

Dynamic simulation of the micro-milling process including minimum chip thickness and size effect

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Abstract. Micro-milling with a cutting tool is one of the most effective process to produce complex three-dimensional micro-parts, including sharp edges and with a good surface quality. Reducing the dimensions of the cutter and the cutting conditions requires taking into account physical phenomena that can be neglected in macro-milling such as a size effect, the minimum chip thickness and the heterogeneity of the material.

The aim of this paper is to introduce some of these phenomena in the dynamic simulation software DyStaMill developed for macro-milling. The software simulates the cutting forces, the vibrations and the surface finish in milling operation to predict chatter-free cutting conditions for example.

The model of the cutting forces is deduced from the local FEM simulation of orthogonal cutting. This FEM model is able to simulate chip formation and cutting forces in an orthogonal cutting test. It is able to reproduce physical phenomena in macro-cutting conditions (including segmented chip) as well as specific phenomena in micro-cutting conditions.

The results of simulation for the machining of Ti6Al4V under macro- and micro-milling conditions are presented discussed. This approach connects together local machining simulation and global models.

Introduction

Nowadays, more and more industrial processes are seeking for miniaturization of components. In order to manufacture smaller parts, new production techniques are needed. Micro-milling with a cutting tool is one of them. It is one of the most effective process to produce complex three-dimensional micro-parts, including sharp edges and with a good surface quality.

Reducing the dimensions of the cutter and the cutting conditions requires taking into account physical phenomena that can be neglected in macro-milling. In order to perform reliable simulation of the process the classical approach used in macro-milling must be extended.

This paper focuses on two main aspects: first of all, a finite element model is developed to simulate local phenomena occurring during chip formation. This model has been developed in order to model micro- and macro-cutting without the use of any numerical tricks. The results of this model are then used as an input in a more global dynamic model of the machining process. This second model is able to simulate milling operations with a complex tool to give access to global values such as cutting forces, vibrations or surface finish.

Characteristics of the local FEM model

The local FEM model (developed with Abaqus/Explicit v6.8) is a 2D plane strain orthogonal Lagrangian cutting one. It only takes into account the area close to the cutting edge of the tool as in such a local model the region of interest is the area where the chip is formed. The Lagrangian formulation implies the use of a chip separation criterion (based on an 'eroding element' method [1] in this model) in order to make it possible for the chip to come off.

The validity of the model in both micro- and macro-cutting is a fundamental feature of it. Changes in the cutting phenomenon from macro- to micro-cutting can then be studied with this single model. Forming saw-toothed chips in macro-cutting and no chip in micro-cutting are some of the difficulties introduced by the multi-scale aspect of the model.

In order to take its influence on chip formation into account, the cutting tool is modelled with a finite edge radius of $20\ \mu\text{m}$. The rake angle is set to 15° and the clearance angle to 2° . The boundary conditions are presented on Fig. 1: the workpiece is fixed while the cutting tool moves horizontally at the cutting speed of $75\ \text{m/min}$.

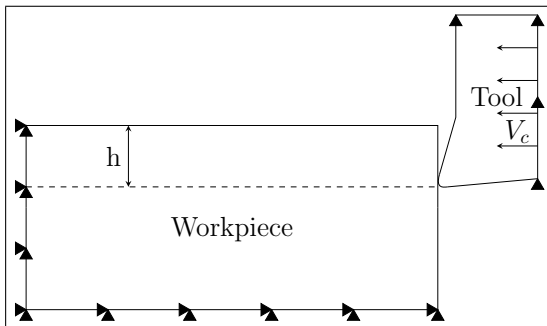


Fig. 1: Geometry and boundary conditions of the model

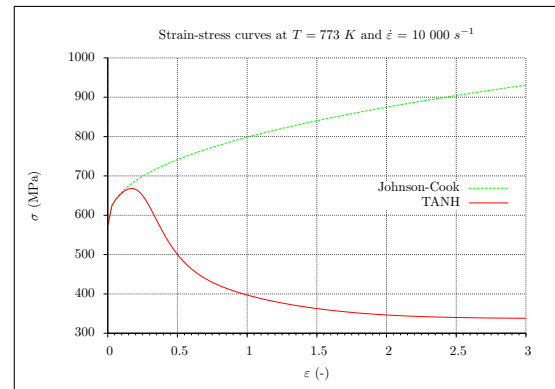


Fig. 2: Shapes of the Johnson-Cook and Hyperbolic TANgent laws

The tool material is tungsten carbide and its behaviour law is linear elastic. The machined material (Ti6Al4V) behaviour is described by the Hyperbolic TANgent (TANH) law introduced by Calamaz et al. in [2]. This law is the well-known Johnson-Cook law modified to model the strain softening effect, as shown on Fig. 2.

Results of the FEM model

The model has been previously validated in macro-cutting in [1] through a comparison of the chip and the cutting forces to experimental cutting results from literature in the same cutting conditions [3]. Concerning the cutting forces, it shows that the gap between experimental and simulated forces is larger for the feed force than the cutting force.

In order to study the influence of the depth of cut on the cutting mechanism, eight different values of the depth of cut (h) have been chosen. As the cutting edge radius of the tool (r) remains constant the depth of cut on cutting edge ratio (h/r) can be defined. It ranges from 0.05 to 14 for the eight cutting conditions considered.

Chip morphology. On Fig. 3 and 4 it can be seen that the chip morphology goes from the saw-toothed chip to the absence of chip formation. Between these, segmented and nearly continuous chips are observed. For the two smaller values of the h/r ratio, no chip is formed and a small amount of material accumulates in front of the tool. The movement of the tool makes this amount growing. When it reaches a thickness greater than the minimum chip thickness, a chip is formed and it is removed from the workpiece.

Elastic recovery. After the tool tip passage an elastic recovery (or elastic spring back) of the cutting material happens. It is plotted versus the depth of cut (on Fig. 5) in order to highlight its role on the cutting mechanism. Fig. 5 shows that the importance of the elastic recovery grows when the depth of cut decreases: it goes from about 0.45% when $h/r = 14$ to nearly 25% for a depth of cut of $1\ \mu\text{m}$. A larger elastic recovery increases the feed force, the slipping forces and the specific cutting energy.

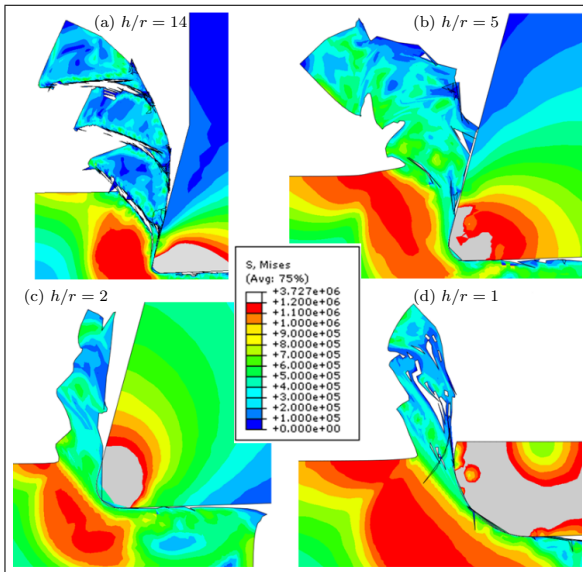


Fig. 3: Chip morphology when $h/r = 14$ to $h/r = 1$ (Von Mises stress contours, 10^3 Pa)

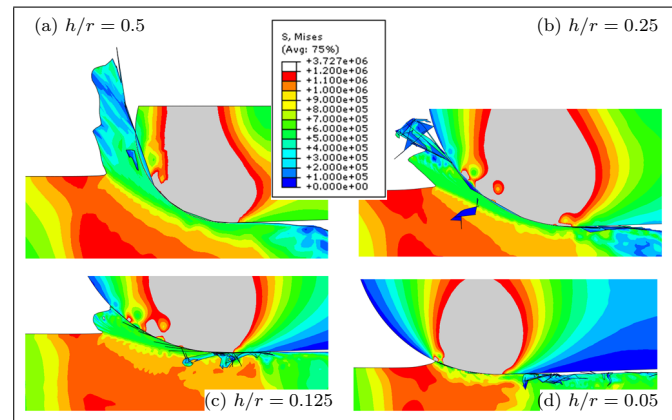


Fig. 4: Chip morphology when $h/r = 0.5$ to $h/r = 0.05$ (Von Mises stress contours, 10^3 Pa)

Specific cutting energy. The reduction of the depth of cut also influences the cutting forces. As the depth of cut decreases, the feed to cutting forces ratio increases and becomes larger than one, showing that a change occurs in the cutting mechanism [1]. The simulations performed with the developed model also allows to highlight the size effect. Actually a nonlinear increase of the mean normalized specific cutting energy (ratio of the mean specific energy from the simulations to the reference cutting energy of Sun et al. [3]) is observed on Fig. 6 when the depth of cut decreases.

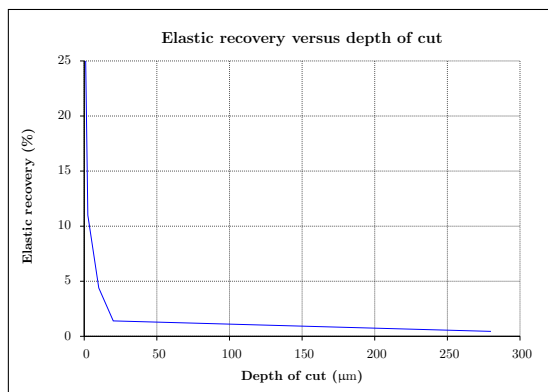


Fig. 5: Evolution of the elastic recovery versus the depth of cut

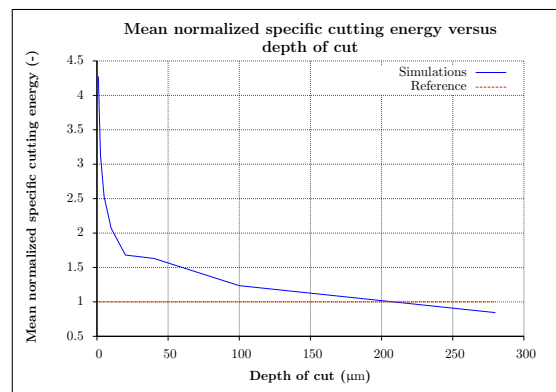


Fig. 6: Illustration of the size effect

Minimum chip thickness evaluation. Based on the previously presented results an evaluation of the minimum chip thickness value can be performed for the cutting conditions and the geometry of the model. The chip morphology, the elastic recovery, the feed to cutting forces ratio and the specific cutting energy lead each to a different minimum chip thickness value as detailed in [1]. In the end the range of values goes from $2.5 \mu\text{m}$ (12.5% of r) to $10 \mu\text{m}$ (50% of r) with a mean value of $5 \mu\text{m}$ (25% of r).

Dynamic modelling of micro-milling operation

Introduction. In order to simulate a complex milling example, finite element models can become difficult to achieve due to high computation time. A more global approach is then necessary to simulate global phenomena such as cutting forces, vibrations and surface finish on industrial problems. However, the results of a local finite element model can be used as an input for the global simulation, making it possible to get a fully numerical simulation approach for micro-milling operations.

The simulation software DyStaMill [4] has been developed at the University of Mons based on this framework: three global models are couple together to simulate milling operation: geometric model, cutting force model and dynamic model. Those models are presented on the later sections in common with the adaption necessary to model micro-milling operations.

Surface generation model. The geometric computation is based on a 2D 1/2 model where the tool is divided along its axis on elementary slices. The movement of the tool is assumed to stay perpendicular to the axis of the cutter (modelling of contour, slot and pocket milling at constant depth of cut). This assumption is more often valid as the rigidity of the system is higher along the tool axis, so the vibrations in this direction are often negligible. For each slices along the axis, the surface generation is based on an eraser of matter model [5]: at each time step, the area swept by the cutting edge is removed from the geometrical model of the workpiece. The chip section, which is an input for the computation of the cutting forces, is also computed by this model.

In order to adapt the model to micro-milling, the minimum chip thickness phenomenon must be taken into account. This can be done quite simply: if the modelled chip thickness is smaller than the minimum chip thickness, no chip is formed and the surface is not updated. As an example, the evolution of the chip thickness for a half immersion down-milling operation with a feed per tooth of $20 \mu\text{m}$ is shown on Fig. 7.

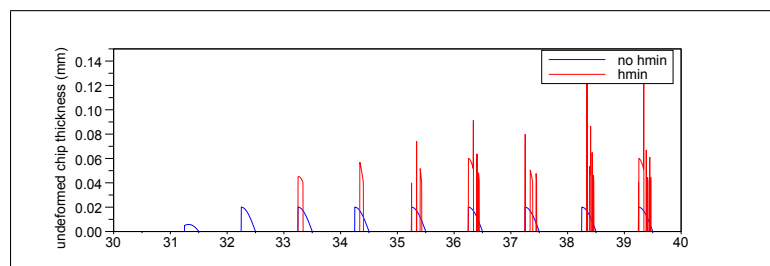


Fig. 7: Minimum chip thickness effect on the chip thickness

If the minimum chip thickness phenomenon is not considered, the chip thickness has a cyclic evolution with a maximum value of $20 \mu\text{m}$. If a minimum chip thickness of $40 \mu\text{m}$ is assumed, the evolution of the chip thickness is irregular (for some revolutions of the tool, no chip is formed at all) and the maximum value of the chip thickness can become much higher.

Cutting forces model. The cutting force acting on each slice of the model is computed using a mechanistic model. At each time step, all the elementary efforts acting on the tool are projected on a global frame and analytically integrated to obtain the global cutting force [6]. In order to take the size effect into account, a nonlinear regression is performed on the specific energy on the cutting and feed directions. The exponential model proposed in [7] leads to a good correlation ($R^2 > 95\%$). The specific cutting forces (K_c on cutting direction and K_f along feed direction) can be modelled as follow (h is the uncut chip thickness):

$$K_{c[MPa]} = 3266,5h_{[mm]}^{-0.243}, K_{f[MPa]} = 19818h_{[mm]}^{-0.834} \quad (1)$$

These coefficients are defined for orthogonal cutting consistent with the FEM. For a milling operation, oblique cutting must be assumed, the transformation from orthogonal to oblique cutting condition can be performed as explained in [7]. As an example half immersion milling is simulated on Ti6Al4V

with depth of cut of 5.08 mm and feed per tooth of 0.05 mm using the cutting forces model defined in equation 1. Fig. 8 shows the comparison between simulated efforts (plain) and the reference (dotted). It shows that our model is able to give a good order of magnitude as compared reference [7]. The difference is higher on the feed direction; this conclusion has already been made on the FEM model.

A micro-milling example is also simulated with the feed per tooth divided by ten. It can be clearly seen on Fig. 9 that the cutting forces have a nonlinear variation with respect to cutting conditions. This nonlinear evolution leads to the fact that in micro-milling, the stability of the operation can be feed dependant, which is not the case in macro-milling.

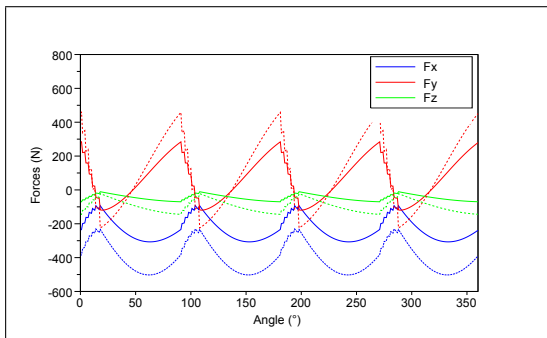


Fig. 8: Simulated cutting forces for a macroscopic milling (plain) case compared with the literature (dotted)

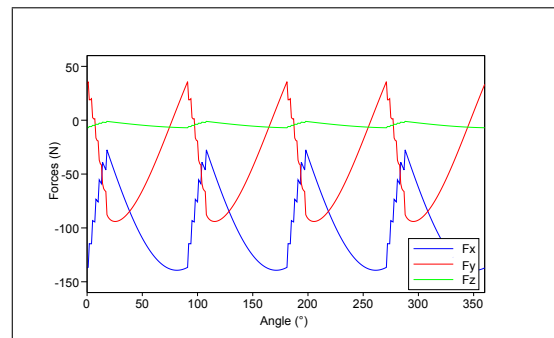


Fig. 9: Cutting forces for a microscopic milling case

Dynamic model. The cutting forces acting on the tool are used as an input for a dynamic model based on the FRF of the machine tool and the cutter, in order to model the relative displacement between the tool and the workpiece. The estimation of the FRF of the complete structure (tool, spindle, bed) can be made by direct measurement (experimental modal analysis) or by receptance coupling [8].

Coupling of the model. The simulation of the complete milling process is based on a coupling of the three models previously presented. At each time step, geometrical computation is made to update the geometry of the workpiece and to compute the chip section along the cutter axis. The cutting forces are then computed by numerical integration of the local efforts along the cutter axis. This effort is then used as an input on the dynamic model to compute the relative displacement between the tool and the workpiece. Those three steps are repeated for each time step of the simulation.

Simulation example

The simulation of a complete example of micro-milling operation has been performed with and without the adaptation of the software to micro-milling in order to see the difference of the conclusions. The cutting forces are computed based on the cutting coefficients extracted from the FEM model and the minimum chip thickness (if considered) is fixed at $5 \mu\text{m}$.

A finishing operation with a 2 mm cutting tool (30 degree helix angle, 3 teeth) is performed. The cutting parameters are selected from a supplier [9] as follow: axial depth of cut 0.1 mm, radial depth of cut 0.6 mm, feed per tooth 0.016 mm, spindle speed 4700 RPM. Without taking the micro-cutting phenomena into account (Fig. 10), the cutting forces are mainly cyclic, the amplitude of the vibration is limited to few microns. While size effect and minimum chip thickness are introduced in the model (Fig. 11), the cutting force increases and the vibration reaches a level of $10 \mu\text{m}$ which can be unacceptable for the required precision of the operation.

This example clearly shows the interest in modelling all the phenomena to achieve a realistic simulation.

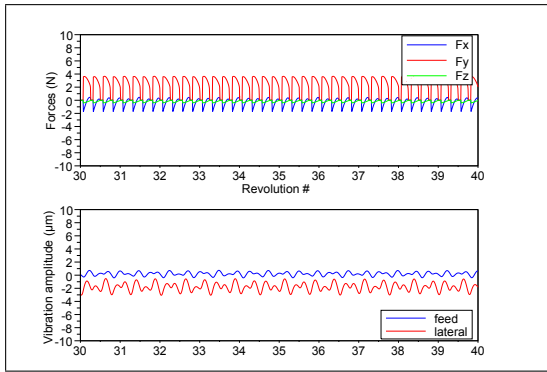


Fig. 10: Forces and vibration of the simulated example without taking micro effects into account

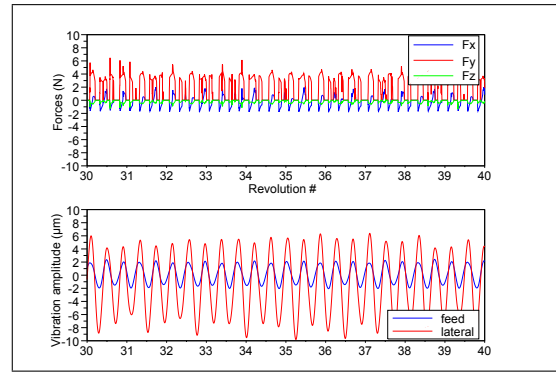


Fig. 11: Forces and vibration of the simulated example including size effect and minimum chip thickness

Summary

The simulation of micro-milling process can be a key element for process planning. Micro-milling operations cannot be simply considered as a downscaling of macroscopic milling. A new approach is necessary to define optimal cutting conditions. The simulation procedure presented in this paper is able to make dynamic simulation of micro-milling operation with a fully numerical approach. Minimum chip thickness and size effect phenomena are taken into account for more accurate simulation.

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