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Improvement of cutting forces modeling based on oriented cutting tests

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Abstract

In order to predict the characteristics of the machined part, such as geometry, surface roughness and fatigue or corrosion resistance, the cutting forces values should be known as precisely as possible.

The edge discretisation methodology can be used to model the three components of the cutting forces. The results are generally considered as suitable, even if the considered cutting operation is complex, because the geometry is well described.

Usually, the local cutting forces model is identified from orthogonal or oblique cutting tests and the local contributions are assumed to be independent of the orientation of the elementary edge in the reference plane P_r .

However, when turning in the tool nose or with round inserts, the tool cutting edge angle κ_r (or Side Cutting Edge Angle) evolves along the active cutting edge and the values of this angle are very small compared to that of 90° used in orthogonal/oblique cutting.

For this study, a new elementary cutting operation, called “oriented cutting”, has been tested. In this configuration, the active cutting edge is rectilinear, without inclination, but oriented by an angle κ_r different from 90° . In addition, cylindrical turning tests have been done.

The measurements, performed in pure copper, show an influence of the tool cutting edge angle on the cutting forces. An interaction between κ_r and the workpiece radius is also highlighted.

Keywords: Cutting forces modeling; Edge discretisation; Oriented cutting tests; Pure copper

1. Introduction

The calculation of cutting forces is of interest to predict the characteristics of the machined part as geometry, surface roughness or material integrity.

One possible way to model the forces is to use the edge discretisation as presented on Figure 1.

This methodology allows considering the local uncut chip thickness [1], which is particularly interesting in finish turning ($a_p < r_\epsilon$).

Indeed, when cylindrical turning in the nose or with round insert, the uncut chip thickness evolves along the active cutting edge.

The maximum uncut chip thickness h_{max} and the local uncut chip thickness $h(\theta)$ can be analytically calculated respectively according to Huang and Liang [2] and Armarego and Samaranayake [3].

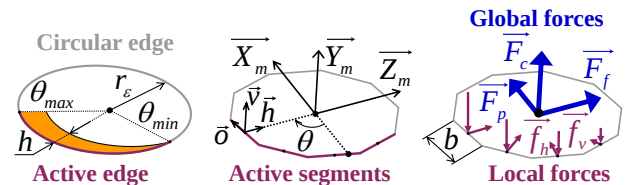


Fig. 1. Edge discretisation principle, illustrated in the case of a round turning insert

The angular sector corresponding to the active cutting edge can be determined by Equations (1) and (2).

$$\theta_{min} = \arcsin\left(\frac{-f}{2r_\varepsilon}\right) \quad (1)$$

$$\theta_{max} = \arccos\left(\frac{r_\varepsilon - a_p}{r_\varepsilon}\right) \quad (2)$$

The local cutting model is often identified by doing orthogonal cutting tests on disks [4-5] or tubes [4,6].

The most often used forces model is expressed in a semi-global basis $(\vec{o}, \vec{v}, \vec{h})$ oriented by both the machine $(\vec{v} // \vec{V}_c)$ and the tool ($\vec{h}$ normal and $\vec{o}$ tangent to the cutting edge) [4].

In a first approximation, the local forces can be expressed only in function of the local uncut chip thickness h as follows (Equation (3)) [7].

$$f_i = (K_{ci} h + k_{ei}) \quad \text{with } i = v \text{ or } h \quad (3)$$

As the tool is finely described by the discretisation, the local cutting geometry can also be taken into account in the model [8].

Thus, a lot of studies add the effect of the local cutting geometry in the model, as the rake angle [4-6,8], the inclination angle [4,6] or the clearance angle [5].

However, in industrial context, the first step needed is to evaluate the forces for a given tool along a tool path in order to select the suitable cutting parameters.

That is why, this study focuses on the effects of the workpiece radius and the tool cutting edge angle and their possible interactions, as these parameters can evolve along a tool path.

The effect of the side cutting edge angle (SCEA, equal to $90^\circ - \kappa_r$) has been yet experimentally studied [9-12]. Unfortunately, the ranges of variations of κ_r are close to 90° (except in [9]). Furthermore, the tests and the observations have been done only at a macroscopic scale. Indeed, the nose of the tool was engaged during the tests and the measured forces are studied in the measurement basis.

Some changes have been observed in the chip morphology when changing κ_r [10-11, 13].

However, the experimental work presented in this paper suggests an explanation, detailed in the following sections, based on the contact between the clearance face and the machined surface.

In the next section, the elements of the experimental device common to all tests are briefly described.

Then, the operation of cylindrical turning is analysed to point the need of taking into account both κ_r and the workpiece radius in the local cutting forces model.

Finally, new elementary cutting tests are presented in order to highlight the effect of κ_r at a mesoscopic scale.

2. Experimental set-up

The machined material for the whole tests is a pure copper Cu-OFE. The homogeneity has been verified by micro-hardness tests from the heart of the workpiece to the surface (average measured hardness: 100 HV_{0.5}).

Cutting tests have been done on a 2-axis lathe Somab Transmab 400 at a cutting speed V_c of 250 m/min with micro-lubrication (Total Valona MQL 3046).

The cutting forces have been measured with a piezoelectric dynamometer Kistler type 9121 and an amplifier Kistler 5019A. The signals have been digitised by a data acquisition card NI PCI-6221 (at a frequency of 2 kHz) and treated with DasyLab software.



Fig. 2. Experimental set-up

The local cutting geometries of the cutting inserts have been measured by stereovision from SEM photographs (Alicona Mex software).

The normal wedge angles β_n are approximately equal to 66° ($\gamma_n = 17^\circ$) and the edge radii r_β are between 11 and 17 μm .

3. Effect of the workpiece radius on the cutting forces

3.1. Orthogonal cutting on disks

It has been shown by Germain [5] that, in the case of orthogonal cutting on disks, when the radius increases the cutting forces could increase for some cutting geometries. This has been supposed to be due to the enlargement of the clearance contact.

3.2. Cylindrical turning – Theoretical investigation

When finish cylindrical turning, in addition to the uncut chip thickness, the local cutting edge angle κ_r (equal to θ in the present case) and the radius of curvature of the workpiece in the plane P_o (where is done the elastic recovery and the friction on the clearance face due to the first motion) evolve along the cutting edge too.

This radius, called local effective workpiece radius, denoted R_o^W and shown on Figure 3, can be expressed by the Equation (4) according to Germain [14].

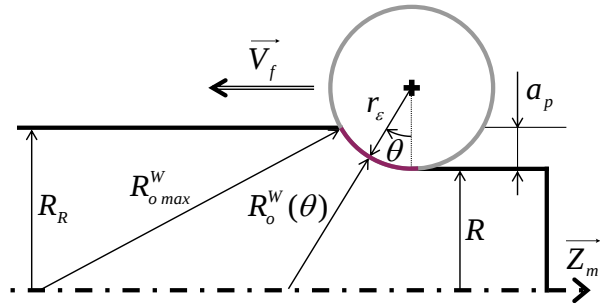


Fig. 3. Local effective workpiece radius when cylindrical turning

$$R_o^W = r_\epsilon \left(\frac{1}{\cos(\theta)} - 1 \right) + \frac{R}{\cos(\theta)} \quad (4)$$

At the cutting point corresponding to $\theta = 90^\circ$, the cutting configuration corresponds to orthogonal cutting on tube.

At $\theta = 0^\circ$, R_o^W is equal to the workpiece radius, but it does not correspond to orthogonal cutting on disk because κ_r is equal to zero.

3.3. Cylindrical turning tests

Five tests of cylindrical turning, with different feeds and depths of cut, have been done at different diameters. Some results are given in Table 1 and on Figure 4.

The depth of cut a_p is small enough compared to r_ϵ to have $R_o^W_{max}$ less than 1.3 times R . So, each group of five tests reflects the effect of a small range of radii.

It should be noted that, due to this reason, θ_{max} is lower than 34° .

Table 1. Measured forces when cylindrical turning in function of the workpiece radius

Test	Parameters			Measured forces for radius					
				$R_R = 87.5 \text{ mm}$			$R_R = 12.5 \text{ mm}$		
N°	f (mm/rev)	a_p (mm)	θ_{max} (°)	F_c (N)	F_f (N)	F_p (N)	F_c (N)	F_f (N)	F_p (N)
1	0.25	1	33.5	472	74	209	393	56	161
2	0.05	1	33.5	143	22	61	131	20	58
3	0.15	0.75	29	225	28	93	207	26	87
4	0.25	0.5	23.6	240	24	104	196	20	80
5	0.05	0.5	23.6	83	9	36	77	9	38

These tests have been conducted with a Sandvik RCGX1204M0-AL H10 ($r_\epsilon = 6 \text{ mm}$) insert mounted on a SRDCL2025M12 holder. The high nose radius r_ϵ has been chosen because:

- The curvature of the active edge is small.
- It is possible to have low ratios a_p / r_ϵ with high cutting forces (noise reduction).

As the wear increases throughout the tests, a second insert – used only for two radii – has been used to verify that there is no change due to wear (Figure 4).

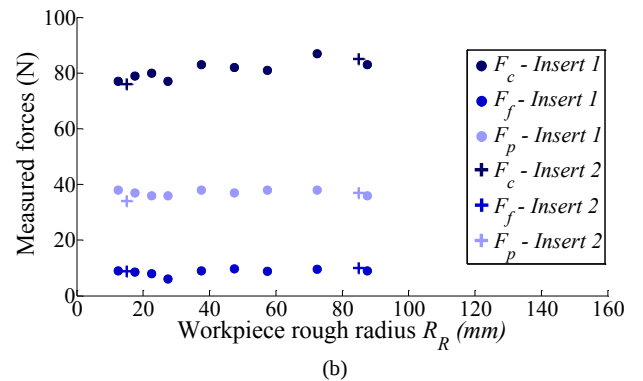
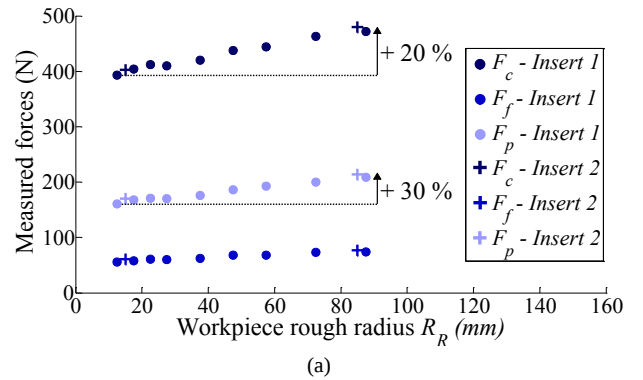


Fig. 4. Measured forces vs. workpiece radius: (a) $f = 0.25 \text{ mm/rev}$, $a_p = 1 \text{ mm}$ (Test N°1); (b) $f = 0.05 \text{ mm/rev}$, $a_p = 0.5 \text{ mm}$ (Test N°5)

As it can be seen on Figure 4 (a), the increase of the forces can reach 30 %.

The comparison between the five tests shows that the effect of the workpiece radius is even more important as the feed and the depth of cut are high.

When a_p increases, the growth of forces with the workpiece radius may be attributed to the evolution of R_o^W along the active cutting edge, which can affect the chip formation and the clearance contact.

Concerning the interaction between the radius and the feed, it could be due to the relative motion of the cutting edge and the machined surface. Indeed, at $\theta = 0^\circ$ the edge “slides” in parallel to the surface while at $\theta = 90^\circ$ the edge comes closer to the surface due to the feed rate. And so, the force acting on the edge and the clearance face due to the elastic deformation of the workpiece can increase, all the more since R_o^W is high.

It should be noted that the variation of forces due to the workpiece radius can be more important for higher a_p , particularly around r_ε ($\theta_{max} \approx 90^\circ$); since, as previously mentioned, θ_{max} does not exceed 34° in this study.

In order to verify these assumptions concerning the effect of the orientation of the edge, elementary cutting tests have been conducted.

The goal of these tests, detailed in the next paragraph, is to reproduce what occurs on each segment of the discretised tool.

4. Elementary oriented cutting tests

Oriented cutting tests have been conducted using two types of configurations: either by cutting a tube or a corner as shown on Figure 5.

The second configuration allows testing very low values of κ_r without risk of excessive bending, even vibrations, of the tube.

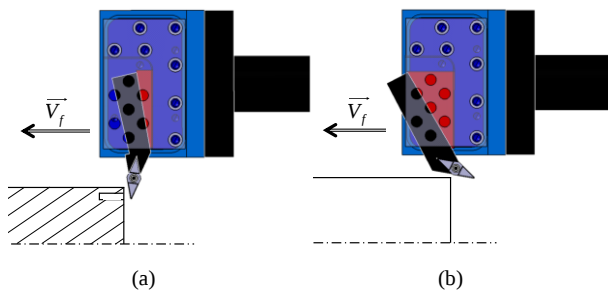


Fig. 5. Oriented cutting configurations: (a) Tube ($\kappa_r = 80^\circ$); (b) Corner ($\kappa_r = 10^\circ$)

The rectilinear cutting edges of Sandvik VCGX160404 AL H10 inserts have been used. The inserts are assembled with a SVJCL2020K16 body (modified to get κ_r equal to 90°) or a SVHCR2020K16 (modified to obtain $\kappa_r = 40^\circ$ on a rear turret lathe).

In order to change the cutting edge angle κ_r , the tool is oriented by a wedge (in red on the Figure 5).

4.1. Experimental procedure of tests on the corner

These tests consist in machining the corner of a cylindrical workpiece with a rectilinear cutting edge and an axial feed rate.

During the tests, three steps can be identified:

- The uncut chip thickness h and the width of cut b increase during the first revolution of cut.
- Then, b increases linearly over time and h is constant on the main part of the edge.
- Finally, h decreases due to the deceleration of the machine.

Because the global cutting forces evolve along the time, they should be divided by the width of cut b to be analysed. To be as accurate as possible, the gauge tool is made by electrical contact between the cutting edge and the workpiece edge, and the tool position is measured by a laser sensor Keyence LK-G82.

As the workpiece radius R is high (rough diameter of 183 mm) and the machine acceleration too (4 m/s^2), the third step does not mask the second one in the present case. However, this point could be troublesome under different conditions, particularly when κ_r is small because the feed becomes substantial.

4.2. Results obtained by the corner tests

Typical signal and chip obtained by these tests are shown on Figures 6 and 7.

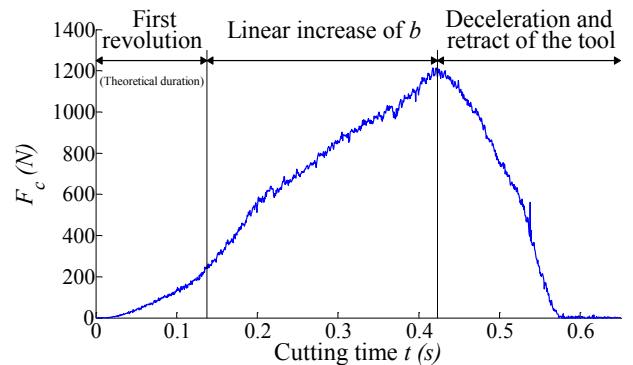


Fig. 6. Measured global cutting force F_c in function of time for $\kappa_r = 10^\circ$ and $h = 0.25 \text{ mm}$

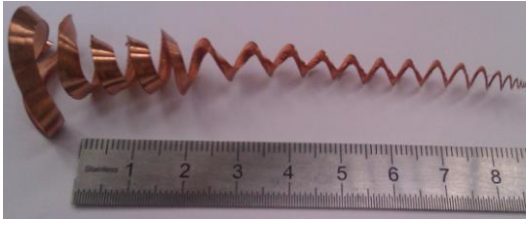


Fig. 7. Chip for $\kappa_r = 10^\circ$ and $h = 0.25$ mm

To be interpreted, the global forces, measured in the basis $(\vec{X}_m, \vec{Y}_m, \vec{Z}_m)$ linked to the dynamometer, have to be transformed into linear cutting forces expressed in the basis $(\vec{o}, \vec{v}, \vec{h})$ linked to the tool as shown on Figure 8.

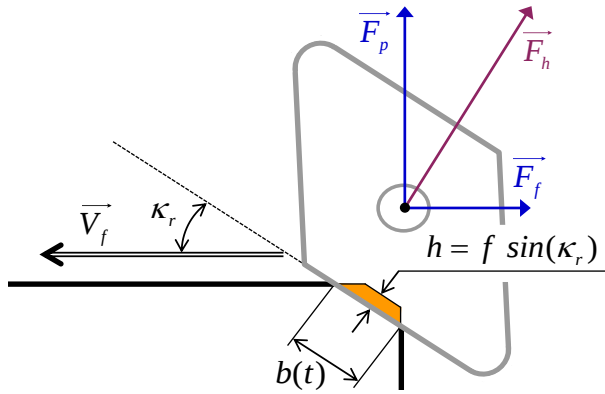


Fig. 8. Global and local forces

A typical evolution of the linear force as a function of the width of cut b is presented on Figure 9. The first revolution corresponds to the part AC of the curve, with a scaling effect due to the small uncut chip thicknesses between the beginning and the point B.

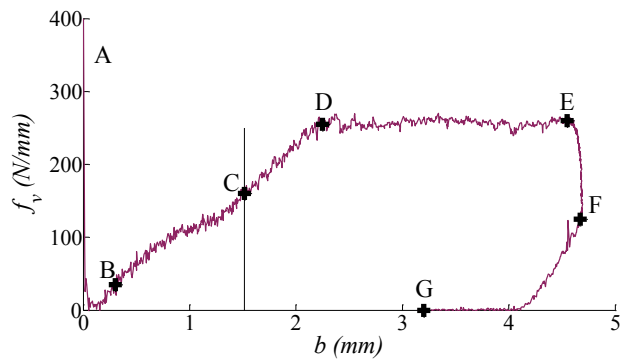


Fig. 9. Linear cutting force f_v (or f_c) vs. the width of cut b for $\kappa_r = 10^\circ$ and $h = 0.25$ mm

The increase between C and D could be attributed to side effects like burrs, which are not negligible for small width of cut. Then, there is a plateau (DE) which should correspond to the value obtained by the tube tests. The part between E and F corresponds to the deceleration, while the end of the evolution to the retract of the tool.

4.3. Effect of κ_r on the forces

On Figures 10 and 11, the mean values of the linear forces f_v (or f_c) and f_h – calculated on the plateau – for corner tests are compared to the values obtained by tube tests. The component f_o is always near zero.

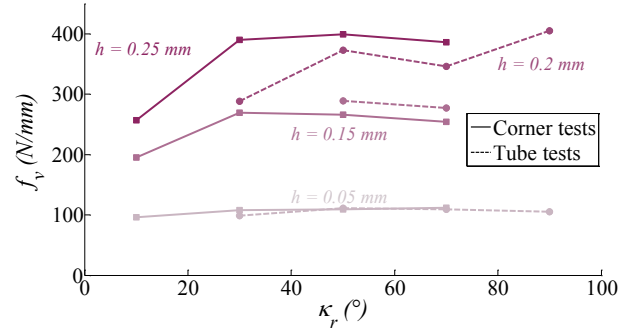


Fig. 10. Linear cutting force f_v (or f_c) vs. κ_r

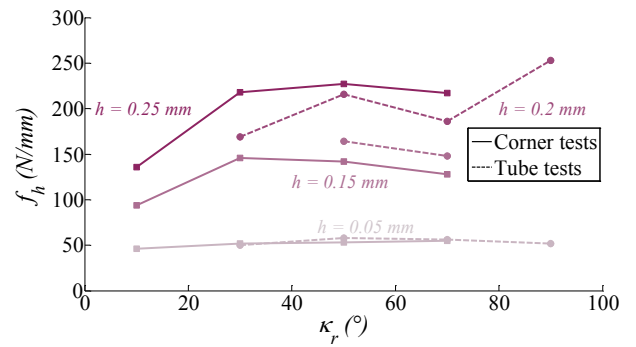


Fig. 11. Linear force f_h vs. κ_r

The graphics show that the new corner tests give forces levels in accordance with the tube tests. So, this method makes possible the realisation of elementary cutting tests without preparing tubes or disks specimens, which is a laborious work.

The trends observed on Figures 10 and 11 seem to consolidate the assumption that if the feed is high enough, the cutting edge angle affects the cutting forces.

However, the experimental results are very scattered, in spite of the attention given to the experimental procedure. It should be noted that, whilst the tube tests have been done with different inserts, all twelve corner tests have been conducted with a unique insert.

Furthermore, the results of the elementary tests do not show the only effect of κ_r , since the change of this angle induces a modification of the effective radius R_o^W .

However, this coupled effect is representative of the cylindrical turning, where both κ_r and R_o^W vary along the cutting edge.

4.4. Observation of the tools

The four tube tests at $h = 0.2$ mm have been realised with four different inserts. As the feed is important, the contact between the clearance face and the machined surface was supposed to increase with κ_r .

In order to confirm this statement, the four inserts have been observed by SEM. The backscattered electrons mode allows distinguishing the copper from the carbide of the insert as shown on Figure 12 (and confirmed by XDS analyses).

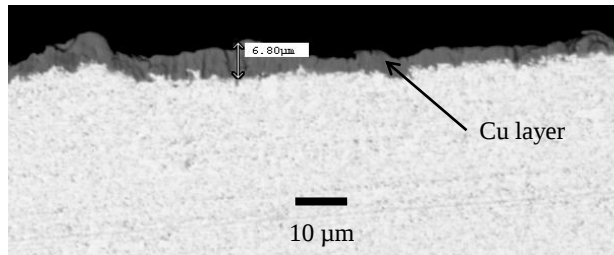


Fig. 12. SEM image of the clearance face after cutting at $\kappa_r = 50^\circ$ and $h = 0.2$ mm.

The contact lengths are between 3 and 8 μm and do not allow to draw conclusion about the effect of κ_r on the tool-workpiece contact on the clearance face.

Due to the high clearance angle, it seems that the contact is located in the rounded cutting edge.

5. Conclusion

The new experimental methodology proposed through the corner tests is helpful to conduct elementary cutting tests without making thin specimens beforehand and avoiding vibrations during the cut.

Even if the tests have to be confirmed and completed, it seems that the introduction of the local cutting edge angle κ_r and the effective workpiece radius R_o^W in the local model may improve the accuracy of the cutting forces model. Thereby, the modeling of the forces along a tool path with varying radii would be enhanced.

Future work on this topic will focus on the decoupling of the parameters κ_r and R_o^W during the elementary cutting tests.

In-situ observations and post-mortem analysis of the clearance contact and the chip formation will also be developed in order to clarify the observed phenomena.

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