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Numerical analysis of the tribological and geometrical impacts of tool wear on the thermomechanical loadings induced by 15-5PH steel turning

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Abstract

Finish turning is one of the key operations governing the residual stresses of functional surfaces. The residual stress state is determined by the thermomechanical loadings applied on the machined surface over time. These thermomechanical loadings depend on the cutting conditions and on the selected cutting tool system (macro geometry, cutting edge preparation, tool substrate, multi-layer coating...). However, this situation evolves over the time due to tool wear. At least two kinds of parameters are modified: the geometry of the tool (crater and flank wear) and the tribological phenomena between the cutting tool (wear of each layer of the coating) and the workmaterial. The thermomechanical loadings can be estimated thanks to a numerical model of the cutting operation. This work aims at investigating the sensitivity of tribological and geometrical parameters on the thermomechanical loadings withstood by the machined surface in an orthogonal cutting operation. Among the key criteria determining the residual stress state, this paper focuses on the analysis of the plastic deformation, the heat generation and the corresponding temperature near the machined surface. A finish turning of a 15-5PH steel with a carbide tool in dry conditions is considered. It is shown that tool geometry is dominantly affecting the thermomechanical loadings, whereas the sensitivity to friction is limited for this case study, despite a threshold effect for friction beyond 0.25.

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Keywords: Tool wear; surface integrity; turning; thermomechanical loading; numerical model

1. Introduction

The aircraft industry is extremely demanding on the fatigue resistance of safety components. During the manufacturing of a part, machining processes affect the residual stress state in the vicinity of the functional surface, which is known to play a major role in the fatigue resistance of the machined component [1–5]. Residual stresses are generated by the thermomechanical loadings induced by the cutting tool as shown by the numerical model developed by Mondelin [6]. In the past, some experimental and numerical studies have been performed to observe the impact of geometrical [7, 8] or tribological [9, 10] modifications of the tool on the residual

stresses. Some previous works highlighted the impact of the tribological aspects by studying the influence of the coating on the residual stresses. It seems to be an element that can really differ depending on the investigated tool material pair. The work of Outeiro et al. [9, 10] shows a different tendency on the residual stress state between a coated or uncoated tool. On the contrary, in the work of Tonshoff et al. [11], no difference in residual stresses was observed between the surface machined between a PCBN tool and cermet tool with Al₂O₃/TiC coating. As a summary, the sensitivity to each parameter is still not completely understood as it seems to highly depend on the case study (workmaterial ⇔ tool material). This paper deals with the machining of a martensitic stainless steel 15-5PH with a carbide tool in dry conditions. A

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previous work has already started to point out the impact of tool wear on the thermomechanical loadings [12] through 4 practical case studies in which all the tribological and geometrical parameters changed simultaneously, which makes the analysis more difficult. This work aims at making a more comprehensive sensitivity investigation so as to identify the relative contribution of each parameter on the thermomechanical loadings. As these parameters are difficult to assess with an experimental approach, a numerical model in orthogonal cutting configuration is used to dissociate and quantify the effect of the tribological, on one side, and geometrical features of a worn tool on the other side.

2. ALE modeling

The cutting process is simulated in Abaqus/explicit via a 2D Arbitrary-Lagrangian-Eulerian (ALE) model based on the work of Courbon et al. [13, 14] (Fig.1.). The contact between the tool and the workpiece is ensured by a master (tool) / slave (workpiece) with penalty contact method and finite coulomb friction coefficient. The thermal conductance between the tool and the workpiece is $10^4 \text{ W/m}^2\cdot\text{K}$. The cutting speed was $120 \text{ m}\cdot\text{min}^{-1}$ and the uncut chip thickness was 0.2 mm .

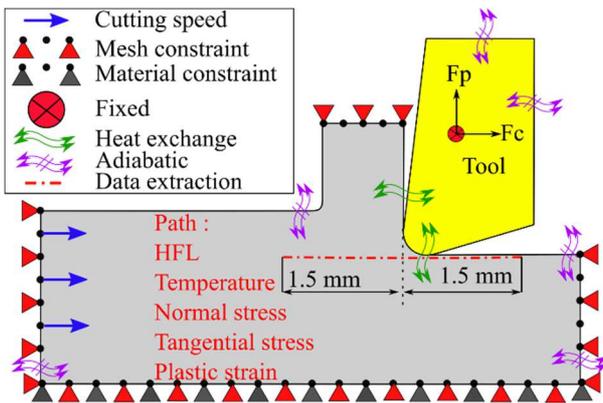


Fig. 1. Boundary conditions of the ALE model and extraction paths of the thermomechanical loadings [15]

A Johnson-Cook flow stress model identified by Mondelin et al. [6] has been used to model the 15-5 PH mechanical behaviour (Table 1, Eq.1.).

Table 1. Johnson-Cook's parameters of the 15-5 PH

A [MPa]	B [MPa]	n	m	C	ϵ_0	T_F [°C]	T_0 [°C]
855	448	0.14	0.63	0.0137	0.001	1440	20

$$\sigma_{eq} = \left[A + B \cdot (\bar{\epsilon}_p)^n \right] \cdot \left[1 + C \cdot \ln \left(\frac{\dot{\epsilon}_p}{\dot{\epsilon}_0} \right) \right] \cdot \left[1 - \left(\frac{T - T_0}{T_F - T_0} \right)^m \right] \quad (1)$$

Previous studies highlighted the importance of friction and heat partition coefficient when modelling a cutting operation [16–20]. Although these papers were focused on the influence of tribological parameters on the chip formation and cutting forces, it is reasonable to assume that friction and heat partition coefficients should also influence the thermomechanical loadings withstood by the machined surface, and therefore could modify the residual stress state.

So it has been decided to conduct the sensitivity analysis of tribological aspects through these two parameters.

A previous paper [12] has shown that the variation of flank face geometry was of primary importance compared to rake face. This single wear mode has thus only been considered in the proposed work. Two geometries have been investigated as described in Figure 2:

- The first one represents a new tool inspired by the geometry of a cutting insert from Sandvik (DNMG 150608 PM 4325)
- The second one aims at representing the same tool, but in a highly worn configuration. The contact length of the worn flank face is increased up to $400 \mu\text{m}$ and tilted with a flank angle of 3° .

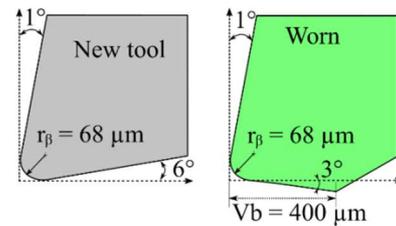


Fig. 2. Geometry of the new tool and the worn tool

3. Sensitivity to the geometry

According to the work of Mondelin et al. [6], the main factors influencing the generation of residual stresses are the heat flux density, the normal stress and the tangential stress applied on the machined surface. With this in mind, the sensitivity investigation has been conducted by analysing these indicators representing the thermomechanical loadings withstood by the machined surface.

The evolution of heat flux density (W/mm^2) has been extracted along the path (Figure 1) and plotted in Figure 3. One can see that between 1.5 and 0.1 mm ahead of the cutting edge, the heat flux density remains equal to 0 whereas it starts to increase when the material reaches the separation point at the cutting edge. A second increase appears when being in contact in the third shear zone (flank face). A large flank wear significantly affects the amount of heat transferred to the machined surface. This total heat flux (THF) can be estimated by computing the area below the curve, which was considered as the indicator of the thermal loading applied on the machined surface. For instance, Figure 3 (a) illustrates that flank wear increases the total heat flux by increasing the contact length.

In the same way, the temperature along the machined surface has been extracted and plotted in Figure 3 (b). The maximum temperature T_{max} has been considered as an indicator. Figure 3 (b) shows that the maximum temperature increases with the tool wear due to a longer exposure time along the the contact area.

The evolution of the normal stress is also assessed along the path and plotted in Figure 3 (c). The maximum normal stress $\sigma_{n,max}$ was considered as relevant in this paper, as it reveals the mechanical loading on the machined surface. The same indicator $\sigma_{t,max}$ is used for the shear stress along the path.

As an example, Figure 3 (c) shows that flank wear increases the normal stress $\sigma_{n,max}$.

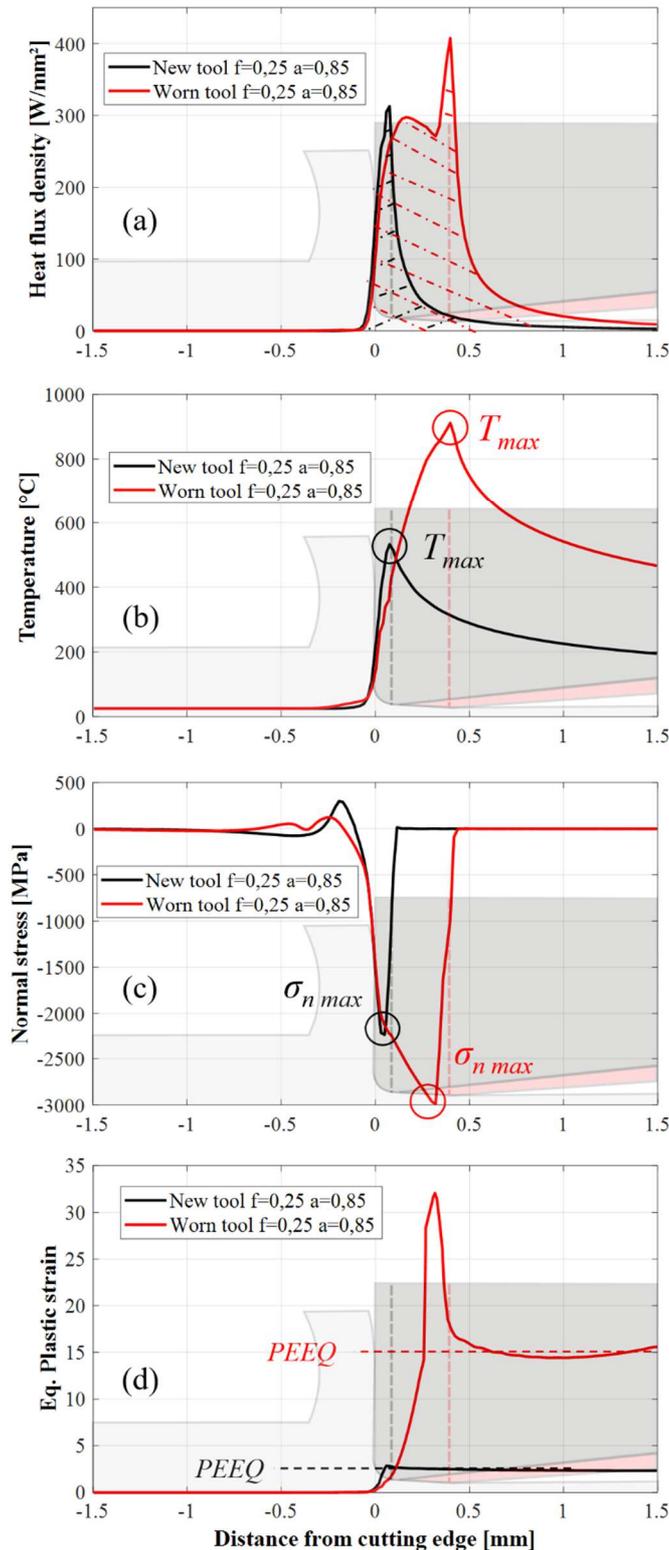


Fig. 3. Evolution of the thermomechanical loadings on the machined surface over time ((a) = heat flux density – (b) temperature – (c) normal stress – (d) plastic strain)

Finally, the cumulative equivalent plastic strain $PEEQ$ at the end of the path (Figure 3 (d)) was analysed, as well as the

macroscopic cutting forces. Figure 3 (d) reveals that plastic strain $PEEQ$ drastically increases with the flank wear.

These preliminary observations confirmed the effect of the tool worn geometry (flank wear). The following sections aim then at proposing a more comprehensive sensitivity analysis on the contribution of both the tribological parameters and tool geometry on these representative indicators THF , T_{max} , $\sigma_{n,max}$, $\sigma_{t,max}$, $PEEQ$.

4. Sensitivity to the heat partition coefficient

The second part of this study aims at observing the influence of the tribological parameters, i.e. heat partition and friction coefficient, on thermomechanical loadings. Table 2 presents the design of experiments with two levels for each parameter. For the high level of the heat partition coefficient, the value of 0.85 was chosen according to the work of Mondelin et al. [6] to represent a value commonly used for this range of speed. The choice of the low level value 0.1 was arbitrary and intended to represent an extreme case compared to the standard level, meaning that only 10% of the generated heat is transferred to the workmaterial.

Two levels of friction coefficient were also considered: a standard value (0.25), also based on experimental data [6], and a very low value (0.01) illustrating a quasi frictionless configuration.

Table 2: Friction coefficient, heat partition and tool geometry for the different numerical simulations

Simulation number	Friction coefficient (f)	Heat partition (a)	Tool geometry
1	0.25	0.85	New
2	0.01	0.85	New
3	0.25	0.1	New
4	0.01	0.1	New
5	0.25	0.85	Worn
6	0.01	0.85	Worn
7	0.25	0.1	Worn
8	0.01	0.1	Worn

Figure 4 presents the sensitivity of the various indicators and their evolution (in percent) when the heat partition coefficient increases from 0.1 to 0.85. This analysis is made for two friction coefficients (0.01 and 0.25) and tool geometries (new \leftrightarrow worn).

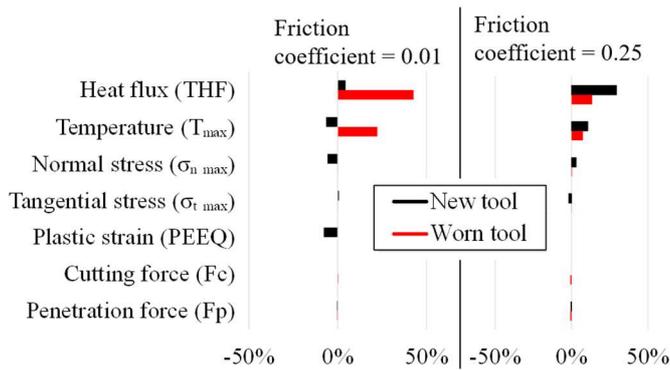


Fig. 4. Impact of an increase of the heat partition from 0.1 to 0.85 on the thermomechanical loadings

It appears that the heat partition coefficient mainly influences heat flux and temperature, whereas it does not affect significantly the mechanical indicators. For the lowest friction coefficient (0.01), the impact is more important as far as the worn tool is concerned. This is due to the high contact length between the workmaterial and the tool. With a friction of 0.25, the heat generated by friction is much higher and the impact of the heat partition coefficient becomes less significant.

5. Sensitivity to the friction coefficient

The simulation parameters are the same as those previously defined and the heat partition is here fixed at 0.85. The friction coefficient is varied from a very low value of 0.01 to a very high coefficient of 0.75. All of these simulations have been performed with a new and a worn tool geometry. The indicators are also extracted in the same way and their variations are presented in the Figure 5.

Before analysing the local indicators of the thermomechanical loadings, it is of interest to analyse the macroscopic outputs. Figure 5 (a) and (b) plots the evolution of the cutting force F_c and penetration force F_p . As expected, an increase of friction tends to increase both forces as far as new tools are concerned. This trend is in agreement with common experimental observations. This is due to the difficulty of the workmaterial to flow on the rake face and on the flank face. This trend is limited in terms of magnitude.

However, as far as the worn tool is concerned, the trend is different. Even if the cutting force F_c is 30% higher for the worn tool than for the new tool, the penetration force F_p becomes 500% higher. It is expected that this large flank wear should induce much more severe thermomechanical loadings on the machined surface compared to a new tool exhibiting a limited contact area on the flank face.

In addition, it can be noted that the penetration force tends to decrease as friction increases, which is not obvious at first sight. In the case of a new tool, it is assumed that friction influences mainly the rake face, being the largest region along the whole tool-material contact zone compared to the flank face. So friction can hardly influence the stresses at this interface. On the contrary, when a worn tool is considered, the

contact area on the flank face becomes as large as the contact zone on the rake face. So the penetration force seems to be affected by this fully different geometry. Local analyses of other indicators (heat flux, stress, plastic strain... on the machined surface) will help to bring a better understanding.

Figure 5 (c) plots the evolution of the total heat flux THF transmitted to the machined surface. It highlights that heat flux is three times higher with a worn tool than with a new tool. This is due to the much longer contact time along the flank face. Moreover, heat flux depends on friction coefficient for values below 0.25. Beyond this level, the heat flux transmitted to the machined surface is independent of the implemented friction coefficient. It is also of interest to note that heat flux is similar for a new and a worn tool in case of frictionless configuration. However the level is not zero because of the heat generated by the plastic deformation in the primary shear zone.

Figure 5 (d) plots the evolution of the maximum temperature T_{max} . The trend is similar to the evolution of total heat flux as there is a direct correlation between them.

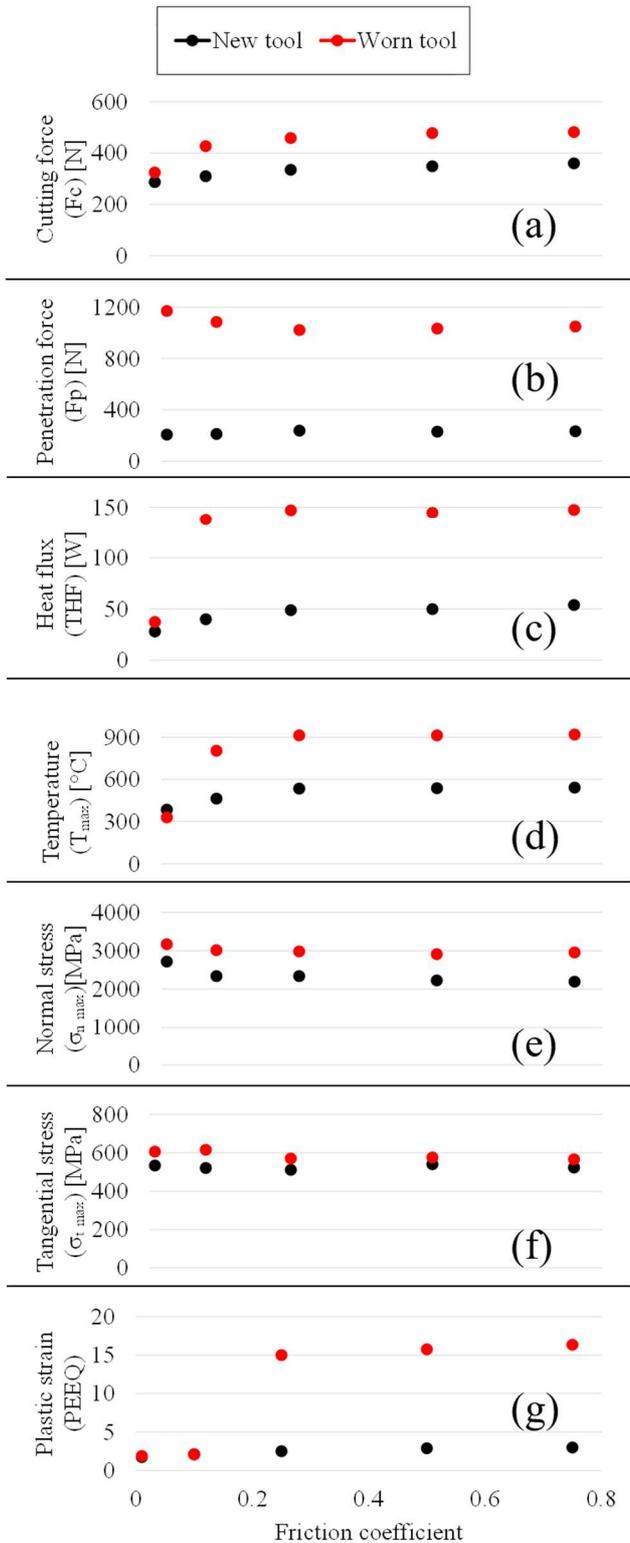


Fig. 5. Evolution of thermomechanical loadings with friction coefficient

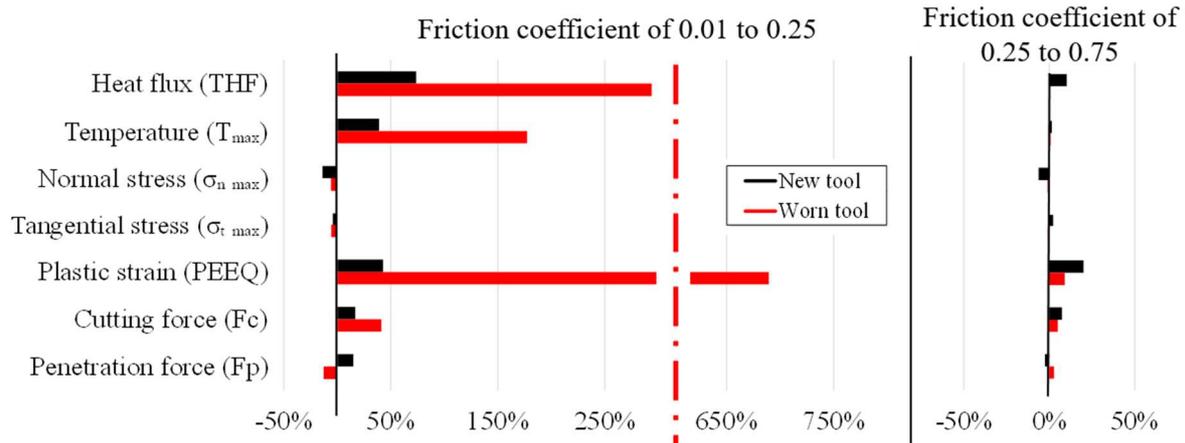


Fig. 6. Impact of the friction coefficient on thermomechanical loadings (left: from 0.01 to 0.25 - right: from 0.25 to 0.75)

Figure 5 (e) plots the evolution of the maximum normal stress $\sigma_{n,max}$. As friction increases, the normal stress decreases. This trend is correlated with the increase of temperature that affects the mechanical properties through the flow stress model (Table 1) providing a strong thermal softening. The same effect can be observed for the tangential stress $\sigma_{t,max}$, but the magnitude is lower than for the normal one $\sigma_{n,max}$ (Figure 5 (f)). The decreasing of the penetration force F_p observed previously is also directly correlated to this phenomenon.

The plastic strain $PEEQ$ (Figure 5 (g)) is also directly affected by an evolution of the friction coefficient and by tool wear. This evolution is correlated with the evolution of the heat flux THF and the temperature T_{max} . An increase of heat flux THF increases the ability of the workmaterial to be plastically deformed (\Leftrightarrow flow stress equation). The magnitude of this evolution is amplified for the worn tool compared to the new tool, with a threshold effect around a friction value of 0.25.

Figure 6 summarises the previous observations on the sensitivity to the friction coefficient. The percentage represents the sensitivity of the indicators. This figure is divided in two parts. On the left side, the friction coefficient varies from 0.01 to 0.25. On the right side, friction varies from 0.25 to 0.75.

It can clearly be observed that an evolution of the friction coefficient beyond 0.25 has almost no impact on the thermomechanical loadings on the machined surface.

On the contrary, when the friction coefficient remains below 0.25, a great impact on the thermomechanical loadings is expected, especially the thermal ones and the plastic deformation. The normal and tangential stresses, as well as the macroscopic cutting forces, are less impacted by a modification of the friction coefficient below 0.25.

6. Discussion

Previous sections have shown that the variation of tool geometry (flank wear) is the dominant factor on the thermomechanical loadings applied on the machined surface. A very high increase of the total heat flux THF , and of the temperature T_{max} induces a severe plastic deformation. On the

contrary, the normal stress $\sigma_{n,max}$ and tangential stress $\sigma_{t,max}$ are only slightly affected. These indicators let us assume that residual stress generation will be primarily affected by tool flank wear, whereas a variation of tribological parameters (friction, heat partition) will play a secondary role in this case study. Other workmaterial and cutting tool material should be investigated before proposing any generalized conclusions.

A better understanding of this statement can be achieved by observing the flow of the material around the tool. Figure 7 illustrates the relative sliding velocity of the material for three friction coefficients (0.01; 0.1 and 0.25). When a limited value below 0.25 is used, a relative motion at the interface between the tool and the workpiece on the flank face can be observed. An increase in the friction coefficient induces an increase in the heat generation and tangential stresses. As a consequence, it's possible to influence the thermomechanical loadings.

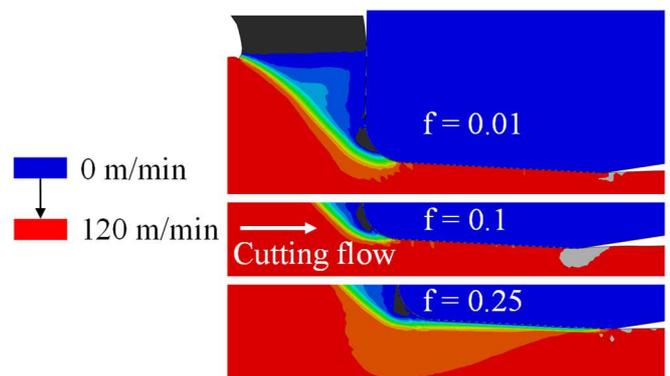


Fig. 7. Evolution of the speed of the material in the cutting direction with the friction coefficient

On the contrary, when the friction coefficient is higher than 0.25, one can observe the formation of a stagnation zone at the interface between the workmaterial and the tool where no relative motion occurs. The shearing of the workmaterial occurs in the bulk and not at the interface. So the evolution of the friction coefficient has no longer an impact on the heat generation or tangential stresses at this interface. The thermomechanical loadings are thus no longer affected and

become independent of the cutting tool properties (friction and heat partition coefficients). The same phenomenon is likely to occur in the case of the new tool, but the contact area on the flank face is too small to be clearly observed.

As a conclusion, it was found that the thermomechanical loadings are determined mainly by the geometry of the cutting tool (especially its flank wear length). Friction phenomena can only play a secondary role, even small, when a relative movement occurs between the workmaterial and the tool, i.e. when the tangential stress at the interface is lower than the shear strength in the bulk of the material.

7. Conclusion

This article presented the sensitivity of the thermomechanical loadings induced by a cutting tool on a machined surface which are the quantities governing the generation of residual stresses. The total heat flux transmitted to the machined surface, the maximum temperature, normal and tangential stress, as well as the near surface plastic deformation were considered. The paper focussed on the influence of flank wear in terms of tribological parameters (friction and heat partition coefficient) and tool geometry.

This study has shown that the tool geometry is the dominant factor controlling the thermomechanical loadings compared to the tribological parameters. A flank wear induces a drastic increase in the total heat flux transmitted to the machined surface, the maximum temperature, the normal stress or the plastic deformation.

In the present case study, it has also been highlighted that there is a threshold effect for the friction coefficient. Beyond a value of 0.25, the effect of a modification of the friction coefficient becomes insignificant because of the formation of a stagnation zone at the tool/workmaterial interface. On the contrary, at lower values, friction was found to have an influence on the thermomechanical loadings.

Finally, it has been shown that heat partition coefficient has a limited influence on the thermal loadings and almost no influence on the mechanical ones, as far as the machined surface was concerned. Moreover, this influence is only observable when cutting with a large flank wear.

The perspective of this work will be to compute the actual residual stresses, based on these thermomechanical loadings once imported in the hybrid model developed by Mondelin et al. [6].

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