Investigations on chip formation in micro-milling

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Abstract

In the current context of miniaturization, micro-machining processes are in full expansion. One of them is micro-milling able to produce parts with features ranging from several mm to several µm.

Due to the down-sizing of the macro-milling process, micro-cutting is not a simple scaling-down of macro-cutting. A significant difference between micro- and macro-cutting is the ratio between the depth of cut and the tool edge radius. This ratio is often smaller than the unit in micro-cutting, implying changes in the chip formation process. The new forming chip way involves the so-called ‘minimum chip thickness’ phenomenon, below which no chip is formed. Estimating the minimum chip thickness value is one of the main challenges in micro-milling. Unfortunately, this estimation is quite difficult because the minimum chip thickness depends on the machined material and the tool geometry. Moreover at this microscopic scale the microstructure of the machined material takes importance and its granular structure must be taken into account. A review of the current state of the art in chip formation and minimum chip thickness in micro-milling is reported in this paper from an experimental and numerical point of view.

In order to model the chip formation process, numerical simulations are performed using the finite element method and a commercial software program, ABAQUS/Explicit v6.7. The model consists in a 2D plane strain orthogonal cutting model of the area close to the cutting edge of the tool, where the chip is formed. The Johnson-Cook plasticity model describes the workpiece material behaviour while the cutting tool is modelled with a finite edge radius. The Lagrangian formulation has been adopted and a chip separation criterion is used to make the chip formation possible. Results of the finite element simulations are presented and compared to results found in literature.

1 Introduction

For a few years, the tendency to miniaturization is gaining in importance and touches many fields, involving an increasing request for micro-components. A growing development of micro-manufacturing techniques is consequently observed. Micro-milling is one of them. It consists in a micro-machining process using a cutting tool (called a 'micro-mill', typical diameter between 100 µm and 500 µm) rotating at high speed to remove material from the workpiece and making it possible to produce parts and features lying between some mm and some µm [1-3]. Up to now micro-milling seems to be the most flexible and rapid way to produce complex three-dimensional forms, including sharp edges and a good surface quality [4]. Micro-milling can handle many machinable materials (metallic alloys, composites, polymers and ceramics) and its applications are found in a lot of different areas (micro-injection moulds, optical and watches components, components for aerospace, biomedical and electronic industries).

In order to present the main differences, concerning chip formation, due to the scaling-down from macro- to micro-milling, a short review of the current state of the art in chip formation and minimum chip thickness in micro-milling is carried out. Then the finite element model developed is presented, before commenting and comparing the results to results found in the literature.

2 Chip formation specificities in micro-milling

2.1 Minimum chip thickness

In micro-milling the depth of cut and the feed per tooth are very small (of the same order of magnitude as the tool edge radius) and no chip is formed below a value called 'minimum chip thickness'. Chae et al. [1] define it as the critical depth of cut (between 5 % and 38 % of the tool edge radius, depending on the machined material [5]) below which no chip can be formed. Three different cases happen in micro-chip formation, as shown on Figure 1 (R_e: edge radius, h: depth of cut, h_m: minimum chip thickness).

Increase of cutting forces, burr formation and surface roughness are the consequences of the slipping forces rise and the ploughing of the machined surface (highlighted by Bissacco et al. [6]) due to the minimum chip thickness phenomenon. Hence minimum chip thickness values must be determined and taken into account to choose adequate cutting parameters. Machined material and tool geometry greatly affect its value, complicating its estimation [7].

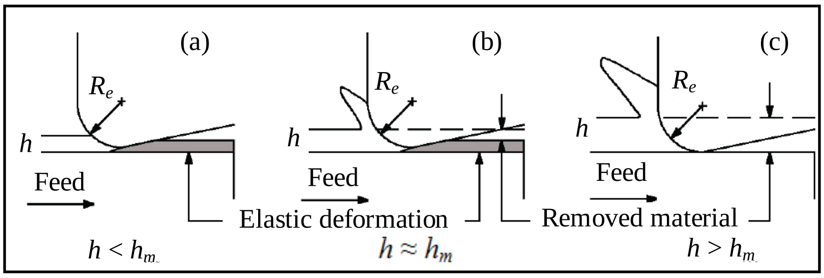

Figure 1: Schematic representation of the minimum chip thickness in orthogonal cutting, inspired of [1]

2.2 Negative rake angle

In micro-milling the macro-cutting assumption stating that the tool is sharp, completely cuts the surface and generates chip is not valid anymore. It is due to the highly negative rake angle caused by the small depth of cut being of the same order of magnitude as the tool edge radius. A highly negative rake angle leads to ploughing of the machined surface and elastic spring back of the workpiece. The spring back fraction occurring under the flank face leads to friction, raising the specific cutting energy.

2.3 Size effect

At small depth of cut Filiz et al. [8] observed the so-called ‘size effect’: a decrease in the depth of cut leads to a non-linear increase in the specific cutting energy. Minimum chip thickness and specific cutting energy are thus closely related. The specific cutting energy could be an indicator making it possible to detect changes (from slipping to shearing) in the cutting mechanism and to monitor the process.

2.4 Influence of the machined material

In micro-milling, as the depth of cut, the tool or feature to produce dimensions are often smaller than the grain size of the machined material, its nature and micro-granular structure have to be taken into account [1,2]. Therefore it cannot be considered as homogeneous and isotropic any longer, contrary to the assumption made in macro-machining. The microstructure of the machined material takes a great importance in micro-milling.

Chae et al. [1] and Dornfeld et al. [2] report cutting forces variations and vibrations during micro-machining due to the lack of homogeneity of the workpiece granular structure. This leads to cutting condition variations (hardness in particular). Modifying the cutting conditions or the machine design is not a solution to eliminate them, as they are due to the nature of the machined material. Finally averaged cutting coefficients from macro-cutting cannot be used anymore.

2.5 Numerical works

A 2D ALE orthogonal cutting finite element model was developed by Woon et al. [9] in order to study the tool edge radius influence on chip formation. This model considers the workpiece material (AISI 4340 steel) as homogeneous and the tool is modelled as a perfectly rigid solid with and without edge radius. Their results show that the chip is formed by extrusion along the tool edge radius when the depth of cut is lower than a breaking value and confirm that the tool cannot be considered as sharp in micro-milling.

In order to study the granular structure of the machined material influence on chip formation, Simoneau et al. [10] developed a 2D Lagrangian orthogonal cutting heterogeneous (AISI 1045 steel) finite element model with a sharp tool. They observed a new chip formation mechanism (Figure 2): the softest material (ferrite) is extruded between the hardest grains (pearlite). They called it ‘quasi-shear extrusion chip’. It proves that it is crucial to model the workpiece material as heterogeneous in micro-cutting.

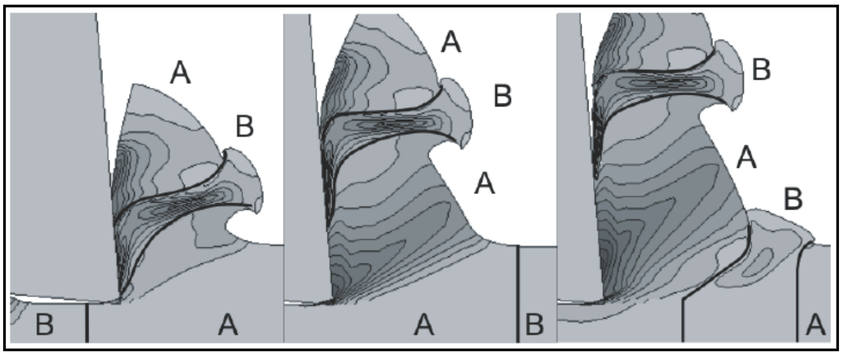

Figure 2: AISI 1045 steel chip formation (A: pearlite, B: ferrite) [10]

3 Numerical model

The chip formation is studied with a 2D plane strain orthogonal cutting model developed with the commercial software program ABAQUS/Explicit v6.7. It only takes into account the area close to the cutting edge of the tool.

An explicit Lagrangian formulation is adopted as our interest is focused on the transient phase of the chip formation and the cutting refusal. Moreover the model must be able to produce saw-tooth chips, which cannot be achieved with an Arbitrary Lagrangian Eulerian (A.L.E.) formulation, contrary to Lagrangian formulation [11].

For a determined material, the minimum chip thickness depends on the depth of cut (h) and the cutting edge radius of the tool (r). Various h/r ratios have been considered in order to study the influence of the depth of cut on the chip formation process. Five different cases have been treated: $h/r = 5$ ($h = 100$ µm), *h/r* = 3 (*h* = 60 µm), *h/r* = 0.5 (*h* = 10 µm), *h/r* = 0.25 (*h* = 5 µm) and *h/r* = 0.05 (*h* = 1 µm).

3.1 Overview

The workpiece is modelled as a rectangular block, while the tool is modelled with a 20 µm cutting edge radius, a 0° rake angle and a 5° clearance angle. The cutting speed is set to 300 m/min. These two parts are meshed with three- and four-node linear elements. Figure 3 presents the initial geometry and mesh of the model when *h/r* = 5 (H: horizontal degree of freedom constrained, V: vertical degree of freedom constrained, R: degree of freedom in rotation constrained).

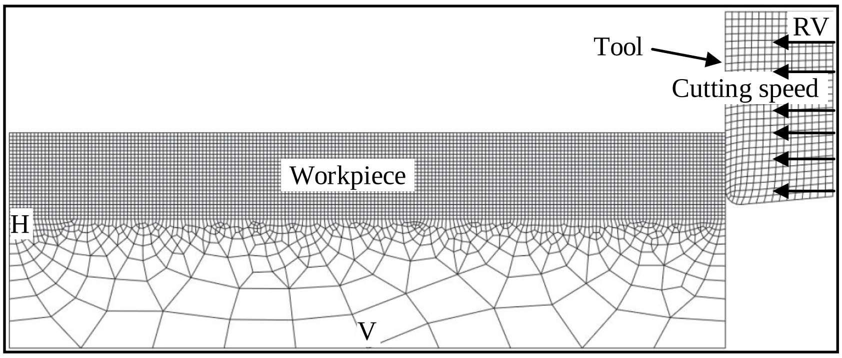

Figure 3: Boundary conditions and initial mesh when *h/r* = 5

The workpiece material is a titanium alloy, Ti_6Al_4V, assumed to be homogeneous. Its behaviour is described by the Johnson-Cook plasticity model [12]. The tool material, tungsten carbide, is also homogeneous and its behaviour is described by a linear elastic law.

Friction at the chip – tool interface is implemented using a limiting shear friction model with a limiting shear stress and a friction coefficient [13]. All of the friction energy is converted into heat and 25% of this friction heat flows into the workpiece [14].

The two parts initial temperature is set to 20°C. Only conduction is considered and all the workpiece faces are adiabatic [15]. The efficiency of the deformation to heat transformation is assumed to be 90% [9, 13, 14].

3.2 Chip separation criterion

Due to the Lagrangian formulation a chip separation criterion based on an “eroding element” method is introduced in the model to make the chip formation possible. This separation criterion is based on crack propagation depending on the stress and strain state of the machined material. This chip formation approach, by ductile failure phenomenon, is composed of two steps.

In the first step, a damage initiation criterion must be fulfilled. The damage initiation criterion adopted is the Johnson-Cook shear failure model [12].

The second step concerns damage propagation, based on the fracture energy approach. This criterion uses the fracture energy, G_f, which is the required energy to open a unitary area crack. After damage initiation, the material behaviour is represented by a stress-displacement relation rather than a stress-strain relation [15]. As soon as the specified value of G_f is reached in a finite element, it is deleted and all of its stress components are put to zero. The suppression of a finite element introduces a crack in the workpiece, making it possible for the chip to come off.

4 Results

Figure 4 shows chip formation and machined material deformation. A chip is undoubtedly formed when *h/r* = 5, 3 and 0.5, which is not true for the last two cases. Therefore it could be interesting to establish a criterion making it possible to give a ruling on the existence of a chip. An interesting point is the presence of a saw-tooth chip when *h/r* = 5 and 3, as experimentally observed. This kind of chip is not found any more for smaller *h/r* values. It can be due to the *h/r* ratio value or even to the short simulation time (some microseconds).

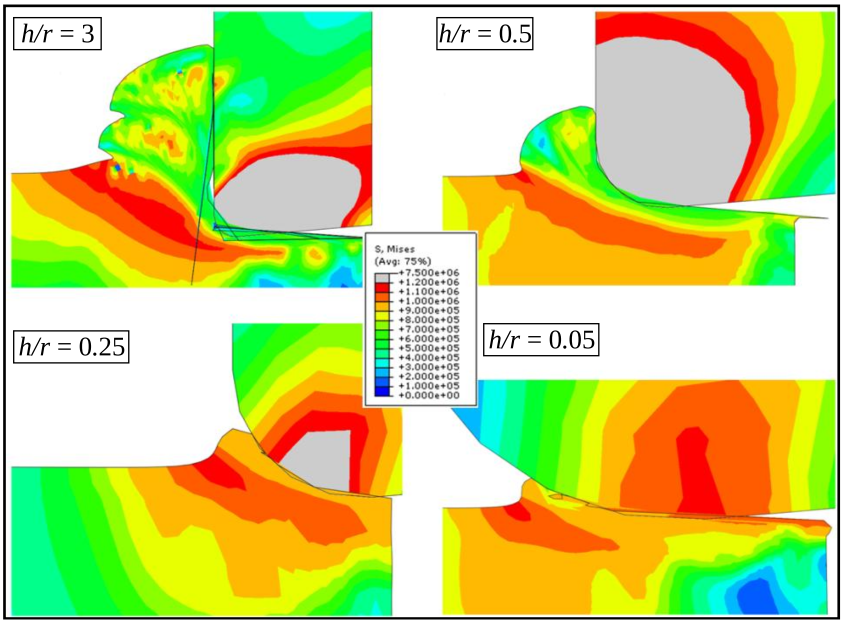

Figure 4: Von Mises stress contours (10^3 Pa) during chip formation

Primary shear zone is clearly seen on Von Mises stress contours when *h/r* = 5 and 3, as in macro-cutting with a sharp tool. The more the *h/r* ratio decreases, the more the primary shear zone fades and from the *h/r* = 0.25 value it cannot be distinguish any longer. It is interesting to highlight that the *h/r* = 0.5 value could be a key value. Indeed a primary shear zone can still be seen but the stress value seems to be smaller.

These results are globally similar to those presented by Woon et al. [9] in the case of an A.L.E. model. Actually the cutting tool can no longer be considered as sharp and the *h/r* value has a great influence on the chip formation in micro-cutting. Changes in the chip formation mechanism are observed when the *h/r* ratio decreases, evolving away from macro-cutting.

Figure 5 shows the cutting and the feed forces for a 100 µm depth of cut. A cyclic evolution can be observed, as expected due to the saw-toothed chip. Indeed when the formation of a slipping plane occurs (corresponding to a tooth formation), a drop in the forces is observed. It also must be highlighted that the cutting force is greater than the feed force, which is also observed in macro-cutting.

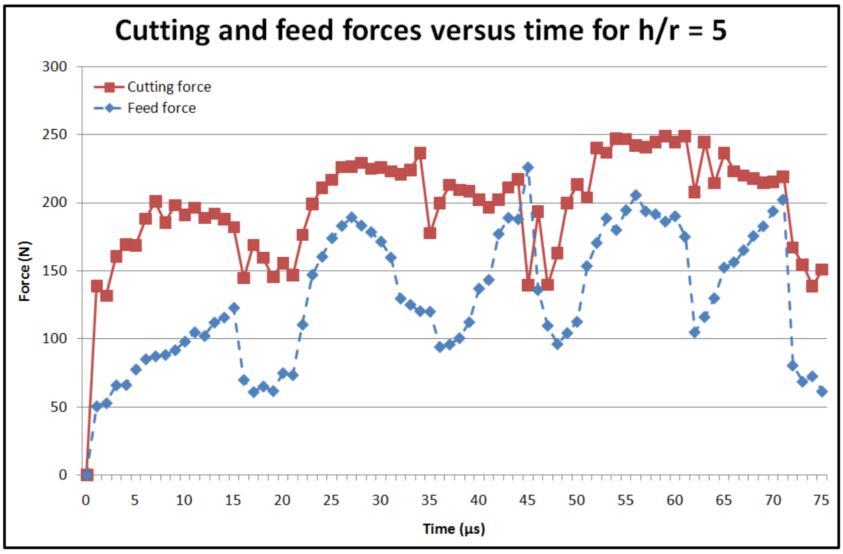

Figure 5: Forces evolutions during cutting when *h/r* = 5

Figure 6 represents the evolutions of the ratio between feed and cutting forces for the five *h/r* simulated ratios. The *h/r* = ∞ value stands for the theoretical forces ratio value when the tool is infinitely sharp. 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. These observations are similar to those experimentally made by Liu et al. [3]. In order to accurately determine the minimum chip thickness value, other *h/r* ratio values between 3 and 0.5 have to be considered. Indeed it seems that the minimum chip thickness value lies in this interval.

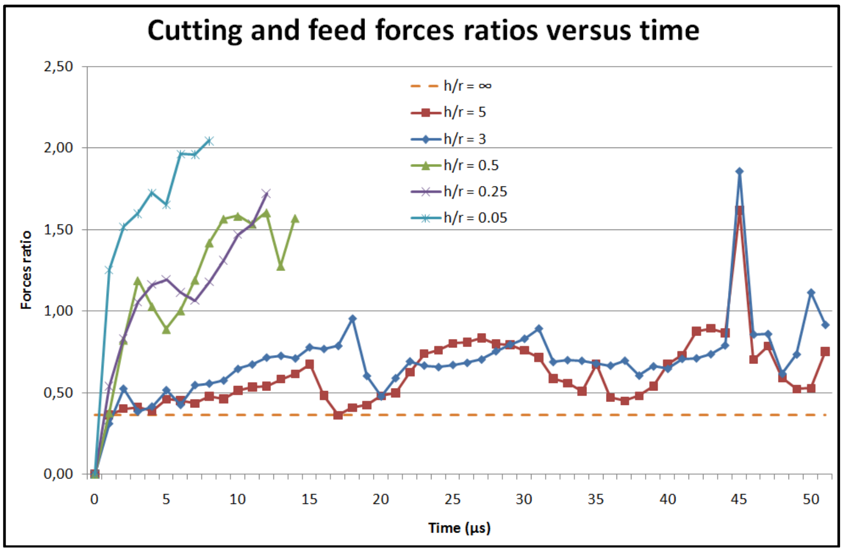

Figure 6: Forces ratios evolutions during cutting for various *h/r* ratios

The evolutions of the ratio between the specific cutting energy and the theoretical specific cutting energy when the tool is infinitely sharp can be seen on Figure 7 for the five simulated *h/r* ratios. For *h/r* = 5 and 3, the average value of the specific cutting energy value is close to the theoretical one. A rise in the specific cutting energy is noticed when the depth of cut decreases, in accordance with the previously presented size effect phenomenon.

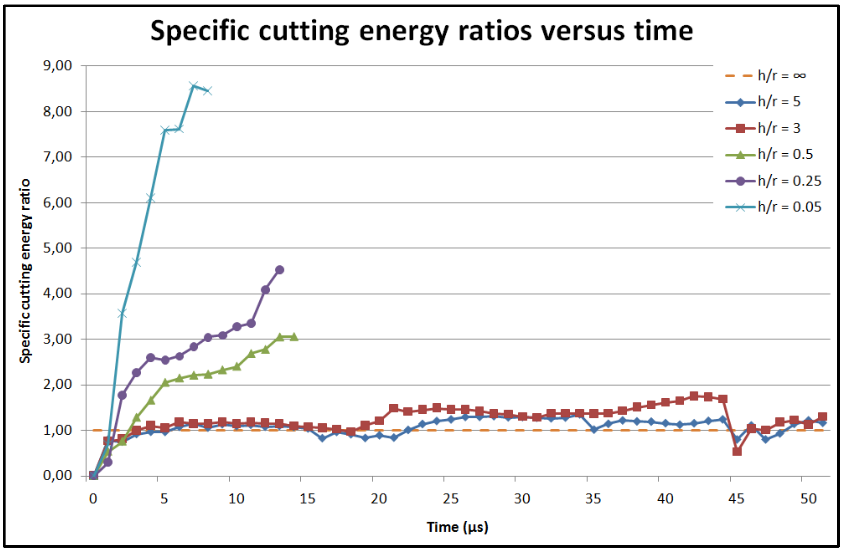

Figure 7: Specific cutting energy ratios evolutions during cutting
for various *h/r* ratios

Lastly highly deformed finite elements can be observed during simulations. Those are not deleted, contrary to what is expected. Some of them can be seen on the previous figures: they are the black lines interfering with the workpiece and the chip near the edge radius of the tool. This problem has to be solved.

5 Conclusion – Outlooks

Changes in the cutting phenomenon are induced by the transition from macro- to micro-milling. One of them is the chip formation involving the minimum chip thickness phenomenon, which has been reported in this paper.

The depth of cut influence on chip formation has been studied with the developed numerical model. A decrease in the depth of cut leads to changes in the cutting process mechanism and the cutting tool can no longer be considered as sharp, contrary to the macro-cutting assumption.

An evolution in the cutting to feed forces ratio has been highlighted when the depth of cut decreases. Beyond a critical value of the depth of cut (10 µm in this paper) the feed force becomes greater than the cutting force. This inversion could be used to determine the minimum chip thickness.

Finally it has been observed that the depth of cut value greatly affects the specific cutting energy. Indeed it rises when the depth of cut decreases, which is known as the size effect.

In addition to the model improvements, it is now crucial to establish a criterion making it possible to give a ruling on the existence of a chip. The specific cutting energy or the ratio between cutting and feed forces could be a good starting point. Lastly an analytical model has to be settled in order to validate the presented model and get a comparison point with it.

6 References

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