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Analytical modeling of material removal process in the case of orthogonal cutting and worn tools

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Abstract —Analytical methods are usually researched because there are very practical to use but those methods don't take into account all the aspects of the contact between the work material and the tool. For those reasons, a “phenomena split approach”, based on the assumption that the material removal is the summation of four major contributions, plowing, elastic compression, spring back and “pure cutting”, was adopted. Consequently it is possible to compute forces, strains and temperatures during tool action, which is important to understand how residual stresses appear in the final surface.

Keywords — worn tools, analytical cutting model; spring back

1. Introduction

Analytical cutting models are usually used by researchers and engineers in industry because they are easy and fast to use [1-3]. Other authors such as Moufki [4] have proposed pertinent thermo-mechanical cutting models but they don't take into account the cutting radius influence, plowing and the spring back. Those assumptions are pertinent in the case of small cutting edge radius but not for bigger ones (worn tools). For all those reasons the authors have presented [5] a new analytical model based on the assumption that all the phenomena existing during the contact (plowing, spring back, elastic compression, chip formation) can be decomposed, in order to have a complete approach (Figure 1).

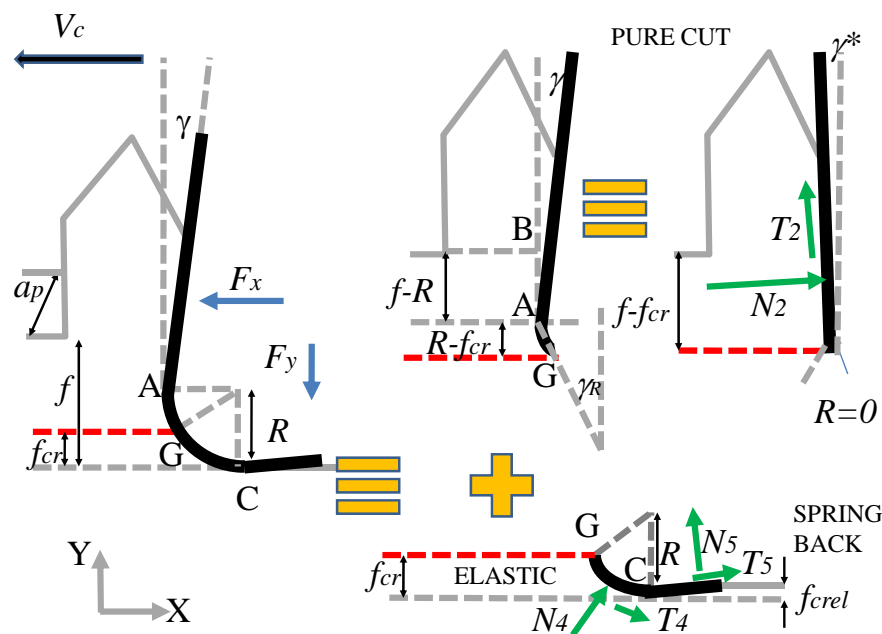


Figure 1 – Sketch of the “Phenomena split- approach”.

The cutting tool removes a specific layer of work material (Fig. 1). f is the theoretical uncut thickness to remove with the tool, R is the cutting edge radius, $f-f_{cr}$ the real layer of work material removed. In fact, the cutting edge radius induced lateral burrs and elastic displacement of the material under the tool [6]. Consequently the real value of the uncut chip thickness ($f-f_{cr}$) transformed into chip is smaller than the theoretical value f .

Concerning the chip formation contribution (“pure cutting”), it is supposed that the cutting process is made with a virtual tool, with a cutting edge radius $R = 0$, and the effective layer of work material removed is $f-f_{cr}$. In this case, the contribution of cutting edge radius on chip formation is taken into account using an equivalent cutting angle [5] like it is acted in equation 1.

$$\gamma^* = -\left(\frac{R-f_{cr}}{f-f_{cr}}\right) \arctan\left(\frac{R-\sqrt{2Rf_{cr}-f_{cr}^2}}{R-f_{cr}}\right) + \left(\frac{f-R}{f-f_{cr}}\right) \gamma \quad (1)$$

This angle is the summation of 2 contributions. The first one is the local cutting angle γ_R caused by the cutting radius; its action is localized in the layer “ $R-f_{cr}$ ” (AG). The second one is the contribution of the angle γ in the “ $f-R$ ” layer (AB). It is noted that, when the f/R ratio is very big, γ^* is close to γ . In the opposite situation, when f/R is close to 1 γ^* is similar to γ_R .

f_{cr} gives the supposed position of the separation line between the material that will become chip and the part of metal that will flow under the tool and will be displaced laterally (plowing).

Plowing, elastic deformation under the tool and spring back are concentrated in the layer defined between the beginning of the chip and the end of the contact under the tool. It is also supposed that it depends only on thermo-mechanical workpiece parameters, cutting depth a_p and f_{cr} value. It will thus be possible to apply the effect superposition principle and study separately all those phenomena.

In the proposed approach, plowing, elastic compression under the tool and spring back are caused by the cutting edge radius and, if it is zero, only the pure cutting condition will exist. Particularly this last condition is represented in new cutting tools with a very small cutting edge radius.

Using continuity principle and according to numerical simulations [6] it is possible to obtain equation 2.

$$f_{cr} = f_{crel} + \frac{h^2}{a_p} = f_{crel} + f_{crpl} = f_{crel} + \frac{(1-\mu)^2 R^2}{a_p} \quad (2)$$

The burr h is considered equal to $(1-\mu) R$ where μ is the adhesive friction coefficient. In equation 2 the first contribution is elastic, due to the sliding of the material under the tool. The second one is plastic caused by burr formation.

In order to solve f_{crel} a rapid execution approach inspired by Hertz theory is applied [6]. It is also supposed that the elastic separation line in front of the tool is equal to the spring back value after tool displacement.

$$\frac{f_{crel}}{R-0.25f_{crel}} = \frac{9\pi^2 \sigma^{y2}}{E^{*2}} \quad (3)$$

According to Tabor, the pressure under the tool in the workpiece, close to point C (Fig. 1) is considered equal to three times the yield stress.

In this paper, the study of the global method is presented and particularly the analytical computation of forces, stresses and temperatures during tool action in the case of worn tools. This method is called “composition method” and it is the addition of the elementary phenomena that exists

during tool action. Forces and temperature computation under the tool are presented and finally the composition analytical computation is compared to experimental tests. This paper will be terminated with some conclusions and outlooks.

2. Analytical model and results

The real tool is regarded as being the stacking of the “virtual” tool (with $R=0$ and the angle of cut equal to γ^*), and the “low” part of the real tool (between the point O and E as it is shown in figure 1) acting on the part of material, which is not transformed into the chip. The horizontal and vertical efforts are consequently the addition of the contributions of “pure cut”, plowing, elastic compression and spring back (equations 4 and 5).

$$F_x = T_2 \sin(\gamma^*) + N_2 \cos(\gamma^*) + N_3|_x + N_4|_x + T_4|_x - N_5|_x + T_5|_x \quad (4)$$

$$F_y = T_2 \cos(\gamma^*) - N_2 \sin(\gamma^*) + N_3|_y + N_4|_y - T_4|_y + N_5|_y + T_5|_y \quad (5)$$

In equations 4 and 5 the firsts two terms concerns the pure cutting contribution. The others are plowing and elastic as it is showed in figure 1. The chip is considered rigid and the static equilibrium of the chip leads to the definition of three simple equations [5]. The thermo-mechanical assumption was made in the shear zones 1 to 5. Here the strain is supposed to be concentrated and computed using Johnson and Cook behavior law. The temperature calculation is made using the definition of specific heat in the shear zones.

In this paper the focus is done on worn tools having a high cutting edge radius, and in this case plowing and elastic contributions are not negligible. Particularly plowing phenomena are important when a_p is small because this phenomena is border dependent. In turning application, in general, it is possible to consider this phenomenon negligible in term of forces and temperature calculation because a_p is bigger than f . The ratio f/a_p is consequently low. In the case of abrasion, and single grain analysis, f/R is small but also f/a_p is big, consequently plowing effects have to be computed. This particular case is not presented in this paper.

Analytical and experimental results are presented in table 1, in the case of AISI 4140 steel, carbide tool, orthogonal cutting. Physical and mechanical data are taken from [5].

Table 1 – Analytical forces in the case of $\gamma = 0$, $a_p = 3$ mm, $f = 0,15$ mm/rev, $V_c = 42$ m/min. In brackets experimental results

R [μ m]	Workpiece	f_{cr} [mm/rev]	Outputs in X direction [N]						
			F_x	$N_{2/x}$	$T_{2/x}$	$N_{4/x}$	$N_{5/x}$	$T_{4/x}$	$T_{5/x}$
30	AISI 4140	0,0038	1091 (1118)	1064	-42	20,29	-5	32	21
150	AISI 4140	0,02	1111 (1241)	1273	-270	101	-25	132	77
			Outputs in Y direction [N]						
30	AISI 4140	0,0038	636 (563)	102	439	78	28	-8	-4
150	AISI 4140	0,02	1265 (1121)	458	750	393	140	-34	-14

From table 1 it is possible to capture that, for $R=30$ μ m, elastic contributions are small. In the case of $R=150$ μ m (worn tool) all the contributions are relevant because f_{cr} is high. Consequently zones 4 (elastic compression) and 5 (spring back) are longer in terms of contact length and forces are not negligible.

In the case of feed forces computation, and in the case of big R , usually, in analytical methods, the elastic compression contribution under the tool is not considered. For this reason a big friction coefficient is usually employed in order to have similar values to F_y measurement. In reality T_2 contribution is less (low friction coefficient μ) but elastic compression N_4 is not negligible.

Finally it is possible to act that shear forces values ($T_{4/y}$ and $T_{5/y}$) are negatives because of the equivalent cutting angle that takes into account in pure cutting the R contribution using an equivalent cutting angle.

3. Conclusions

In this paper an analytical model of material removal is presented. This model is based on the new assumption that cutting operation can be defined as a sum of four contributions: pure cutting, plowing, compression under the tool and spring back at its rear.

The cutting radius of the tool is modeled using an equivalent cutting angle, which is new compared to the cited works [1-3]. The f/R ratio is important and defines 2 different conditions. If it is big the cutting radius R can be considered null, but if it is low, it is necessary to model the radius R . It is the industrial case of damaged tools. The separation line between chip (pure cutting) and elastic and plastic phenomena under the tool are also analytically modeled.

With this new approach it is possible to simply model forces, stresses and temperatures at the interface between worn tool and workpiece in every zone, particularly zones 4 and 5 located between the separation line f_{cr} and the end of the contact at the rear of the tool. This last zone is important because it is the location of the last contact between tool and workpiece.

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