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A 3D modelling strategy to predict efficiently cutting tool wear in longitudinal turning of AISI 1045 steel

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This work presents a numerical strategy to predict efficiently cutting tool wear in longitudinal turning. The full 3D cutting tool is discretized in elementary 2D sections. A FE based procedure is developed to compute in parallel the local contact pressure and sliding velocity along each section and update the tool profiles based on a tribologically identified wear equation. Results are merged to generate the 3D worn tool geometry while an iterative scheme is applied to achieve long simulated cutting time. Experimental cutting tests shown that a good agreement can be achieved in a reasonable computation time without any tuning parameter.

Cutting, Wear, Modelling

1. Introduction

Fast and accurate wear prediction is still an up-to-date research challenge in the machining scientific community. Efficient simulations in real machining conditions are highly demanded in industry whether to be used as a flexible cutting tool design methodology, process outputs evaluation or surface integrity assessment.

As reviewed in [1], the strong advances achieved in computational techniques during the late 1990s opened the way to the numerical modelling of machining processes, mainly via the Finite Element (FE) method. It provided a new insight into the driving mechanisms and especially the existing strong thermo-mechanically coupled phenomena. 2D cutting models have been successfully established to investigate fundamental process variables, chip formation and thermal issues [2,3] and led to the development of the first 2D tool wear simulations [4,5]. Recent studies proposed to improve the prediction by taking into account tribological [6] or physics based wear equations [7], confirming the relevance of such approaches. However, despite their indisputable scientific interest, they hardly meet the industrial requirements due to their validity limited to orthogonal cutting.

Over the last decade, the relentless growth in computational power increased the possibilities and enabled 3D FE metal cutting simulations. Whereas 3D extensions in orthogonal cutting were performed [8], the works presented by Aurich & Bil [9], Kishawy et al. [10] or Özel et al. [11] showed the potential to model a full 3D turning operation. As far as wear is concerned, very little published research is available trying to predict tool wear in actual 3D cutting configurations. Attanasio et al. [12] were the first to tackle this aspect and proposed a 3D updating procedure for the dynamic prediction of the tool wear in turning. Binder et al. [13] took into account important features such as

coating and edge rounding while recently Attanasio et al. [14] successfully transposed their developments in drilling.

This limited work is due to the fact that 3D simulation of progressive wear remains a challenging task in tribology, especially when long contact times of several minutes or tenth of minutes are targeted. Full 3D or 2D FE simulations are indeed commonly limited to a few milliseconds. The general methodology thus amounts to computing the local loadings at the tool-material interface and subsequently updating the tool geometry in an incremental procedure [6][12-14]. A large number of iterations is then needed and the high computation cost required in a 3D framework for one simulation only results in a practically unusable solution for the industry. As an example, the computational time needed to run a simulation of 15 min of cut in 3D drilling [14] is close to 90 h. Moreover, the second major drawback is that key input data such as friction coefficient or wear models are not based on tribological considerations but instead require a preliminary experimental identification/calibration via a numerical inverse method and tool wear tests. These two weaknesses appear as strong limitations when an iterative optimisation procedure has to be developed to enhance the design of a cutting tool or the performance of a given machining process.

This work aims thus to propose a simulation methodology to achieve a fast prediction of cutting tool wear in a 3D longitudinal turning operation, taking into account tribologically identified friction and wear models.

2. Experimental setup

2.1. Investigated 3D configuration

AISI 1045 cylindrical bars with a diameter of 80 mm were cut using TPUN 160308 inserts made of TiCN+Al₂O₃ coated cemented carbide (4% cobalt content) with a cutting edge radius

r_β of 55 μm . Once fitted on a CTGPL 2020 tool holder, it resulted in a rake angle γ_n of 6°, a clearance angle α_n of 5°, an inclination angle λ_s of 0° and an orientation angle κ_r of 91° (Fig. 1a).

Two sets of cutting conditions were selected: a cutting speed v_c of 200 m/min with a feed rate f of 0.18 mm and a cutting speed v_c of 164 m/min and a feed rate f of 0.22 mm, while the depth of cut a_p was fixed to 2 mm. The tests were conducted under dry conditions up to a cutting time of 10 min approximately and repeated 4 times. The flank wear was measured at different time intervals using an optical microscope (Fig. 1b) while 3D surface topographies and SEM/EDS analyses were performed on the final worn tool geometry after being cleaned in boiling hydrochloric acid (Fig. 1c). Standard wear parameters were extracted (Fig. 1d).

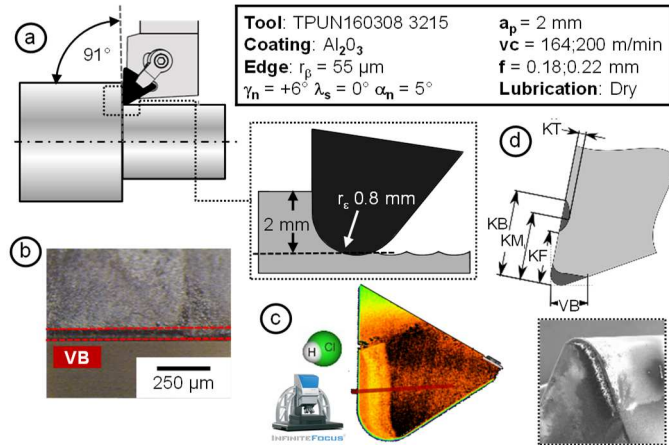


Fig. 1. Experimental setup: a) longitudinal turning configuration, b) Vb flank wear measurement, c) 3D topography and d) tool wear parameters.

2.2. Tribological tests

The tribological investigation was based on an open tribometer proposed by [15]. The tool-material interaction was tested by scratching a pin with a spherical geometry, made of Al_2O_3 coated carbide (~ 4 μm thick) against a cylindrical bar made of AISI 1045. After each friction test, a cutting tool refreshed the surface ploughed by the pin, to remove the affected layer of work material and a belt finishing operation was applied.

The sliding velocity V_{sl} , defined by the rotation speed of the spindle, ranged from 100 to 400 m/min, and the normal load was set to 1000 N via a hydraulic jack, leading to a contact pressure σ_n of approximately 1.5 GPa. Friction pins were ground and polished to achieve a roughness R_a close to 0.3 μm .

The apparent friction coefficient μ_{app} was computed as the ratio of the tangential force to the normal load measured by a piezoelectric dynamometer. A friction model (Eq. 1) was thus identified for the considered tool-material pair, with V_{sl} in m/s:

$$\mu_{app}(V_{sl}) = 0.22 + (0.55 - 0.22)e^{-0.381 \cdot V_{sl}} \quad (1)$$

The same test bench was then employed to conduct wear tests based to the methodology described in [6]. The normal load was adjusted to 750 N to limit the formation of a large built-up with the longer cumulated contact times (approx. 5min) and three sliding velocities V_{sl} of 100, 170 and 200 m/min were selected. Each test was repeated two or three times to assess a potential deviation. The Figure 2 illustrates some of the friction and recorded wear data. Based on the acquired knowledge [6], a wear model was identified leading to the Equation 2, with V_{sl} in m/s, σ_n in Pa and $\frac{\partial W}{\partial t}$ in $\mu\text{m}/\text{s}$:

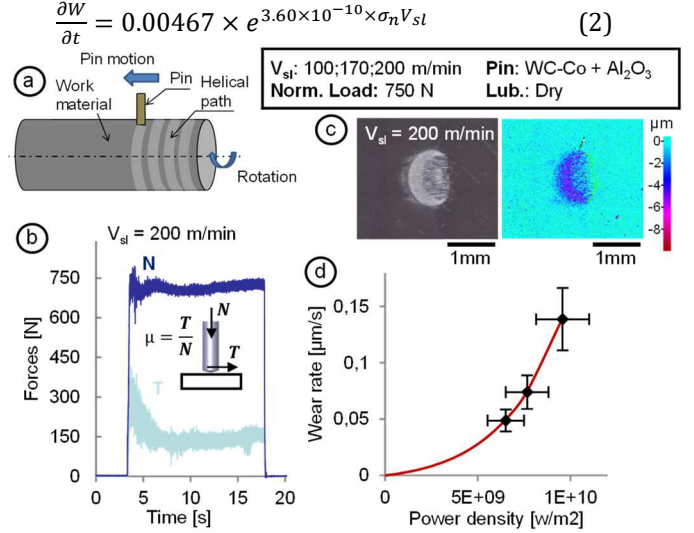


Fig. 2. Tribological setup (a), b) example of recorded forces, c) optical and 3D surface topography of the worn pin and d) fitted wear data.

3. Fast computing modelling strategy

3.1. General concept

The basic idea of the present paper is not to model the full 3D problem but to discretize it in elementary 2D sections. The main hypothesis is thus that wear on a given section is independent from the phenomena occurring on the neighbouring ones. If this could be seen as a strong assumption especially from the thermal point of view, cutting a AISI 1045 makes it acceptable as being less temperature sensitive than some other work materials. It predominantly leads to an abrasive wear mode, known to be much less temperature dependent, and thus enables the methodology to be developed without computing the local temperature and taking it into account in the wear model. The whole procedure is developed on Matlab© and Python© whereas the FE simulations are computed with Abaqus© Finite Element suite.

3.2. Tool discretization

The first step is to decompose the problem from a geometrical point of view. The actual 3D cutting insert geometry is imported in STL format (Fig. 3a). Based on the defined cutting operation (longitudinal turning in the present case) and the cutting conditions, the cutting section engaged on the tool is calculated (Fig. 3b). The latter is then discretized accordingly into a given number of 2D sections S_i as illustrated in the Figure 3c. Once these sections are geometrically defined, the corresponding tool 2D profile is extracted (Fig. 3c) as well as the exact local uncut chip thickness $h(S_i)$ for each of them (Fig. 3d). At this step, a transfer matrix M is computed to ensure the proper coordinate transposition from the 3D to the 2D configuration and vice versa.

The major advantage of this methodology is that, from this step on, each section can be simulated independently in parallel computing (Fig. 3e). In the present case, a 2D Explicit orthogonal cutting model is employed to run the thermomechanical simulation and predict the local thermomechanical loadings at the tool chip interface (Fig. 3f) for each section. The interested reader will be able to find all the details and input data in [15,16]. The local friction model identified in Section 2.2 (Eq. 1) was implemented as a fundamental input data in these

simulations to consistently take into account the investigated tool-material pair.

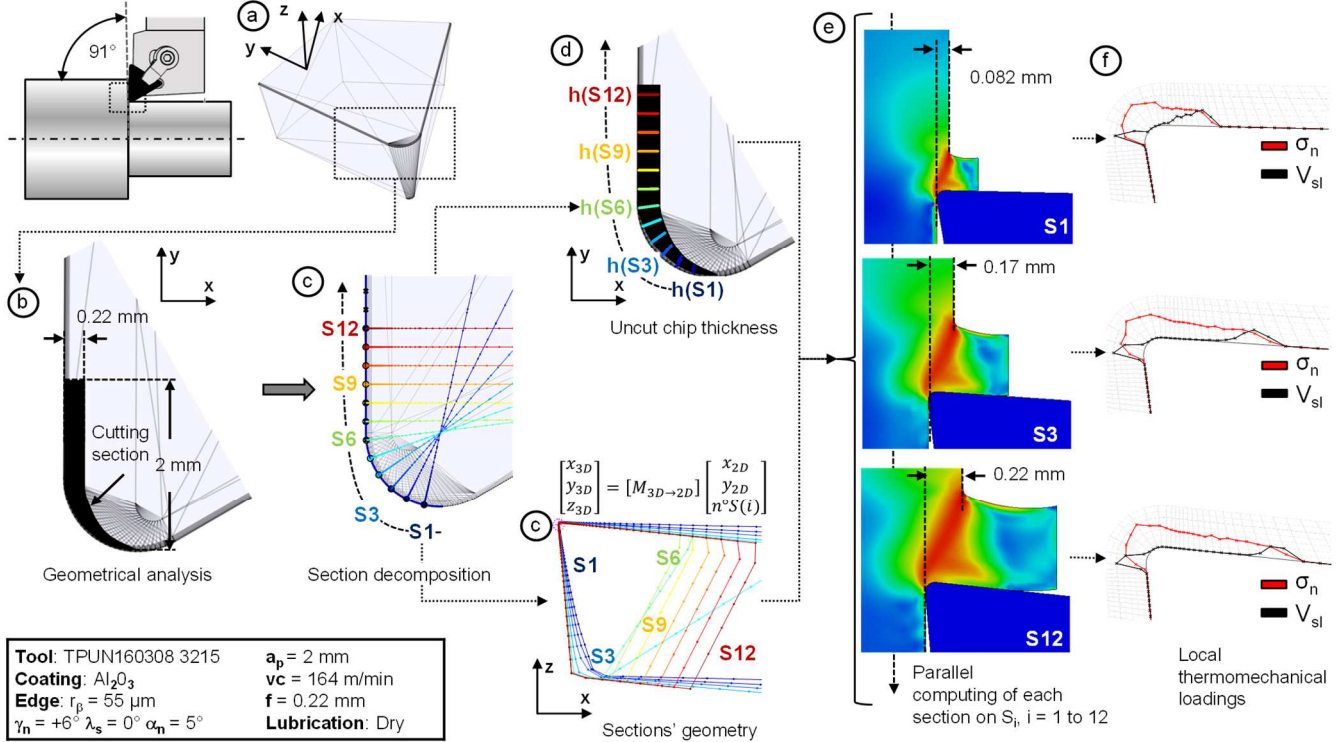


Figure 3. Segmentation procedure of the 3D problem: a) import of the STL 3D tool geometry, b) identification of the cutting section, c) decomposition of the cutting tool in elementary 2D sections, d) computation of the uncut chip thickness for each section, d) extraction of the actual section geometry, e) 2D ALE Explicit simulation of each section and f) extraction of the simulated local thermomechanical loadings.

3.3. Wear simulation and 3D visualisation

The 2D wear prediction methodology described in [6] is run on each of the selected sections. Once the local loadings are extracted (Figs. 4a-b), a geometry updating algorithm is applied to compute the local wear rate based on the local contact pressure σ_n , local sliding velocity V_{sl} (Fig. 4c) and the wear model identified from the tribological tests in Section 2.2 (Eq. 2).

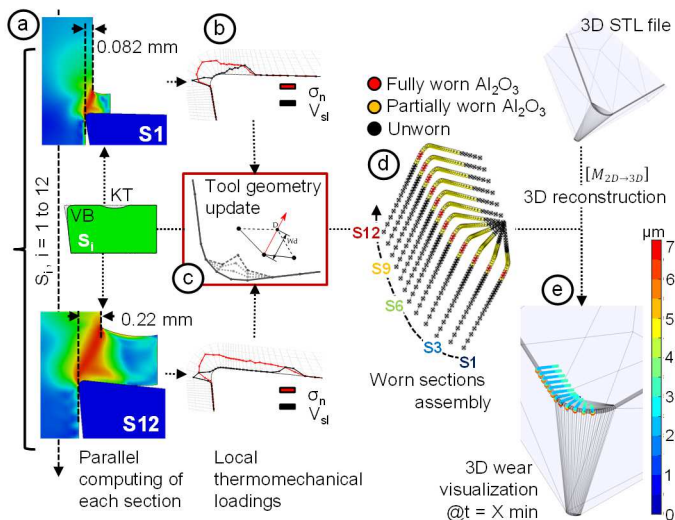


Figure 4. Modelling strategy to generate the full 3D worn tool geometry after 10min of simulated cutting time.

The worn geometry is computed for each 2D tool profiles in an iteration process for a given time interval Δt_{wear} during which the local loadings are considered to be constant and the nodes swept sequentially to be moved. Once Δt_{wear} is achieved, the worn

geometries are imported into the Abaqus© Explicit solver to conduct the next thermomechanical simulations with the updated tool geometries. This loop is repeated for a given number of iteration N , leading to a final simulated cutting time of $Nx\Delta t_{wear}$. Δt_{wear} was here set to 60s and a smooth wear evolution without any sudden modification of the tool geometry was observed.

The simulated cutting time in the 2D ALE cutting model was reduced to 1.5 ms in order to reach rapidly the steady state by implementing initial velocity fields at some specific regions of the chip and using a $15 \text{ }\mu\text{m}$ mesh size. This resulted in a computation time between 15 and 25 min with an Intel® Core™ i7-8665U @2.11Ghz – 32Go RAM, depending on the simulated section.

Worn sections are then combined (Fig. 4d) for every iteration. Trackers can be used at this step to locate the wear status of each node (colour legend in Fig. 4d). Finally, the tool 3D STL model is used with the M transfer matrix to transform the new 2D section coordinates into the actual tool 3D system (Fig. 4e).

In the end, between 3 to 5 hours of CPU time were needed to reach a simulated cutting time of 10 min, depending on the selected cutting conditions. This appears as a major achievement as a practical application at the industrial scale could be here definitely possible, including an iterative optimisation procedure.

4. Results and discussion

The whole methodology was thus applied to the cutting conditions mentioned in Section 2.1. 2D surface profiles (Fig. 5a) were extracted on the cutting inserts at the locations specified in Figures 5c and 5d. The EDS maps in Figure 5c clearly show the formation of a crater at a certain distance from the cutting edge

and a worn region on the flank face. The alumina coating is still present over the first 250µm on the rake, as well as at the end of the flank wear zone, confirming that wear occurred without

reaching the TiCN (depth > 4 µm) as shown by the 2D profiles of the rake face (Fig. 5a). The wear parameters could be extracted as summarised in Figure 5b.

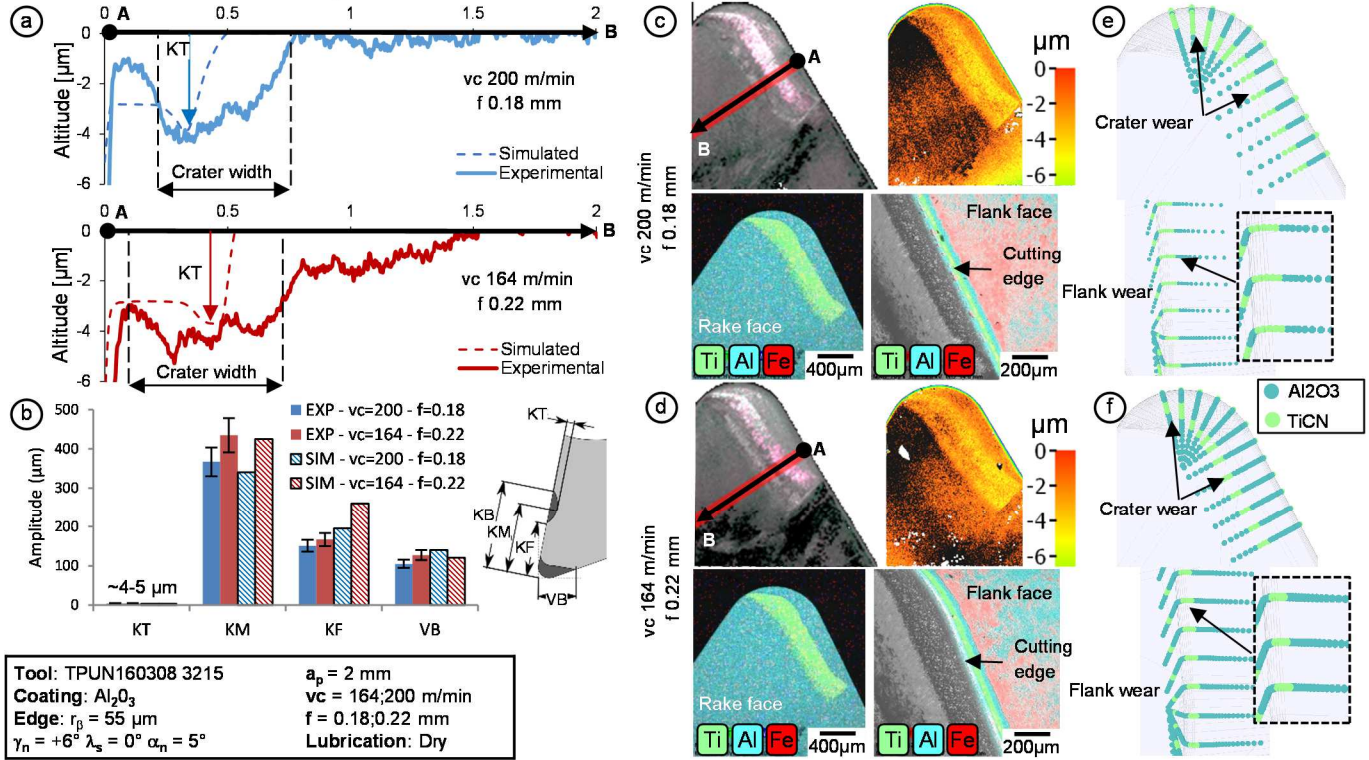


Figure 5. Correlation with the experimental data obtained after 10min of cutting: a) experimental and simulated worn profiles for a given section from A to B, b) summary of the main tool wear parameters, c-d) experimental tool topography and associated SEM/EDS analyses for the two cutting conditions, e-f) corresponding qualitative comparison with the 3D simulated worn geometries.

Wear also occurred over the whole tool-chip contact length and a crater can be seen on the 3D wear predictions (Figs. e-f). *KF* and *KM* both increase when increasing *f*, in agreement with the experimental trends (Fig. 5a-b), whereas the crater width is slightly underestimated. On the simulated flank face, the alumina layer was worn and the TiCN layer is visible as reported in the experiments. Finally, deviations between -13% and -17% on *KT*, -2% and -7% on *KM*, -6% and +29% on *VB* values were achieved. This appears to be in reasonable agreement considering the various uncertainties in the wear measurements both on tools and pins, identification of the wear model, as well as some potential mesh discretisation effect as already emphasized by Rech et al. [6].

5. Conclusions

This paper has presented a numerical methodology to achieve a fast prediction of tool wear in a 3D turning operation.

The 3D problem is discretized into independent 2D elementary sections subsequently simulated in parallel in a FE based wear procedure, before being merged to provide the 3D worn geometry. Long cutting times of 10min could be simulated in a computationally efficient way, i.e. less than 5h of CPU time. 3D wear could be observed and 2D features could be measured.

Longitudinal turning wear tests have been carried out and wear parameters have been extracted for two sets of cutting conditions. The simulations have shown a good agreement despite a smaller *KT* amplitude and confirm the ability of this methodology to achieve consistent and reliable prediction.

Moreover, no tuning parameters or calibration procedure were used as both implemented friction and wear models were identified from dedicated tribological tests.

As a perspective, the proposed strategy could be easily applied to complex tool geometries with chipbreakers or even other 3D machining processes such as milling by implementing a time varying uncut chip thickness in the 2D ALE cutting model.

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