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Numerical and Experimental Investigations in Orthogonal Milling of 15-5PH Stainless Steel

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Abstract. The present work presents the development of a numerical model to assess the machining performance in milling of a 15-5PH stainless steel. Aan experimental campaign was conducted using PVD coated TPUN inserts under three levels of cutting speed and feed: 100-170-240 m/min & 0.25-0.35-0.45 mm/rev. Forces were recorded using a Kistler 9257A dynamometer. For each experimental test, chips were mounted and polished to evaluate the chip thicknesses and contact lengths measured on inserts' rake face. Regarding the numerical simulation, a 2D Arbitrary-Lagrangian-Eulerian (ALE) was then developed in the study. A tool motion was implemented to mimic the chip thickness evolution occurring during the milling process. These simulations allowed to numerically predict the chip thicknesses, contact lengths and cutting forces which were further compared to the experimental data.

Introduction

Nowadays, numerical simulations are widely used in order to simulation machining operations. They offer the possibility to study the tool-chip contact interface and allow the prediction of various machining outputs such as cutting forces, temperature, surface integrity or tool wear. Modeling of turning operations has been considered by a large number of papers [1-3] mainly focusing on orthogonal operations [4-8]. Even if milling is a common machining operation, very little work focused on its modeling [9-11] and even less regarding the wear simulation [12]. One of the key point of milling which makes the simulation more complex is that this process is characterized by a progressive variation of chip thickness while the tool is cutting. Whereas full 3D simulations of the whole milling process would be extremely costly, there is a need to develop such models in order to predict the local thermomechanical loadings applied onto the cutting tool and ultimately, predict the tool wear.

In this work, a 2D ALE model was thus developed to simulate an orthogonal milling operation via an innovative approach taking into account the variation of chip thickness during the cut. The model is applied to the orthogonal cutting of a 15-5PH martensitic stainless steel with a coated carbide tool with in mind to predict chip thicknesses, contact lengths and cutting forces. At first the simplified orthogonal milling setup is described. A Design-Of-Experiment (DoE) is conducted with three levels of cutting speeds and feeds. Based on this DoE, chips were collected, contact lengths measured and forces recorded. Finally, the 2D numerical model is described and the outputs correlated with the experimental results.

Experimental Setup

Machined material. The workmaterial used in this study is the 15-5PH which is a precipitation hardened martensitic stainless steel. The chemical composition is presented in Table 1.

Table 1. Chemical composition of 15-5PH - in %

Element	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Nb + Ta	Fe
min	-	-	-	-	-	14.00	-	4.80	2.50	5.C	The remaining
max	0.01	1.00	1.00	0.025	0.005	15.50	0.60	5.50	4.50	0.45	

Single-tooth orthogonal milling. The experimental tests were carried out on a C40U 5-axis vertical machining center. Due to the complexity of milling operations, it was decided to first work on a simplified version of milling known as orthogonal milling operation. A down-milling operation was selected meaning that the chip thickness will decrease while the tool is engaged in the workpiece. The experimental setup is composed of a 3mm stainless steel plate which is machined by contouring. The toolholder used for the orthogonal cutting operations had a diameter of 60mm and was designed to host 2 TPUN inserts with a radial and an axial cutting angle of zero. However, in this campaign, only one insert was used for tests in order to simplify the experimental results. The tool was balanced with a wedge on the free slot and the balance measured below G6.3 at the selected cutting conditions. The tool was finally centered to the workpiece plate in the axial direction.

For each cutting tests, the cutting forces were recorded using a Kistler 9257A dynamometer on which the steel plates were clamped. The highest tested cutting speed was 240 m/min, which means that the actual cutting time was 5 ms per cut cycle. Thus it was decided to acquire the data at a 10 kHz sampling rate it order to record at least 50 acquisition points while the tool is cutting.

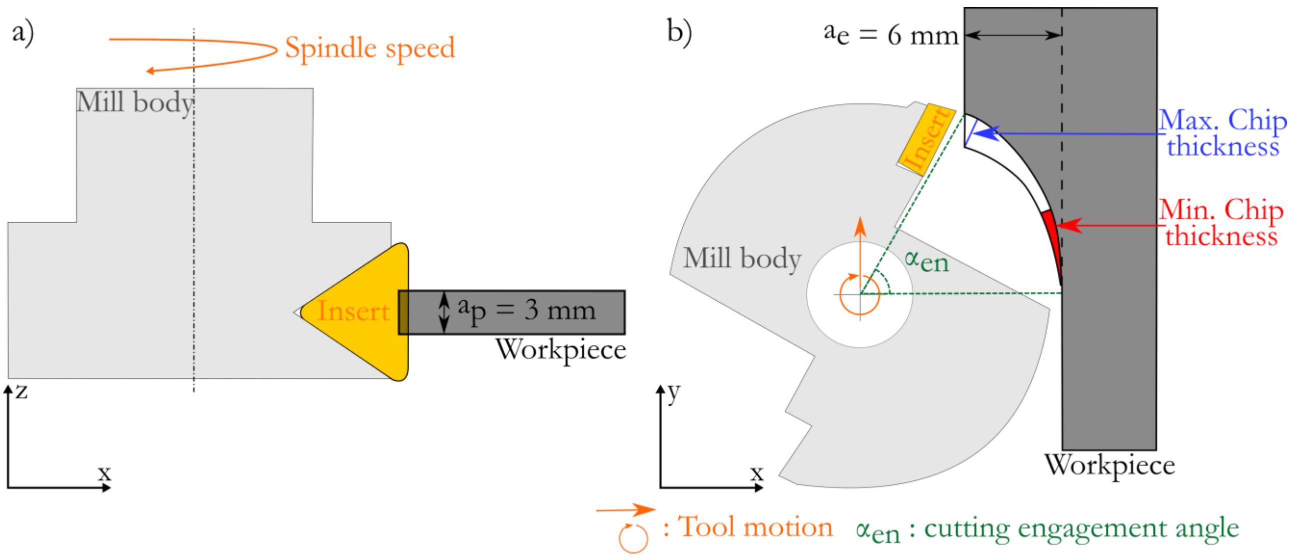

Figure 1. Orthogonal milling operation experimental setup a) Side view b) Top view

The tests were performed for three levels of cutting speed, *Vc*: 100 – 170 & 240 m/min and three levels of feed, *fz*: 0.25 – 0.35 – 0.45 mm/rev. The axial depth-of-cut, *ap*, was kept constant at 3 mm. The radial depth-of-cut, *ae*, was set at 10% of toolholder diameter thus 6 mm. All the tests were performed under dry conditions.

Cutting Insert. The studied cutting tool is a PVD coated TPUN tungsten carbide. The coating is composed of a 5 µm TiAlN layer on a WC-10Co fine grained substrate. It has a cutting edge preparation of 30 µm. Once fitted in the tool holder, the insert is characterized by a rake angle, γ, of 0° and a clearance angle, α, of 10°.

Numerical Model

2D ALE numerical model. In this study, a 2D ALE (Arbitrary Lagrangian Eulerian) numerical model was employed. Such numerical approach is well known in the literature [13-14] especially to simulate turning operations. The developed model is described in Figure 2. It is composed of a 2D rigid tool body and a deformable workpiece. The simulations were run using the commercial Finite

Element package ABAQUS©. The 15-5PH workmaterial thermomechanical behavior was modelled by a Johnson-Cook flow stress model with the parameters listed in Table 2:

Table 2. Johnson-Cook parameters for 15-5PH [15]

A [MPa]	B [MPa]	n	C	$\dot{\varepsilon}_0$ [/s]	m	T_m (°C)	T_o (°C)
855	448	0.14	0.0137	1	0.63	1440	20

A coulomb friction model was used in the study and a constant friction was set at 0.3. The heat partition was set to 0.85, meaning that 15% of heat is transmitted to the cutting tool. Thermal conductance was set at 10^4 W/m².K [16].

As stated before, 2D ALE are mostly used to simulate turning operations. It was necessary to develop a method in order to simulate the variation of chip thickness in the process. The specificity of the developed model is that a vertical motion is progressively applied on the tool in order to mimic the variation of chip thickness induced by milling operations. This tool motion is defined as displacement and time which were determined using a Matlab Code presented in the following subsection.

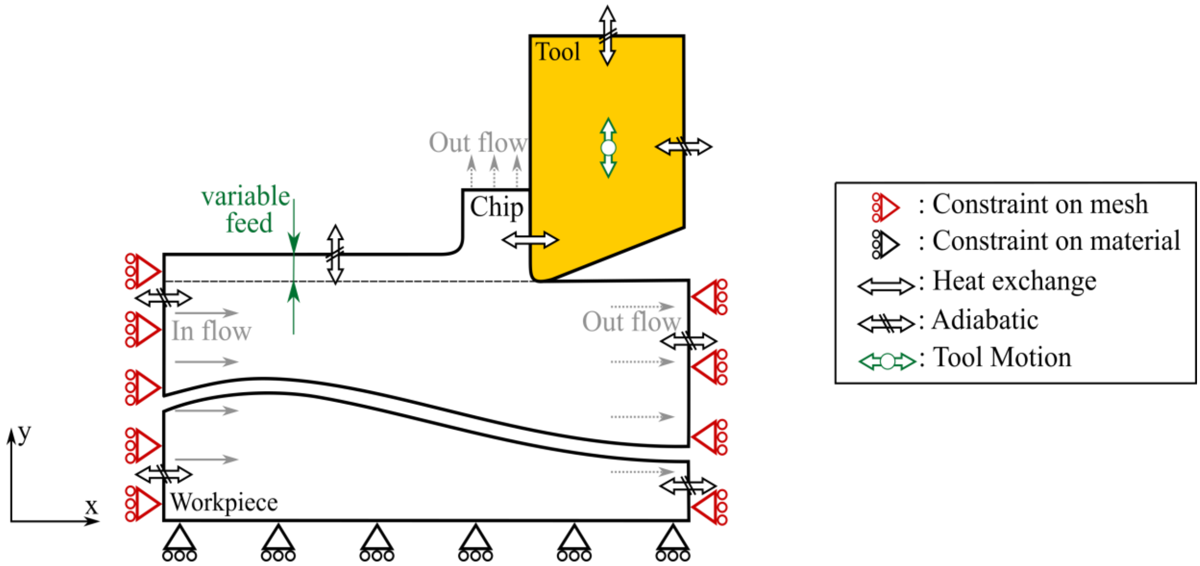

Figure 2. 2D ALE model used in the study

A sensitivity study was performed by changing the mesh size at the interface from 6x6 microns to 10x10 microns and no impact on either chip thickness contact length or cutting forces was witnessed. However, by increasing the mesh size by a factor of 1.7, the computation time dropped from 26 hours to only 1h30 minutes on a standard 3.7 GHz processor and 16 Go RAM computer.

Cycloid trajectory. Due to the combination of rotation (spindle speed) and linear motion (table feed) of the toolholder, a cycloid trajectory is induced to the rotating insert. This trajectory can be written as:

$$\begin{cases} X = -1 \cdot \left[(R+r) \cdot \cos\left(\frac{\pi}{2} - \theta\right) + r \cdot (\theta - \sin\theta)\right]. \\ Y = -1 \cdot \left[(R+r) \cdot \sin\left(\frac{\pi}{2} - \theta\right) + r \cdot (1 - \cos\theta)\right]. \end{cases} \quad (1)$$

Where X and Y are the insert edge position, θ the rotation angle (°), *R* is the toolholder radius (mm) and *r* the radius of an imaginary circle (mm) lying in the toolholder. In order to satisfy the pure rolling condition of the imaginary circle, the value of *r* has to be set so the tangential velocity will be equal to the linear feed of the center of the cutter (Eq.2). Its value was investigated by [17] and set at:

$$r = \frac{N \cdot f}{2 \cdot \pi} \quad (2)$$

With *N* the number of insert, set at 1 in this case, *f* the feed per tooth (mm/tooth/rev).

The equation (1) can be simplified as the following:

$$\begin{cases} X = -1 \cdot [(R + r) \cdot \sin\theta + r \cdot (\theta - \sin\theta)] = \ R \cdot \sin\theta + r \cdot \theta. \\ Y = -1 \cdot [(R + r) \cdot \cos\theta + r \cdot (1 - \cos\theta)] = \ R \cdot \cos\theta + r \quad . \end{cases} \tag{3}$$

Hence, a Matlab code was developed using these equations. By performing two successive revolutions, the chip thickness evolution could be identified for each cutting condition considered in this study. Figure 3 highlights the chip thickness evolution depending of the insert angular position for the three considered feed rates: 0.25 – 0.35 and 0.45 mm/rev. The chip thickness evolution in the case of full milling operation is shown in Fig.3.A. However, as the radial depth-of-cut is set at 6 mm, it means that the engagement angle (α_{en}) is 36° and the considered chip thickness evolution in this particular case is plotted in Fig.3.B.

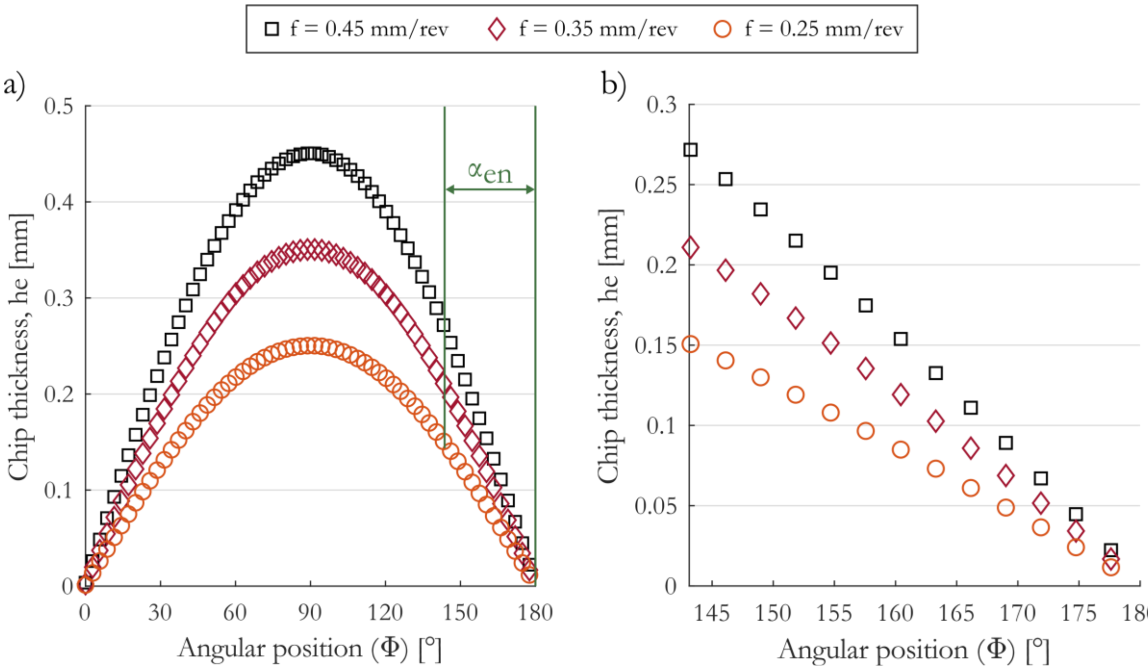

Figure 3. Chip thickness evolution for a) a full milling cycle b) in the case of down-milling with a radial depth-of-cut of 6 mm

Finally, the last step consisted in getting the cutting time which was determined by the cutting speed *Vc* (m/min) thus the spindle speed *n* (rev/min) which is in direct link with the previously determined angular positions. Figure 4 highlights the milling time for the three studied cutting speeds: 100 – 170 & 240 m/min at a feed rate of 0.35 mm/rev. It can be seen that the milling time are respectively of 12, 7 & 5 milliseconds. Thus, these maximum cutting times defined each 2D ALE simulation duration whereas the evolution of chip thickness depending on the milling time was implemented as the displacement amplitude for the vertical tool motion in the numerical simulations.

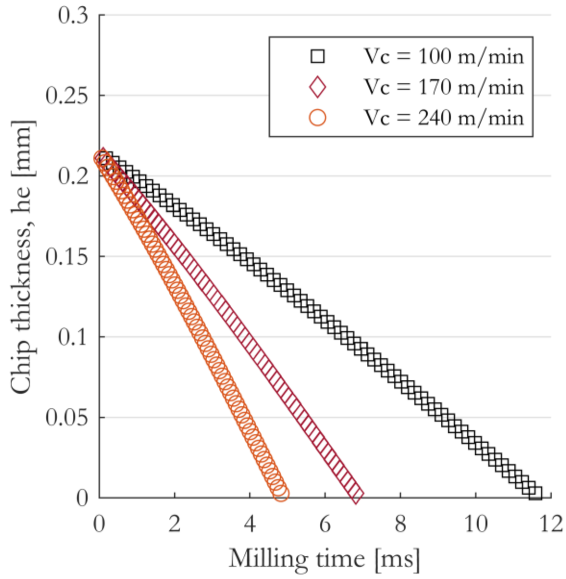

Figure 4. Chip Thickness evolution for three cutting speeds at a feed of 0.35 mm/rev

Results and Discussion

Contact Lengths. In this first subsection, the experimental and computed contact lengths will be compared. This geometrical parameter is of great importance as it impacts the cutting forces but also plays a major role in the wear prediction which will be considered in future works. The figure 6 shows the experimental and numerical comparison of the contact lengths on tool rake for the three levels of cutting speed and feeds. The experimental contact length was measured using an ALICONA confocal microscope. They correspond to the length of the worn coating on tool rake face which has been removed due to the friction with the chip. Thus, figure 6 compares the maximum contact length which was obtained when the tool entered the workpiece (maximum chip thickness at the beginning because of down-milling operation). Regarding the numerical contact length, it was measured at the very beginning when the chip thickness is the highest to enable a comparison with the experimental results. The numerical contact length was measured between the tool edge preparation and the last node on tool rake face in contact with the chip. A close agreement between the computed and experimentally measured contact lengths could be observed. There seems to be a constant error in the numerical prediction which is independent of the cutting speed or feed. In average the error of prediction is of 23% with a standard deviation of 2%.

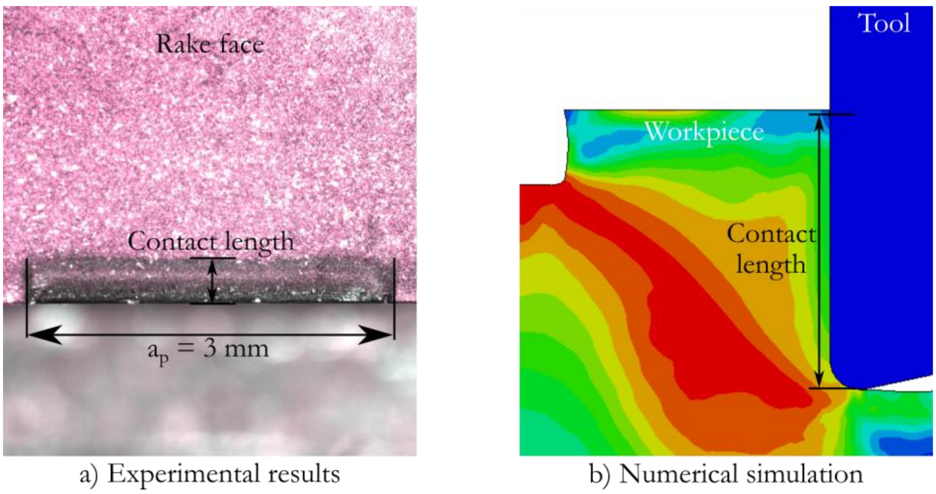

Figure 5. Contact length measurement a) experimental b) numerical

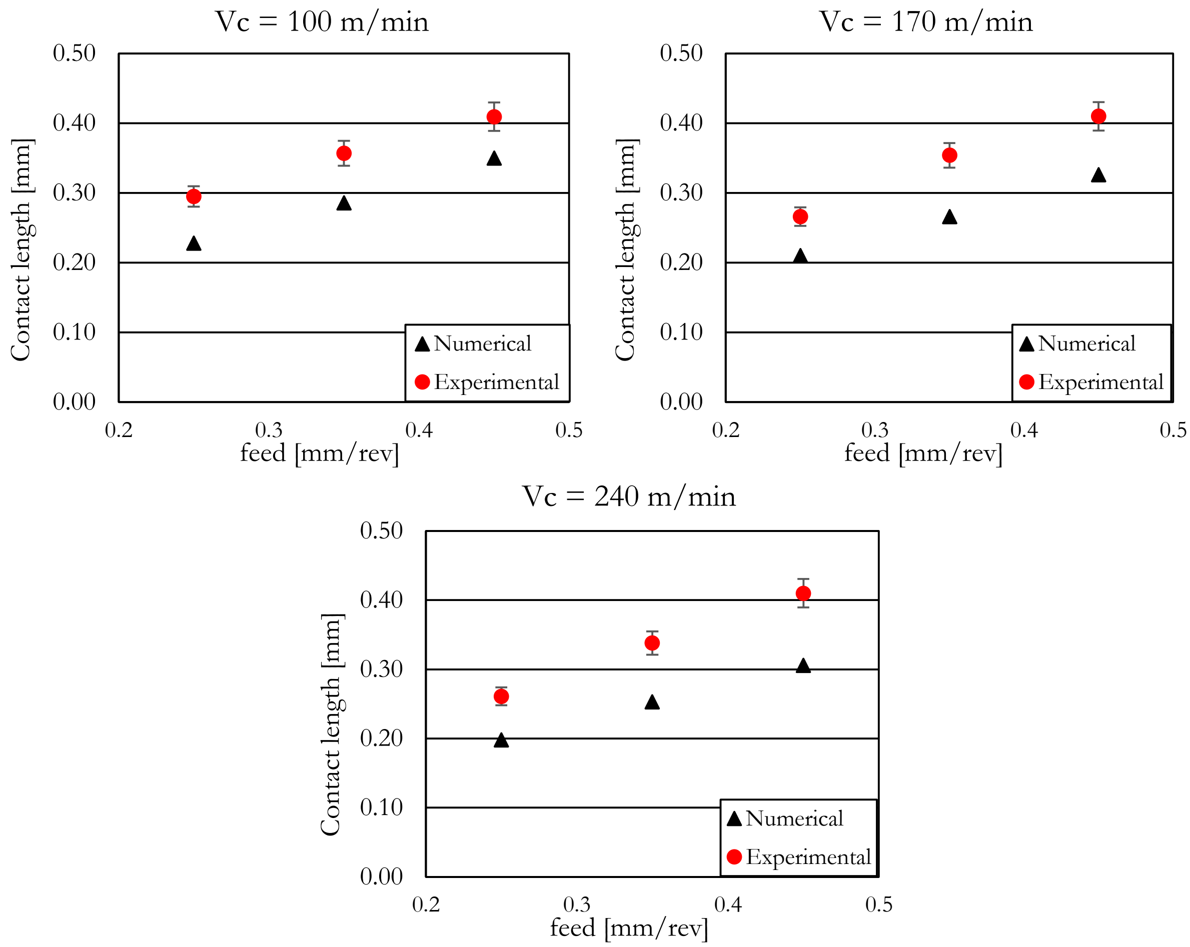

Figure 6. Contact lengths compared between experimental and numerical result

Chip Thickness. The main objective was to compare the experimental and numerical chip thickness. It is important to compare this geometrical parameter as it plays an important role on the cutting forces which will be described in the following subsection. After each experimental test, the chips were collected, then mounted and polished in order to measure their thickness as shown in Fig.7.

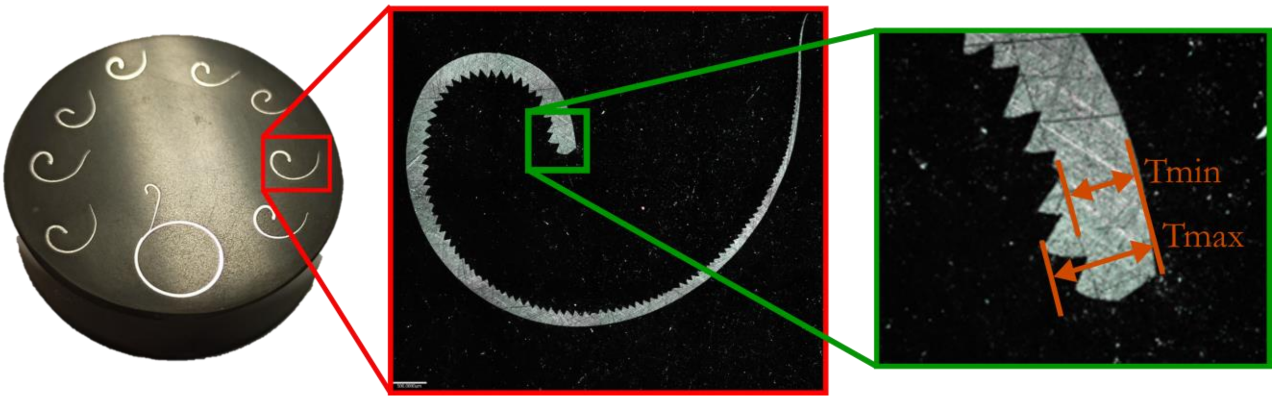

Figure 7. Experimental chip thickness measurements after being mounted and polished

As the numerical model doesn't take into account the chip segmentation, an average of the maximum and minimum chip thicknesses was considered.

The figure 8 highlights the experimental and numerical thicknesses measured for the 9 studied cases. It shows a very good agreement between the experimental and numerical results for all the cutting conditions. It can be concluded that the 2D ALE model seems to properly predict the physics of the material removal process.

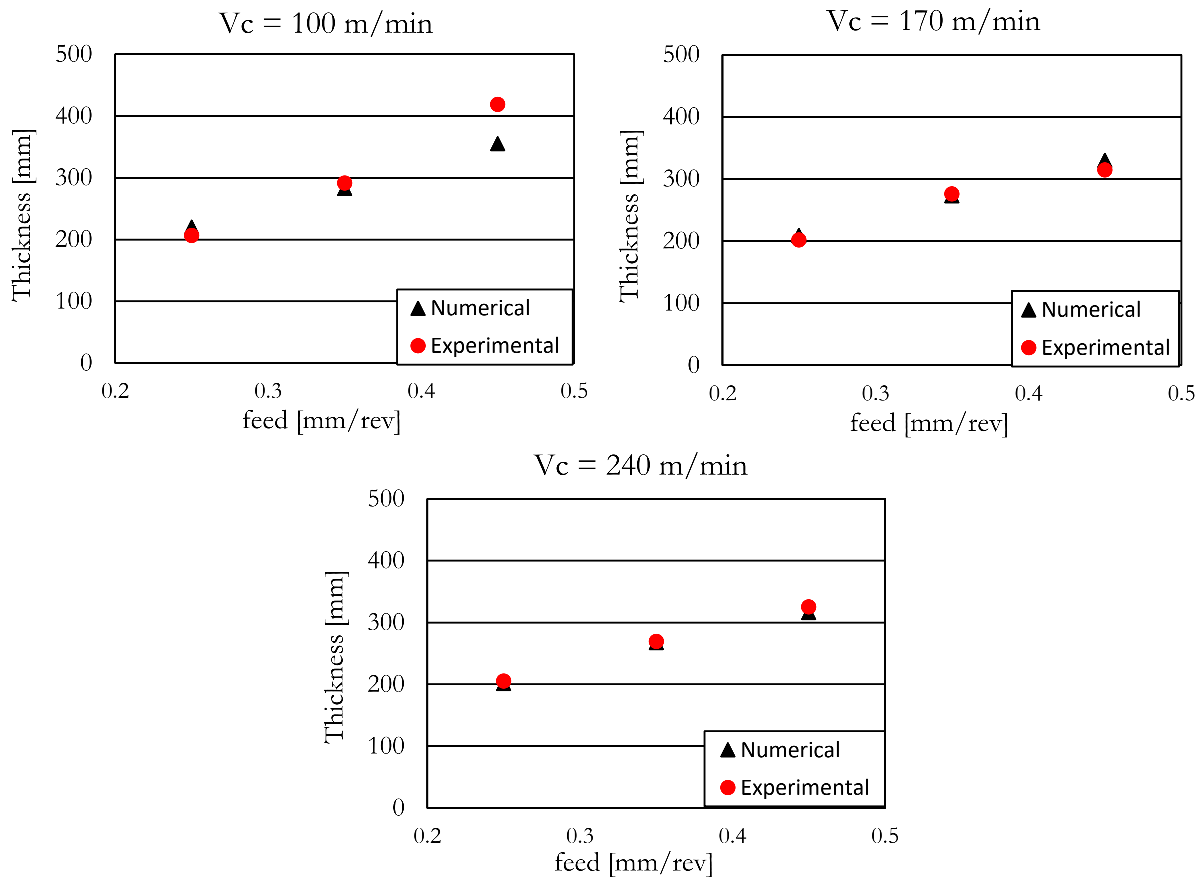

Figure 8. Chip thickness comparison between experimental and numerical results

Machining Forces. As previously described, the experimental cutting forces were recorded using a Kistler Dynamometer. Regarding the simulated cutting forces, cutting forces were recorded for each node on the tool edge and were then summed to provide the total cutting and feed forces. In order to simplify the numerical and experimental comparison, only the resultant force will be compared in the study. The numerical resultant force will be considered as:

$$RF_{num} = \sqrt{(F_c)^2 + (F_f)^2} \tag{5}$$

With *Fc*, the cutting force in the cutting speed direction (x direction on Fig.2), and *Ff*, the feed force in the feed direction (y direction on Fig.2).

The experimental resultant force will be defined as:

$$RF_{exp} = \sqrt{(F_x)^2 + (F_y)^2} \tag{6}$$

With *Fx* and *Fy* the forces signals recorded by the Kistler dynamometer in the plane XY (See Fig.1.B).

Figure 9 shows the comparison between the experimental signal (red) and the numerical results (black) for the three levels of cutting speed at a feed of 0.45 mm/rev. Experimental results were obtained after using a Gaussian filter to reduce signal noise. Indeed the orthogonal milling operation induces high dynamics phenomena and a noise can be observed on the recorded forces. This noise can also be explained by the relatively low stiffness of the assembly due to the low thickness of the machined workpiece (3 mm). The results presented below highlights a close comparison both in terms of trends and amplitudes. The numerical results highlight that at a constant feed value there is no impact of the cutting speed on the maximum force resultant as it can be seen at a cutting time of 0 ms (Fig.9).

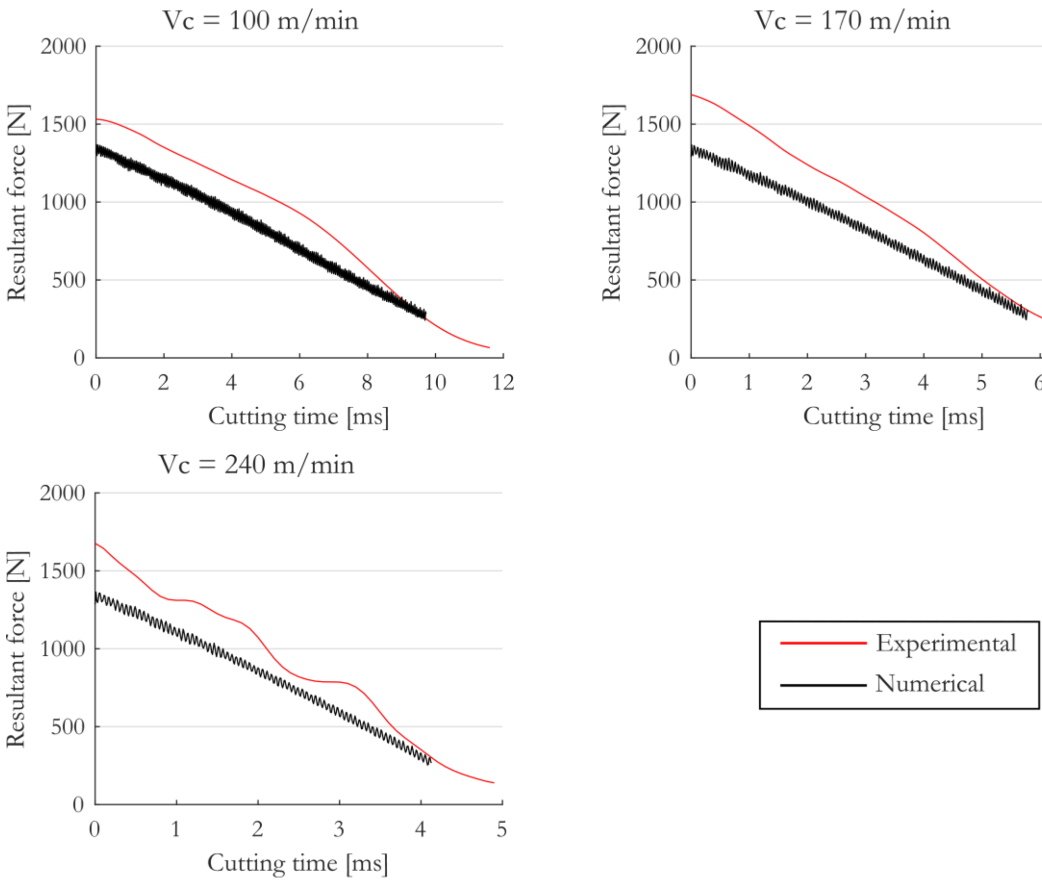

Figure 9. Resultant forces evolution at Vc = 100 - 170 - 240 m/min for a feed of 0.45 mm/rev

The spectrogram presented in Fig.10 displays the force prediction error (%) in the studied cutting condition range. This spectrogram presents the force prediction at the maximum resultant value that corresponds to the maximum chip thickness at cutting time 0 ms (Fig.9). In all the different cases, the numerical simulation appeared to underestimate the cutting condition by 12 to 28 % (Fig. 10). It can be noticed that the best prediction is reached at high feed or high speed conditions. The predicted force at 0.25 mm/rev and 100 m/min showed the worst result with an error of 28%. Four theories could explain the underestimation of the numerical model. A first assumption is that the material behavior might not be in total agreement with the machined workpiece. A second explanation is that at low cutting speeds, the friction coefficient (set to 0.3) might be underestimated. The third explanation is that the material is strain hardened after each test. That means that after a test *i*, the experimental test *i+1* might have higher forces due to the higher hardness of the workpiece. The last theory that can also be mentioned is that the averaged prediction error of 20% is pretty close of the 23% error of contact length prediction.

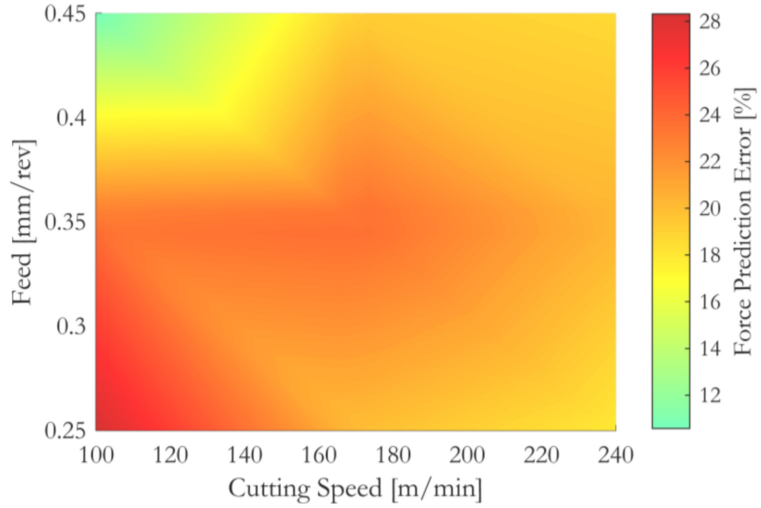

Figure 10. Spectrogram of force prediction error [%]

Conclusion

The present work proposed to simulate an orthogonal milling operation. An innovative method was developed to mimic the chip thickness variation induced by milling operation in a 2D ALE model. This chip thickness variation was reached with a tool vertical motion obtained after a cycloidal trajectory approach. The analysis of contact length showed satisfactory results with a difference of 23% between the computed and experimentally measured lengths, while the maximum chip thickness was well predicted by the 2D model. Finally, the cutting forces were compared using the resultant force. It resulted in a relatively good agreement with an underestimation of 20% by numerical model.

Findings from this experimental and numerical study are considered satisfactory and authors will focus in wear prediction for orthogonal milling operation in future works.

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