Simulation and experimental analysis of cutting forces in 2D ½ milling with small feed per tooth

Master thesis

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June 2014
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Summary

The increasing trend among several manufacturing industries of producing precise and complex micro-pieces with three-dimensional geometries and shapes has forced researchers to develop new micro-techniques. Micro-milling is a key technology characterized by a material removal performed by mechanical interaction between a tool with sharp edges and a workpiece. Cutting force prediction at micro-scale is an important research field in order to enable correct choice of cutting parameters, correct design of micro tools and estimation of machining tolerances.

This work aims to determine if the finite element model taken as an input for a global dynamic model is accurate enough to simulate experimental measurements, therefore a simulation approach and experimental tests are performed to be compared. The dynamic simulation software employed is DyStaMill which has been developed in the faculty of engineering. The software is based in three fundamental aspects: modeling of the cutting forces, modeling of the surface generation and prediction of the displacement between the tool and the workpiece.

The experimental plan followed comprises slot milling tests and shoulder milling tests with small feed per tooth and several cutting parameters to titanium (Ti6Al4V) workpieces. The calculations for the developed cutting force model are compared to the experimental findings. The comparison shows significant differences between measurements and simulation on the values of the efforts. These differences can be explained by the cutting edge radius which is different between simulations and experiments and to a possible effect of cutter run-out. Finally, an inverse analysis confirmed the validity of the model when correct input parameters are given.

Keywords: machining, numerical simulation, experimental tests, micro-manufacturing
Résumé

La tendance industrielle actuelle est à l’accroissement de la production de micro-pièces précises avec de géométries complexes tridimensionnelles. Ceci a forcé les chercheurs à développer de nouvelles techniques de micro-fabrication. Parmi ces techniques, le micro-fraisage est une technologie clé caractérisée par un enlèvement de matière sur une pièce grâce à un outil présentant des arêtes vives. La prédiction de la coupe à l’échelle microscopique est un domaine de recherche important pour permettre le choix correct des paramètres de coupe, le développement des géométries d’outils de coupe et la prédiction des tolérances dimensionnelle, géométrique et d’état de surface.

Ce travail a pour but de vérifier les possibilités de couplage entre une prédiction de la formation du copeau et des efforts de coupe par une approche aux éléments finis avec un modèle dynamique du fraisage. Le modèle dynamique (logiciel DyStaMill développé à l’École) utilisé est basé sur trois aspects fondamentaux: la modélisation des efforts de coupe, la génération de la surface usinée et l’estimation du déplacement relatif entre la pièce et l’outil.

Les simulations réalisées ont été comparées à des mesures expérimentales. Le plan expérimental suivi comprend des essais de fraisage de rainures et d’épalements dans du titane (Ti6Al4V) avec différents paramètres de coupe.

La comparaison des approches montre des écarts significatifs entre les prédictions et les mesures, pouvant être liés à une différence de rayon de l’arête de coupe entre le modèle et la réalité, ainsi qu’à la possible présence de faux-rond de l’outil. Une analyse inverse a finalement confirmé la validité de l’approche, sous réserve de l’utilisation de paramètres d’entrée adaptés.

Mots-clés: usinage, simulation par ordinateur, essais expérimentaux, micro-fabrication
Acknowledgement

The author would like to express her especial appreciation to Professor Edouard Rivière-Lorphèvre for his valuable and constructive suggestions during the planning and development of this project. Warmly thanks are also expressed to Doctor François Ducobu for his helpful guidance and valuable information. Their willingness to give their time generously and their patient assistance have been very much appreciated.

Special thanks should be given to Professor Enrico Filippi and Université de Mons for offering the author the chance of completing her studies in the mechanical department. The opportunity of an Erasmus exchange given by the Escola Tècnica Superior d'Enginyeria Industrial de Barcelona was really appreciated. The author also wishes to acknowledge the help provided by the Catalan and Spanish governments for funding her exchange studies.

The author would also extend her thanks to the technicians of the center “Techno Campus” in Charleroi (Belgium) for enabling her to perform the experiments there and for their help offering the resources to achieve the measurements.

Finally, this work would not have been possible without the great encouragement and kindly support the author has received from her closest family and friends.
## Contents

1. Aim of the work ............................................................................................................. 6
2. Introduction .................................................................................................................. 7
   2.1 Micro-machining processes ....................................................................................... 7
      2.1.1 Subtractive processes ....................................................................................... 8
      2.1.2 Additive processes ......................................................................................... 10
      2.1.3 Deforming processes ....................................................................................... 10
      2.1.4 Hybrid processes ............................................................................................. 11
   2.2 Modeling .................................................................................................................. 12
3. Micro-milling ................................................................................................................ 14
   3.1 State of the art on force prediction in micro-milling .................................................. 14
4. Presentation of experimental tests .................................................................................. 19
   4.1 Experimental setup ................................................................................................. 19
   4.2 Experimental plan .................................................................................................... 21
   4.3 Signal analysis ......................................................................................................... 24
5. Presentation of simulation approach ............................................................................. 27
   5.1 Analysis of simulation approach ............................................................................. 28
6. Analysis and comparison of results ............................................................................. 32
   6.1 Experimental tests ................................................................................................. 32
   6.2 Comparison experiment-simulation ......................................................................... 38
7. Conclusions and future work ....................................................................................... 46
8. References ................................................................................................................... 48

Annexes
   A. Samples drawing
   B. Signal analysis program code
1. Aim of the work

To get started, a bibliographical study of some subjects of micro-machining is necessary. A research of the most common and in the process of being developed manufacturing techniques has to be done in order to acquire a widely knowledge about the main characteristics and purposes of them. As this project will be focused on the specific micro-cutting process of micro-milling and the cutting forces displayed during the operations, the main difficulties presented in the machining operations are also needed to be studied. Besides, it is required to be aware of the principal fields of development of analytical and mechanistic cutting force models for predicting the efforts in micro-milling, so one goal of the work is to make a state of art of this specific topic.

Once the information is collected and processed, an experimental plan is needed to be carried out so as to observe and study what the effects of the cutting efforts are. The experimental tests will be performed on titanium (Ti6Al4V) workpieces with a carbide cutting tool. Experiments will consist on several slot milling and shoulder milling tests with small feed per tooth and different cutting parameters.

But the main aim of this present work is to validate a finite element model of cutting forces by comparing simulated and experimental measurements. Therefore, a global simulation approach with input parameters from FEM model is necessary to analyze the results and be able to be compared with experimental tests. The comparison between both approaches simulation and experimental, will determine if the cutting force model is accurate enough to reproduce the effects of the efforts in micro-milling operations.
2. Introduction

Machining has always been one of the most frequent processes of production. It is commonly used to manufacture mechanical components. Nowadays, the increasing demand of high-accuracy miniaturized components by various industries, such as aerospace, biomedical, electronics, environmental, communications, and automotive, has forced researchers to develop new micro-manufacturing techniques. These emerging miniaturization technologies will become the essential technologies of the future and will bring about a totally new way of interaction between people, machines and the physical world. Most of the components belong to a range of a few to a few hundred microns and own complex micro-features over a wide range of material types. Some examples of micro-machined features and parts are shown in Figure 1.

![Figure 1: (a) Micro-milled trenches with stepped walls, (b) neurovascular device component, and (c) micro-gear [1]](image)

2.1 Micro-machining processes

These days the trend for micro-manufacturing is more focused on miniaturizing or downscaling both conventional and non-conventional methods. Additionally, there are also emerging methods, such as the hybrid manufacturing methods, which combine two or more processes together. The adjustment from conventional macro-manufacturing to micro-manufacturing is not only feasible but also successful in numerous proved cases. Nevertheless, significant efforts are still needed to better understand material behaviors at micro-scales and process capabilities. Manufacturing processes can be categorized according to the type of energy used in the process itself, such as mechanical, chemical, electrochemical, electrical and laser processes. According to the way in which products are to be made, manufacturing processes can also be classified into subtractive, additive, forming, and hybrid processes [2]. Following, there is a short description about the basic characteristics of the
different processes in micro-machining in addition to the commonly materials used, the precision accomplished and the principal domain for which the process is developed.

2.1.1 Subtractive processes

- Micro-Mechanical Cutting: Micro-mechanical machining is a fabrication method for creating miniature devices and components with features that range from tens of micrometers to a few millimeters in size. Several types of cutting processes are suitable for micro-machining, such as drilling (micro-holes), milling (micro-grooves and micro 3D shapes), turning (micro-pins), and fly cutting (micro-convex structures) [3].
  - Materials: Metals, polymers and infrared crystals [4].
  - Precision: Micro-form-accuracy and nano-meters finish [5].
  - Domain: Micro-components for various systems such as those operating on electronic, mechanical, fluidic, optical, and radiative signals as well as producing dies and moulds for other manufacturing processes [5].

- Micro-EDM: Electrical-Discharge-Machining is a machining process based on material removal by melting and, partly, vaporization [3]. It is able to process functional materials like hardened steel, cemented carbide and electrically conductive ceramics with submicron precision [5].
  - Precision: Submicron [5].
  - Domain: Automotive engine nozzles, spinnerets, micro-moulds and dies, fiber-optics and MEMS, aerospace, medical and biomedical applications, micro-electronics and micro-tools [6]. Figure 2 shows a mold for a 500-μm-long micro-car model.

![Figure 2: A micro-mold fabricated by EDM and a replicated plastic model [3]](image)
Simulation and experimental analysis of cutting forces in 2D ½ milling with small feed per tooth

- **Micro-ECM:** Micro Electrochemical Machining is a machining process based on the electrochemical dissolution of a metal. The material dissolution occurs when the workpiece is made an anode in an electrolytic cell. The cathode tool is separated from the anode by a narrow electrolytic spacing through which electrolyte flows with high velocity. The fundamental mechanisms of electrochemical micro-machining are presented in Figure 3 [7]. It is capable of processing various materials, including high-strength materials. Other attractive characteristics include burr-free surface produced, no thermal damages, no distortion of part and no tool-wear [5].

  - **Materials:** Electrically conductive materials, chemically resistant materials, titanium, copper alloys, super alloys and stainless steel [7].
  - **Precision:** ±1μm [5].
  - **Domain:** Widely used in biomedical, electronic and MEMS applications [7].

![Schematic diagram of the Electrochemical micro-Machining](image)

Figure 3: Schematic diagram of the Electrochemical micro-Machining [7]

- **Micro-LBM:** Laser Beam Machining is a machining process where the laser beam is focused to a small spot [3].

  - **Materials:** Hard-metal, steel, non-ferrous metals, ceramic, glass and polymers [4].
  - **Precision:** ±10μm [3].
  - **Domain:** Hole drilling, removal of surface defects, mask repair, fabrication of optical waveguides, micro-fluidic channels and fabrication of photonic devices [6].
2.1.2 Additive processes

- **Micro-casting**: Replicating process with the aim of mass production which needs a micro-mold insert. Metal injection molding (MIM) and ceramic injection molding (CIM) are methods being developed [3].
  - *Precision*: ±10μm.
  - *Domain*: Stainless steel invasive surgery implant, mold insert for plastic micro-molding, micro-gear, heat sink and structural micro-components [6].

- **SL**: Stereolithography is one of the rapidly advancing methods based on the principle of lamination. The most advanced method of SL is polymerization with laser beam [3].
  - *Precision*: Tenths of micrometers [3].
  - *Domain*: Automotive engineering and widely develop in biomedical engineering [8]. Micro-shapes with very high resolution as shown in Figure 4.

![Figure 4: A micro-bull fabricated using SL. The scale bar corresponds to 2 μm [8]](image)

2.1.3 Deforming processes

- **Micro-forming**: A plastic forming technology. The major issues examined are related to understanding of material deformation mechanisms and material/tool interfacial conditions, materials property characterization, process modeling and analysis, qualification of forming limits, process design optimization, and so on, with emphasis on the related size effects [5].
Simulation and experimental analysis of cutting forces in 2D ½ milling with small feed per tooth

- **Materials**: Metals.
- **Precision**: ±100μm
- **Domain**: Manufacture of pins for IC-carriers, fasteners, micro-screws, leadframes, micro-cups and connectors, as well as medical implants [9].

### 2.1.4 Hybrid processes

- **LiGA**: A micro-fabrication process combining deep X-ray lithography, electroplating and molding manufacturing. Enables the highly precise manufacture of high-aspect-ratio micro-structures with large structural height ranging from hundreds to thousands of micrometers thickness [5].
  - **Materials**: Metals, ceramics and polymers [4].
  - **Precision**: It is possible to build high-aspect ratio shapes, 500 μm tall with 85 μm wide feature. Features as small as 1 μm thick and 10 μm wide have been obtained in materials such as gold, platinum, aluminum and silicon nitride [10]. In Figure 5 it can be seen an example of small different shapes.
  - **Domain**: Actuators, mechanisms, spinnerets, optical components, biomedical devices [11].

![Figure 5: Example of UV-LiGA](image_url)

In Table 1 an schematic summary of all the aspects commented and explained before is presented.
### Table 1: Summary of the different processes in micro-machining

<table>
<thead>
<tr>
<th>Name</th>
<th>Process</th>
<th>Materials</th>
<th>Precision</th>
<th>Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro-cutting</td>
<td>Subtractive</td>
<td>Metals, polymers, infrared crystals</td>
<td>Nanometers</td>
<td>Micro-components, dies, moulds</td>
</tr>
<tr>
<td>Micro-EDM</td>
<td>Subtractive</td>
<td>Hard-metal, steel, non-ferrous metals</td>
<td>Submicron</td>
<td>Automotive, biomedical, electronics</td>
</tr>
<tr>
<td>Micro-ECM</td>
<td>Subtractive</td>
<td>Titanium, copper alloys, super alloys, stainless steel</td>
<td>Micrometer</td>
<td>Biomedical, electronics, MEMs</td>
</tr>
<tr>
<td>Micro-LBM</td>
<td>Subtractive</td>
<td>Hard-metal, steel, non-ferrous metals, ceramic, glass, polymers</td>
<td>Ten micrometers</td>
<td>Drilling, optical, micro-fluidic, photonics</td>
</tr>
<tr>
<td>Micro-casting</td>
<td>Additive</td>
<td>Metals</td>
<td>Ten micrometers</td>
<td>Medical, moulds, micro-components</td>
</tr>
<tr>
<td>SL</td>
<td>Additive</td>
<td>Metals, polymers, ceramics, biodegradable resin materials</td>
<td>Tenths of micrometers</td>
<td>Automotive, biomedical</td>
</tr>
<tr>
<td>Micro-forming</td>
<td>Deforming</td>
<td>Metals</td>
<td>Hundred micrometers</td>
<td>Micro-components, medical implants</td>
</tr>
<tr>
<td>LIGA</td>
<td>Hybrid</td>
<td>Metals, ceramics, polymers</td>
<td>Micrometers</td>
<td>Automotive, optical, biomedical</td>
</tr>
</tbody>
</table>

2.2 Modeling

One of the difficulties in micro-machining is the microscopic level of the phenomena. Moreover, it is also difficult to conduct experiments, make in-process observations and measure results after the experiment. Analytical modeling is still considered quite difficult at the current level of understanding of material behavior. Most analytical modeling efforts are based on kinematics from empirical observation combined with classical cutting models at the macro-level. The applicability and accuracy of these models are subject to many limitations. That is the reason why modeling based on numerical relationships, often accompanied by computer simulation, has become the tool of choice for many researchers [12].
Finite Element Modeling (FEM) has been a widespread simulation technique but it has one critical restriction for micro-machining. FEM is based on principles of continuum mechanics. Therefore, material properties are defined as bulk material properties whereas the material actually behaves in a discontinuous way in a great number of cases of micro-machining. Nonetheless, in most cases of isotropic micro-machining, FEM can still be a suitable modeling method because the process can be reasonably treated in continuum space.

Molecular Dynamic (MD) simulation technique is based on interatomic force calculations. It can include micro-material characteristics as well as dislocations, crack propagations, specific cutting energy, and so on. However, this attractive technique has some limitations. It requires a good representation of interatomic forces among various combinations of atoms involved in cutting, referred to as a potential, which are highly difficult to achieve in a successful way. Since intensive computational power is required, most models are limited to a very small space, such as a nanometer or an angstrom level.

More recently, multi-scale modeling techniques combining FEM and MD have been proposed to overcome the disadvantages of each method and allow the coverage of a wider range of behavior. The main goal is to develop these techniques to cover both atomic and continuum levels of simulation [12].
3. Micro-milling

This work will be focused in micro-mechanical cutting, more specifically in micro-milling. This process is 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. The material removal is performed by a miniature cutting tool rotating at high speed [13]. The down-scaling from macro to micro-milling is not as simple as reducing the dimension of all the process. Unlike conventional macro-machining processes, micro-machining displays different characteristics due to its significant size reduction.

In micro-milling, the cutting edge radius of the mill is comparable in size to the chip thickness. As a result, no chip is formed when the chip thickness is below the minimum chip thickness. Instead, part of the work material plastically deforms under the edge of the tool, and the rest elastically recovers. This change in the chip formation process, known as the minimum chip thickness effect, shown in Figure 6, and the associated material elastic recovery, causes increased cutting forces and surface roughness at low feed rates. Furthermore, when the chip actually forms during cutting with a finite edge radius tool, ploughing under the edge contributes to an increase in the specific energy, also known as size effect. This both effects are widely studied and developed by many researchers [14].

![Figure 6: Schematic representation of the minimum chip thickness phenomenon](image)

3.1 State of the art on force prediction in micro-milling

Measurement of cutting forces during machining provides valuable information about cutting tool condition and represents the state of machining. This leads to the fact that cutting efforts are measured by employing table dynamometers or load cells in the literature to monitor
machining process. However, in micro-milling, measurement of cutting forces is a challenging task and requires high precision equipment [15].

A number of works have been presented on the development of analytical and mechanistic models for predicting the forces in micro-milling. Following there is a short list of well developed analytical cutting force models briefly described.

· Vogler et al. [16, 17] developed a mechanistic force model for heterogeneous materials. Experiments were performed on two compositions of ductile iron, pure ferrite and pearlite workpieces. The minimum chip thickness effect was included in the computation algorithm in two different models: a slip-line plasticity force model and an elastic deformation force model. Finite element simulations were performed to calibrate the parameters of the micro-milling force models for both the ferrite and pearlite phases. Force magnitudes were predicted with average percent errors of 18.5% and 18% for machining pearlite and ferrite, respectively. In Figure 7 it can be observed a comparison of simulated and experimental cutting forces for the ferrite phase.

Figure 7: Simulated and experimental cutting forces for ferrite calibration (high feed) [16]

· Zaman et al. [18] developed a three-dimensional analytical cutting force model incorporating the theoretical chip area with the variation in tool rotation angle for micro end milling. The machining parameters were pre-hardened steel Rochling 2316 with two fluted, coated (AlTiN) micro grained carbide tool with flat end and 30° helix angle and 1 mm in diameter. The mathematical model was validated experimentally and it was found that the proposed model could be used to simulate the cutting forces at 90% average accuracy.
· Jun et al. [19] developed a dynamic micro end milling model to predict cutting forces and vibrations in the presence of alignment errors at the spindle and manufacturing errors at the cutting edges. Besides, it was also developed a chip thickness model for micro end milling that included the effects of minimum chip thickness, elastic recovery, and the elastic-plastic nature in the ploughing/rubbing process.

· Bissacco et al. [20] presented a theoretical cutting force model for micro-milling by considering the cutting edge radius size effect, the tool run-out and the deviation of the chip flow angle from the inclination angle. The model was verified experimentally in micro-milling of Al6082-T6 workpiece material and it was concluded that predicted and measured forces showed good agreement, as it can be observed in Figure 8. Furthermore, it was observed that the force unbalance produced by tool run-out is effectively compensated by the tool deflections in the radial direction.

![Figure 8: Comparison between measured and calculated cutting force components [20]](image)

· Filiz et al. [21] used an analytical model of the transverse vibration of rotating micro end mills in the presence of three-dimensional tilt and rotary axis misalignment. The developed analytical model, and the spectral Tchebychev solution used to numerically solve the model, were capable of accurately capturing the dynamic behavior of micro end mills. It was also shown that the geometric characteristics of micro end mills had a dominant effect on their dynamic behavior.

· Lai et al. [22] modeled the material strengthening behaviors by using a modified Johnson–Cook constitutive equation. A finite element model for micro-scale orthogonal machining
Simulation and experimental analysis of cutting forces in 2D ½ milling with small feed per tooth

The process was developed including the material strengthening behaviors, micro tool edge radius and fracture behavior of the workpiece material. An analytical micro-milling force model based on the finite element simulations using the cutting principles and the slip-line theory was developed. Experiments were conducted on OFHC copper workpiece material and good agreements were obtained between the predicted and the experimental results. It was also found that size effect in micro-machining is caused by the size effect of material behaviors at the micron level. In Figure 9 it can be seen that the milling force predicted by the model with material strengthening behaviors matches well with the experimental data and can captures the size effect.

![Figure 9: Comparisons of milling force between results with and without considering size effect [22]](image)

· A mechanistic model, considering both the shearing and ploughing dominant cutting modes, was developed to predict micro-milling forces of Al7075 material [23]. This model assumes that there is a critical chip thickness that determines whether the cutting regime is shearing or ploughing dominant. Due to the high rotational speeds of micro end mill, the bandwidth of the conventional table dynamometer could not provide accurate measurements and the Kalman filter (KF) method was used to compensate for the unwanted dynamics and identify the cutting constants.

· Afazov et al. [24] developed a new cutting force model in micro-milling of AISI 4340 steel using the finite element model considering the trajectory of the tool, run-out, spindle angular velocity, uncut chip thickness, tool edge radius, rake angle, tool-workpiece contact, chip formation and the thermo-mechanical behavior of the workpiece material. It was shown that the predicted and the measured forces were in very good agreement. The temperature increased with increasing the velocity and the uncut chip thickness. It was found that the
cutting forces in the cutting direction decreased by increasing velocity whereas tangential forces were independent from velocity as observed in Figure 10. The forces in tangential and cutting directions slightly increased with increasing the edge radius. This was due to the fact that the contacting length at larger radii was longer and this created more friction.

![Figure 10: Cutting forces obtained in: (a) the cutting direction; (b) the tangential direction](image)

The main goal of this present work is to validate a finite element model presented in [13] by performing an analysis of the cutting forces in micro-milling. The results of this model will be used as an input to a global dynamic model of the machining process, developed in [25, 26]. The lagrangian finite element method model is characterized by allowing to study changes on the cutting mechanism from macro to micro-cutting. This 2D plane strain orthogonal cutting model is focused on the area where the chip is formed, close to the cutting tool. The cutting tool is modeled with a finite cutting edge radius of 20 μm whereas its rake and clearance angles are 15° and 2° respectively. The tool material is tungsten carbide and the workpiece material is Ti6Al4V.

This work presents an experimental investigation of several test cases with different cutting conditions. The effects of the cutting forces of these experiments will be compared to the results of the global simulation. The comparison between the two approaches will determine if the cutting force model from FEM simulation is suitable enough to reproduce micro-milling operations.
4. Presentation of experimental tests

An experimental approach is performed in order to check the behavior of the cutting force values. This measurement data achieved will be analyzed and compared afterwards with the simulation results so as to verify the proposed modeling scheme.

4.1 Experimental setup

Two different types of machining tests were planned to be carried out: slot milling and shoulder milling. Slot milling consist in machining a narrow channel on the surface of the workpiece, whereas shoulder milling performs peripheral cuts on the workpiece. Figure 11 shows a schematic representation of both operations.

![Figure 11: Representation of (a) slot milling and (b) shoulder milling. Adapted from [27]](image)

Experiments consist in a downmilling of titanium alloy Ti6Al4V test workpieces with a carbide cutter. Table 2 shows the characteristics of the tool.

<table>
<thead>
<tr>
<th>Name</th>
<th>JS513</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shank</td>
<td>Cylindrical</td>
</tr>
<tr>
<td>Diameter</td>
<td>$D$</td>
</tr>
<tr>
<td>Number of flutes</td>
<td>$z_n$</td>
</tr>
<tr>
<td>Helix angle</td>
<td>$\epsilon$</td>
</tr>
</tbody>
</table>

Table 2: Tool parameters

In order to register the experimental efforts, a MiniDyn 9256C Kistler dynamometer showed in Figure 12 was used. It was screwed and fixed on the milling machine table. The
dynamometer allows to measure the three orthogonal components of the forces that are being performed in the workpieces. The dynamometer is connected to a charge amplifier from which the output voltage signals are fed into a tape recorder and the signals are recorded at a sampling frequency. Then, the signal is registered by a computer software which creates a data file that can be processed afterwards.

Figure 12: Picture of the Kistler dynamometer fixed to the milling machine

The titanium workpieces are clamped on the dynamometer while the experimental tests are being performed so they have to couple with it. Figure 13 shows a workpiece being machined by the cutting tool.

Figure 13: Picture of a workpiece, the dynamometer and the cutting tool during a milling operation

The pieces have been designed following the specifications of the Kistler dynamometer leading a rectangular sample of 40 mm x 40,5 mm, as shown in the sample drawing of the
Appendix A. It has to be pointed out that the experiments are done along the shortest side, i.e., lengthways the 40 mm side (see Figure 14).

Figure 14: Picture of the titanium piece clamped to the dynamometer

4.2 Experimental plan

Following, Table 3 and 4 contain a list of tests which have been experimentally done. Fifteen slot milling tests and fifteen shoulder milling tests were planned to be performed, most of them twice. In the tables it can be seen all the values which determine the type and parameters of the experimental test. This values are the cutting speed ($v_c$), the axial depth of cut ($ADOC$), the radial depth of cut ($RDOC$) (see Figure 15), the feed per tooth ($f_x$), the spindle speed ($n$), the feed speed ($v_f$) and the experimental time ($t$) of each test.

Figure 15: Schematic representation of (a) axial depth of cut and (b) radial depth of cut. Adapted from [27]
The relations between the cutting parameters are presented in the equations below. Equation 1 computes the spindle speed, in Equation 2 the feed speed is obtained and the Equation 3 measures the time needed to carry out one experimental test.

\[ n = \frac{v_c \cdot 1000}{\pi \cdot D} \]  \hspace{1cm} (1)

\[ v_f = n \cdot z_n \cdot f_z \]  \hspace{1cm} (2)

\[ t = \frac{L}{v_f} \]  \hspace{1cm} (3)

Where \( D \) is the diameter of the tool, \( z_n \) is the number of teeth and \( L \) is the shortest length of sample, as aforementioned.

The axial depth of cut selected to perform both types of tests is 2 mm whereas the radial depth of cut which is used in shoulder milling is 1 mm. So as to settle on the experimental values of every test, two of them, one of every type, have been established with the default values parameters found in the cutting data of the tool’s catalog. On that basis, three cutting speed values with five feed per tooth values in a range of \( \pm 20\% \) the default cutting data values have been combined in order to develop the remaining tests. It has to be noticed that the first tests with the default values have been bolded in the tables.

So Table 3 presents the slot milling tests, with test number one bolded referred to the default values. It should be pointed out that the last three tests marked with an asterisk (*) were performed with a continuous flow of lubricant, which effect will be analyzed afterwards.

<table>
<thead>
<tr>
<th>Test</th>
<th>( v_c ) [m/min]</th>
<th>( ADOC ) [mm]</th>
<th>( f_z ) [( \mu )m]</th>
<th>( n ) [rev/min]</th>
<th>( v_f ) [mm/min]</th>
<th>Experiments</th>
<th>( t ) [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>2</td>
<td>6</td>
<td>9550</td>
<td>172</td>
<td>2</td>
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<td>4</td>
<td>48</td>
<td>2</td>
<td>6</td>
<td>7640</td>
<td>138</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>48</td>
<td>2</td>
<td>6,6</td>
<td>7640</td>
<td>151</td>
<td>2</td>
<td>16</td>
</tr>
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<td>48</td>
<td>2</td>
<td>7,2</td>
<td>7640</td>
<td>165</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>60</td>
<td>2</td>
<td>4,8</td>
<td>9550</td>
<td>138</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>8</td>
<td>60</td>
<td>2</td>
<td>5,4</td>
<td>9550</td>
<td>155</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>9</td>
<td>60</td>
<td>2</td>
<td>6,6</td>
<td>9550</td>
<td>189</td>
<td>2</td>
<td>13</td>
</tr>
</tbody>
</table>
Simulation and experimental analysis of cutting forces in 2D ½ milling with small feed per tooth

Table 3: Parameters of experimental slot milling tests

Table 4 shows the shoulder milling tests. These begin machining a slot with the default values of the first test in Table 3, marked here in Table 3 with an asterisk (*). This fact will allow to verify if there are great differences in the cutting forces in the same conditions between two different workpieces. Second test is bolded making reference to default parameters took from the tool’s catalog.

Table 4: Parameters of experimental shoulder milling tests
Besides the ordinary experimental values a test have been done with unconventional parameters so as to show which will be the effects. The feed per tooth has been decreased until 2 μm. Table 5 shows the cutting parameters of this test.

<table>
<thead>
<tr>
<th>Test</th>
<th>$v_c$ [m/min]</th>
<th>$A DOC$ [mm]</th>
<th>$f_x$ [μm]</th>
<th>$n$ [rev/min]</th>
<th>$v_f$ [mm/min]</th>
<th>Experiments</th>
<th>$t$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>2</td>
<td>2</td>
<td>9550</td>
<td>57</td>
<td>2</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 5: Parameters of experimental side milling test with really small feed per tooth

4.3 Signal analysis

In order to process the signal registered by the dynamometer some aspects have to be taken into account. The dynamometer could not be well calibrated, so the zero value would not correspond to the reality. Moreover, before the cutting tool starts to machine the workpiece, the signal is already being recorded, therefore there is a part of the signal which shows no efforts and does not have to be processed to compute the results. The same happens when the cutting tool finishes machining. There is some time where the dynamometer keeps recording although the operation is finished.

Here above are the steps which have been followed to analyze the signal. First of all, in Figure 16 a raw signal of the cutting force in feed direction for the whole measurement time can be observed. It should be noticed that, as expected, the signal while no effort is being made does not exactly correspond to the zero value, so it has to be properly corrected. The example signal presented in this chapter corresponds to the first test performed of slot milling with a cutting speed of 60 m/min and a feed per tooth of 6 μm.

So as to correct the values, the mean value of an amount of the first 35000 measurements of the signal is computed. Then, the mean value is subtracted from all the measurements for a first correction. This adjustment is not completely exact since only a few of the values have been taken into account, but it should be enough to find the time step where the tool begins and finishes machining.
After the correction, the first and final significant efforts are searched by given a threshold. This threshold has been established on 3 N after reaching a satisfactory result after several trials. Figure 17 presents the signal of the total force with the first adjustment and with a limited area corresponding to the significant values which will be computed afterwards.
Once the significant values are found, a second correction can be performed with more precision taking all the values close to zero. To do that, the mean value is recomputed taking now the non-significant measurements from the beginning and the end of the signal and subtracted to the rest. The final signal for the force along feed direction is presented in Figure 18. It can be observed that the zero value is now well corrected.

![Signal of force along feed direction against time corrected and limited](image)

Figure 18: Signal of force along feed direction against time corrected and limited

In order to perform this entire signal analysis a program employing the software MATLAB has been created and used. The code of this program is presented in Annex B.
5. Presentation of simulation approach

Milling operations are very complex processes affected by some many parameters that it is quite impossible to take all the factors into account at the same time in a simulation. A local approach with a finite element model simulation is useful sometimes, but with complex operations, results can be difficult to achieve because of their long computation time. A more global approach is then used to simulate these cases. In this work a dynamic model simulation has been performed to analyze the cutting forces of the operations.

The simulation software employed is DyStaMill which has been developed at the University of Mons [25]. This software is based on three aspects so as to simulate milling phenomena: prediction of the relative displacement between the workpiece and the tool, modeling of the material surface and modeling of the cutting forces. These three global models are coupled together in order to become a complete and efficient global model [26].

In order to get relative movements between the tool and the workpiece, cutting forces acting on the tool are taken as an input for the dynamic model of the system. Displacements obtained can be used to describe material surface generation and therefore, to compute chip thickness [25].

The surface generation model is a geometric computation where the tool is divided on elementary layers along its axis, as shown in Figure 19. For each slice and at each time step, the area swept by the cutting edge is removed from the geometrical model of the workpiece. The minimum chip thickness phenomena is also taken into account by this model [26].

![Figure 19: Discretisation of a tool into slices](image)

The cutting force model is based on analytical integration of all the elementary efforts produced to the tool. Equation (4) presents the general equation used to compute cutting
forces for each disc, where $dF$ is the elementary effort, $K$ is the specific pressure, $h$ is the undeformed chip thickness and $da$ the height of each slice.

$$dF = K \cdot h \cdot da$$  \hspace{1cm} (4)

The dynamic simulation developed in [25] takes Equation (4) as its basis. From this equation a numerical model is presented in [26] to get specific pressure. This exponential model is presented above. The specific cutting forces are modeled as $K_c$ on cutting direction and $K_f$ along feed direction, in Equation 5 and Equation 6 respectively. The $h$ is the uncut chip thickness.

$$K_{c[MPa]} = 3266,5h^{-0.243}_{[\mu m]}$$  \hspace{1cm} (5)

$$K_{f[MPa]} = 19818h^{-0.834}_{[\mu m]}$$  \hspace{1cm} (6)

In order to validate the model obtained from FEM simulation, several simulations were performed. The cutting force results will be analyzed and compared with the experimental ones in the later sections. The different test cases have the same parameters used in the experimental approach. The data for the simulation is a downmill of three cutting edges, a diameter of 2 mm, an helix angle of 20º, axial depth of cut of 2 mm and radial depth of cut of 1 mm when shoulder milling is simulated. During the computation, the exponential model aforementioned is taken as an input and the tool is divided in 100 layers.

5.1 Analysis of simulated results

Once the simulations have been performed, its results can be analyzed. Figure 20 presents the behavior of the three orthogonal efforts in one revolution from a slot milling test with a cutting speed of 60 m/min and a feed per tooth of 6 μm. It should be pointed out that the $x$ component of force is performed along feed direction, $y$ component of force is perpendicular to feed direction and $z$ component of force is in the direction of the cutter axis.
Simulation and experimental analysis of cutting forces in 2D ½ milling with small feed per tooth

Figure 20: Orthogonal forces from a simulated slot milling test

The efforts in one revolution from a shoulder milling test with a cutting speed of 75 m/min and a feed per tooth of 10 μm are presented in Figure 21.

Figure 21: Orthogonal forces from a simulated shoulder milling test
From Figures 20 and 21 it can be observed that the force along the cutting axis is zero while the other efforts vary between two values. The three repetitions showed in every plot refer to every of the three teeth that the cutting tool has. This repetitions show when the teeth are removing material and when not.

Several tests cases have been simulated in order to be compared to experimental cutting forces in the same conditions. Hence, the simulation results have been computed to extract the root mean square and plotted in a graph against feed per tooth.

Figure 22 shows the cutting efforts against feed per tooth in slot milling simulation. It should be pointed out that as far as the cutting force model does not take into account the cutting speed, the values of the forces do not change from one simulation to another. Nevertheless, values change with respect to the feed per tooth, showing a slightly increasing tendency, with the exception of the force along the cutting tool axis which values are zero.

![Figure 22: Cutting forces against feed per tooth in slot milling simulation](image)

Concerning the shoulder milling simulation, a same statement as before could be done. Figure 23 presents the three orthogonal efforts of the cutting force in shoulder milling simulation, although the increasing tendency is less clear in this case.
Figure 23: Cutting forces against feed per tooth in shoulder milling simulation
6. Analysis and comparison of results

6.1 Experimental tests

The data results have been computed in order to extract the root mean square of each of the three orthogonal efforts (x, y and z) and the resulting total force. As aforementioned, the x component of force is the one along feed direction, y component of force is performed perpendicularly to feed direction and z component of force is in the cutter axial direction.

In Figure 24, it can be observed the total force against feed. The effort shows a logical increasing trend against feed. In the same plot, the measurements of the tests with really small feed per tooth are also presented (diamond). These measurements follow the linear trend, which means that the non-linear singularities have been reached. The experimental tests performed with a constant flow of lubricant, marked as circles, reflect no significant changes in the total force from the other tests.

![Figure 24: Total force against feed per tooth in slot milling tests](image)

Regarding the three orthogonal components of the force, a similar assessment can be done for Figure 25 and 26, presenting both Fx and Fy forces respectively. The increasing tendency is also seen in the two plots and tests with really small feed per tooth are in good correlation with it.
Nevertheless, Figure 27 with axial force presents two considerable aspects. On one hand, the increasing trend clearly observed in all the previous plots is not followed so accurately. On the other hand, tests with a constant flow of lubricant show a substantial effect in two of the three cutting speed.
The erratic behavior of the trend along with the visible effects of the fluid might be due to the chip separation. In the course of the slot milling tests, a bad chip separation was noticed. The machined slots in the workpiece were not completely clean after machining the non-lubricated tests. In contrast, after performing the slot milling tests with a constant flow of lubricant, the slots were entirely out of chip, as shown in Figure 28.

This effect could be also related with the change in the direction of the axial force noticed in the signal of the effort. Figure 29 shows this behavior of the axial force against time in one of the slot milling test with a cutting speed of 60 m/min and a feed per tooth of 6 μm.
In terms of shoulder milling, the results show pretty clearly the linear regression and the increasing tendency expected. This statement can be observed in Figures 30, 31 and 32, representing the total force, Fx force and Fy force respectively.
At this point it should be mentioned that the force results of the second repetition of the tests are quite equal than the first ones. It is not showed a big difference between the measurements of two tests with the same cutting parameters.
Figure 33 presents the axial force of shoulder milling. The trend continues being a linear regression in increasing tendency. However, unlike the plots of the other two orthogonal components of the force, the order of the disposition of the cutting speed values has changed.

As an explanation of this behavior it could be guessed that this differed patron in the axial force is due to chip separation as occurred in slot milling tests. During the machining of the shoulder milling tests, the chip separation was irregular and some chip was left out on the workpiece. Figure 34 shows this effect.
Once the experimental results have been presented and analyzed several conclusions can be drawn. There is a repeatability between experimental tests with the same cutting conditions. The efforts slightly change when the test is performed twice with the same cutting parameters. This effect leads to the fact that a change in the sample workpiece does not influence much in the results of the cutting efforts.

In a general vision, all the efforts plotted against feed per tooth show a linear increasing tendency as expected. Only the behavior of the force along the direction of cutting tool axis is quite erratic. In this effort it can be also observed that the experimental tests performed with a constant flow of lubricant show great differences from the test with no fluid. This effect could be explained by the bad chip separation observed in the course of the experiments. The machined workpieces had chip left after performing both slot and shoulder tests.

6.2 Comparison experiment-simulation

Several test cases of global simulation for the developed cutting force model have been included here and are compared with the experimental findings. Both the results of the experimental and simulation approach are graph as time dependant lasting one revolution in order to be an easier comparison.

The test case picked to be compared in slot milling is the one with the default values, that is a cutting speed of 60 m/min and a feed per tooth of 6 μm. Figure 35 shows the comparison between simulated total effort (bolded) and the experimental (plain). The simulation plot shows, as expected, three clearly lobes referring to the three teeth that the tool has. At first appearance, the experimental force only presents two of the three lobes which leads to the fact that not every tooth of the tool is working in the same way.
In order to make a better statement about the similarities between the simulation and the experimental forces and take a closer look to the tooth removal effect, the three orthogonal efforts are presented. In Figure 36 the force along feed direction is compared. It shows that at the beginning of the experimental revolution, a great amount of material is removed by only one tooth and later the removal is less intense.
In the plot of the force perpendicular to feed direction in Figure 37, the effect described is less clear, but it can be observed that not all the teeth of the tool are removing the same amount of chip from the workpiece.

![Graph showing force perpendicular to feed direction](image)

Figure 37: Simulated force perpendicular to feed direction (bolded) compared with the experimental in a slot milling test.

Finally, the axial force is presented in Figure 38. The values of the simulation and the experimental efforts are quite similar but showing two small lobes in the experimental tests referring to two of the three teeth of the tool.
Following a shoulder milling test case is compared between global simulation and experimental approach. The chosen shoulder milling test has a cutting speed of 75 m/min and a feed per tooth of 10 μm, which are the default parameters found in the cutting data. In Figure 39 the comparison between the simulated and experimental total effort is presented. It can be clearly observed that there is only one tooth of the tool removing all the material meanwhile the other two teeth barely take chip out.
In Figure 40, the same effect of one tooth material removal is observed in the force along feed direction. It should be pointed out that the simulation model makes a good approximation of the lobe in the tooth that is removing all the material from the workpiece.

![Graph showing force along feed direction](image)

Figure 40: Simulated force along feed direction (bolded) compared with the experimental in a shoulder milling test

In both Figures 41 and 42 the effects are less visible. The experimental force perpendicular to feed direction shows a small lobe one step of the revolution and no more effort for the rest. In the plot of the cutting axis force the efforts in both simulated and experimental approaches are nearly zero.
Taking into account all the effects observed in the previous plots, it can be state that the tool has one tooth which is taking out almost all the material from the workpiece whereas the other two teeth are not machining as expected. This different behavior between the teeth leads to a possible run-out of the tool as a result of problems with physical dimensions or with an arrangement of the components between the tool and the milling machine. The effects of an
off-centered tool in the milling machine combined with a misalignment between the rotational axis of the cutting tool and the central axis of the system could be very substantial in micro-milling operations.

Concerning the validity of the model, although the trend in the plots between the simulation and the experimental efforts is the same, the values of the forces are pretty different to consider the model correct. This discrepancies can come from the fact that some cutting conditions are different. The main different aspect is that the cutting edge radius of 20 μm on the finite element model, therefore in the simulations, is quite big compared to the cutting edge radius which might be present on the real cutter.

As the agreement between the model and the experimental tests is not good enough, it could be done an inverse analysis in the simulation software DyStaMill. In [28] a cutting force model taking the run-out of the tool into account was developed. This model along with the inverse analysis will be used to check the behavior. This global simulation allows to know which should be the optimal parameters for a given measurement. The test case chosen is the slot milling test with the default values. The results are presented in Figure 43.

![Figure 43: Optimal efforts for a slot milling test obtained with an inverse analysis](image)

The analysis suggests that there is an important run-out of the cutter which leads to the fact that one tooth takes most of the material in one revolution. This fact is in good agreement with the stated in the previous comments. The run-out obtained in the analysis is of 50 μm. In addition, as a result, the cutting force model with the optimal parameters is presented in
Equation 7 and Equation 8, representing the specific pressure along cutting direction and along feed direction respectively.

\[ K_{c[MPa]} = 25000h_{[\mu m]}^{-0.42} \quad (7) \]

\[ K_{f[MPa]} = 60500h_{[\mu m]}^{-0.42} \quad (8) \]

Another explanation for the bad agreement with the model and the experimental approach could be because of the effect of the minimum chip thickness. However, this fact could not be tested because inverse analysis module do not take this effect into account.
7. Conclusions and future work

The increasing demand of high-accuracy complex three-dimensional shapes of micro-pieces in several industries has forced to develop new technologies of manufacturing. New techniques are being adapted to micro-manufacturing by down-scaling the parameters from a macro-level and studying the effects that these new micro-size operations involve. Micro-cutting is an essential process characterized by material removal with a cutting tool.

Micro-milling is one of the process included in the field of micro-cutting. This micro-manufacturing technique is required for some special features such as sharp edges, tight tolerances and good surface finish and it also has a great productivity. This process can also produce complex tridimensional forms and shapes in many materials.

A global simulation approach employing DyStaMill software takes a finite element model as an input for the modeling of cutting forces. The validation of this numerical model is carried out by comparing the simulation computations with experimental findings.

Simulation results show different cutting force patrons in both slot milling and shoulder milling tests. The force along the cutter axis is zero while the other two forces show three repetitions in one revolution according to the three teeth that the tool has. In addition, the root mean square of the simulation cutting forces show a slightly increasing tendency against feed per tooth.

With the experimental measurements it can be concluded that a repeatability is presented between tests with same cutting parameters, therefore the change in the workpiece barely affects. The plots of the root mean square of the forces against feed per tooth in both slot milling and shoulder milling tests present an increasing trend as expected. Only an erratic behavior is observed in the axial force along a substantial difference between the results of the tests with a constant flow of fluid and the non-lubricated tests. A first guess has been made by assuming that the bad chip separation was causing the strange behavior since the machine workpieces had chip left in its slots and shoulders.

The comparison between the simulation and the experimental approach show a run-out of the cutting tool meaning that one tooth removes all the material from the workpiece. The comparison also indicates that the model is capable enough to simulate force behavior in the experimental tests but the values of the force efforts show a big difference. This could be because of the different cutting edge radius between FEM simulation and the real one.
Concerning the aim of the work of verifying that the FEM model could be taken so as to simulate micro milling operations, after analyzing the results it can be concluded that the model is not correct enough. Nevertheless, the simulation with inverse analysis taking into account the run-out of the tool shows that the model itself is able to reproduce the cutting forces signal but the parameters of the specific pressure must be properly adapted.

As a future work it could be performed an inverse analysis on all the signals to see if the trend is the same concerning the run-out of the tool and the values of the parameters of the specific pressure. Once this analysis is performed, the model could be improved with new optimal parameters.

The erratic behavior with the experimental force along the cutting axis direction must be investigated since the bad chip separation is only a guess and the change on the direction on the signal could not have been explained.

Finally, it should be tested both hypothesis of minimum chip thickness and tool run-out to clearly verify which is the effect causing the behaviors presented in the cutting forces.
8. References


Simulation and experimental analysis of cutting forces in 2D½ milling with small feed per tooth


Annex A. Samples drawing

All dimensions in millimeters.
The ↑ shows the place where the experiments will begin and the direction of cut.
Annex B. Signal analysis program code

```matlab
function [rmsx, rmsy, rmsz, rmsF]=signal_analysis(file)

%Parameter which determines the distance between two values to consider if any of them are significant
threshold=3;

%Open the file to read the content
fid=fopen(file,'r');
A=textscan(fid,'%f %f %f %f','headerlines',20);
A=cell2mat(A);
fclose(fid);

%Columns from the measurements file
t=A(:,1)';
x=A(:,2)';
y=A(:,3)';
z=A(:,4)';

%Mean values from the first 35000 measurements
mx1=mean(x(1:35000));
my1=mean(y(1:35000));
mz1=mean(z(1:35000));

%Fisrt correction of the values to shift for the zero
x1=x-mx1;
y1=y-my1;
z1=z-mz1;

%Total force with the values of first correction
F1=sqrt(x1.^2+y1.^2+z1.^2);

%Look for the first significant value with a given threshold
i=2;
while i<=length(x1)
    if abs(x1(i)-x1(i-1))<threshold
        i=i+1;
    else
        t0=t(i);
        break
    end
end

%Look for the last significant value with a given threshold
k=length(x1);
while k>=length(x1);
    if abs(x1(k)-x1(k-1))<threshold
        k=k-1;
    else
        t1=t(k-1);
        break
    end
end
```

% Position of the significant values
pt0 = find(t == t0);
pt1 = find(t == t1);

% Plot of the total force against time with lines to delimit the significant area
if (0)
    plot(t, F1, '.');
    hold on
    plot([t0 t0], [0, 70], 'r');
    plot([t1 t1], [0, 70], 'r');
    hold off
    xlabel('Time [s]')
    ylabel('Force [N]')
end

% Mean values from the non-significant values
mx2 = mean([x(1:pt0) x(pt1:length(x))]);
my2 = mean([y(1:pt0) y(pt1:length(y))]);
mz2 = mean([z(1:pt0) z(pt1:length(z))]);

% Second correction of the values to shift for the zero
x2 = x - mx2;
y2 = y - my2;
z2 = z - mz2;

% Compute the total force and the rms value of each effort with the values of the second correction
F2 = sqrt(x2.^2 + y2.^2 + z2.^2);

rmsx = sqrt(mean(x2(pt0:pt1).^2));
rmsy = sqrt(mean(y2(pt0:pt1).^2));
rmsz = sqrt(mean(z2(pt0:pt1).^2));
rmsF = sqrt(mean(F2(pt0:pt1).^2));