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**Abstract** — In this paper, an analytical approach is proposed to model chip formation in the case of turning process. Numerical simulations of chip genesis are performed in order to fit efficiently the proposed analytical model. In particular, the variables like temperature and internal stress distribution are studied using finite element modeling. Numerical model setting is made with experimental and literature data using forces and the thickness of the primary shear zone.
**Keywords** — Johnson-Cook, analytical, cutting model, chip formation.

## 1 Introduction

Turning and abrasion processes are widely used in different industries to cut different engineering parts. Usually the optimization of these processes is made by experimental methods often expensive and not able to be extrapolated to other machining configurations. To overcome these drawbacks some numerical simulations were carried out by many researchers but the major inconvenience of those methods are the long computing time, the high cost of numerical software etc.

For all these reasons, in manufacturing industry, a highly interest in analytical methods like that of Merchant [5] is usually researched because it is very practice and simple to use. Recently, Gilormini, Molinari and Oxley [2,6,8] have the computation of the temperatures and shear zones thicknesses but the methodology to obtain those values is in general long and complicated for industrial community. In fact the differential equations presents in those thermo-mechanical models need time to be solved and also, in the same way, some parameters not easy to find in bibliography.

For all this reasons, the aim of the present paper is to present at the scientific communities a methodology to calculate the major numbers of variables of the material removing (cutting and ploughing forces, temperatures, spring back…). Here the equations can be directly used by engineers.

The proposed analytical modeling of the chip formation is performed using universal mechanical formulation and balance, and is improved by both numerical simulations and experimentations data (figure 1).

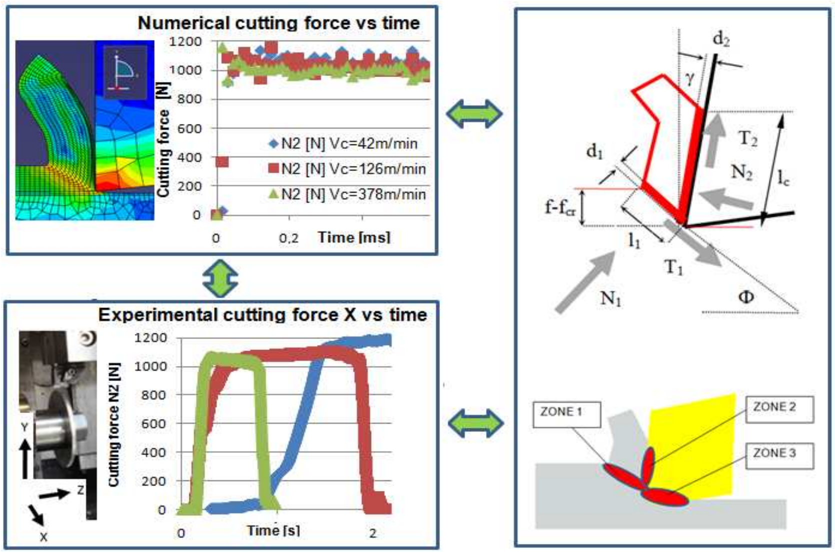


Fig. 1 – Description of the analytical model and the experimental and numerical methods used

In this case, first the experimental tests, the machines, materials employed and the measured data like forces and chip thickness are presented. Then numerical simulation using ABAQUS Explicit is developed in order to identify more accurately influences physical phenomena. Afterwards, an analytical modeling is proposed and numerical improvements are presented.

## 2 Experimental tests

In this section the experimental cutting tests are presented. In order to replicate orthogonal cutting conditions, the machining operation was done on disc with a diameter of 70 mm and a thickness ($a_p$) of 3 mm, which presents in the same time the cutting depth (Fig. 1).

The cutting tool is in a carbide grade (ref. TPKN 16 03 PP R SM30) with cutting edge radius R of 30 μm and the machined material is a steel alloy AISI 4140.

The values of the thickness of the material to cut ($a_p$) and the cutting radius of the tool (R) were chosen to minimize ploughing effects in order to have a real cutting process. Measures of forces in (x, y z) are done with dynamometer Kistler 9257 A with natural signal frequency 2000 Hz.

Details of the averages of forces, angle of the primary shear zone Φ and the thickness of the chip $e_c$ are presented in the table 1. The primary shear angle Φ is computed using equation 1

$$\phi = \mathrm{Arc}\tan\left(\frac{f}{e_c}\right) \tag{1}$$

**TABLE 1.** Experimental values of X, Y forces and the chip thickness $e_c$ in the case of machining of AISI 4140, tool in carbide material (R=30μm), f=0.15mm, γ=0.

| **Vc [m/min]** | **X [N]** | **Y [N]** | **$e_c$ [mm]** | **Φ [Rad]** |
|---|---|---|---|---|
| 42 | 1120 | 490 | 0.31 | 0.45 |
| 126 | 1100 | 560 | 0.22 | 0.58 |
| 378 | 1060 | | 0.18 | 0.65 |

## 3 Numerical model

Numerical simulations based on Abaqus\Explicit were performed in order to both understand the physic of cutting and improve the analytic method. Johnson and Cook law is used for the workpiece material behavior [1].

The workpiece is numerically modeled in 3 parts [4,10]. In the part “final piece” only the behavior law of Johnson and Cook is defined and for the part “chip” and “transition” also the Johnson and Cook damage law is taken into consideration.

In order to find the good mesh dimensions for the numerical simulations it is decided to study, in a first time, the influence of the mesh size versus the primary shear zone thickness and the cutting force as showed in figure 2. In this specified study frictionless assumption is done for the chip-tool contact.

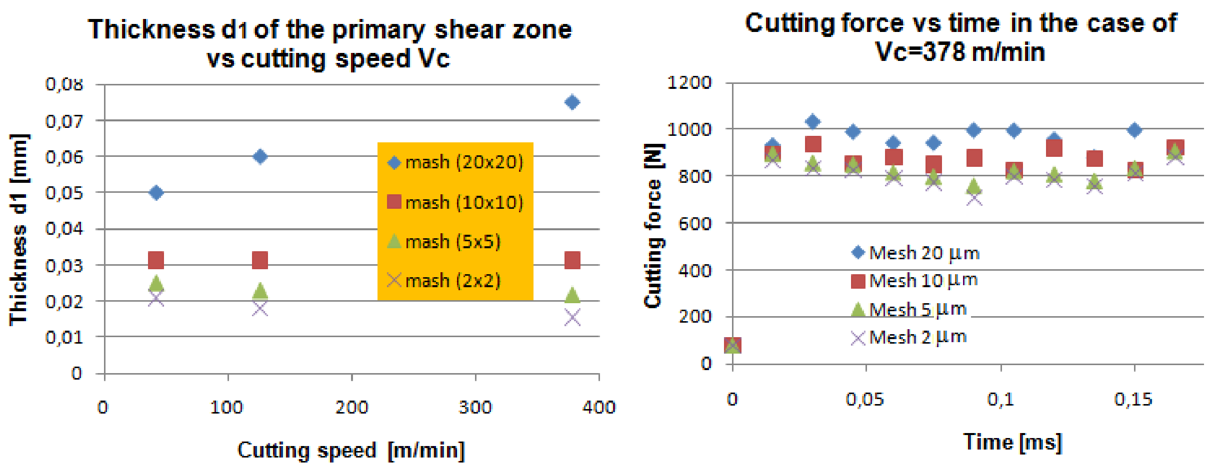


Fig. 2 – Numerical simulations in case of AISI 4140 steel, f=0.15 mm, $\gamma$=0, $\mu$=0, thickness of the primary shear zone vs cutting speed for different cutting speeds. For Vc=378 m/min the cutting forces are represented

In figure 2, it is possible to underline that for small mesh size values the primary shear zone thickness is small too. This is due to localization phenomena, which induce high temperature and afterwards material softening leading to lower forces and then lower thickness.

The computed primary shear zone thickness for mesh size from 5 to 10 µm is closed to experimental values (25 µm) given by Shaw [11].

For all these reasons, the mesh size 10x10 µm is adopted in this study and seems in agreement with literature [1].

The "surface to surface" interaction option and the penalty contact method are chosen in ABAQUS\EXPLICIT.

In particular, the friction adhesive coefficient between tool and workpiece is determined by Zemzemi method [12].

Using mesh dimension 10x10 µm and the previous adhesive friction coefficient [12], it is then possible to perform numerical simulation and compare results to experimental cutting forces primary shear zone angle $\Phi$, chip thickness $e_c$ (table 2)

**TABLE 2.** Numerical results: X and Y forces, $\Phi$ and the chip thickness $e_c$ in case of AISI 4140 steel, carbide tool f=0.15 mm, $\gamma$=0

| | **X [N]** | **Y [N]** | **$e_c$ [mm]** | **$\Phi$ [Rad]** |
|---|---|---|---|---|
| Vc=42m/min | 1150 | 520 | 0.32 | 0.46 |
| Vc=126m/min | 1090 | 550 | 0.25 | 0.54 |
| Vc=378m/min | 1070 | 590 | 0.20 | 0.63 |

It is important to underline that, in order to have a good description of the vertical forces (Y) during the cutting process, the ALE formulation is also adopted. In particular with ALE the cutting edge influence is described with more accuracy than lagrangian one.

## 4 Analytical model and numerical improvements

Orthogonal cutting represented by a 2D model is studied. The cutting tool removes a specific layer of work material. f is the theoretical uncut thickness to remove with the tool, R is the cutting edge radius considered zero in this paper.

The chip is assumed rigid except in zone 1 and 2 (figure 1) where all the deformations are concentrated. The thicknesses of these zones are $d_1$ and $d_2$. In both zone, the assumption of thermo-viscous-plastic-hardening material behavior is made.

$N_2$ is the orthogonal force and $T_2$ is the tangential or friction force on the flank face of the tool. $T_1$ and $N_1$ are the tangential and normal forces applied on the primary shear zone.

It is supposed that in zone 2 Coulomb's law (equation 2) can be applied with friction coefficient $\mu_{ad}$.

$$T_2 = \mu_{ad}(V_{g2})N_2 \qquad (2)$$

Different parameters, related to chip formation, can be expressed when balances of forces and moments applied to chip in static mechanical are written (like Merchant approach [5]). Consequently, it is possible to write equations 3, 4, 5.

$$N_2 = \frac{T_1(\cos(\Phi) + Tan(\Phi)\sin(\Phi)}{\cos(\gamma) + \mu\sin(\gamma) - \tan(\Phi)(\mu\cos(\gamma) - \sin(\gamma))} \qquad (3)$$

$$N_1 = \frac{N_2(\mu\cos(\gamma) - \sin(\gamma))}{\cos(\Phi)} + T_1 Tan(\Phi) \qquad (4)$$

$$l_c = a\frac{l_1 N_1}{N_2} \qquad (5)$$

In equation 5, "a" depends on the distributions given to $N_1$ and $N_2$. $\Phi$ is obtained by equation 6 like in Merchant's method where the minimum cutting power $P_C$ is considered.

$$Min\{P_C\} = Min\{V_C(T_2\sin(\gamma) + N_2\cos(\gamma))\} \qquad (6)$$

It is important to underline that, if $T_1$ is constant like Merchant supposed, the values of $\Phi$, computed with equation 6 is over evaluated and forces are under evaluated.

For this reason, it is decided to apply, in a first step, Pijpanen formulation [9] to calibrate the model (equation 7).

$$T_1 = T_{10} + cN_1$$ With $T_{10}$ the simple shear force equal to $$T_{10} = \int_0^{l_1} \tau_{10}\, dl_1 \qquad (7)$$

Where $\tau_{10}$ is the simple shear stress characterizing the material and $l_1$ is the length of the primary shear zone.

It is important to note that equation 6 is the generalized Coulomb friction law where the first term is the "cohesive" contribution and the second one the "adhesive" term. The evolution of the coefficient *c* versus the cutting speed is presented in table 3. To compute analytically the coefficient *c* the followings steps are applied:

•  $\Phi$ values based on experimental measurements are used in the analytical model as an input parameter.

•  Analytical calculation is executed using different values of coefficient *c*. The computation is considered terminated when analytical $\Phi$ value is equal to experimental one.

Like showed in table 3 the Pijpanen coefficient computed with the analytical method is function of the cutting speed. Typically the bigger values of *c* are in correspondence of small cutting speed. This trend is similar to the friction coefficient trend between 2 surfaces.

In order to verify the values of *c* coefficient obtained analytically with equation 7, it is proposed a FEM validation (Fig. 3). In this last case $T_{10}$ is constant, $T_1$ and $N_1$ are calculated with numerical simulations and, than, it is possible to compute *c* numerically. The numerical and analytical results are similar.

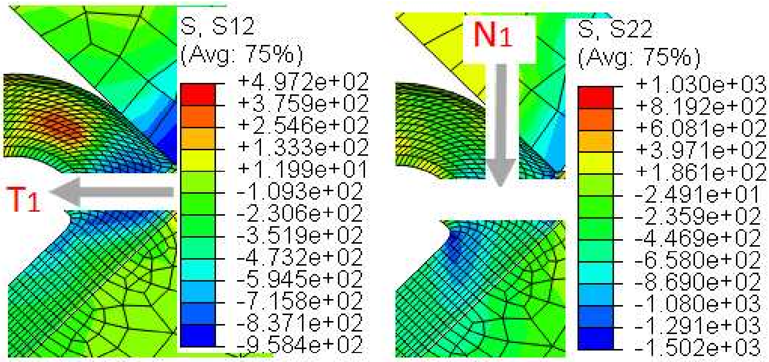


Fig. 3 – The employed methodology to compute *c* in case of Vc=42 m/min

**TABLE 3.** Comparative between *c* values computed with analytical approach and numerical

| | Vc=12 [m/min] | Vc=42 [m/min] | Vc=126 [m/min] | Vc=378 [m/min] |
|---|---|---|---|---|
| *c* numerical | 0.7 | 0.6 | 0.4 | 0.2 |
| *c* analytical | 0.65 | 0.6 | 0.45 | 0.25 |

It is important to note that the method used to compute $T_1$ using *c* coefficient needs experimental or numerical approach for every configuration of parameters, in particular the values of this coefficient in equation 7. To overcome this drawback it is proposed in this paper also a different method using numerical simulations. In fact the ratio $l_c/l_1$ remains constant when varying $V_C$ where lc is the contact length between chip and tool and $l_1$ is the length of the primary shear zone (table 4).

**TABLE 4.** Numerical values of the ratio $l_c/l_1$ in case of different cutting speed and coefficient *m* in Johnson and Cook law

| | Vc=42 [m/min] | Vc=126 [m/min] | Vc=378 [m/min] | Pure plastic 595 MPa | m=0.2 | m=20 |
|---|---|---|---|---|---|---|
| $l_c/l_1$ | 0.68 | 0.7 | 0.67 | 0.72 | 0.69 | 0.73 |

This yields to obtain a new equation (8) to solve the system.

$$\frac{l_c}{l_1} = 0.7 \,. \qquad (8)$$

Afterwards, like showed in figure 6 and 7 it is possible to capture that normal stresses in zone 1 and 2 have similar values close to Tabor calculation ($3\sigma^y$). The region defined between zone 1 and 2 is totally plastically deformed and the triaxiality is important.

From those considerations it is possible to extract equation 9 where the normal stress $n_1$ is function of the tangential one $\tau_1$ and le normal force $N_2$ in the second shear zone is a function of $\tau_1$.

$$n_1 = n_2 = \sqrt{3}\ \tau_1 . \qquad \text{and} \qquad N_2 = n_2 l_c = \sqrt{3}\ \tau_1 l_c \tag{9}$$

Equation 8 is verified for different behavior law like showed in figure 4. For those reasons it is considered, in a first time, that it can be applied for different types of materials.

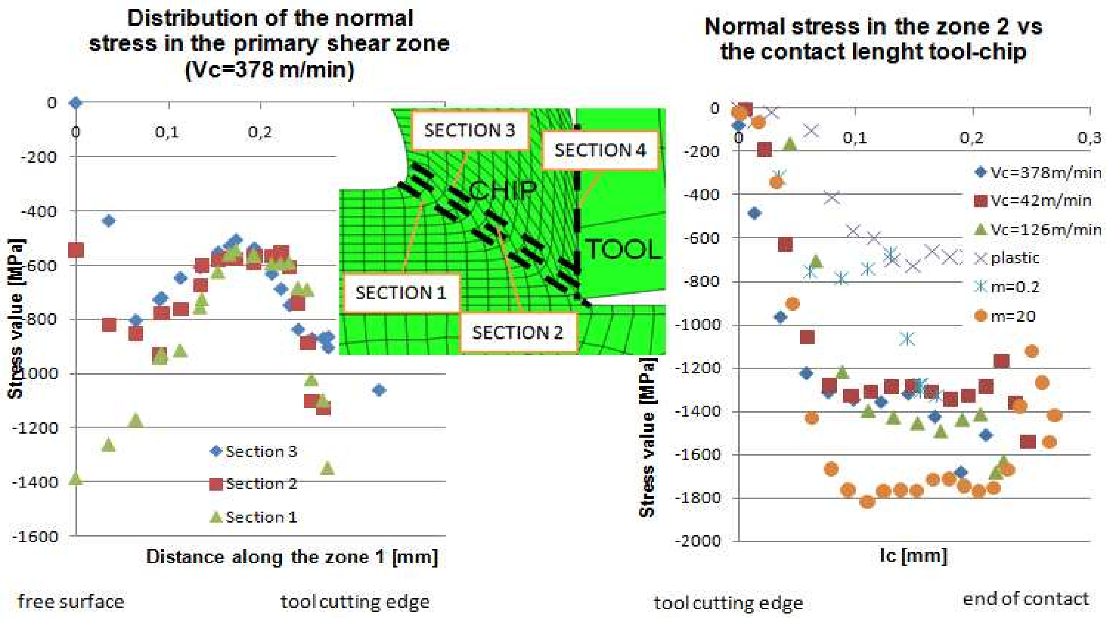


Fig. 4 – Normal stress distribution in zone 1 and 2 in different cutting conditions and different sections

It is important to underline that equations 8 and 9 replace equation 6 and 7, respectively. The total numbers of variables and equations are the same but now the model is predictive.

Equation 8 and 9 in the proposed analytical model gives the calculation of cutting force and Φ according to experimental data (table 5), and this calculation don't need to minimize the cutting energy like Merchant. Many researchers think today that the employment of the equation of the minimum of the cutting energy to solve the problem is wrong; Molinari [7] suggest a correction of the Merchant formulation using the instability theory of the primary shear zone.

The primary shear force and stress is computed with Johnson and Cook law (equation 10 and 11).

$$T_1 = \tau_1 l_1 \tag{10}$$

$$\tau_1 = \left[\frac{A}{\sqrt{3}} + \frac{B\gamma_{d1}^{n}}{\sqrt{3}^{n+1}}\right]\left[1 + CLn\left(\frac{\dot{\gamma}_{d1}}{\dot{\gamma}_{d10}}\right)\right]\left[1 - \left(\frac{T_{empl} - T_0}{T_f - T_0}\right)^m\right] \tag{11}$$

Now let study the calculation of the temperature in zone 1 to solve equation 11. For this reason the unitary volume of the zone where the deformation is concentrated is evaluated by equation 12, HH' is the displacement caused by the force $T_1$, Q is the plastic energy converted into heat. The average value of temperature in zone 1 $T_{emp1}$ is computed with equation 12 (definition of specific heat).

$$T_{emp1} = T_{emp10}(1-\delta_1)\frac{Q}{\rho W C_V} \quad \text{where} \quad Q = 0.9\, T_1\, HH' \text{ and} \qquad W = l_1 d_1 \qquad (12)$$

In equation 12 $\delta_1$ is the partition heat coefficient considered zero in this paper. In fact for modern cutting technology (Vc>100 m/min) the adiabatic hypothesis in zone 1 can be adopted [6] like it is possible to see in figures 5 and 6.

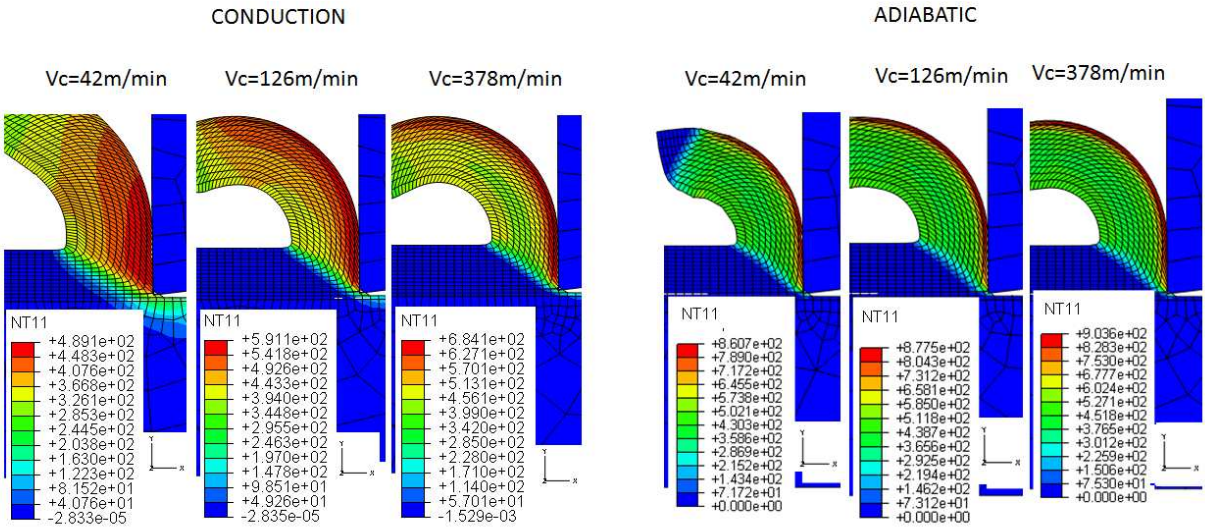


Fig. 5: Numerical simulations. Conduction and adiabatic case are represented.

This result can be applied also to abrasion process where the local speed is significantly higher.

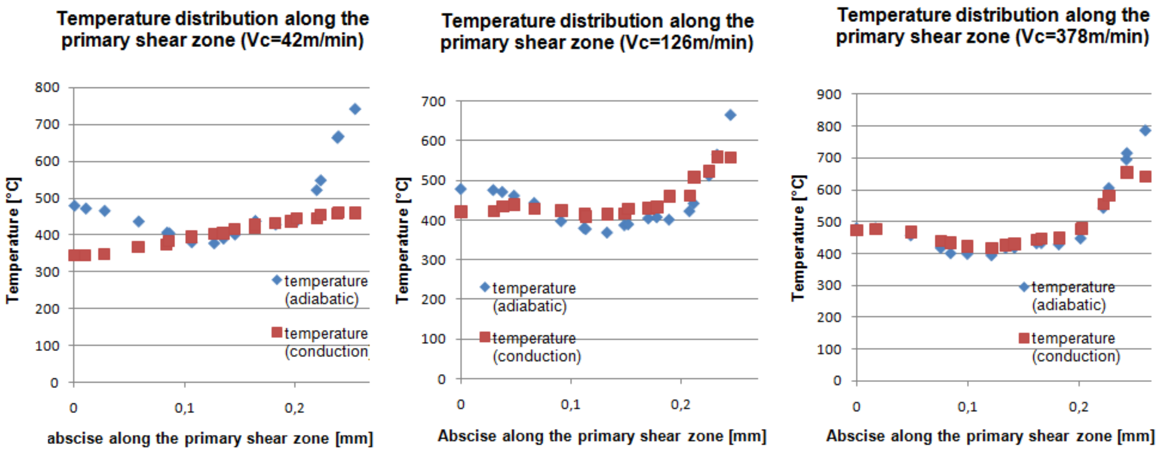


Fig. 6: Numerical temperature distribution in zone 1 for conduction and adiabatic case.

**TABLE 5.** Analytical section. Values of X force, Y force, angle $\Phi$, temperature in zone 1 and the contact length tool-chip $l_c$ in case of 42CD4, tool in carbide material (R=30µm), f=0.15mm.

| **Vc [m/min]** | **X [N]** | **Y [N]** | **$\Phi$ [Rad]** | **$l_c$ x f** | **$T_{emp1}$ [°C]** |
|---|---|---|---|---|---|
| 42 | 1100 | 470 | 0.48 | 1.9 | 420 |
| 126 | 1050 | 520 | 0.57 | 1.5 | 450 |
| 378 | 1030 | | 0.62 | 1.3 | 550 |

# 5 Conclusions

In this paper numerical simulation to improve a chip formation analytical model [10] is presented. This model assumes that the chip can be considered rigid but all the deformations are concentrated in the shear zones. This model is based on numerical simulations and experimental results.

The main aim was to find simple model, which can be easily used in industry. In fact the output variables of the study (Forces, Temperatures, $\Phi$, $l_c$) are computed with simple equations.

It is complete, taking into account the shear zones, the temperatures, and the contact length.

The present model can be qualified as predictive. In fact the calculation of the variables of the model are only function of the input parameters (working and workpiece parameters), and it is not required any experimental setting like chip thickness. In particular, the assumption that the tangential force in the primary shear zone is the sum of two terms ($T_{01}$ and $cN_1$) is rejected. Afterwards, the minimization of the cutting power proposed by Merchant is also discarded. Two new equations (8 and 9) are found using numerical simulations and are very important to solve the problem.

As a perspective the present analytical model can be exploited to predict residual stresses after machining and study a complex case of industrial cutting.

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