An ALE Model to Study the Depth of Cut Influence on Chip Formation in Orthogonal Cutting

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Abstract: Nowadays producing parts and features ranging from several mm to several µm is becoming a common demand. Micro-milling is one of the processes able to fulfil it. The concepts of micro-milling are similar to macro-milling however some changes are induced in the scaling-down. The minimum chip thickness phenomenon, the importance of the microstructure of the machined material and the size effect are the main differences between the two processes. The ALE FEM model presented aims to study the depth of cut influence on chip formation in orthogonal cutting. The TANH law is used in this model to describe the behaviour of Ti6Al4V and allows the formation of a saw-toothed macro-chip. When the depth of cut decreases the model shows that the chip formation evolves away from macro-cutting. The specific features of micro-cutting reported in literature are highlighted in the results. Finally a minimum chip thickness prediction is performed.

Keywords: ALE, Ti6Al4V, chip formation, minimum chip thickness, size effect

1 INTRODUCTION

Producing parts and features ranging from several mm to several µm is becoming a requirement in the current miniaturization context. One of the most flexible and fastest way to produce complex tridimensional micro-forms including sharp edges with a good surface finish in many materials (metallic alloys, composites, polymers and ceramics) is micro-milling [Chae et al., 2006]. It removes materials with a miniature cutting tool (typical diameter between 100 µm and 500 µm) rotating at high speed. Its range of applications is very large: micro-injection moulds, watch components, optical devices, components for the aerospace, biomedical and electronic industries are a few of them.

2 CHIP FORMATION SPECIFICITIES IN MICRO-CUTTING

The concepts of micro-milling are similar to macro-milling. However the scaling-down of the process induces some changes in the process and the micro-cutting phenomenon cannot be considered as a simple scaling of macro-cutting.

A significant difference between micro- and macro-cutting is the so-called ‘minimum chip thickness’ phenomenon, below which no chip is formed [Chae et al., 2006], as shown on Figure 1. It happens because the ratio between the depth of cut and the tool edge radius (h/r) is often smaller than the unit in micro-cutting, implying changes in the chip formation process. The estimation of the value of this minimum chip thickness is one of the present challenges in micro-milling. This value must be determined in order to be able to correctly choose the cutting parameters. As the minimum chip thickness depends on the machined material and the tool geometry, this estimation is unfortunately quite difficult.

Moreover at this microscopic scale the microstructure of the machined material takes importance and its granular structure must be taken into account [Chae et al., 2006]. Another phenomenon observed in micro-cutting is the 'size effect' [Filiz et al., 2007]: a decrease in the depth of cut leads to a non-linear increase in the specific cutting energy.

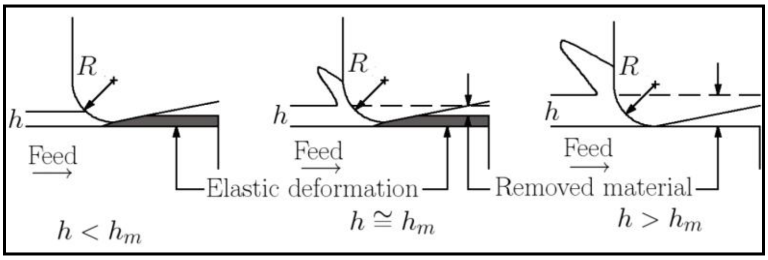

Figure 1: Schematic representation of the minimum chip thickness in orthogonal cutting, inspired from [Chae et al., 2006] (R: edge radius, h: depth of cut, h_m: minimum chip thickness)

3 MODEL PRESENTATION

This paper presents an Arbitrary Lagrangian Eulerian (ALE) Finite Element Method (FEM) model to study the depth of cut influence on chip formation in orthogonal cutting. Orthogonal cutting is a very frequent 2D simplification implemented in numerical simulation in order to model chip formation. Commercial software ABAQUS/Explicit v6.7 is used to perform numerical simulations.

The developed model consists of a 2D plane strain orthogonal cutting model taking into account the area close to the cutting edge of the tool, where the chip is formed. The cutting tool is modelled with a rake angle of 15°, a clearance angle of 2° and a finite edge radius of 20 µm in order to take into account its influence on chip formation. The cutting speed, V_c, is set to 75 m/min. The initial geometry and boundary conditions of the model are presented on Figure 2. The two parts are meshed with three- and four-node linear elements. For the macro-cutting case (§4) the workpiece is made of around 18 000 elements and the tool about 400.

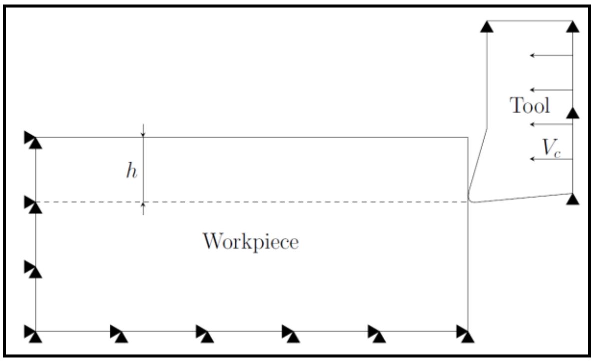

Figure 2: Initial geometry and boundary conditions of the model

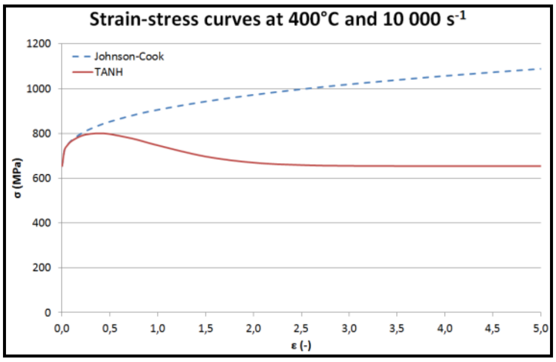

Figure 3: Comparison between the Johnson-Cook and the TANH laws

The workpiece material is a titanium alloy, Ti6Al4V, while the tool material is tungsten carbide. This model is a simplification of micro-cutting because it does not include all of its features. Indeed Ti6Al4V is considered as homogeneous, which is a simplification of its actual granular structure. The workpiece material behaviour is described by the Hyperbolic TANgent (TANH) material model introduced by Calamaz et al. in [Calamaz et al., 2008]. It consists of a Johnson-Cook law modified to be able to model the strain softening effect, as shown on Figure 3. Strain softening is observed in macro-cutting and could explain the formation of saw-toothed Ti6Al4V chips. Taking account of it should lead to a more realistic chip. The tool material behaviour is described by a linear elastic law.

The ALE formulation has been adopted for the workpiece. It combines the features of pure Lagrangian and Eulerian analysis. In this method the mesh is not attached to the material and can move to reduce distortions and to update the free chip geometry. The chip formation is thus simulated via adaptive meshing and plastic flow of work material. This implies that the proposed numerical model does not need a chip separation criterion. Its absence is a great advantage from a numerical point of view.

Friction at the tool – chip interface is implemented using Coulomb's friction and all the friction energy is converted into heat. The two parts initial temperature is set to 25°C. Only conduction is considered and all the workpiece faces are adiabatic.

4 RESULTS IN MACRO-CUTTING

The model is firstly used to compare the modelled saw-toothed macro-chip (h = 280 µm, Figure 5a) and cutting forces to experimental orthogonal cutting results from literature (Figure 4, [Sun et al., 2009]) in the same cutting conditions.

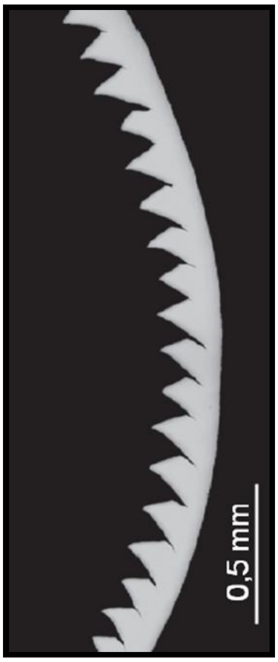

Figure 4: Reference saw-toothed macro-chip [Sun et al., 2009]

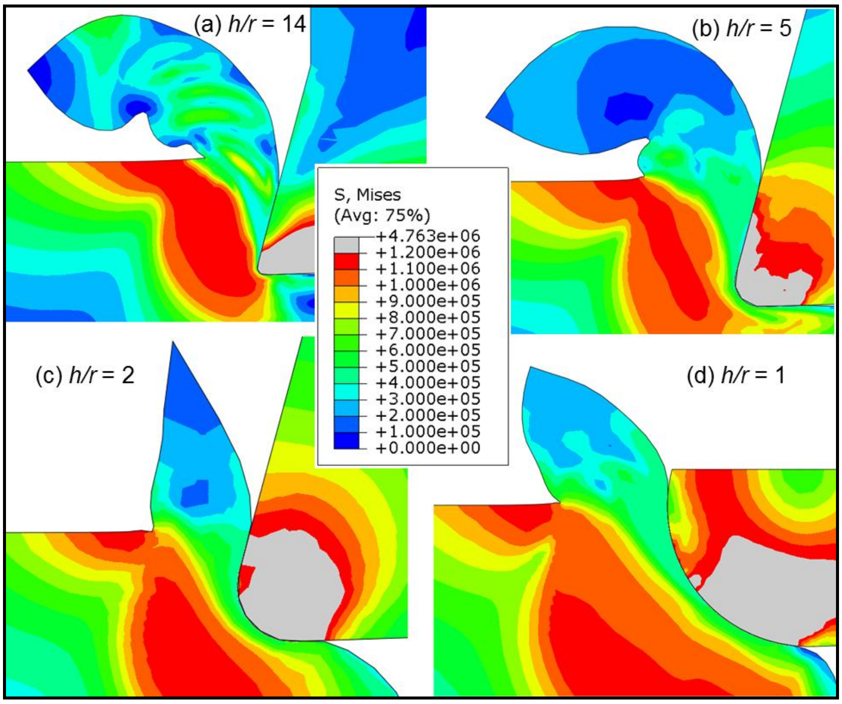

Figure 5: Von Mises stress contours (10^3 Pa) during chip formation with h/r = 14 to h/r = 1

The Figure 5a shows that the teeth are not as deep as the reference chip. Moreover they seem to fade away when the tool moves forward, because of the mesh movement. As expected the primary shear zone vanishes during the formation of a slipping band initiating a tooth. Adding a damage criterion could lead to a chip morphology looking more like the reference of Sun et al. [Sun et al., 2009], as suggested by Calamaz et al. [Calamaz et al., 2008].

A cyclic evolution of the cutting force (CF) can be observed on Figure 6. Such behaviour is typical of saw-toothed chip formation: a drop in the force corresponds to the formation of a tooth. A link can be made between this evolution and the (disappearing) teeth. The comparison with the reference force shows that the simulated one is smaller. This difference could be due to the choice of parameters of the TANH law [Calamaz et al., 2008].

For the same reasons, the cyclic evolution of the feed force (FF) can be linked to teeth formation: when FF is minimal, CF is maximal, and vice versa. It is also smaller than the reference force. The force level is influenced by the friction at the tool – chip interface, which is difficult to measure and model.

This model is thus able to model qualitatively the chip formation of Ti6Al4V in orthogonal cutting. It is therefore suitable for the study of the depth of cut influence on chip formation.

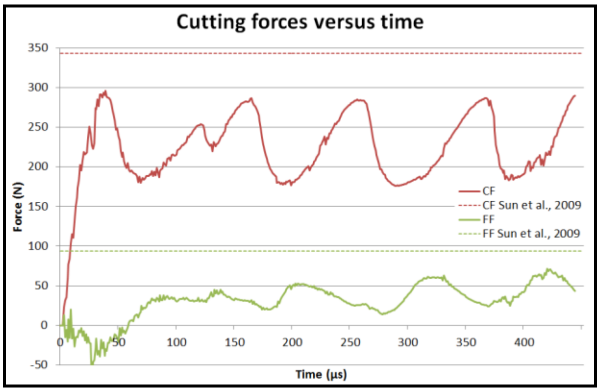

Figure 6: Cutting forces evolutions when h/r = 14

5 INFLUENCE OF THE DEPTH OF CUT

As for a determined material the minimum chip thickness depends on the depth of cut and the cutting edge radius of the tool, different decreasing values of the depth of cut have been considered (the cutting edge radius remaining constant, Table 1).

h (µm)	280	100	40	20	10	5	2.5	1
h/r	14	5	2	1	0.5	0.25	0.125	0.05

Table 1: Definition of the different cases

5.1 Chip morphology

The results (Figures 5 and 7) show different chip morphologies from saw-toothed chip to the cutting refuse including continuous chip. The decrease of the depth of cut leads to a chip morphology evolving away from macro-cutting: under $h/r = 0.25$, the material seems to be pushed, deformed by the tool and not sheared anymore. The resulting roll moves forward with the tool when its stationary shape is reached. The primary shear zone fades when h/r decreases and it cannot be distinguished any longer from the $h/r = 0.25$ value. The critical value of the ratio concerning the change in the mechanism of chip formation is between 0.25 and 0.5.

During the cutting process, an elastic spring back (or elastic recovery) of the workpiece is observed after the passage of the tool tip. It has been evaluated for each simulated case in order to highlight its role in the cutting mechanism. The vertical distance between several points on the machined and the upper surface of the workpiece has been measured, giving a good estimation of the elastic spring back of the workpiece. An increase of this elastic spring back is observed while the depth of cut decreases: it goes from 0.37% of *h* for 280 µm to 31% of *h* for 1 µm. Its role is taking an increasing importance for small depths of cut. Indeed its proportion, relatively to *h*, increases, which contributes to increase the feed force, the slipping forces and the specific cutting energy.

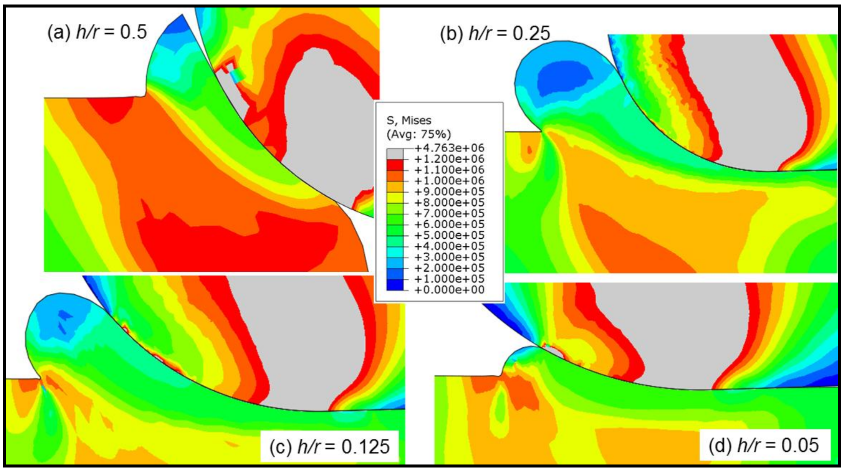

Figure 7: Von Mises stress contours (10^3 Pa) during chip formation with h/r = 0.5 to h/r = 0.05

5.2 Cutting forces

We have seen that when *h/r* decreases, the teeth are less deep then they disappear. The same observation can be made with the cyclic forces evolutions. Figure 8 presents the evolutions of the ratio between the feed and the cutting forces. The more the *h/r* ratio decreases, the more the forces ratio increases. When the *h/r* ratio becomes smaller than the unit, the feed force becomes greater than the cutting force. A change in the cutting mechanism is thus observed: an inversion between cutting and feed forces has occurred. Jun et al. [Jun et al., 2006] also observed experimentally this phenomenon. If the critical value of the ratio is set to 2 (arbitrary chosen value greater than 1), the minimum chip thickness value is around 5 µm.

The specific cutting energy is the ratio of the cutting force on the area of the chip section. The mean specific cutting energy obtained by simulation for each case divided by the reference cutting energy from Sun et al. [Sun et al., 2009] is plotted on Figure 9. The size effect is highlighted on this Figure: a non-linear increase in the specific cutting energy happens when the depth of cut decreases. With this criterion, the critical value of *h/r* is between 0.25 and 0.5.

5.3 Minimum chip thickness prediction

According to the model results a minimum chip thickness prediction can be performed for Ti6Al4V with the geometry and the cutting conditions considered. With the chip

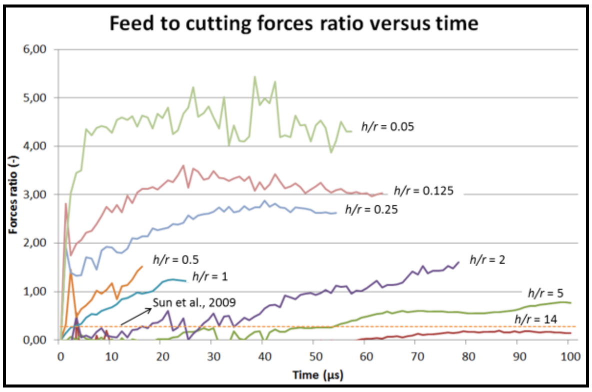

Figure 8: Forces ratio evolutions for various depth of cut

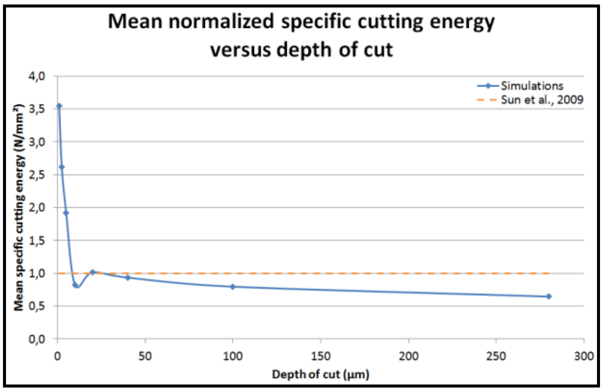

Figure 9: Size effect

morphology and the specific cutting energy criterions the minimum chip thickness value is situated between 5 µm and 10 µm. This range is confirmed by the third criterion leading to a value around 10 µm and literature [Filiz et al., 2007 and Ducobu et al., 2009]. It means that the minimum chip thickness value in these cutting conditions is of the order of 25% - 50% of the cutting edge radius of the tool.

6 CONCLUSIONS

The transition from macro- to micro-cutting induces some changes in the cutting phenomenon. A study of the depth of cut influence on chip formation in orthogonal cutting is presented in this paper through a 2D ALE finite element model. It shows that the chip formation evolves away from macro-cutting when the depth of cut decreases. The minimum chip thickness, the increase of the importance of the slipping forces and the scaling effect, specific features of micro-cutting reported in literature, are highlighted in the results and a minimum chip thickness prediction is performed.

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