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A numerical approach to investigate the influence of cutting fluid on tool wear in machining AISI 1045 steel

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Abstract. The proposed work presents the development of a numerical model to take into account cutting fluids when turning of an AISI 1045 steel with a TiN coated tool. At this stage, the study considered the impact of a cutting fluid only based on its thermal properties and ability to reduce friction. Three heat exchange scenarios were explored: dry machining (h = 20 $W.m^{-2}.K^{-1}$), use of a straight oil lubrication with low pressure (h = 200 $W.m^{-2}.K^{-1}$) and cooling with an emulsion based lubrication (h = 1000 $W.m^{-2}.K^{-1}$). Regarding friction, three levels of static friction (µs = 0.3, 0.5 and 0.7) have been considered. Following an analysis of thermomechanical loads (stress, sliding speed, and temperature) exerted on the tool, a Usui wear law was employed for each case to simulate cutting tool wear. Results indicate that friction exerts a significant impact compared to the convection coefficient.

Introduction

The application of cutting fluids in machining operations constitutes a standard practice in contemporary industrial settings. Its purpose is to evacuate the chips but also to cool the cutting tools and thus limit the evolution of tool wear.

Numerical simulations are widely used in order to simulate 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]. However, while machining operation simulations reach the point that they can now predict tool wear, very few models take into account the use of cutting fluids. Consequently, this study aims to develop and customize a numerical simulation procedure to identify the key parameters that quantify the influence of a cutting fluid on the wear of cutting tools during the turning of an AISI 1045 steel.

In order to perform this study, the authors used an iterative wear procedure developed by Rech in 2018 [4] and based on a 2D Arbitrary-Lagrangian-Eulerian (ALE) model. The present simulations then focused on the machining of an AISI 1045 steel with a TiN-coated tungsten carbide tool under cutting conditions representative of an industrial application.

In this preliminary study, the assumption that the cutting fluid could be simply modelled by friction and convection coefficients was considered. Three different levels for each coefficient were covered to assess the influence of the cutting fluid on tool wear. A phenomenological equation, developed by Usui, was implemented in the numerical model to study flank wear (VB) evolution over the cutting time.

Numerical model & case study

In order to assess only the impact of the cutting fluid as a preliminary study, a simple cutting configuration was selected. Orthogonal turning of an AISI 1045 steel was investigated at a cutting speed of 200m/min, feed rate of 0.2mm/rev, using a TiN coated carbide tool with a rake angle of 7°, clearance angle of 3° and cutting edge radius of 50µm. This configuration was based on the work of Giovenco [5] and Courbon et al. [6] performed at LTDS during the last decade. The basis of the wear simulation is a 2D orthogonal cutting model ALE developed in ABAQUS/Explicit©. It was found that such models are well known in the literature. They have been successfully used to predict: cutting forces, tool temperature, stresses in the workpiece and chip formation. The present model consists of a deformable workpiece and a fully fixed rigid cutting tool (Figure 1). The tool is rigid while a material flow is applied through the part. This material flow is defined by three Eulerian free boundaries located: on the left at the material inlet, at the top of the chip and on the right at the outlet of the modeled part. The heat exchange is allowed by a contact thermal conductance between the tool and the part. The value of the conductance has been set to 10^4 W/m².K based on the work of Courbon et al. [6]. The workpiece is meshed with 4-node coupled temperature displacement elements (CPE4RT). The model is composed of 9000 elements mainly located at the contact interface which is the region of interest in our case.

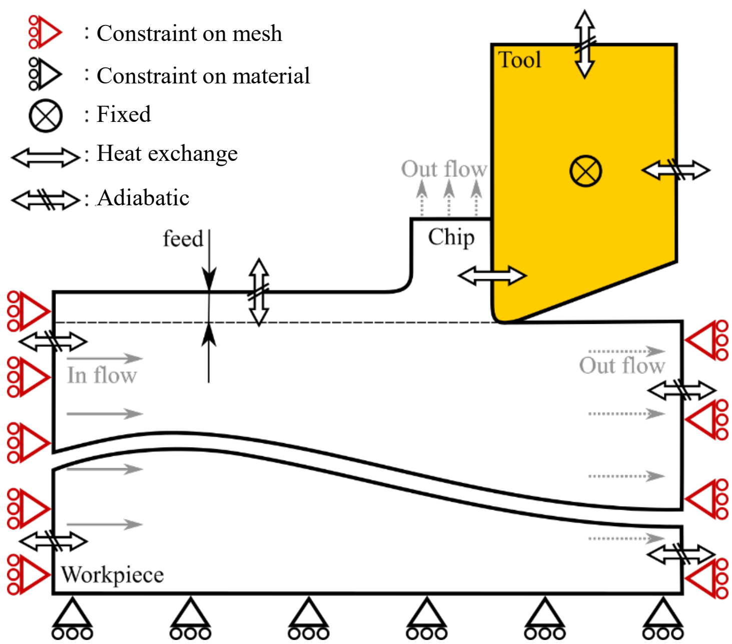

Figure 1 - 2D ALE model used in the study

As for the flow stress model, a well-established Johnson-Cook strain rate dependent equation was used with the parameters identified by Jaspers & Dautzenberg (2002) [7]

Friction was implemented through a varying Coulomb model with an exponential decay (Eq.1) as plotted in Figure 2:

$$\mu(V_{sl}) = \mu_k + (\mu_s - \mu_k) \cdot e^{-d_c \cdot V_{sl}} \tag{1}$$

Where µ is the coefficient of friction, Vsl is the sliding velocity, µk is the kinetic friction coefficient, µs is the static friction coefficient, dc is defined as the decay coefficient.

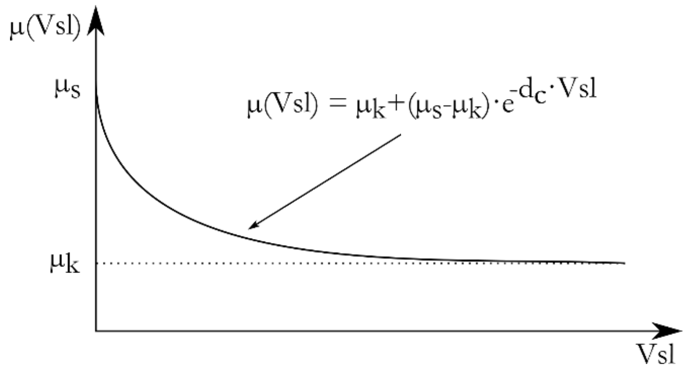

Figure 2 - Modeling of friction as a function of sliding speed used in ABAQUS

As this first thermo-mechanically coupled model only simulates a few milliseconds of the real cutting process, a second pure thermal simulation is employed to compute the steady-state heat transfer in the tool with Abaqus/Implicit®. Nodal heat fluxes from the ALE simulation are used as boundary conditions and applied to the corresponding node as heat inputs into this thermal model. After these two steps, the local thermomechanical loadings can be extracted and plotted along the cutting tool geometry.

Implementation of a cutting fluid in the numerical models

To consider the influence of the cutting fluid on these thermomechanical loads, modifications were introduced in both the 2D Arbitrary Lagrangian-Eulerian (ALE) model and the 2D implicit simulation. Dedicated regions were defined in both models, corresponding to the surfaces interacting with the cutting fluid. From a thermal perspective, the first assumption was that this interaction could be adequately represented by a simple heat exchange coefficient.

Figure 3 illustrates the surfaces subject to the convection coefficient, identified in green.

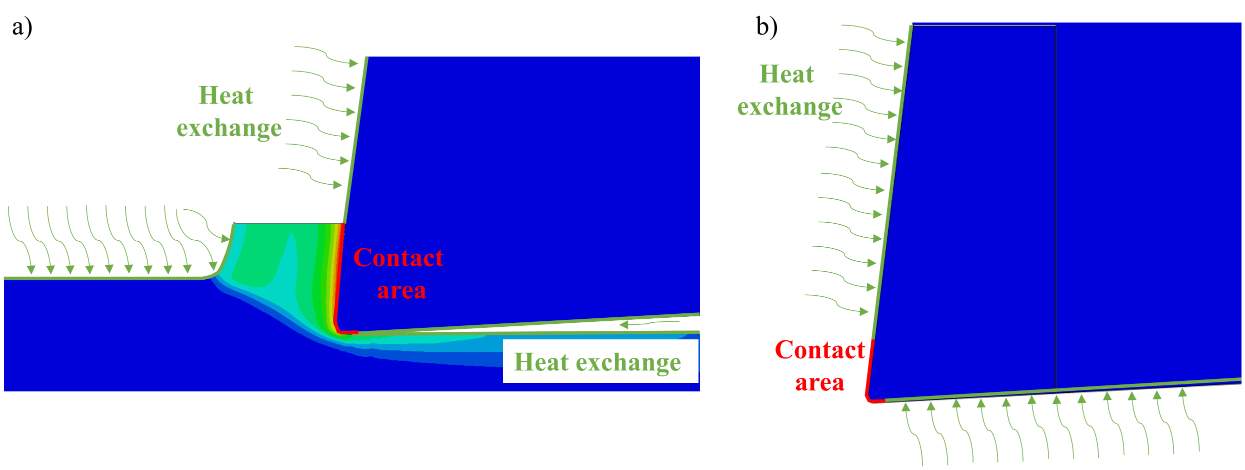

Figure 3 - Heat exchange related to the cutting fluid applied in a) 2D ALE model and b) 2D implicit calculation

These surfaces primarily include the rake face of the tool (the portion not in contact with the chip), the tool clearance face, the surface of the work material ahead of the cutting zone, and the freshly machined surface. A second assumption was that the thermal impact of the cutting fluid does not affect the tool-chip contact area (depicted in red), characterized by exceptionally high contact pressure.

The bibliography shows very different and variable results concerning the calorific value of cutting fluids according to the works of Luchesi (2012) [8] or Kurgin (2012) [9] (Figure 4) a)

Conditions	Fluid	h (W · m $^{-2}$· K $^{-1}$)
Free convection	Gases	5–30
	Water	100–900
Forced convection	Gases	10–300
	Water	300–11.500
	Viscous oils	60–1300
	Liquid metals	5.700–114.000
Phase change	Boiling liquids	3000–57.000
	Condensing vapors	5.700–114.000

b)

Coolant type	h (W/m^2 C)	Biot ratio
Free convection (air)	22	0.0004
Air flow @ 4 bar	248	0.005
Air flow @ 5 bar	270	0.006
Air flow @ 6 bar	294	0.006
MQL (40 mL/hr, 4 bar)	204	0.004
MQL (40 mL/hr, 6 bar)	300	0.007
MQL (110 mL/hr, 4 bar)	223	0.005
MQL (110 mL/hr, 6 bar)	225	0.005
Flood coolant with water-based fluid	5,230.0	0.298

Figure 4 - Heat exchange coefficient established by a) Luchesi (2012) [8] and b) Kurgin (2012) [9]

Given the wide variations that could be reported, the following values were selected for this first sensitivity study in order to extract some first trends: Dry machining, h = 20 W/m^{2}K - Straight oil lubrication, h = 200 W/m^{2}K - Emulsion based lubrication, h = 1000 W/m^{2}K.

Finally, the potential lubricating effect of the fluid can be reasonably implemented by changing accordingly the friction model at the tool-material interface. Considering the velocity dependent friction model presented in Eq. 1, Rech et al. 2013 [10] showed that under dry conditions, a static friction, μs which corresponds to low speed friction, of 0.5 and a dynamic friction, μk at high speed, of 0.2 could be commonly reached. Assuming that the lubricating effect would mainly change the frictional behavior at low sliding velocity, the dynamic friction was kept constant at 0.2, as well as the decay coefficient at 1, whereas the static friction was changed from 0.3 to 0.5 and 0.7.

The graphical representation of the 3 resulting friction models is presented in Figure 5.

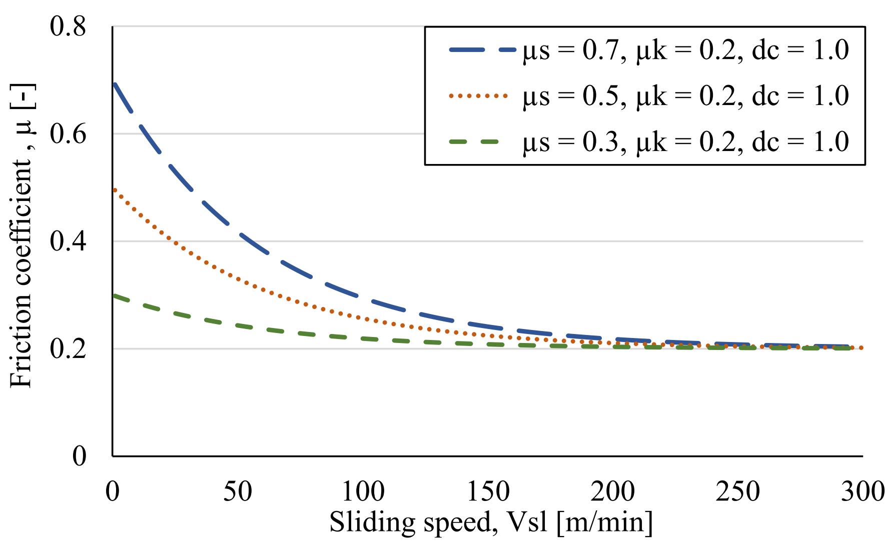

Figure 5 - Graphical representation of the 3 cases studied for static friction µs of 0.3, 0.5 and 0.7

Impact of a cutting fluid on the local thermomechanical loadings

The impact of the cooling and lubricating properties of a cutting fluid on the loadings applied along the tool-material interface was first investigated separately.

Influence of convection on the local thermomechanical loadings

Figure 6 shows the impact of the 3 investigated lubrication conditions modelled via 3 different convection values on the thermomechanical loads, i.e. cooling effect of the fluid.

Interestingly, it can be seen that convection does not influence the distribution or magnitude of mechanical loads (pressure and sliding velocity) applied to the tool. Nevertheless, an increased convection seems to affect the steady-state temperature simulated in the implicit model.

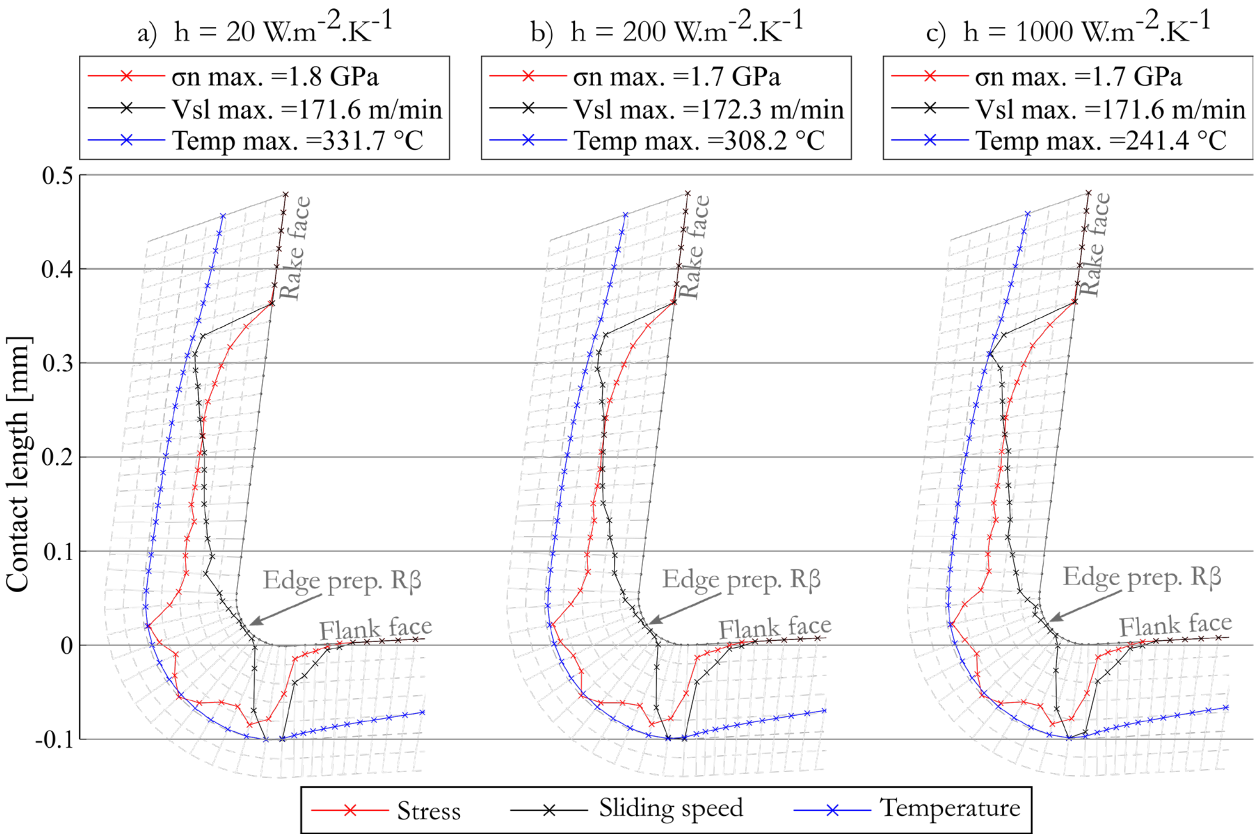

Figure 6 - Heat exchange (h) impact on thermomechanical loadings for 3 levels a) h = 20 W.m^{-2}.K^{-1}, b) h = 200 W.m^{-2}.K^{-1} and c) h = 1000 W.m^{-2}.K^{-1} with μs = 0.5, μk = 0.2 and dc = 1

Influence of friction on the local thermomechanical loadings

On the other hand, Figure 7 presents the different thermomechanical loading profiles simulated for the 3 different static friction coefficient, i.e. lubricating effect of the fluid. It could be seen that the contact pressure and maximum sliding speed are almost identical while surprisingly, the maximum temperature is considerably limited by an increase of μs.

When focusing on the loadings simulated with μs = 0.3, the sliding velocity in black is found to be high all along the tool-material contact zone, except for a small section around the material separation point at the edge radius. This material flow, combined to local friction, will therefore generate a significant amount of heat, resulting in an induced temperature of 340°C.

When increasing μs to 0.7, a stagnation zone appears on the rake face of the tool. This sticking zone is attributed to the higher friction coefficient compared to the previous case, hindering the chip from sliding over the rake face. This limited relative motion leads to minimal heat generation, consequently restricting the temperature increase.

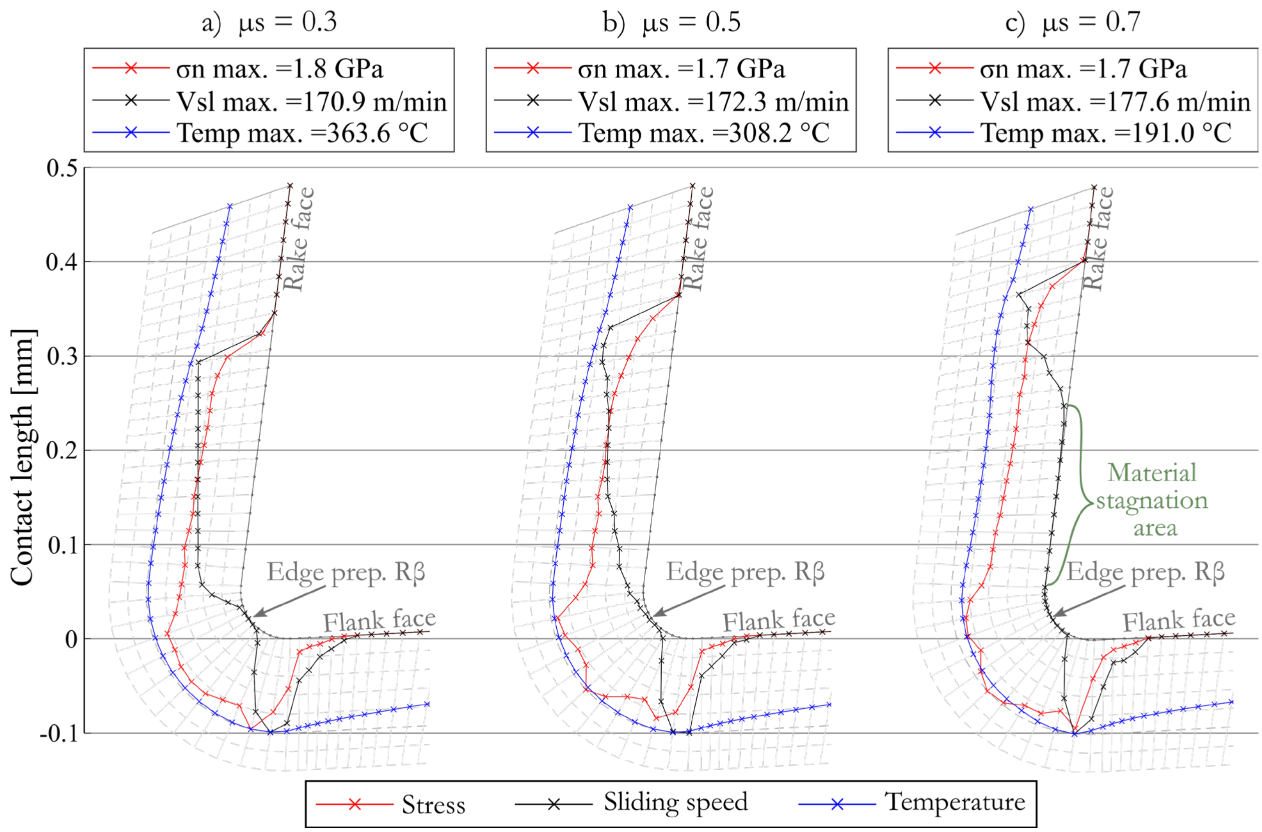

Figure 7 - Static friction coefficient (µs) impact on thermomechanical loadings for three levels a) µs = 0.3, b= µs = 0.5 and c) µs = 0.7, with h = 200 W.m⁻².K⁻¹

Impact of a cutting fluid on the wear of a cutting tool

Modeling of cutting tool wear

A multi-step tool wear modeling procedure was developed by Rech et al. (Rech, et al. 2018 [4]) with the principle illustrated in Figure 8. Based on the two already presented models, the thermomechanical loads at the tool-material interface are estimated and the tool geometry is updated by locally moving the nodes according to a wear equation. The numerical evolution of the VB flank wear can be simulated and compared for the various input data configuration representing the 3 lubrication methods.

Usui et al. [11][12] proposed a wear rate model to simulate crater and flank wear taking into account temperature (T). This model was based on the Archard adhesive wear model in which 2 constants A and B were added (Eq 2). Kitagawa et al. [13] [14] validated the model for carbide tools in carbon steel turning. Klocke and Frank [15] evaluated the model developed by Usui for the cutting and flank wear zones for CBN tools in hard turning.

$$\frac{\partial W}{\partial t} = A \cdot \sigma_n \cdot V_{sl} \cdot e^{-\frac{B}{T}} \quad (2)$$

Where $\partial W/\partial t$ is the wear rate, σn the contact stress, Vsl the local sliding speed, T the temperature. This model was thus implemented in the present study based on the parameters identified by Yen et al. [16] and Senthilkumar, et al. [17] with A = 0.0000000078 and B = 5302.

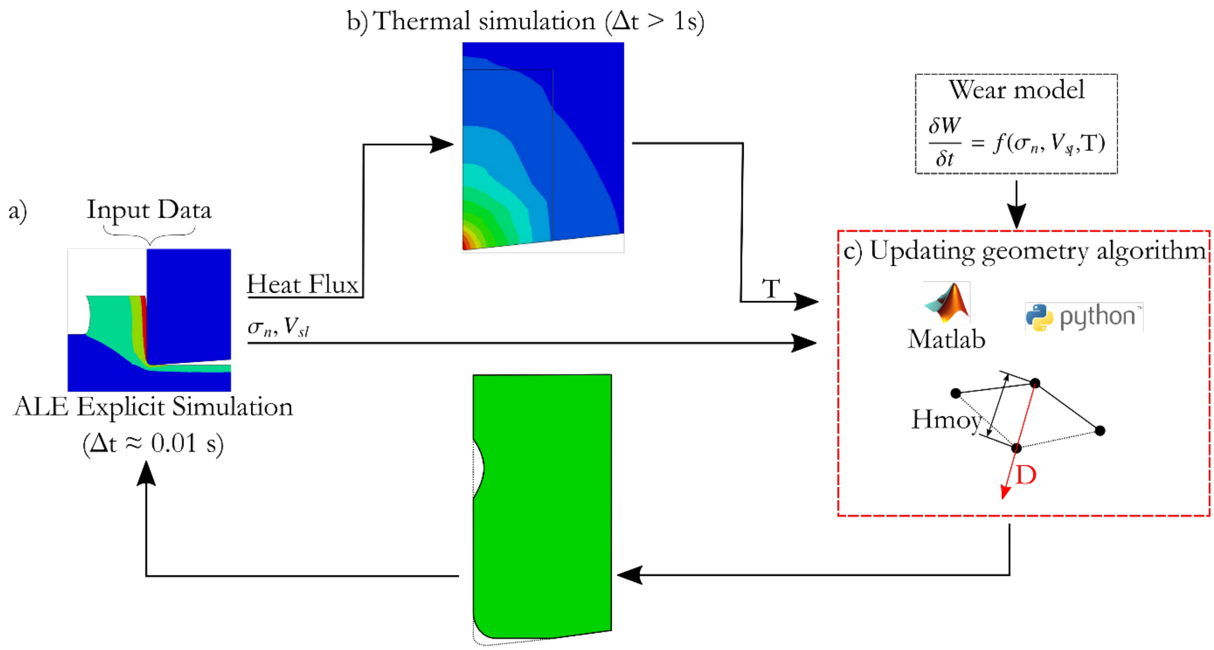

Figure 8 - Iterative procedure to model tool wear

Influence of convection on tool wear

The numerically predicted evolution of the flank wear (∂VB/∂t) is presented in Figure 9. The three cases are displayed with convective exchange at 20 W/m²K (yellow curve), 200 W/m²K (orange curve) and 1000 W/m²K (blue curve).

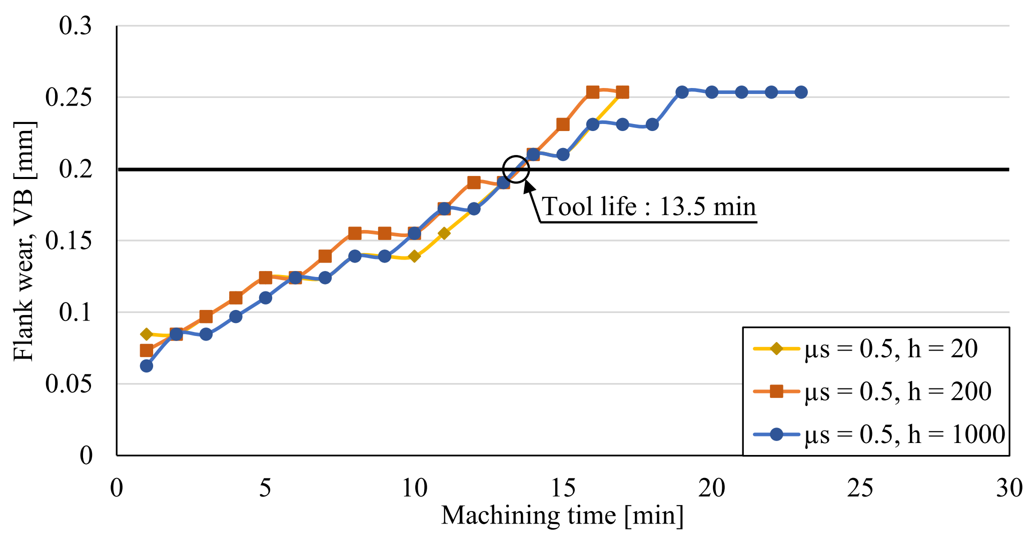

Figure 9 - Influence of convection on cutting tool-life

The wear criterion (VB max) has been set at 0.2 mm (black line), which corresponds to the tool life of the studied cutting tools. It can be seen that despite the changes in convection, the tool life remains the same at approximately 13 min. The convection, applied with the different assumptions, does not impact the tool life despite the fact that the wear equation was temperature dependent.

Influence of friction on tool wear

The impact of friction on wear was then considered. In the previous section, it was shown that friction influenced both the mechanical and thermal loadings. The results are presented in Figure 10, displaying the 3 studied static friction µs namely 0.3, 0.5 and 0.7.

In this case, the impact of the friction formulation on the cutting tool life is significant. In particular, it can be seen that it increases from 12 to 28 min when µs increases from 0.3 to 0.7.

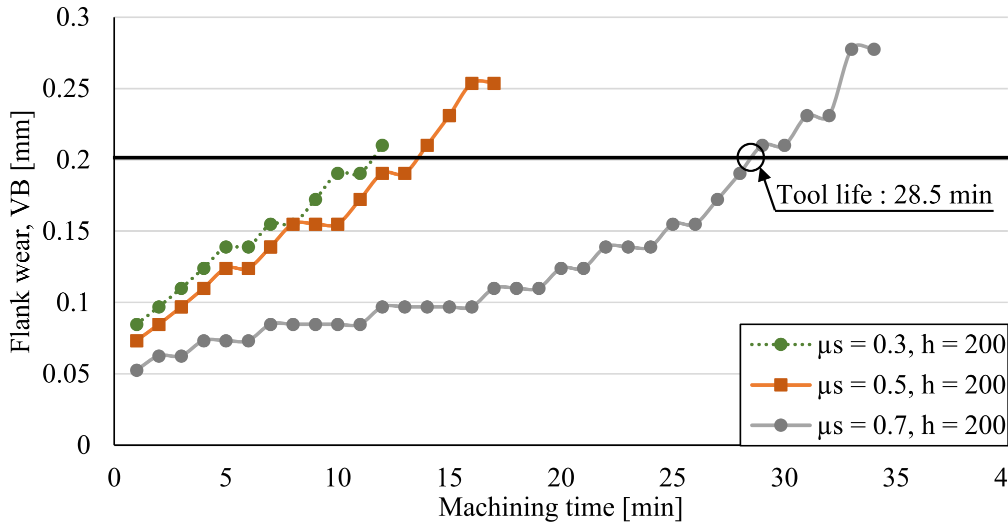

Figure 10 - Influence of static friction µs on cutting tool-life

Critical discussion of the results

The obtained results reveal an intriguing inconsistency, diverging from the commonly reported trend where the use of a cutting fluid is expected to enhance tool life by reducing wear. This deviation is clearly attributed to the strong assumptions made and the oversimplified representation of cutting fluid effects within the numerical simulation. The simplistic implementation of the cutting fluid's impact through convection and friction coefficients led to an inaccurate representation of the actual machining conditions.

When examining the influence of convection, an unexpected impact on the steady-state temperature was observed, indicating a potential limitation in the representation of heat dissipation mechanisms in the current model. This suggests that the selected values of the convection coefficient were underestimated, and higher orders of magnitude, related to forced convection or phase changes of a water-based lubricant, should be considered.

The study of friction presented also intriguing findings. Surprisingly, an increase in µs led to a considerable limitation of the maximum temperature, suggesting a counterintuitive relationship between friction and temperature rise. A significant decrease in tool life was consequently observed with lower static friction coefficients. This noteworthy effect emphasizes the need for a more detailed modelling approach of how friction, lubrication, and heat dissipation interact in machining processes. Indeed, the effective local lubrication regime occurring at the tool-chip interface, has to be deeper investigated as it governs the actual lubrication effect and heat transfer within the contact.

Moreover, the Usui wear equation was used as proposed by the authors, meaning identified under dry machining conditions. This was intentionally done but emphasizes the need for proper identification corresponding to the actual lubricated scenario.

The observed discrepancies highlight the necessity for refining the model to better capture the complex relationships governing tool wear under the influence of cutting fluids. Further

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investigations should aim to develop more realistic representations of lubricant effects, to achieve results consistent with industrial observations and expectations.

Conclusion

The present study proposed to assess the impact of a cutting fluid on the thermomechanical loadings withstood by the cutting tool and the resulting wear. A numerical approach was developed to simply take into account both thermal and tribological aspects of the fluid. As a first step, two strong assumptions were made by modelling the fluid only with a local heat exchange coefficient and a tailored friction model. Simulations were then run to extract key numerical outputs such as local contact pressure, sliding velocities and ultimately the evolution of the predicted tool flank wear.

The simulations revealed that the fluid's thermal properties primarily affected tool temperature, with limited impact on wear in continuous cutting operations like turning. From the friction perspective, the iterative wear procedure demonstrated a high sensitivity to the different friction formulations, resulting in a more than twofold increase in tool life compared to the reference configuration when friction increases. Indeed, changing the friction formulation by reducing the static friction coefficient had a substantial effect on sliding speed profiles and, consequently, tool temperature due to changes in frictional dissipated energy.

These unexpected results underline the limitations of the model, which represents the cutting fluid solely through a heat exchange coefficient and a modified static friction coefficient, applied on a predefined region of the tool material contact. This oversimplified representation do not fully capture the various effects of cutting fluids suggesting that their influence extends beyond the only cooling and friction reduction. More physical phenomena such as phase changes, penetration of the fluid within the contact or even tribochemical action of additives definitely occur and must be taken into account.

Finally, the coefficients of the Usui model were kept constant and identified under dry conditions. Future work should include a comprehensive investigation of the sensitivity to the wear equation through numerical studies and experimental tribological tests to identify accurate wear model constants.

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