machining simulation plays an important role. More researchers have studied the flow stress identification, generally based on the strain, strain rate and temperatures of the only primary shear zone (PSZ), and there is not much about the influence of the secondary shear zone (SSZ) on the determination of the flow stress equation.
The conditions of the SSZ are different from the PSZ, in particular it is characterized from higher value of strain (10-20) and strain rate. This modifies the material parameters obtained considering only the PSZ.
In this paper the PSZ with the SSZ have been considered together in order to determine the flow stress of the material. Some material models have been taken into account: the simplified Johnson-Cook model, the power law model and the Oxley model. The computation of material parameters is based on the inverse methodology (Oxley model excluded). The experimental data have been taken from the bibliography.
Some FEM simulations have been performed in order to analyze the effect of the material models deriving from different approaches.

KEYWORDS: Orthogonal Cutting, Flow stress identification, Secondary Shear Zone, FEM.

1 INTRODUCTION

The flow stress definition of the workpiece is an important issue in the FEM simulation of machining. During the machining the workpiece material is subjected to high strain (up to 4), strain rate (up to 10^6 s^{-1}) and severe temperature (up to 1000 $°C$), and these conditions are difficult to obtain with conventional tensile and compression tests.
Several researchers have studied the flow stress definition. Often Hopkinson's bar technique is used. Anyway, with the Hopkinson's bar test, the strain can go up to ε=1.5, strain rate can rise to $\dot{\varepsilon}$ = 5000 s^{-1} and temperature can reach T = 1000 K.
The other approach is based on the use of cutting models, analytical or even numerical, in combination with inverse identification algorithms.
Analytical models are based on the Oxley's machining theory ([4]).
The FEM model has been used with several materials.
Umbrello [2] investigated the influence of the constants used in Johnson-Cook's material constitutive equation in the machined components of austenitic stainless- steel AISI 316L.
All these methods are based on the stress, strain and strain rate on the primary shear zone.

The secondary shear zone is characterized from higher value of strain (10-20), and strain rate. Several flow-zone models have been used to explain tribo-layer phenomena (Trent [3], Oxley [4] and Qi and Mills [5]). Guo [6] proposed a mechanical behavior characterization of the SSZ.
In this paper an analytical model of the primary shear and secondary shear zone has been used. Three material constitutive equations have been considered: the simplified Johnson –Cook model, the power law and the Oxley model. The material parameters of the first and the second material model have been determined using an inverse procedure, where the experimental data were taken from the bibliography. The Oxley model was determined using the data of PSZ and SSZ.
Finally FEM simulations have been performed considering the flow stresses that derive from different approaches.

2 MECHANICAL AND THERMAL CHARACTERIZATION OF THE PSZ AND SSZ

The flow stress identification is based on the evaluation of strain, strain rates, temperature and shear stress on the primary shear zone and the second shear zone. These quantities are not measured, but estimated by measuring

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certain physical parameters (such as cutting forces, chip thickness, and contact length) with well known models.

2.1 PSZ definition

The strain and the strain rate in the PSZ have been evaluated:

$$\varepsilon_{PSZ} = 1/\sqrt{3} \cdot \left(cos\gamma/\left(\sin\varphi \cdot \cos(\varphi-\gamma)\right)\right) \quad (1)$$

While the strain rate is estimated by the parallel sided shear zone theory (Oxley [4]).

$$\dot{\varepsilon}_{PSZ} = \left(1/\sqrt{3}\right) \cdot (1000/60) \cdot C \cdot (V_c/f) \cdot \left(\sin\varphi \cdot cos\gamma/\left(\cos(\varphi-\gamma)\right)\right)\ [s^{-1}] \quad (2)$$

$$\tau_{PSZ} = sin\varphi \cdot \left(F_c \cdot cos\varphi - F_f \cdot sin\varphi\right)/(W \cdot f)\ [N/mm^2] \quad (3)$$

Where:

γ is the rake angle; φ is the shear angle; V_c is the cutting velocity in *m/min* and f the feed rate in *mm/rev*; W is the depth of cut in *mm;* F_c is the cutting force and F_f is the thrust force.

C is a constant depending of the workpiece material. For steels, C=5.9 can be considered a good approximation.

2.2 SSZ definition

The estimation of the strain is based on the SSZ thickness, δt_2, and the tool chip contact length, h [6].

$$\varepsilon_{SSZ} = 0.5 \cdot h/\left(\sqrt{3} \cdot \delta t_2\right) \quad (4)$$

The strain rate is defined as

$$\dot{\varepsilon}_{SSZ} = (1000/60) \cdot V_c/\left(\sqrt{3} \cdot \delta t_2\right)\ [s^{-1}] \quad (5)$$

t_2 is the chip thickness in *mm*.

The shear stress is:

$$\tau_{SSZ} = \left(F_c \cdot sin\gamma + F_f \cdot cos\gamma\right)/(h \cdot W)\ [N/mm^2] \quad (6)$$

2.3 Thermal characterization

The average primary shear plane zone T_{PSZ} can be calculated as follows. Here, ρ_W, c_W, k_W are density, specific heat and conductivity of the workpiece material, ρ_t, c_t, k_t refer to the cutting tool material, respectively in $[kg/m^3], [J/(kg \cdot K)], [W/(m \cdot K)]$.

The shear energy per unit volume is:

$$u_s = \tau_{PSZ} \cdot \varepsilon_{PSZ} \cdot \sqrt{3} \cdot 10^6\ [J/m^3] \quad (7)$$

The first heat partition coefficient is:

$$R_1 = \left[1 + 1.328 \cdot \sqrt{\frac{k_W \cdot \varepsilon_{PSZ} \cdot \sqrt{3}}{(\rho_W \cdot c_W \cdot (V_c/60) \cdot (f/1000))}}\right]^{-1} \quad (8)$$

Then:

$$T_{PSZ} = R_1 \cdot u_s/(\rho_W \cdot c_W) + T_0\ [°C] \quad (9)$$

The average temperature T_{SSZ} of the SSZ can be approximated as follows.

The total energy per unit volume is:

$$u_{TOT} = F_c/(f \cdot W) \cdot 10^6\ [J/m^3] \quad (10)$$

The friction energy per unit volume is:

$$u_f = u_{TOT} - u_s\ [J/m^3] \quad (11)$$

Then:

$$B = 0.754 \cdot u_f/(\rho_w \cdot c_w) \cdot \sqrt{\frac{(t_2/1000) \cdot (V_c/60) \cdot (f/1000) \cdot \rho_w \cdot c_w}{((h/1000) \cdot k_w)}}\ [°C] \quad (12)$$

$$A = 2/\pi \cdot [ln(W/h) + (2 \cdot h/(3 \cdot W)) + 0.5] \quad (13)$$

$$C = u_f \cdot V_c \cdot f \cdot A/k_t\ [°C] \quad (14)$$

$$R_2 = (C - T_{PSZ} + T_0)/(C + B) \quad (15)$$

The temperature is:

$$T_{SSZ} = T_{PSZ} + R_2 \cdot B\ [°C] \quad (16)$$

2.4 Experimental design

The experimental data were collected from Tounsi et al. [7] and Pujana et al. [1]. In these articles orthogonal cutting test on the materials, reported in the Table 1, have been performed.

The physical properties of the cutting tool are in the Table 2.

The input data are cutting velocity, feedrate, depth of cut and the tool rake angle.

The experimental data used in the paper are: cutting forces and chip thicknesses.

The other quantities are obtained from empirical models. The reason is to homogenize the data in two papers.

From Oxley [4] the thickness of the secondary shear zone can be evaluated:

$$\delta t_2 = 0.049 \cdot t_2 \quad (17)$$

The tool-chip contact length h was estimated by the following empirical equation (Guo [6]):

$$h = 2.05 \cdot t_2 - 0.55 \cdot f \quad (18)$$

The shear angle is calculated by measuring of the chip thickness t_2 in accordance with the following formulae:

$$f/t_2 = sin(\varphi)/cos(\varphi - \gamma) \quad (19)$$

Table 1: *List of the workpiece materials*

Mat.	N.	Hardness	$\sigma_0 = \lvert\tau_0\rvert\sqrt{3}$ (MPa)
316L	1	28 HRC	502
35NCD16	2	31 HRC	880
42CD4U	3		693
S300	4		250
42CrMo4	5	292 HB	880
20NiCrMo5	6	166 HB	502

Table 2: *Physical characteristics of the cutting tool*

K $(W/(m \cdot K))$	ρ (kg/m^3)	C_p $(J/(kg \cdot K))$
59	15000	400

3 FLOW STRESS IDENTIFICATION

In this section the constitutive equations and the inverse procedure will be presented.

3.1 Introduction

The constitutive equations used are:

1- The simplified Johnson-Cook model:

$$\sigma = (B\varepsilon^n)\left(1 + C ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right)\left(1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right) \quad (20)$$

2- The power law equation:

$$\bar{\sigma} = C(T)\bar{\varepsilon}^n\left(\frac{\dot{\bar{\varepsilon}}}{1000}\right)^m \quad (21)$$

$$C(T) = C_m(T - 600) + C_{600}$$

.

3- The Oxley model:

$$\sigma = \sigma_1\varepsilon^n \quad (22)$$

with $\sigma_1, n = f(T_{mod})$.

The problem of determining of the material constants, in relation to the equation (20) and (21), is:

$$(B, n, C, m) = \min\left(\sum_{i=1}^{N}\left[\frac{B\varepsilon(i)^n}{\sqrt{3}|\tau(i)|}\left(1 + C\cdot ln\left(\frac{\dot{\varepsilon}(i)}{\dot{\varepsilon}_0}\right)\right)\left(1 - \frac{T(i) - T_0}{T_{mel\ ting} - T_0}\right) - 1\right]^2\right) \quad (23)$$

$$(C_m, C_{600}, n, m) = \min\left(\sum_{i=1}^{N}\left[\frac{C_m(T(i) - 600) + C_{600}}{\sqrt{3}|\tau(i)|}\left(\bar{\varepsilon}(i)^n\left(\frac{\dot{\bar{\varepsilon}}(i)}{1000}\right)^m\right) - 1\right]^2\right) \quad (24)$$

The determination of the parameters was performed with MATLAB™. The algorithm is based on the gradient.

The Oxley model was calibrated through the following equations (Oxley [4]):

$$n = [1 + 2\cdot(\pi/4 - \varphi) - tan\theta]/C \quad (25)$$

Where $\theta = arctan(F_f/F_c) - \gamma + \varphi$, is the angle between the resultant force with the shear plane.

$$\sigma_1 = \sqrt{3}\cdot\sigma_{PSZ}/\varepsilon_{PSZ}{}^n \text{ and } \sigma_1 = \sqrt{3}\cdot\sigma_{SSZ}/\varepsilon_{SSZ}{}^n \quad (26)$$

The effect of strain-rate and temperature is combined in a single parameter in order to obtain the velocity-modified temperature T_{mod}.

$$T_{mod} = T[1 - \upsilon\cdot ln\dot{\varepsilon}] \quad [°C] \quad (27)$$

Where $\upsilon = 0.09$.

3.2 Results

The material parameters were determined using the data of PSZ, SSZ and merge them together (said "All"). The results of the power-law model are shown in the Table 3.

The material parameters of the simplified Johnson-Cook are different from each other, but depend strongly of the upper and lower bounds of the optimization scheme. This is due to the numerous local minima. Subsequently, the simplified Johnson-Cook will not be considered.

The power law model exhibits a better behaviour with regard to the inverse procedure: is robust respect to the initial guess and the boundary conditions.

Considering these results, in the next section, 2D FEM simulations have been performed in order to analyze the effect of different material parameters.

4 FEM SIMULATION

In this chapter, 2D FEM simulations will be presented, illustrating the set up of the simulation and the results.

Table 3: *Parameters of the power law model*

Material	Data	C_m	C_{600}	n	m
316L	PSZ	0	977.6	0.146	0
	SSZ	-0.0063	12.04	1.54	0.166
	All	-0.0528	500.5	0.296	0.024
35NCD16	PSZ	-0.089	633.3	0.878	0.0494
	SSZ	0	0.006	4.49	0.368
	All	-0.027	326.3	0.244	0.244
42CD4U	PSZ	0	980.7	0	0.0689
	SSZ	0	54.9	0	0.641
	All	-0.143	134.8	0.615	0.464
S300	PSZ	0	544.4	0	0.0203
	SSZ	0	0.811	1.37	0.556
	All	-0.102	15.1	1.41	0.351
42CrMo4	PSZ	0	981.5	0.695	0
	SSZ	-0.0302	74.9	0	0.492
	All	-0.148	262.8	0.377	0.189
20NiCrMo5	PSZ	0	820.8	0.194	0
	SSZ	0	109.2	0	0.33
	All	-0.0552	182.4	0.311	0.232

4.1 Introduction

The commercial FEA software Deform™-2D v. 9.0, a lagrangian implicit, was used to simulate the machining. The workpiece was initially meshed with 5500 elements, while the tool, modelled as rigid, was meshed and subdivided into 5000 elements.

The friction law used is shear constant, with the constant *m*=0.6. The heat global coefficient was set to $h = 10^5$ *N/s/mm/K*, assuming perfect thermal contact.

The conditions of simulations are shown in the Table 4.

Table 4: *Conditions of FEM simulations*

Material	V_c (m/min)	f (mm/rev)	γ *(degrees)*
316L	67.2; 128.4	0.1;0.2	0
35NCD16	60; 120	0.1;0.2	0
42CD4U	100	0.1;0.2	6
S300	200	0.1;0.2	6
42CrMo4	300;150	0.1; 0.2	6
20NiCrMo5	300;160	0.1; 0.2	6

Only power law material and Oxley model have been tested. Two power law models have been considered: one is referred to the PSZ parameters and the other one is referred to the merging of PSZ and "All" parameters. The combination has been made in this way:

if $\varepsilon \geq \varepsilon_{trans}$ and $\dot{\varepsilon} \geq \dot{\varepsilon}_{trans}$ and $T \geq T_{trans}$ then use the "All" parameters, else use "PSZ" parameters.

4.2 Results

For each workpiece material, the two constitutive equations are taken into account.

Only one cutting condition is considered. This refers to the lowest value of cutting speed and the lowest feedrate.

The Figure 1 show the results of the FEM simulation when the power law model is used. In this case $\varepsilon_{trans} = 0.4$; $\dot{\varepsilon}_{trans} = 9000\ s^{-1}$; $T_{trans} = 500\ °C$.
With PSZ parameters the comparison of the cutting forces can be considered acceptable, while with "All" parameters the cutting forces are low. It can be observed that the predicted values are lower than experimental values ("EXP" in the figure).
The Figure 2 shows the results of the FEM simulation when the Oxley consitutive equation is used. It may be noted that the predicted cutting forces are underestimated.
Finally, the comparison of maximum temperature on the tool rake, originating from the two material models, is shown in the Figure 3.

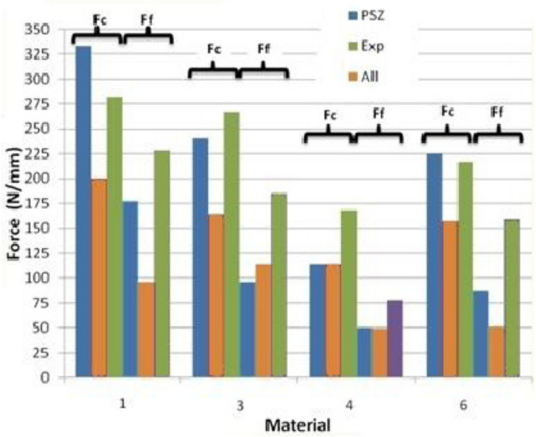

***Figure 1:** Cutting forces with power law constitutive equation*

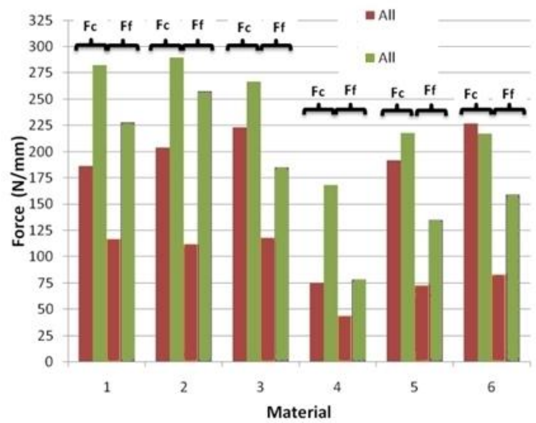

***Figure 2:** Cutting forces with Oxley constitutive equation*

The lowest temperatures are referred to the "all" parameters for the power law model. This is similar to the Oxley model, where PSZ and SSZ are combined together.

5 CONCLUSIONS

The experimental data, which come from the SSZ, modify the material parameters. The FEM simulation shows that the presence of the SSZ data makes soften the material. This is confirmed by the Oxley model, made from the combination of the PSZ and SSZ.
The cutting forces are underestimated. The chip thickness and the contact length are not in good agreement.
In the future different models of materials will be used for the PSZ and SSZ zone separately. This may improve the characterisation of workpiece material, which is under very different conditions during the machining, from PSZ to SSZ.

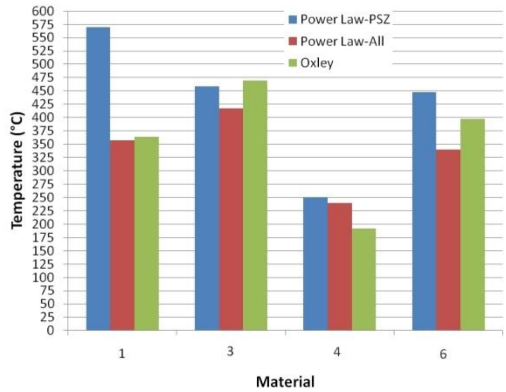

***Figure 3:** Comparison of maximum temperatures of the tool for different material models*

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