Chip Formation and Minimum Chip Thickness 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. Although micro-milling is based on the same principle as macro-milling, the phenomena of micro-cutting are not a simple scaling of macro-cutting. A significant difference is the chip formation involving the phenomenon of minimum chip thickness. In micro-milling the depth of cut and the feed are very small, of the same order of magnitude as the tool radius and below a certain value no chip is formed. This paper reports the current state of the art of chip formation and minimum chip thickness in micro-milling from an experimental and numerical point of view. It presents the differences and difficulties of micro-milling compared to macro-milling on chip formation, as well as experimental and numerical work in this area. Finally, results of finite element simulations to quantify the minimum chip thickness and model the chip formation are presented.

1 INTRODUCTION

These days, miniaturization is rising in importance, increasing the need for micro-components for more and more industrial fields. Therefore micro-machining processes are in full expansion. One of them is micro-milling, whose applications are varied in terms of machinable materials (metallic alloys, composites, polymers and ceramics) and areas (micro-injection moulds, watch components, optical devices, components for the aerospace, biomedical and electronic industries).

Micro-milling is a micro-manufacturing technology by removal of material making it possible to produce parts and features ranging from several mm to several µm. It requires a miniature tool (called a micro-mill) with a diameter between 100 µm and 500 µm, which is often in tungsten carbide in order to allow ferrous material machining. Micro-milling seems to be the most flexible and the fastest way to produce complex tridimensional micro-forms including sharp edges with a good surface finish [1].

Although based on the same principle as macro-milling, the phenomena of micro-cutting involved in micro-milling are not a simple scaling of macro-cutting. A significant difference between these two cutting processes is the chip formation involving the so-called 'minimum chip thickness' phenomenon.

2 CHIP FORMATION

2.1 Minimum chip thickness

In micro-milling the depth of cut and the feed are very small, of the same order of magnitude as the tool edge radius. Below a certain value, called 'minimum chip thickness', no chip is formed.

The concept of minimum chip thickness is that the depth of cut or feed per tooth must be over a certain critical chip thickness before a chip will form [2]. Its value is often between 5 % and 38 % of the tool edge radius [3]. Figure 1 depicts three situations taking place in micro-milling:

- The uncut chip thickness (*h*) is **less** than the minimum chip thickness (h_m, Figure 1 (a)). The cutter (edge radius R_e) deforms elastically the workpiece and no chip is formed.
- The uncut chip thickness is **almost equal** to the minimum chip thickness (Figure 1

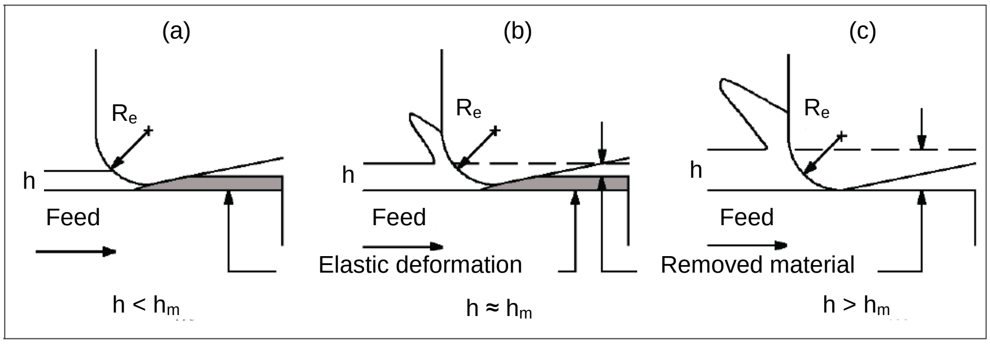

Figure 1: Schematic representation of the minimum chip thickness in orthogonal cutting [2].

(b)). Although the workpiece slightly deforms, a chip is formed by material shearing. The elastic spring back of the workpiece leads to a removed depth of workpiece material smaller than the desired depth of cut.

- The uncut chip thickness becomes **greater** than the minimum chip thickness (Figure 1 (c)). The elastic deformation of the workpiece decreases dramatically and the removed depth of material becomes equal to the desired depth of cut.

The minimum chip thickness phenomenon leads to a rising of slipping forces and ploughing of the machined surface, contributing to the increase of cutting forces, burr formation and surface roughness. In order to correctly choose the cutting condition, it is therefore crucial to estimate its value. The strong dependency of the minimum chip thickness to the machined material and the tool geometry complicates this evaluation.

Bissacco et al. [4] highlighted the ploughing phenomenon. They noticed that a part of the plastically deformed material on the sides of the micro-mill remains attached to the workpiece and that another part is projected in the form of waves in the direction opposite to the feed (Figure 2).

When the depth of cut is lower than a critical chip thickness, chips are formed in a discontinuous way (situation between Figure 1 (a) and Figure 1 (b)). Kim et al. [5] classify the deformations in two types:

- the forced deflection of the tool;
- the elasto-plastic deformation of the workpiece material.

They observed that a new non-detached chip is formed as soon as the effective depth of cut of the tool exceeds the minimum chip thickness.

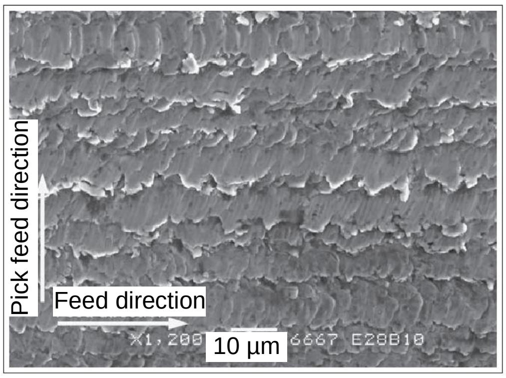

Figure 2: Machined micro-milled surface [4].

2.2 Negative rake angle

In macro-cutting, the depth of cut is generally greater than the cutting edge radius of the tool so the classical chip formation models consider that the sharp tool completely cuts the surface and generates chips.

In micro-cutting, this assumption is not valid: the small depth of cut of the same order as the cutting edge radius of the tool leads to a highly negative rake angle (Figure 3).

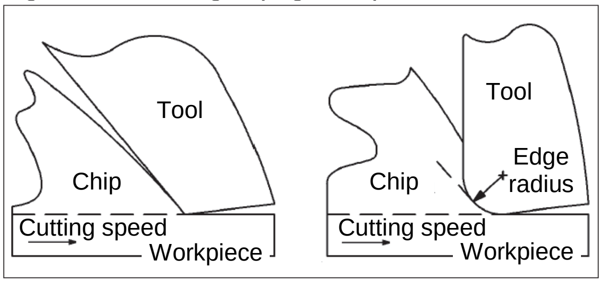

Figure 3: Chip formation, orthogonal cutting [6].

A highly negative rake angle involves ploughing of the machined surface and elastic spring back of the workpiece. A portion of this spring back (occurring under the flank face) results in sliding, raising the specific cutting energy.

2.3 Size effect

For a small depth of cut, the ‘size effect’ phenomenon appears. It consists of a non-linear increase in the specific cutting energy when the depth of cut decreases. The specific cutting energy is the ratio between the total cutting force acting on the tool in the cutting direction and the chip section [3, 7].

The scaling effect would be caused by [3]:

- the ploughing of the machined material due to negative rake angle;
- the pressure on the flank face due to elastic spring back of the machined material;
- the strain rate dependency;
- the dislocation density;
- the strain hardening of the machined material at micrometrical scale [8].

The influence of the dislocation density can be explained as follows [9]: materials contain defects, such as microscopic cracks and dislocations. Therefore when the size of the removed chip decreases, the probability of meeting this type of defect decreases, increasing the specific cutting energy.

The specific energy is thus closely related to the minimum chip thickness. It can be an indicator to detect changes in the cutting mechanism (from slipping to shearing) and to monitor the cutting process.

2.4 Literature review of experimental and numerical works

According to Liu et al. [10], a sudden change of the thrust component of cutting force could be used in order to determine the minimum chip thickness in micro-end milling. This change would find its origin in the transition of a state dominated by slipping forces to one dominated by shearing forces when the depth of cut increases.

In another article, Liu et al. [11] present an analytical model predicting the value of the minimum chip thickness based on the basic thermo-mechanical properties of the machined material (cutting temperature, strain, strain rate), which are also predicted by the model. It is based on the transition between plastic deformation and micro-cutting criterion during a scratch. It takes into account the softening effect and the work hardening of machined material. This model allows researchers to study the effects of the cutting speed and the tool edge radius on the minimum chip thickness. Experimental validations were carried out on two steels (AISI 1018 and AISI 1040) and aluminum (Al6082-T6). For AISI 1040 steel, results show that an increase in cutting speed and tool edge radius leads to an increase in minimum chip thickness. This is due to the predominance of softening on work hardening. Indeed, an increase in the cutting speed and/or the tool edge radius raises the cutting temperature, inducing steel softening. Steel being then more ductile, chips are formed less easily. So, from the chip formation point of view, a relatively low cutting speed is preferable for carbon steels. An increase in the carbon rate of steel (passage from AISI 1018 to AISI 1040) also leads to a rise in the temperature and thus in the minimum chip thickness. For Al6082-T6, results show that the minimum chip thickness is not greatly modified when the cutting speed and the tool edge radius vary. This means that softening and work hardening have the same importance and that their effects cancel each other.

Jun et al. [12] observed that the minimum chip thickness for ferrite is higher than for pearlite and that slipping forces are greater for ferrite than for pearlite when the thickness of the chip is lower than its minimal thickness.

Vogler et al. [13, 14, 15] investigated the minimum chip thickness effects on cutting forces in an experimental and numerical way. They observed that, because of the minimum chip thickness, a tooth of the tool can pass into the workpiece material without forming any chip when the feed per tooth is very small. The chip is only formed when the accumulation of cutting thickness is higher than the minimum chip thickness. This phenomenon influences the spectrum of cutting forces: it is possible to highlight a sub-harmonic of the tooth-passing frequency. They also showed that the critical ratio between the minimum chip thickness and the tool edge radius depends on the machined material. Indeed, according to whether pearlite or ferrite is machined, its value is of, respectively, 0.2 and 0.35.

As the minimum chip thickness depends on the machined material properties, Son et al. [16] considered the influence of friction between the workpiece and the tool (in diamond). They were able to give an analytical expression of the minimum chip thickness (h_m), depending on the tool edge radius (R_e) and the friction angle between the tool and an uncut or continuous chip (β):

$$h_m = R_e\left[1-\cos\left(\frac{\pi}{4}-\frac{\beta}{2}\right)\right] \quad (1)$$

They also observed that the roughness of the machined surface was the best at the minimum chip thickness; the chip generated was then continuous. Lastly, they observed a burnishing of the machined surface, which took less importance at the minimum chip thickness.

A peculiarity of micro-milling compared to macro-milling is the highly negative rake angle occurring during the cutting process. In this way a parallel can be drawn with the grinding process, also involving a highly negative rake angle. In grinding, Ohbuchi and Obikawa [17] developed a thermo-elasto-plastic finite element model. It consists of a 2D orthogonal cutting model with large negative rake angle. This model can thus be a good starting point for the negative rake angle modeling in micro-milling. They observed that, in front of the tool tip, a small triangular portion of the chip slips with difficulty along the cutting edge and is always observed for a highly negative rake angle. It is called the 'stagnant chip' (Figure 4). Its size increases for a more negative rake angle and is proportional to the undeformed chip thickness. This stagnant chip acts like a built-up edge, except that its shape and size do not change during the cutting process and that it does not detach from the tool. Lastly they observed that there is a cutting speed and an undeformed chip thickness value, depending on the rake angle, for which the material removal is optimal.

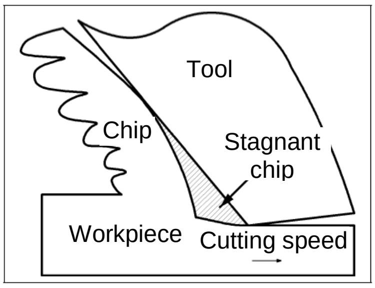

Figure 4: Schematic representation of the stagnant chip in orthogonal cutting [17].

Woon et al. [18] have developed a 2D orthogonal cutting finite element model and proposed a mechanism of chip formation for a homogeneous material. The model has the following main characteristics:

- Dynamic explicit plane strain model with temperature-displacement coupling and Arbitrary Lagrangian Eulerian (ALE) formulation.
- The workpiece is fixed while the tool can move.
- Workpiece made up of AISI 4340 steel and considered as homogeneous. Its behavior is described by a Johnson-Cook plasticity model.
- Tool with and without edge radius, modeled as a perfectly rigid solid.
- Contact between chip and tool modeled by a Coulombic friction law and a constant friction coefficient.
- Boundary conditions: the base of the workpiece is constrained horizontally and vertically and the left side is horizontally constrained. The tool can move horizontally; the displacement vector is applied to its back face.

Their model shows that when the depth of cut is lower than a breaking value, the chip is formed by extrusion along the edge radius of the tool, while the remainder of non extruded material is pressed by the tool against the workpiece to form the machined surface, which introduces residual compressive stresses. This change in the chip formation process is due to high shearing and hydrostatic stresses around the deformation area. This study also confirms the invalidity of the assumption that the cutting edge of the tool is sharp in micro-milling.

3 INFLUENCE OF THE MACHINED MATERIAL

3.1 Overview

In micro-milling, the depth of cut, the tool or feature dimensions to produce are often smaller than the grain size of the workpiece material. This implies that its nature and micro-granular structure have to be taken into account [2, 6]. It cannot thus be regarded any longer as homogeneous and isotropic, which constitutes an important difference compared to macro-machining. Hence the microstructure of the part has a significant importance.

The lack of homogeneity of the granular structure of the part during machining leads to variations in the cutting conditions (hardness in particular). This induces variations in cutting forces and generates vibrations [2, 6]. Those are due to the nature of the part. It is difficult to eliminate them by modifying the cutting conditions or the design of the machine. Moreover it is not possible to use averaged cutting coefficients as in macro-cutting.

3.2 Literature review of experimental and numerical works

In macro-milling, the forming chip is composed of many grains, contrary to micro-milling for which the chip is made up of only one or a few grains. Therefore during the material shearing, only one grain may be concerned. This leads to an increase of efforts and stresses on the tool depending on the orientation of each grain. This can explain fluctuations of cutting forces at high frequencies [19]. Vogler et al. [15] developed a model accurately representing these fluctuations for heterogeneous materials. It consists of a mechanistic model of micro-end-milling taking into account the different material phases when it is heterogeneous. They observed, in the cutting forces signal, that frequencies can be explained by the different material phases. Moreover they highlighted a correlation between the existence of high frequencies and bad surface roughness. Lastly they noticed that when the tool moves from a metallurgical phase to another, variations of cutting forces appear, inducing a high level of vibrations and a reduction in lifespan of the tool.

Simoneau et al. [20, 21, 22] developed an orthogonal cutting heterogeneous finite element model in order to study chip formation and surface defects when machining AISI 1045 steel. The model considers that no built-up edge is formed and that the tool edge radius is infinitely small. The principal characteristics of the finite element model are:

- Dynamic explicit 2D model with temperature-displacement coupling.
- The workpiece is fixed while the tool can move.
- Workpiece made up of two materials (A and B) representing the granular structure of AISI 1045 steel. Material A is three times stronger than material B and their behavior is described by a Johnson-Cook plasticity model. Thermal properties of the two materials are identical and are those of AISI 1045 steel.
- Tool modeled without edge radius.
- Contact between chip and tool modeled by an algorithm of penalty with a Coulombic friction coefficient.
- Boundary conditions: the base of the workpiece is fixed and the tool can move horizontally; the displacement vector is applied to its back face.

They highlighted that it is essential for the model to be heterogeneous, chip formation and surface defects being related to the microstructure of the machined workpiece material.
During the chip formation, it would seem that the softest material (ferrite) is extruded between the hardest grains (pearlite), as shown in Figure 5 (a). Simoneau et al. also noticed important plastic deformations at the grain boundaries and at the interface between the tool and the workpiece. Figure 5 (b) presents a chip formation following the mechanism proposed by the authors, which they call ‘quasi-shear-extrusion chip’.

4 MODELING

In micro-machining, as all is held on a microscopic scale, it is difficult to perform observations during machining and to take experimental measurements. Moreover the process itself is very complicated: it implies elasto-plastic deformations and cracks with large strain rates and temperatures inducing variations of the materials properties. Numerical modeling is (often) accompanied by computer simulations. It makes it possible to overcome some limitations of the experimental approach and is therefore a good compliment to it [6, 23].

Several modeling approaches are used in micro-milling. They are briefly reviewed in this section.

4.1 Analytical and mechanistic modeling

At the present materials behavior knowledge stage, an analytical modeling of the micro-cutting phenomenon is very difficult, analytical modeling establishing relations between cutting forces and mechanical aspect such as friction, geometry and mechanical materials behavior [24]. Almost every analytical modeling of cutting forces is based on kinematics from experimental observations, combined with traditional cutting models in macro-machining [6, 23]. The validity and the precision of these models are thus subject to many limitations.

Mechanistic modeling is based on relations between process variables and cutting forces or energies. These relations take account of the geometrical characteristics of the cutting process and some data are obtained experimentally. These data characterize the considered tool-workpiece couple [24].

4.2 Molecular Dynamics simulation

Molecular Dynamics simulation is based on calculation of interatomic forces. It makes it possible to take into account characteristics of materials at the microscopic level like dislocations, crack propagation and the specific cutting energy [6, 23]. It is generally reserved for nanometrical cut because it requires large computing power and gives only a local representation of the material’s behavior [6, 25].

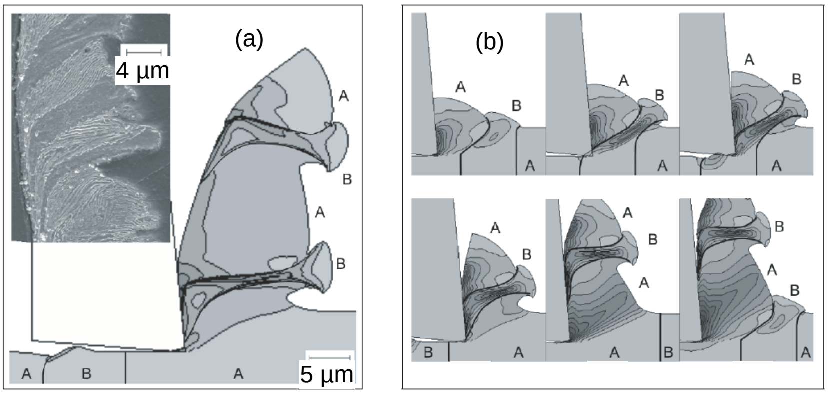

Figure 5 (a): Extrusion of ferrite (B) between pearlite grains (A) during chip formation [22].
Figure 5 (b): AISI 1045 steel chip formation [22]

4.3 Finite element method

The finite element method is a popular technique of simulation. Modeling generally concentrates on interactions between the tool and the workpiece in the area close to the cutting edge of the tool, where the chip is formed. In order to reduce computing cost, problems are dealt with 2D (orthogonal and oblique cut) [20].

4.4 Multi-scale modeling

Multi-scale modeling is a recent technique combining the finite element method and molecular dynamics simulation [6, 23]. It dispenses with the disadvantages of the two methods from which it results.

5 FINITE ELEMENT MODEL DEVELOPMENT

5.1 General description

In order to study the chip formation in micro-milling, a thermo-mechanical numerical model has been developed with a commercial finite element software program, ABAQUS/Explicit v6.7. It consists of a 2D plane strain orthogonal cutting model and takes into account only the area close to the cutting edge of the tool. The machined material is a titanium alloy, Ti6Al4V while the tool material is tungsten carbide.

The workpiece is modeled as a rectangular block measuring 3 mm long and 0.9 mm thick with a step of the depth of cut value in height at its half-length. Its bottom surface is constrained with a symmetry condition and its left face is constrained vertically. The cutting speed is 300 m/min. The tool is modeled with a finite edge radius of 20 µm, a rake angle of 0°, a clearance angle of 5° and is fixed in space.

Friction at the tool-chip interface is implemented using a Coulombic friction law and a constant friction coefficient. It is assumed that all of the dissipated heat due to friction is converted into heat and that 25% of this heat flows into the chip [26].

The workpiece material is assumed to be homogeneous and its behavior is described by a Johnson-Cook plasticity model. The mechanical formulation adopted for the workpiece is the Arbitrary Lagrangian Eulerian (ALE) formulation, which combines the features of pure Lagrangian and Eulerian analysis. In the ALE formulation, the mesh is not attached to the material and can move to avoid distortions and to update free chip geometry. The chip formation is simulated via adaptive meshing and plastic flow of the workpiece material. This implies that there is no chip separation criterion in the proposed model. The workpiece can be seen as a pipe into which the material flows. The entrance (left face of the workpiece) and the exit (the right face) are modeled as Eulerian boundaries, allowing material to flow through them. All other surfaces are modeled as 'classical' Lagrangian boundaries. The shape of the bottom surface of the workpiece is fixed (because of the symmetry boundary condition) while the shape of the upper surface is free to deform.

The tool and workpiece are meshed with, respectively, about 400 and 2300 four-node elements. The meshes are refined in the close area around the tool edge radius. Their initial temperature is 20°C. Only conduction is considered in the present model and it is assumed that the transformation of deformation to heat efficiency is 90%, as generally observed [18, 26, 27].

5.2 Numerical results

As for a chosen machined material the minimum chip thickness depends on the depth of cut (*h*) and the tool edge radius (*r*), the *h/r* ratio is defined.

Four different cases have been treated via depth of cut variation: *h/r*=5 (*h*=100 µm), *h/r*=3 (*h*=60 µm), *h/r*=0.5 (*h*=10 µm) and *h/r*=0.25 (*h*=5 µm).

Chip formation and material deformation are shown in Figure 6 (a). It represents nodal displacements: the arrow indicates the displacement direction and its size the magnitude. For *h/r* of 5, 3 and 0.5, the displacement direction is the same (upper left) and a chip is formed. But for *h/r*=0.25 the material flows towards the cutting edge of the tool and no chip clearly forms.

When looking to the Von Mises stress contours (Figure 6 (b)), the primary shear zone can be seen for *h/r*=5 as in macro-cutting with a sharp tool. When *h/r* decreases, the primary shear zone fades and for *h/r*=0.25 there is no primary shear zone anymore. The results are globally similar to those presented by Woon et al. [18].

6 CONCLUSION

The transition between micro- and macro-milling processes leads to some changes in the cutting phenomenon. One of the most important is the chip formation involving the minimum chip thickness phenomenon. A review of it from an experimental and numerical point of view has been carried out in this paper.

Then a 2D plane strain orthogonal cutting model has been developed using the finite element method in order to model the chip formation and the minimum chip thickness influence. The simulation results show, as previously highlighted by Woon et al. [18], that the *h/r* value has a great importance in micro-cutting and that the cutting tool can no longer be considered as sharp. It can be noted that the chip formation mechanism evolves away from macro-cutting when the *h/r* ratio decreases.

Following this work, it could be interesting to analytically model the minimum chip thickness in order to get a comparison point with the presented model and validate it.

7 REFERENCES

[1] Weule, H., Hüntrup, V., Trischler, H., 2001, Micro-cutting of steel to meet new requirements in miniaturization, Annals of the CIRP, 50:61-64.

[2] Chae, J., Park, S.S., Freiheit, T., 2006, Investigation of micro-cutting operations, Int. J. Machine Tools and Manufacture, 45:313-332.

[3] Filiz, S., Conley, C.M., Wasserman, M.B., Ozdoganlar, O.B., 2007, An experimental in vestigation of micro-machinability of copper 101 using tungsten carbide micro-endmills, Int. J. Machine Tools and Manufacture, 47:1088-1100.

[4] Bissacco, G., Hansen, H.N., De Chiffre, L., 2006, Size effect on surface generation in micromilling of hardened tool steel, Annals of the CIRP, 55:593-596.

[5] Kim, C.J., Mayor, J.R., Ni, J., 2004, A static model of chip formation in micro scale milling, ASME, 126:710-718.

[6] Dornfeld, D., Min, S., Takeuchi, Y., 2006, Recent advances in mechanical micromachining, Annals of the CIRP, 55:745-768.

[7] Liu, K., Melkote, S.N., 2007, Finite element analysis of the influence of tool edge radius on size effect in orthogonal micro-cutting process, Int. J. Mechanical Sciences, 49:650-660.

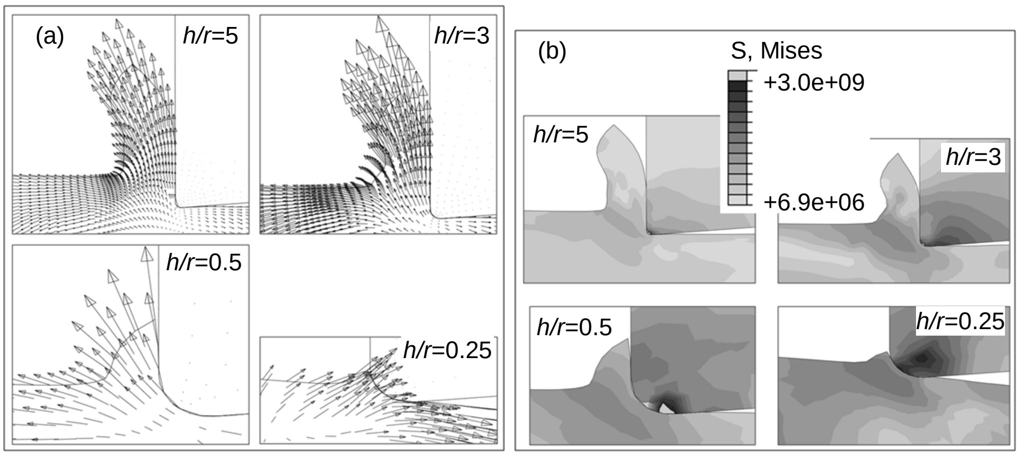

Figure 6 (a): Nodal displacements during chip formation.
Figure 6 (b): Von Mises stress contours during chip formation.

[8] Lai, X., Li, H., Li, C., Lin, Z., Ni, J., 2008, Modelling and analysis of micro scale milling considering size effect, micro cutter edge radius and minimum chip thickness, Int. J. Machine Tools and Manufacture, 48:1-14.

[9] Zaman, M.T., Kumar, A.S., Sreeram, S., 2006, A three-dimensional analytical cutting force model for micro end milling operation, Int. J. Machine Tools and Manufacture, 46:353-366.

[10] Liu, X., DeVor, R.E., Kapoor, S.G., Ehman, K.F., 2004, The mechanics of machining at the micro scale: assessment of the current state of the science, J. Manufacturing Science and Engineering, 126:666-678.

[11] Liu, X., DeVor, R.E., Kapoor, S.G., 2006, An analytical model for the prediction of minimum chip thickness in micromachining, ASME, 128:474-481.

[12] Jun, M.B.G., DeVor, R.E., Kapoor, S.G., 2006, Investigation of the dynamics of microendmilling, Part II: model validation and interpretation, ASME, 128:901-912.

[13] Vogler, M.P., DeVor, R.E., Kapoor, S.G., 2004, On the modeling and analysis of machining performance in micro endmilling, Part I: surface generation, J. Manufacturing Science and Engineering, 126:685-694.

[14] Vogler, M.P., DeVor, R.E., Kapoor, S.G., 2004, On the modeling and analysis of machining performance in micro endmilling, Part II: cutting force prediction, J. Manufacturing Science and Engineering, 126:695-705.

[15] Vogler, M.P., DeVor, R.E., Kapoor, S.G., 2003, Microstructure-level force prediction model for micromilling of multi-phase materials, J. Manufacturing Science and Engineering, 125:202–209.

[16] Son, S.M., Lim, H.S., Ahn, J.H., 2005, Effects of the friction coefficient on the minimum cutting thickness in micro cutting, J. Machine Tools and Manufacture, 45:529-535.

[17] Ohbuchi, Y., Obikawa, T., 2003, Finite element modeling of chip formation in the domain of negative rake angle cutting, ASME, 25:324-332.

[18] Woon, K.S., Rahman, M., Fang, F.Z., Neo, K.S., Liu, K., 2007, Investigations of tool edge radius effect in micromachining: a FEM simulation approach. J. Materials Processing Technology, 167:316-337.

[19] Bissacco, G., Hansen, H.N., De Chiffre, L., 2005, Micromilling of hardened tool steel for mould making applications, J. Materials Processing Technology, 167:201-207.

[20] Simoneau, A., Ng, E., Elbestawi, M.A., 2006, Chip formation during microscale cutting of medium carbon steel, Int. J. Machine Tools and Manufacture, 46:467-481.

[21] Simoneau, A., Ng, E., Elbestawi, M.A., 2006, Surface defect during microcutting. Int. J. Machine Tools and Manufacture, 46:1378-1387.

[22] Simoneau, A., Ng, E., Elbestawi, M.A., 2006, The effect of microstructure on chip formation and surface defects in microscale, mesoscale, and macroscale cutting of steel, Annals of the CIRP, 55:97-102.

[23] Liu, X., DeVor, R.E., Kapoor, S.G., Ehman, K.F., 2004, The mechanics of machining at the micro scale: assessment of the current state of the science, J. Manufacturing Science and Engineering, 126:666-678.

[24] Uriarte, L., Azcárate, S., Lopéz de Lacalle, L.N., Lamikiz, A., 2008, Mechanistic modelling of the micro end milling operation, Proc. IMechE, Part B: J. Engineering Manufacture, 222:23-33.

[25] Kapoor, S.G., Bayne, J.W., 2004, Current state of micro-scale machine tool systems and machining research.

[26] Nasr, M., Ng, E.G., Elbestawi, M., 2007, Effects of workpiece thermal properties on machining-induced residual stresses – thermal softening and conductivity, Proc. IMechE, Part B: J. Engineering Manufacture, 221:1387-1400.

[27] Özel, T., Zeren, 2007, Numerical modelling of meso-scale finish machining with finite edge radius tools, E., Int. J. Machining and Machinability of Materials, 2:451-468.