

# Chip Formation in Micro-cutting

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**Abstract:** The miniaturisation context leads to the rise of micro-machining processes. Micro-milling is one of the most flexible and fast of them. Although it is based on the same principles as macro-cutting, it is not a simple scaling-down of it. This down-sizing involves new phenomena in the chip formation, such as the minimum chip thickness below which no chip is formed. This paper presents a review of the current state of the art in this field from an experimental and a numerical point of view. A 2D finite element model is then developed to study the influence of the depth of cut on the chip formation. After the model validation in macro-cutting, it highlights the phenomena reported in literature and allows to perform a minimum chip thickness estimation.

**Key words:** Chip formation, micro-cutting, minimum chip thickness, orthogonal cutting, saw-toothed chip, Ti6Al4V.

## 1. Introduction

Micro-milling is a micro-manufacturing technology by removal of material with a miniature cutting tool. It allows to produce pieces and features ranging from several mm to several  $\mu\text{m}$ , which is very interesting in the current context of miniaturization. Micro-milling is the most flexible and fastest way to produce complex tridimensional micro-forms including sharp edges and a good surface finished in many materials: metallic alloys, composites, polymers and ceramics [1-2]. Its applications are very varied. Micro-injection moulds, watch components, optical devices, components for the aerospace, biomedical and electronic industry are a few examples.

The micro-cutting phenomenon is not a direct scaling of macro-cutting, although micro-milling is based on macro-milling. The down-sizing of the process implies some changes in the cutting phenomenon.

This paper provides the current state of the art of chip formation and minimum chip thickness in micro-cutting from an experimental and numerical point of view. The main differences and difficulties

between micro and macro-cutting are presented, as well as experimental and numerical work in this field. A numerical model is thus developed to study the chip formation in micro-cutting.

The paper is organized as followed: Section 2 deals with micro-cutting chip formation; Section 3 presents the numerical model; Section 4 is about the model validation in macro-cutting; Section 5 presents the results in micro-cutting and it ends with the conclusions at Section 6.

## 2. Chip Formation

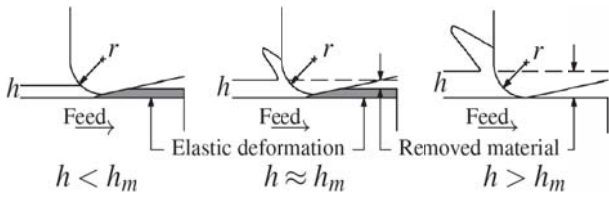
### 2.1 Minimum Chip Thickness

The main difference between macro and micro-cutting cutting processes concerns the chip formation involving the so-called “minimum chip thickness” phenomenon [1]. It can be quickly explained like this: in micro-cutting the depth of cut reduces dramatically and reaches the same order of magnitude as the tool edge radius. If it becomes smaller than a certain depth, i.e., the minimum chip thickness, no chip is formed as shown in Fig. 1.

Depending on the material, Chae et al. [1] evaluate it between 5% and 38% of the tool edge radius.

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**Fig. 1** Schematic representation of the minimum chip thickness in orthogonal cutting ( $r$ : edge radius of the tool,  $h$ : depth of cut,  $h_m$ : minimum chip thickness), inspired from Ref. [1].

The minimum chip thickness leads to a rising of slipping forces and ploughing of the machined surface (highlighted by Bissacco et al. [3]), contributing in the increase of cutting forces, burrs formation and surface roughness.

In micro-milling, Ducobu et al. [4] show that when the feed per tooth is smaller than the minimum chip thickness, several tool rotations are needed to form a chip. They also show that the stability of the operation can be feed dependent, contrary to macro-milling.

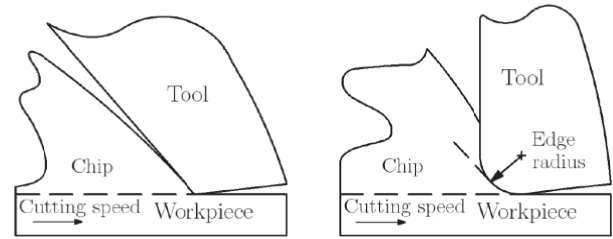
## 2.2 Negative Rake Angle

The macro-cutting assumption stating that the tool is sharp, completely cuts the surface and generates chips is not valid in micro-cutting. This is due to the highly effective negative rake angle caused by the small depth of cut being of the same order of magnitude as the tool edge radius (Fig. 2).

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 a small depth of cut, Filiz et al. [6] observed the so-called “size effect”: a decrease in the depth of cut leads to a nonlinear 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.



**Fig. 2** Schematic representation of the negative rake angle in orthogonal cutting, inspired from Ref. [5].

Ducobu et al. [4] show that the introduction of the size effect and the minimum chip thickness in their dynamic model leads to an increase in the cutting force and vibrations. They even become too high compared to the required precision.

## 2.4 Influence of the Machined Material

Moreover at this scale, the microstructure of the material takes importance and the granular structure of the workpiece material must be taken into account. Indeed, in micro-cutting, as the dimensions of the depth of cut, the tool or feature to produce are often smaller than the grain size of the machined material, its nature and micro-granular structure have to be taken into account, as highlighted in Refs. [1, 5]. Therefore, it can no longer be considered as homogeneous and isotropic, contrary to the assumption made in macro-cutting. The microstructure of the machined material takes therefore a great importance in micro-cutting.

Chae et al. [1] and Dornfeld et al. [5] report variations in cutting forces and vibrations during micro-machining due to the lack of homogeneity of the workpiece granular structure. This leads to variations in cutting conditions (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 any more.

## 2.5 Finite Element Modelling

Up to now, very few finite element modelling about micro-cutting can be found in the literature. None dealing with the Ti6Al4V titanium alloy were found.

A 2D ALE (Arbitrary Lagrangian Eulerian) orthogonal cutting finite element model was developed by Woon et al. [7] in order to study the influence of the tool edge radius 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. The results of their research 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 sharp in micro-cutting.

Liu et al. [8-9] developed a 2D strain gradient plasticity-based finite element model in which they introduce material strengthening mechanisms to explain the size effect in micro-cutting. The simulations were performed with an aluminium alloy (Al5083-H116) exhibiting a small strain rate hardening exponent, thus minimizing strain rate effects. Two main strengthening factors were considered: the strain gradient strengthening and the cutting temperature decrease in the secondary shear zone, with decrease in the depth of cut. It shows that the strain gradient strengthening is the dominant mechanism in micro-cutting conditions. The tool edge radius of course plays a role in the size effect but only a part of it.

In order to study the influence of the granular structure of the machined material 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: the softest material (ferrite) is extruded between the hardest grains (pearlite). They called it a “quasi-shear extrusion chip”. This shows that it is crucial to model the workpiece material as heterogeneous in micro-cutting of this material.

### 3. Numerical Model

In order to study the influence of the depth of cut on chip formation in orthogonal cutting, numerical simulations are carried out. A 2D plane strain

Lagrangian orthogonal cutting model is developed using the finite element method thanks to the commercial software ABAQUS/Explicit v6.8.

An important characteristic of this model is its validity not only in micro-cutting but also in macro-cutting. This allows to study changes in the cutting mechanism from macro- to micro-cutting with one single model. The ability to form saw-toothed chips in macro-cutting is one of the requirements (and difficulties) introduced by the multi-scale aspect of the model.

The model only takes into account the area close to the cutting edge of the tool, where the chip is formed. The cutting tool is modelled with a finite edge radius and it is taken into account thanks to the fine mesh of the workpiece. Its rake and clearance angles are set, respectively, to  $15^\circ$  and  $2^\circ$ . Fig. 3 presents the initial geometry and boundary conditions of the model. The cutting speed,  $V_c$ , is equal to 75 m/min. For the macro-cutting case, the mesh is made of around 19,000 three- and four-node linear elements.

The workpiece material is the titanium alloy Ti6Al4V. Its behaviour is described with the TANH (TANGent Hyperbolic) law [11], a Johnson-Cook law modified to take the strain softening into account. The model does not take the granular structure of Ti6Al4V into account and constitutes therefore a simplification of micro-cutting. The tool material is tungsten carbide and its behaviour is described by a linear elastic law. Due to the Lagrangian formulation, a chip separation criterion based on an “eroding element” method is introduced in

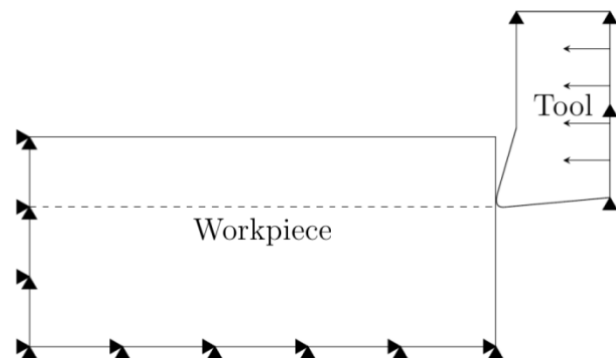


Fig. 3 Boundary conditions and initial geometry.

the model to make chip formation possible. This physical chip separation criterion is based on the temperature dependent tensile failure of Ti6Al4V. Coulomb's friction is used to model friction at the tool chip interface and all the friction energy is converted into heat, which is usually assumed [12]. The workpiece and tool initial temperature is set to 25 °C. Only conduction is considered and all the parts faces are adiabatic.

#### 4. Model Validation in Macro-cutting

The results are first validated in macro-cutting conditions through the comparison of the modelled saw-toothed chip morphology and cutting forces to experimental cutting results in the same cutting conditions (depth of cut of 280  $\mu\text{m}$ ).

Experiments were performed on a lathe in orthogonal cutting conditions. As shown in Fig. 4, the workpiece specimen is a shaft comporting flanges in the form of successive slices (diameter 60 mm) of equal thickness (2 mm). The tool and tool holder were custom made by SECO in order to provide the same characteristics as the numerical model. The tool width (6 mm) is larger than that of the disks. The cutting processes are performed in a plunge cutting mode on each slice in dry cutting conditions. The tool was fixed on the lathe in a way to provide a high rigidity, particularly in the cutting direction. The chips were collected to be observed latter on a microscope. In order to avoid workpiece displacements and vibrations, a tailstock was used.

The morphology of the modelled chip (Fig. 5a) is very close to the experimental one (Fig. 5b). For each tooth, a slipping band is formed in the primary shear zone, as expected. It vanishes as the tool moves forward, initiating the tooth formation.

Fig. 6 shows that the CF (cutting force) has a cyclic evolution. This is due to the formation of a saw-toothed chip: a drop in the force happens during the formation of a tooth, as already shown by Bäker et al. [13]. The force exhibits seven cycles corresponding to the seven teeth formed. The magnitude of the simulated force

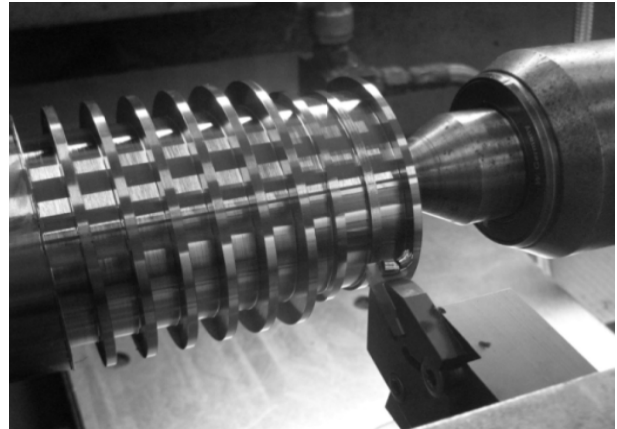


Fig. 4 Experimental setup.

(Table 1) is of the same order of magnitude though smaller than the experimental one. This difference could be explained by the parameters choice of the TANH law [11].

Although the gap in magnitude is larger for the FF (feed force), similar observations are made and a link can be drawn between its cyclic evolution and the teeth formation (moreover when CF is maximal, FF is minimal, and vice-versa). The gap in the feed force magnitude might be caused by the high influence of the friction at the tool chip interface, which is difficult to measure and model.

#### 5. Results in Micro-cutting

The model is then used to highlight the specific features of micro-cutting presented in the first part of the paper. A minimum chip thickness prediction based on the numerical results is finally performed.

For a determined material, the minimum chip thickness depends on the depth of cut ( $h$ ) and the cutting edge radius of the tool ( $r$ ). Eight  $h/r$  decreasing ratios have been considered in order to study the influence of the depth of cut on the chip formation process, the cutting edge radius remaining constant:  $h/r = 14, 5, 2, 1, 0.5, 0.25, 0.125$  and  $0.05$ .

From these observations it can be concluded that this model is able to reproduce the chip formation of Ti6Al4V in orthogonal macro-cutting with a satisfactory fidelity. The influence of the depth of cut on chip formation can therefore be studied.

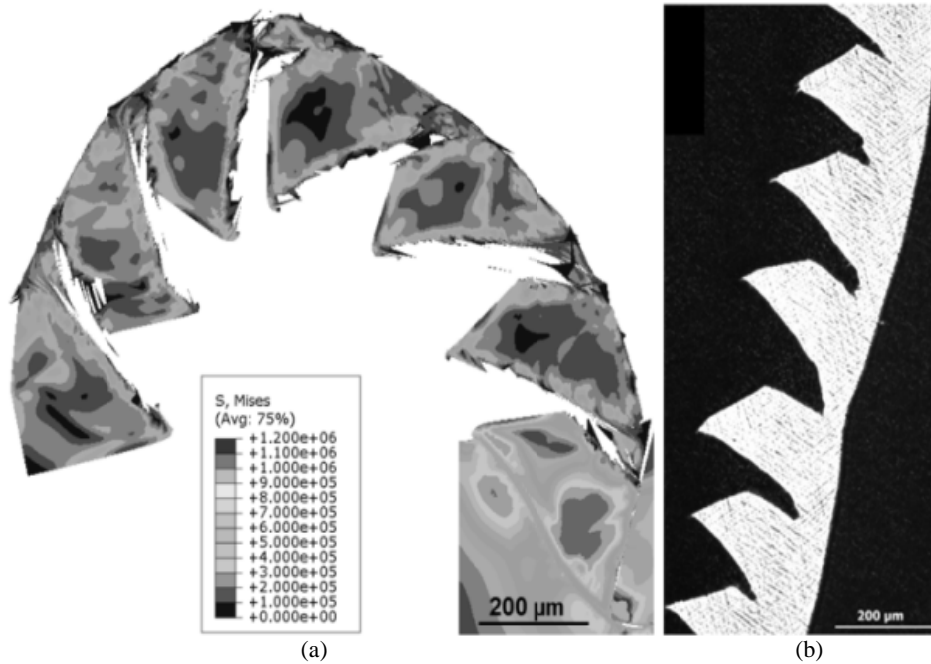


Fig. 5 (a) Modelled and (b) experimental chip morphologies.

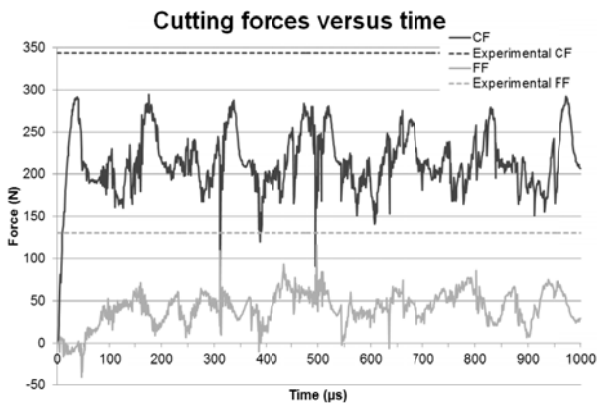


Fig. 6 Macro-cutting forces.

Table 1 Comparison between modelled and experimental RMS (root mean square) forces values.

Value	Experiments (N·mm <sup>-1</sup> )	Modelling (N·mm <sup>-1</sup> )	Difference (%)
Cutting force	344	218	37
Feed force	130	46	65

5.1 Chip Morphology

Figs. 7 and 8 show chip formation and machined material deformation for the eight  $h/r$  ratios values. A chip is undoubtedly formed when  $h/r = 5$  to  $0.5$ , which is not true for  $h/r = 0.25$  to  $0.05$ . The chip morphology goes from saw-toothed to no chip including segmented and nearly continuous chip. When  $h/r < 1$ , the effective

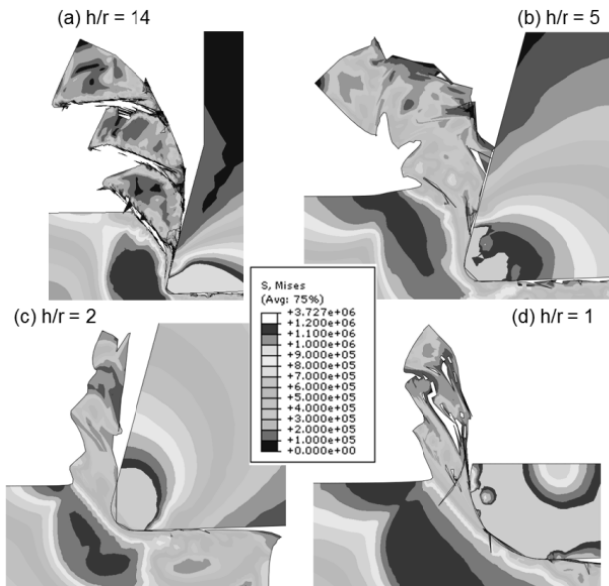
rake angle is negative and only the value of the cutting edge radius of the tool influences the chip formation.

The decrease of the depth of cut leads to a chip formation mechanism evolving away from macro-cutting: under  $h/r = 0.25$  the material seems to be less sheared than pushed and deformed by the tool. This was also numerically noticed by Woon et al. [7]. According to them such a chip is formed by extrusion along the edge radius of the tool.

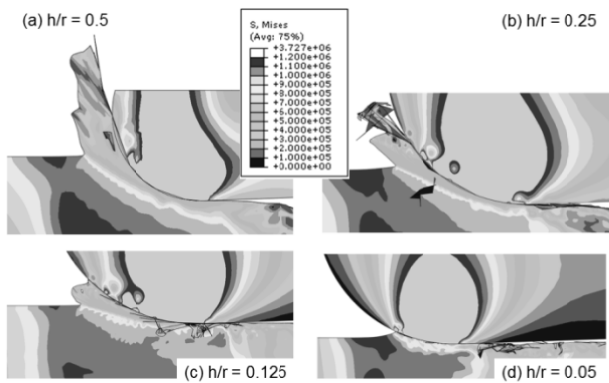
For  $h/r$  values under  $0.25$ , no chip is formed and a small amount of material accumulates in front of the tool. This small amount grows when the tool moves forward until it reaches a thickness greater than the minimum chip thickness and is then removed from the workpiece. The fact that the chip is only formed when the accumulation of cutting thickness is higher than the minimum chip thickness has also been observed by Ducobu et al. in Ref. [4] and Vogler et al. in Ref. [14].

The fading of the primary shear zone occurs when  $h/r$  decreases and it cannot be distinguished any longer when  $h/r$  is smaller than  $0.25$ .

In micro-cutting the cutting tool can no longer be considered as sharp and the  $h/r$  value has a great influence on the chip formation. It can be concluded



**Fig. 7** Chip morphologies for 14 to 1  $h/r$  values (Von Mises stresses contours ( $10^3$  Pa)).



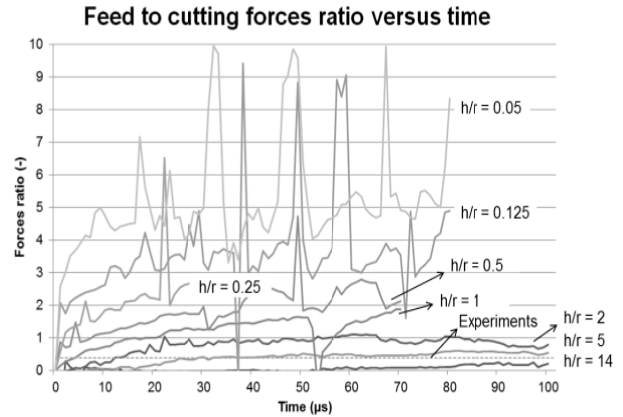
**Fig. 8** Chip morphologies for 0.5 to 0.05  $h/r$  values (Von Mises stresses contours ( $10^3$  Pa)).

that changes in the chip formation mechanism happen for a value of the  $h/r$  ratio situated between 0.125 and 0.25.

**5.2 Cutting Forces**

As the  $h/r$  ratio decreases, the teeth are less marked and tend to disappear resulting in forces becoming a constant value. The evolution of the ratio of the feed force to the cutting force when the  $h/r$  ratio decreases is shown in Fig. 9.

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



**Fig. 9** Cutting forces ratio.

thus observed: an inversion between cutting and feed forces has occurred. These observations are similar to those made experimentally by Jun et al. [15]. With a feed to cutting forces ratio criterion value of 2, the minimum chip thickness value would be between 5  $\mu$ m and 10  $\mu$ m.

**5.3 Specific Cutting Energy**

The evolutions of the ratio between the mean specific cutting energy from simulations divided by the experimental cutting energy for the macro-cutting case, called the mean normalized specific cutting energy, can be seen in Fig. 10 for the eight simulated  $h/r$  ratios.

A nonlinear rise in the specific cutting energy is noticed when the depth of cut decreases, in accordance with the previously presented size effect phenomenon. Its evolution becomes exponential around 5-10  $\mu$ m. According to the size effect, the minimum chip thickness value is thus of the order of 5-10  $\mu$ m.

**5.4 Workpiece Elastic Recovery**

During the cutting process, an elastic recovery of the workpiece is observed. Plotting it versus the depth of cut in Fig. 11 shows a nonlinear increase of it for small depths of cut. This rise (from about 0.45% of  $h$  for 280  $\mu$ m to about 25% of  $h$  for 1  $\mu$ m) contributes to increase the feed force, the slipping forces and the specific cutting energy. The elastic recovery of the workpiece could therefore be an indicator to evaluate the minimum chip thickness value. According to Fig. 11,

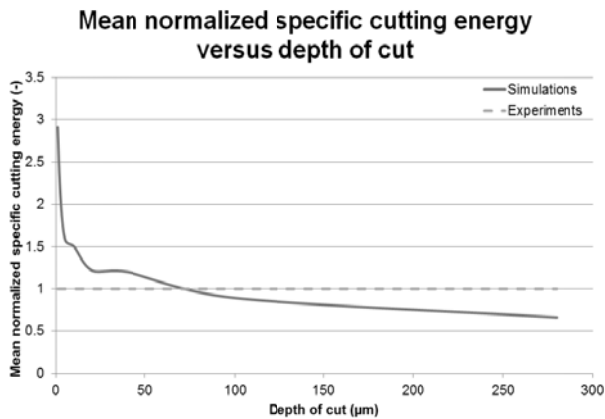


Fig. 10 Mean specific cutting energy.

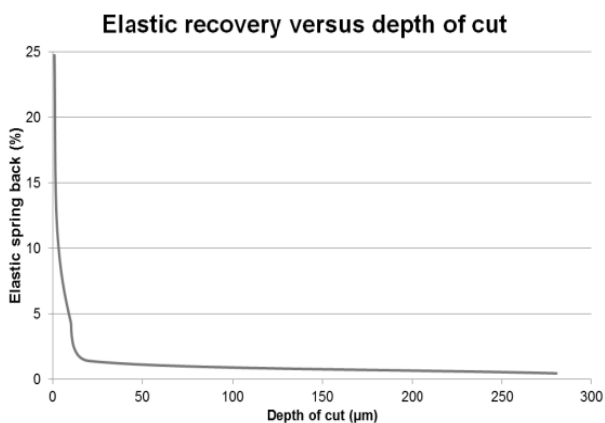


Fig. 11 Elastic recovery of the workpiece.

the minimum chip thickness value is less than  $10\ \mu\text{m}$ : the elastic spring back evolution becomes exponential under this value.

### 5.5 Minimum Chip Thickness Prediction

Each method results in a probable minimum chip thickness value. It is obvious that the minimum chip thickness is less a precise and single value than a range of values with unclear limits. The result of all the criteria previously presented is that the minimum chip thickness value is of the order of  $5\ \mu\text{m}$  (25% of  $r$ ) with a lower limit around  $2.5\ \mu\text{m}$  (12.5% of  $r$ ) and an upper limit inferior to  $10\ \mu\text{m}$  (50% of  $r$ ). This order of magnitude is confirmed in Refs. [6, 14].

## 6. Conclusions

The down-sizing of the milling process induces some changes in the cutting phenomenon. One of them is the chip formation, involving the minimum chip

thickness phenomenon, which is reviewed from an experimental and numerical point of view in this paper.

In order to model the chip formation, a 2D Lagrangian plane strain orthogonal cutting model has been developed using the finite element method. The numerical results highlight the phenomena reported in literature and bring a numerical contribution to their comprehension.

An estimation of the minimum chip thickness is also performed, leading to a value around 25% of the cutting edge radius of the tool.

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