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Use of the CEL method for estimating the minimum chip thickness when orthogonal cutting Ti6Al4V

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Abstract

The production of micro-components or macro-components with micro-features requires adaptions of their manufacturing process. When micro-machining, the dimensions of the tool, but also some cutting parameters are reduced. Indeed, to avoid breaking the tool due to too large cutting forces, a reduction of the feed is required. This leads to the minimum chip thickness phenomenon in which no chip is formed if the feed is too small by comparison to the cutting edge radius. The determination of the minimum chip thickness value is of great importance for the practitioner. In this work, a finite element modelling approach is followed to investigate the minimum chip thickness in the orthogonal cutting configuration for the Ti6Al4V titanium alloy. The material removal process is modelled with the Coupled Eulerian-Lagrangian (CEL) approach to avoid any mesh distortion. The model allows studying the cutting mechanisms when the uncut chip thickness reduces to reach values as small as the uncut chip thickness and even below it. With the model, the minimum chip thickness value is estimated for Ti6Al4V and the considered cutting conditions. The influence of the uncut chip thickness on the cutting forces, their ratio and the specific cutting energy are also considered. These numerical results are then compared to orthogonal cutting experiments carried out in the same conditions to validate them.

CEL; Cutting; Experiments; Finite element modelling; Minimum chip thickness; Ti6Al4V

1. Introduction

Adaptations in macro-manufacturing processes are required when producing macro-components with micro-features or micro-components. In micro-machining, a reduction of feed is necessary to avoid breaking the tool with too large cutting forces [1]. Dimensions of the tool are also reduced, but current tool manufacturing capabilities do not allow the cutting edge radius to be reduced enough [2]. Cutting refusal may therefore happen due to a too small feed by comparison to the cutting edge radius. This is usually called the minimum chip thickness phenomenon and leads to ploughing instead of cutting [1]. The minimum chip thickness value is of great importance in practice as it directly influences the quality of the machined surface [3]. Its evaluation is however not direct as it depends on many parameters (tool geometry, machined material, etc.) [4]. Almost no finite element model is currently available in the literature to estimate the minimum chip thickness value and highlight the cutting refusal.

The finite element approach is adopted in this work in the simplified configuration of 2D orthogonal cutting for the Ti6Al4V titanium alloy. To avoid mesh distorsion of Lagrangian and Arbitrary Lagrangian-Eulerian (ALE) methods, the Coupled Eulerian-Lagrangian (CEL) approach[5,6] is used for the first time to model cutting conditions that may lead to the cutting refusal. Thanks to the CEL formulation, no element distortion occurs in the workpiece, which is its main advantedge.

The main characteristics of the CEL model are introduced in the following section. Then, the numerical results are presented and compared to an experimental reference in orthogonal cutting before concluding on the developed model.

2. CEL model for Ti6Al4V orthogonal cutting

The model developed in this study uses the CEL approach with a Eulerian Ti6Al4V workpiece and a Lagrangian TiN coated carbide tool. The 2D orthogonal cutting configuration involves a rectangular workpiece and the removal of its upper layer, of thickness h (the uncut chip thickness), by the horizontal movement of the workpiece. The tool has a rake angle of 15°, a clearance angle of 2° and a cutting edge radius, r, of 10 µm. The cutting speed is fixed at 30 m/min, while the uncut chip thickness has six decreasing values (40 µm, 20 µm, 10 µm, 5 µm, 2.5 µm and 1 µm) to cover configurations ranging from chip formation by cutting to cutting refusal in dry conditions.

The machined material is modelled with the Johnson-Cook constitutive model [7]. The set of parameters from Seo *et al.* [8] is adopted as it turned out to be the most suitable for the Ti6Al4V used in the experiments. Coulomb's friction is assumed between the tool and the workpiece with a friction coefficient of 0.2 as experimentally determined by Rech *et al.* [9].

To reduce computation time, the size of the workpiece depends on the uncut chip thickness (i.e. it reduces with it). For all the cutting conditions, at least eight elements are included in the height of the uncut chip thickness (e.g., an elements size of 0.125 µm for the uncut chip thickness of 1 µm).

3. Results

Figure 1 shows the two different chip formation mechanisms: when $h/r > 1$, material is cut and a chip is formed, while when $h/r < 1$, material is deformed and a small amount of material accumulates in front of the tool. This volume of material grows with the cutting length to form a chip when it reaches the minimum chip thickness, as observed in previous studies [10].

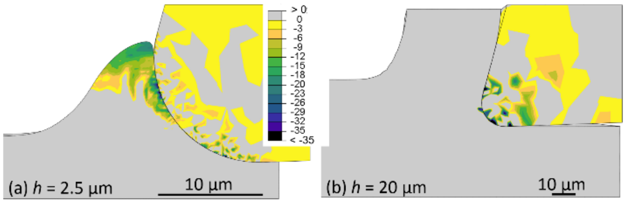

Figure 1. Cutting process for (a) *h* = 2.5 µm and (b) *h* = 20 µm (contours of horizontal speed/mm·s^{-1}).

To determine the *h* value at which cutting refusal is occurring, the horizontal speed of the material (indicator never used previously) is analysed. Values in the opposite direction of the cutting speed (i.e. from right to left in figure 1) are observed for *h* = 2.5 µm and *h* = 1 µm; there are no negative values for larger values of *h*. The minimum chip thickness value is therefore larger than 25 % of the cutting edge radius of the tool.

Table 1 shows evolution of cutting forces (cutting force, *Fc*, and feed force, *Ff*), their ratio (*Ff*/*Fc*) and the specific cutting energy normalised by the specific cutting energy at *h* = 40 µm (*SCEn*), as well as comparison between numerical and experimental values. Experiments were carried out in a strictly orthogonal cutting configuration with the same cutting conditions as the CEL model [11].

When *h*/*r* > 1, the cutting force is well estimated by the model (and thus also *SCEn*) but the feed force is, as often in finite element modelling, far from the experimental value. When *h*/*r* < 1, both numerical forces are very low by comparison to experimental values. This means that material behaviour is not adequate anymore in these cutting conditions and that it should include size effect via strain gradient effect for example [12]. A previous work with a Lagrangian finite element model did not allow to highlight it [13]; it is assumed that elements distortion in the Lagrangian model influenced the results by hiding this lack in the modelling.

From a more global point of view, the CEL model is able to capture the trends when *h* decreases. Indeed, forces ratio and *SCEn* evolutions with *h* are in accordance with the experiments in macro-cutting conditions. When *h* decreases, the inversion of the forces ratio is also captured, even if their magnitude is not (and therefore also *SCEn*).

From the results both of chip formation and of forces-related indicators, the minimum chip thickness value is estimated between 5 µm and 2.5 µm, i.e. between 50 % and 25 % of the cutting edge radius of the tool. This value is in accordance with an experimental value of at least 25 % of *r* [13].

4. Summary

A CEL finite element model has been developed to study the chip formation when the uncut chip thickness decreases, including the cutting refusal. Results analysis, including comparison with experimental tests, showed that the model is able to highlight the change in the cutting mechanism when the uncut chip thickness is reduced. This allowed to estimate the minimum chip thickness between 50 % and 25 % of the cutting edge radius of the tool.

5. Conclusion

The CEL finite element model developed in this study is able to highlight the change in the cutting mechanism when the uncut chip thickness is reduced, allowing to estimate the minimum chip thickness value at 0.25 *r*-0.5 *r*; a range in accordance with the experimental tests and previous works. Although inversion of the cutting forces ratio has correctly been observed, the magnitude of the cutting forces is too low when *h*/*r* < 1. This means that, thanks to the absence of elements deformation, the model demonstrate that the size effect should be included when modelling the material behaviour in micro-cutting conditions.

6. Future work

To improve the level of the cutting forces for uncut chip thickness values lower than the cutting edge radius, the size effect should be introduced in the material behaviour.

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Table 1. Experimental (Exp) and numerical (Num) forces results with *Fc*: cutting force, *Ff*: feed force and *SCEn*: normalised specific cutting energy.

h/µm	Fc_{Exp}/N·mm^{-1}	Fc_{Num}/N·mm^{-1}	Ff_{Exp}/N·mm^{-1}	Ff_{Num}/N·mm^{-1}	$(Ff/Fc)_{\text{Exp}}$	$(Ff/Fc)_{\text{Num}}$	$SCEn_{\text{Exp}}$	$SCEn_{\text{Num}}$
40.0	85.6	81.2	40.6	16.8	0.5	0.2	1.0	1.0
20.0	51.3	47.9	34.2	14.8	0.7	0.3	1.2	1.2
10.0	38.3	33.1	32.0	18.6	0.8	0.6	1.8	1.6
5.0	22.0	5.6	26.9	4.3	1.2	0.8	2.1	0.6
2.5	21.2	2.2	27.0	2.3	1.3	1.1	4.0	0.4
1.0	14.2	0.2	23.7	0.3	1.7	1.6	6.6	0.1