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Investigations on the flank wear and modelling of the contact radius effect in turning of Ti6Al4V titanium alloy

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Abstract

Machining of difficult-to-cut materials like Ti6Al4V titanium alloy leads to significant flank wear on the cutting tool. In order to ensure the respect of final part specifications, flank wear has to be controlled. In literature, predictive models had been developed. However, these models can be enhanced by taking into account new parameters depending on the part geometry. This study deals with the analysis of the contact radius effect on flank wear. Results highlight that the contact radius favors the flank wear. Afterwards, a phenomenological model is proposed and improves flank wear modelling.

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1. Introduction

This study finds its origin in the machining of turbojet drums. Those parts have a complex geometry, high dimensions and thin thickness, which lead to variable contact conditions between the cutting tool and the machined part during long contour turning pass. Moreover, titanium alloys are well known for being “difficult-to-cut” materials which generate significant tool wear and high cutting forces. Those elements would affect surface roughness and dimensions. To avoid this problem, the industrial partner is looking for simulating machining operations. As a first step in order to predict part deflections, cutting forces have to be known. However, cutting forces are evolving with respect to the cutting time due to the influence of the tool wear, especially flank wear. Therefore a precise modelling of the flank wear is necessary. The aim of this study is to enhance the flank wear modelling by taking into account a new parameter: the contact radius between the machined part and the cutting tool clearance face (Fig. 1).

In literature, Ravindra et al. [1] correlate flank wear to two cutting force components. In the same manner, Jawaid et al. [2] precise this remark by pointing out the effect of the feed rate on flank wear. Ezugwu et al. [3] complete those observations by associating flank wear evolution with regard to force ratios variation. Conversely, Smithey et al. [4] focus on the influence of the flank wear on the cutting forces. Smithey et al. also suggest a worn tool force model which defines the contribution to the cutting force generated by the flank wear. This approach is completed by Sun et al. [5] in order to model cutting forces gathered during milling. Regarding those contributions, it exists a strong interaction between cutting forces and flank wear, as precised by Oraby et al. [6] and Sun et al. [7].

Therefore, many scientists focus their research on the flank wear modelling. First approaches deal with a tool life time as a representation of the time needed to reach a critical flank wear value as detailed by Taylor [8] and Attanasio et al. [9]. Attanasio et al. [10], based on an empirical approach, suggest that the flank wear is in a second order relationship with the cutting velocity, the cutting time and the feed rate. While,

Zanger et al. [11], based on a physical approach and a synthesis of several contributions, define a wear rate, as an exponential inversed function of the absolute temperature at the interface, to forecast the flank wear land width. However, those models do not take into account the effect of the part geometry. The influence of the $R_{c,c}^o$ part radius on cutting forces is highlighted by Campocasso et al. [12] and Dorlin et al. [13,14], in cases of Cu-c2 pure copper and Ti-6Al-4V titanium alloy turning. As cutting forces and flank wear are linked through a strong interaction, the aim of this paper is to study the effect of the contact radius on the flank wear.

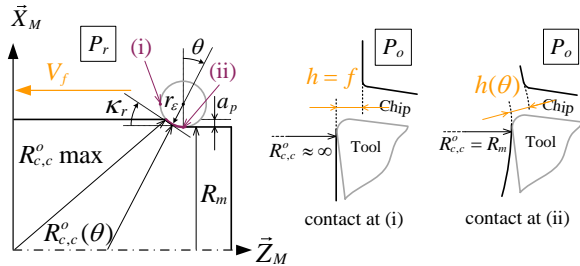


Fig. 1. Representation of the $R_{c,c}^o$ radius in cylindrical turning [13].

2. Experimental details

Cutting tests are realised on an instrumented NC 2-axis lathe. The workpiece material is Ti-6Al-4V titanium alloy, which hardness homogeneity has been verified. Two cutting tools are used in this research work, a 213202 ARNO ProfilCut linear cutting edge insert ($r_{\beta} = 5 \mu m$) for orthogonal cutting and a LCGR1705-500-RP Seco Tools MDT round insert ($r_{\beta} = 18 \mu m$; $r_c = 2.5 mm$) for cylindrical turning and face turning tests, which are representative of a simple contour turning test. Both are constituted of uncoated tungsten carbide and present the same geometry when mounted in tool holders ($\alpha_n = 7^\circ$; $\gamma_n = 7^\circ$; $\lambda_s = 0^\circ$) [15]. The cutting trials are conducted assisted by lubrication with a Blasocut 2000 CF coolant. Cutting parameters (especially $V_c = 90 m/min$) are defined with respect to the NF-E66-520-4 standard [16]. Cutting forces are gathered thanks to a Kistler 9121 dynamometer sensor, a Kistler 95019B charge amplifier, and an acquisition card. Flank wear is measured thanks to dynamic-focusing microscope (InfiniteFocus ALICONA) and according to the ISO3685 standard [17]. Finally, cutting force model coefficients are determined thanks to an algorithm developed under Mathematica software and the Levenberg-Marquardt optimisation method.

3. Analysis of the contact radius effect on flank wear in orthogonal cutting

In order to observe the contact radius effect on flank wear, two orthogonal cutting configurations are employed. The orthogonal cutting of a disk, where the contact radius is equal to the machined part radius, and the orthogonal cutting of a tube, where the contact radius tends to infinity [14]. Cutting trials are realised within the same insert (i.e. one insert for each part of Fig. 2, but on different zones of a same insert for a part) and workpiece to limit discrepancies. The experimental

design is also declined under two values of uncut chip thickness $h = \{0.1; 0.15\} mm$ and a unique value of cut width $b = 3 mm$ (for disk and tube) in order to evaluate the effect of the uncut chip thickness on flank wear. The results are presented in Fig. 2.

It has been observed that flank wear measurements during disk configuration tests for an uncut chip thickness value equal to 0.1 mm are unexploitable because of adhesion. Therefore, the comparison between tube and disk configurations for evaluating the contact radius effect on flank wear is presented for $h = 0.15 mm$ in Fig. 2.(a).

$$h = 0.15 mm; V_c = 90 m/min; b = 3 mm$$

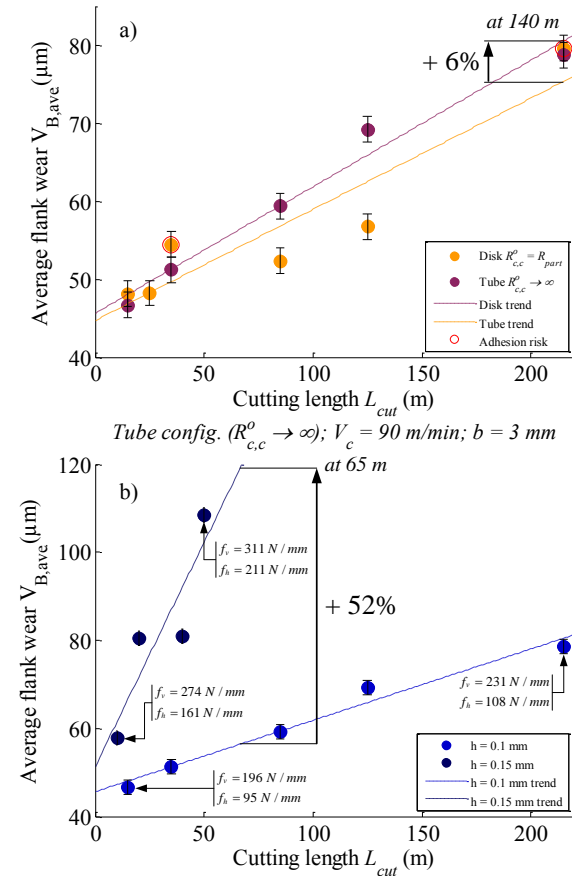


Fig. 2. (a) contact radius effect on flank wear; (b) uncut chip thickness effect on flank wear in orthogonal cutting.

The first observation is that the flank wear is growing with respect to the cutting length, even if some measurements may be overestimated due to adhesion, as mentioned.

Secondly, the flank wear measured from the tube configuration trials seems to be higher than the one measured from the disk configuration trials. At a cutting length of 220 m, the increase of the flank wear thanks to contact radius variation is about 6%. This gap seems to grow with respect to the cutting length, as highlighted by the first order trend curves. Besides, as observed in Fig. 2.(b), for a same level of cutting length in tube configuration trials (i.e. independently of the contact radius effect), the flank wear is more important

for an higher value for uncut chip thickness. At a cutting length of 65 m, the increase of the flank wear with respect to the uncut chip thickness is reaching 52%.

Lastly, results confirm that the cutting forces are highly sensitive to the cutting length and the uncut chip thickness. Therefore, based on those observations, the contact radius effect on flank wear does exist. However, this effect is secondary in comparison with the effect of the uncut chip thickness and cutting length on flank wear.

4. Determination of the contact radius effect on flank wear in cylindrical turning and face turning

In order to evaluate the contact radius effect on flank wear in contour turning, two turning operations are compared. Indeed, as explained by Dorlin et al. [13,14], for identic cutting parameters, cylindrical turning and face turning with a round insert do not present the same contact radius evolutions with respect to the uncut chip thickness variation all along the cutting edge. Furthermore, in face turning the $R_{c,c}^o$ contact radius is evolving during the pass.

Therefore, to determine the contact radius effect on flank wear, local flank wear is compared at different levels of cutting length between cylindrical turning and face turning trials. Comparison are realised for same values of uncut chip thickness (i.e. for a same sections at a same θ angle) but different values of contact radius $R_{c,c}^o$. Trials are realised within the same insert (i.e. cylindrical turning tests are carried out by pulling the tool holder to the right) and tool wear evolutions are detailed in Fig. 3. (a) and (b).

Cutting trials are developed under three levels of feed per revolution $f = \{0.1; 0.175; 0.25\} \text{ mm/rev}$ and a unique value of depth of cut $a_p = r_e = 2.5 \text{ mm}$ in order to cover large ranges of contact radius and uncut chip thickness. Local flank wear is measured in 3 sections for $\theta = \{22.5; 45; 67.5\}^\circ$. The results are presented in Fig. 3. (c).

Among all the data collected, some are unexploitable due to several factors. Difficulties linked to the turning process appeared, when $f = 0.1 \text{ mm/rev}$, in some sections at several levels of cutting length, significant adhesion has been observed on the flank face, which is altering the flank wear measurements. This remark is in accordance with observations made for orthogonal cutting tests when $h = 0.1 \text{ mm}$. Therefore, a precise analysis of the contact radius effect at this level of uncut chip thickness may be compromised. Furthermore, when $f = 0.25 \text{ mm/rev}$ and for some advanced levels of cutting length, the tool shape is modify by plastic deformations; It has been observed in sections where $\theta = \{45; 67.5\}^\circ$, which corresponds to significant values of uncut chip thickness. It leads to the formation of a crater on the rake face and a roll on the flank wear. Consequently results presented in Fig. 3. (c) are extracted only from trials where $f = 0.175 \text{ mm/rev}$ and points which may be overestimated by adhesion are identified. Contact radius and uncut chip thickness values are detailed in Table 1.

The first observation is that flank wear is increasing with respect to the cutting length. From a cutting length of 25 m to 125 m (i.e. in the controlled wear zone), flank wear grows respectively of 52% and 53% for cylindrical turning in section

with $\theta = \{22.5; 67.5\}^\circ$. Then, the flank wears also increase when the contact radius is growing. According to observations, at a cutting length equal to 75 m, the flank wear observed in face turning with $\theta = \{45; 67.5\}^\circ$ (i.e. when the contact radius is higher) is respectively 25% and 43% bigger than the ones observed in cylindrical turning. Whereas, the flank wear observed in face turning with $\theta = 22.5^\circ$ (i.e. when the contact radius is lower) is 40% smaller than the one observed in cylindrical turning.

Table 1. Contact radius and uncut chip thickness values in different sections for the cutting length reached during experimental campaign.

L_{cut} (m)	$R_{c,c}^o$ (mm)					
	Face	Cyl.	Face	Cyl.	Face	Cyl.
25	212	92	114	121	86	225
50	188	92	100	121	76	225
75	160	92	85	121	65	225
100	124	92	66	121	50	225
116 / 125	90	92	48	121	36	225
θ ($^\circ$)	22.5		45		67.5	
h (mm)	0.07		0.13		0.16	

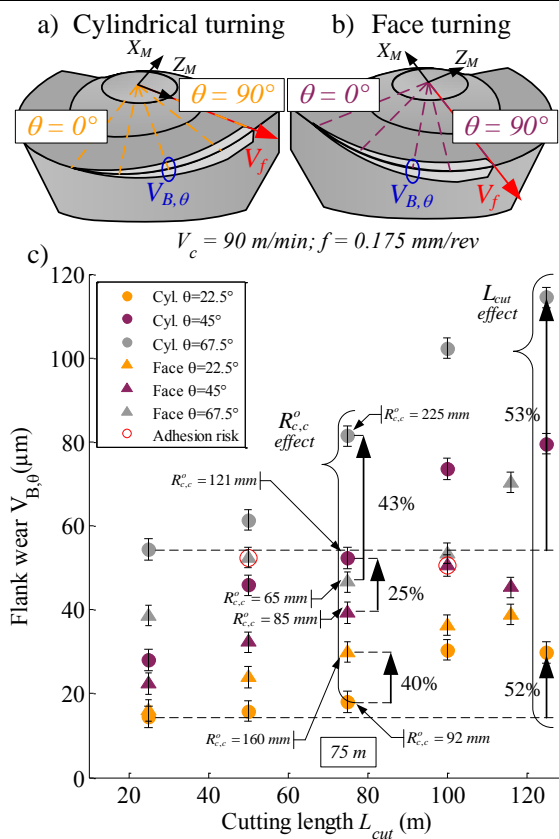


Fig. 3. (a) worn insert after cylindrical turning trial; (b) worn insert after face turning trial; (c) contact radius effect on local flank wear in cylindrical turning and face turning.

Finally, results at the global scale presented in section 4 approve the observations made at the local scale mentioned in section 3. The effects of the cutting length and contact radius

on the flank wear are confirmed. Nevertheless, the flank wear seems less sensitive to contact radius than cutting length or uncut chip thickness. Those influences have to be taking into account in future modelling.

5. Modelling

Based on previous conclusions, a correlation coefficients analysis is used to build the new models. Only the trials where $f = 0.175 \text{ mm/rev}$ are taking into account in further analysis. According to the correlation coefficients results, two phenomenological models have been proposed to predict flank wear as explained by equations (1) and (2). The proposed model in equation (1) takes into account the effects of the uncut chip thickness and the cutting length on flank wear. While, the second model, defined in equation (2), also takes into account those effects plus the effect of the contact radius on the flank wear. The flank wears modelled by each model are compared to the flank wears measured experimentally in contour turning. The domain of validity for each model is $\theta \in \{5^\circ; 85^\circ\}$ due to the clearance face contacts radius which tends to infinity. Then, the modelling errors obtained from each model are compared in order to evaluate the contribution of the contact radius to the flank wear prediction.

$$V_{B,h,L_{cut}} = k_1 h + k_2 L_{cut} h + k_3 \quad (1)$$

$$V_{B,h,L_{cut},R_{c,c}} = V_{B,h,L_{cut}} + k_4 L_{cut} R_{c,c} + k_5 L_{cut} h R_{c,c} \quad (2)$$

with $\theta \in \{5^\circ; 85^\circ\}$

Those models have been confronted to 28 flank wear measurements collected in contour turning and obtained in sections where $\theta = \{22.5; 45; 67.5\}^\circ$ and cutting length equal to $L_{cut} = \{25; 50; 75; 100; 125\} \text{ m}$ (Two trials of this $2^1 3^1 5^1$ experimental design have been removed of input data due to adhesion risk). The modelling errors between flank wears modelled and flank wears measured are presented in Table 2.

Table 2. Modelling errors between measured and modelled flank wear (Residual DOF = 25 for model (1); Residual DOF = 23 for model (2)) and coefficients values from inverse identification. 250 segms. for discretization.

	Ave.	Max.	Min.		
Model (1)	20 %	34 %	2 %		
	$k_1(-)$	$k_2(\text{mm}^{-1})$	$k_3(\text{mm})$		
	1.73×10^{-1}	2.66×10^{-6}	2.62×10^{-3}		
Model (2)	10 %	24 %	0 %		
	$k_1(-)$	$k_2(\text{mm}^{-1})$	$k_3(\text{mm})$	$k_4(\text{mm}^{-1})$	$k_5(\text{mm}^{-2})$
	1.78×10^{-1}	1.19×10^{-6}	6.27×10^{-3}	3.85×10^{-10}	1.48×10^{-8}

According to the results presented in Table 2, the inverse identification underlines the contact radius effect on flank wear. Indeed, by taking into account the contact radius effect on flank wear, the flank wear modelling is significantly improved. The minimum, maximum and average modelling errors are respectively reduced by 2%, 10% and 10%. This represents an advanced in flank wear modelling, that's more regarding to cutting force modelling because cutting forces are highly sensitive to flank wear.

6. Conclusion

The aim of this research work is to enhance the flank wear modelling in contour turning of Ti6Al4V titanium alloy by taking into account the contact radius influence. Based on the analysis of this effect, a phenomenological model including its contribution has been proposed to enhance flank wear prediction. The hierarchy of the effects on flank wear is:

- this study confirms that the uncut chip thickness and cutting length have significant effects on flank wear. Flank wear increases with respect of this two parameters;
- the contact radius has also an effect on flank wear. Flank wear rises when contact radius grows;
- the flank wear seems more sensitive to uncut chip thickness and cutting length effects than contact radius effect.

Those results represent an advance in implementing flank wear in future cutting force modelling. Indeed, as mentioned in Fig. 2.(b), the cutting forces are highly sensitive to flank wear. Therefore, a small improvement in flank wear modelling could lead to significant consequences in cutting force modelling.

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