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Phenomenological study of chip flow/formation and unified cutting force modelling during Ti6Al4V alloy turning operations

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Abstract

Mechanistic approach for prediction of cutting forces are showing limits when it comes to enhance the cutting force modelling for specific applications of high-value added and thin parts, which are made of difficult-to-cut materials such as titanium alloys. This is the reason why precise cutting force modelling is needed in order to avoid deflection during machining. Therefore, this contribution aims to improve the description of the chip formation in cutting force modelling thanks to an original experimental set-up built up to observe in-situ the chip flow and measure the cutting forces during Ti6Al4V turning. This study highlights the fact that the chip flow direction has a significant effect on cutting forces and can be influenced by several parameters. In view of the results obtained, a generalised chip flow direction model is suggested. Chips morphology observation is also conducted with the purpose of providing experimental observations physical meaning. Afterwards, a cutting force model is proposed which takes into account the chip flow direction influence.

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Keywords: Cutting forces modelling, Chip flow, Chip morphology, In-process observation, Round tool

1. Introduction

The present study deals with the machining of turbojet drums; these parts, as most of the aeronautical parts, are requiring more and more sophisticated machining processes due to the complex geometries needed to achieve lighter parts made of “difficult-to-cut” materials like titanium alloys. Turbojet drums have high dimensions and thin thickness, which lead to variable cutting tool engagement and edge angle during long contour turning pass when using round tool insert. In order to minimize tool wear and high cutting forces issues responsible for the part deflection during machining, industries are looking for simulating solutions allowing to optimize them. Research investigations propose some modelling approaches in order to evaluate cutting forces [1]. Mechanistic approach [2] is under developments since decades because it is suitable for short time computation and

for easy model identification associated to quite precise prediction. The cutting forces are usually modelled using edge discretization methodology, generalised geometrical cutting model in constant enhancement [3], and specific scientific points are still debated. Cutting forces models are introducing ploughing effect to take into account the edge radius r_β [4]. Campocasso et al. exhibit a significant influence of the nose radius r_n on the cutting forces during turning operation [5]. The global chip flow direction has to be considered; thus, mechanical approaches [6-7], as mechanistic ones [8], propose their own formulation of it. This issue is closely linked to the cutting force segment dependency in the edge discretization methodology. Molinari et al. [6-7] define the contribution of the lateral stress into the chip induced by its flow onto the cutting forces. These lateral forces constrain all elementary chips to flow in the global direction of the chip.

3. Analysis of chip flow direction & formation

3.1. Chip flow direction analysis and parameterization

From the videos recorded, several specific instants are chosen where the chip is not disturbing the observation and during a steady cutting forces state as for the pictures shown in Fig. 1a. Pictures are then analyzed to extract averaged over the different pictures some chip geometrical descriptors as the maximum, minimum, and average chip direction angles, respectively noted as $\zeta_{c,\theta_{min}}$, $\zeta_{c,\theta_{max}}$, and $\zeta_{c,global}$. Fig. 2 presents all results including the force resultant and passive force angles taken in the reference plane, as defined on Fig. 1a.

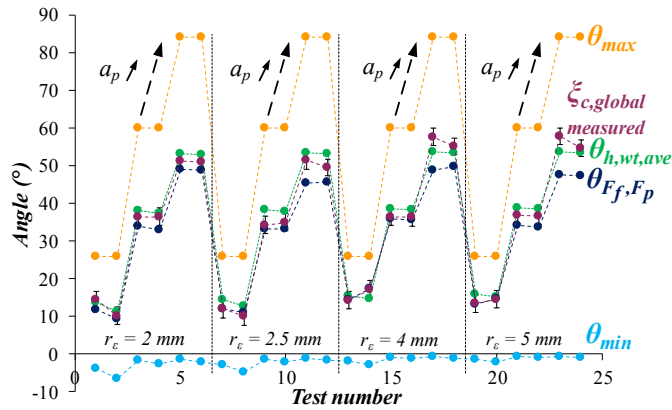


Fig. 2. Chip flow direction $\zeta_{c,global}$ compared to the angular limits of cut area and the force resultant direction angle $\theta_{Ff,Fp}$.

A first observation underlines that, for any condition, the chip flow direction angle measured in-situ is always contained in the angular limits $[\theta_{min}; \theta_{max}]$ of the cut section, which make sense when considering there is no obliquity angle over the cutting edge. The $\theta_{Ff,Fp}$ angle follows the $\zeta_{c,global}$ angle which represents the effective measured chip flow direction, nonetheless it exists a slight difference between these angles. This difference can be explained by the fact that the force resultant angle includes also the edge effect and not only the cut effect; the latter being linked to the chip flow.

Fig. 2 also shows that the chip flow direction is mostly affected by the depth of cut a_p for any nose radius r_e , and seems to not depend on the feed value. The evaluation of $\zeta_{c,global}$ is analyzed on Fig. 3 as a function of the a_p/r_e ratio for both maximum cut thicknesses. It demonstrates a rather linear relation of the chip flow angle with the proposed ratio.

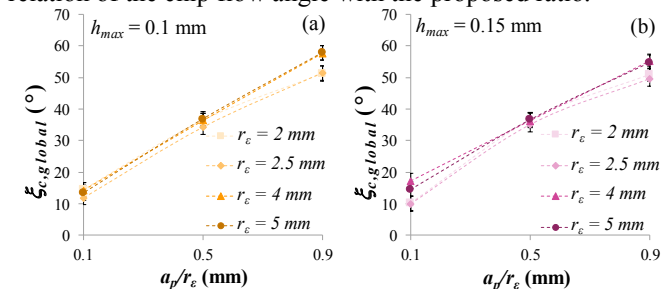


Fig. 3. Global chip flow direction considering 4 nose radii for: (a) $h_{max} = 0.10$ mm, and (b) $h_{max} = 0.15$ mm.

The cutting geometry being constant all along the tool edge with no inclination angle, a new geometrical criterion is proposed to predict the chip flow direction. Eq. 3 defines $\theta_{h,wt,ave}$, the average orientation angle weighted by the cut thickness. It is computed using the exact analytical

formulations of the cut thickness h defined in [3], and considering the circle to circle distance (zone I), and the circle to line distance (zone II), both pictured in Fig. 1b. The zone II cannot be neglected for low depth of cut and high feed, as shows the cut area in Fig. 2 ($a_p = 0.1 \times r_e$). Table 1 and Fig. 2, demonstrate that $\theta_{h,wt,ave}$ geometrical criterion predicts very well the measured values of $\zeta_{c,global}$ angle; the absolute mean error is around 2° , and 4° in maximum.

$$\theta_{h,wt,ave} = \frac{\int_{\theta_{min}}^{\theta_{max}} h(\theta) \cdot \theta \cdot d\theta}{\int_{\theta_{min}}^{\theta_{max}} h(\theta) \cdot d\theta} \quad (3)$$

These investigations are completed by the analysis of the chip morphologies presented in Fig. 4. Tubular chips are produced, with a pitch which is as smaller as a_p/r_e ratio, in relation with low $\zeta_{c,global}$ angle.

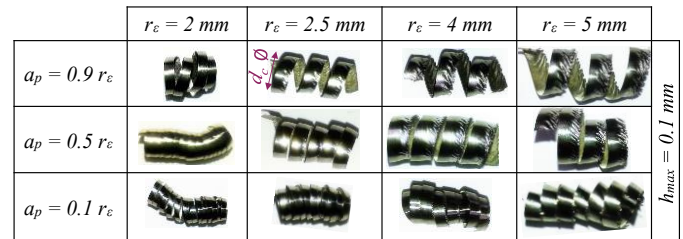


Fig. 4. Morphology of chips generated during Ti6Al4V cylindrical turning with round insert (images with different magnifications).

Two chip geometrical criteria are characterized and exposed on Fig. 5: the tubular chip diameter (d_c), and the width of chip torn zone (w_t). Regarding d_c , it appears an homothetic relation and the ratio $(d_c/(a_p/r_e))$ decreases with the (a_p/r_e) ratio. As a first rough approach, a linear regression is proposed to define these relationships, cf. Fig. 5a. As shown in Fig. 5b, for $a_p > 0.1 \times r_e$, the chip is torn on the thinner side, i.e. where the cut thickness is lower and more brittle. On one hand, it is assumed that internal stress into the chip along the cutting edge is resulting from the cut thickness variation along the cutting edge itself. On the other hand, this stress is balanced by the tool nose radius which allows the chip to curve.

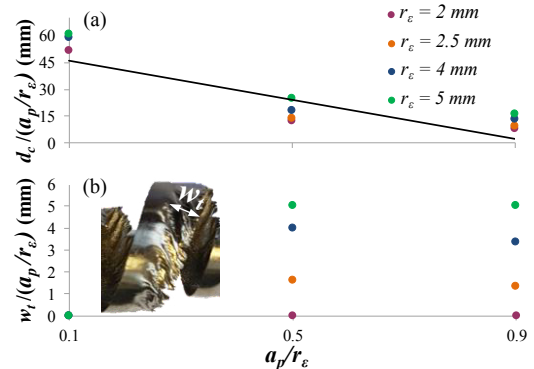


Fig. 5. Chip characterization: d_c chip diameter (a), w_t width of chip torn zone (b)

4. Unified cutting force modelling

4.1. Chip flow modelling and identification

Chip flow direction angle observations sustain the Eq. 1 connecting the global chip flow direction angle and the depth of cut. However, this simple modelling can be improved in order to extend its application validity domain for different nose radii as Eq. 4 based on Fig. 3 observations.

