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Micro milling cutting forces on machining aluminium alloy

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Key Words: micro milling, mechanistic models, cutting forces

INTRODUCTION

Miniaturization has increased over the last decade and, as a consequence, manufacturing of micro parts for bioengineering and aerospace applications are one of the areas there is a need of research and development. Micro milling is a flexible machining process that allows the fabrication of high quality parts.

Cutting force analysis plays a vital role in studying the micro milling processes. The stress variation on the shaft of a micro-tool is much higher than that on a conventional tool, as in micro milling operations the feed per tooth to tool radius ratio has to be higher than in conventional milling to keep productivity at a reasonable level [1]. Due to the small size of the micro-tools, it is very difficult to notice the damage in the cutting edges and an inappropriate selection of the cutting conditions can cause the tool to brake unexpectedly. The micro-tools used in this operation have a diameter of less than 2 mm.

In machining of metallic components, the size of the part plays an important role, called size effects. Even if the relationship between the main geometrical features is kept constant, the process behavior changes. Vollertsen et al. [2] presented a review on effects of size effect and their use: the article presents the typology of size effects, a description of size effects on strength and tribology and size effects on formability and machinability.

Camara et al. [3] presented a state of art on micromilling with emphasis on the work material requirements, tool materials and geometry, cutting forces and temperature, quality of the finished product, burr formation, process modeling and monitoring and machine tool requirements.

Two process mechanisms, ploughing and chip formation, are involved in micromachining. A critical cutting thickness needs to be exceeded to involve both phenomena. Ramos et al. [4] studied the minimum uncut chip thickness.

Besides the ploughing mechanism, where part of the material is plastically pushed against the workpiece surface when $t_c < t_{cmin}$, there is also the mechanism of elastic deformation, when the deformation forces are proportional to the interference volume between the tool and the workpiece when $t_c \ll t_{cmin}$ [5].

Similarly, Malekian et al. [6] used the minimum uncut chip thickness, under which the material is not removed but ploughed, and claimed that this effect causes an increase

of machining forces that affect the surface integrity of the workpiece.

Microstructure has a significant effect on microscale cutting. Simoneau et al. [7] investigates the effect of grain size and orientation during microcutting in FE modeling of the primary shear zone. Their research group [8] analyzed the orthogonal cutting in microscale. Tests were conducted on steel and the resulting chips examined, showing that the chip formation changes from continuous to “quasi-shear-extrusion” chip due to the uncut thickness size. The results indicate that the pearlite and softer ferrite grains play distinct roles in the plastic deformation process.

Abouridouane et al. [9] investigate size effects by down scaling the twist drilling using a Lagrangian formulation proposed in the implicit code. He also presented a new three-dimensional multiphase finite element computation model for the simulation of micro drilling two-phase ferritic-pearlitic carbon steels [10]. This article analysed the cutting mechanism, the ploughing phenomena, tribological and heat transfer mechanisms at the microscale.

Jin and Altintas [11] presents the prediction of micro-milling forces using cutting force coefficients evaluated from the finite element simulations of orthogonal micro-cutting process and compared to experimental turning results. The milling forces in their model are calculated based on the local geometry and chip load.

Bao and Tansel [1] proposed an analytical force model for micro end milling process based on Tlustý's model [12] but using a new expression for the chip thickness. They computed by the trajectory of the tool tip and observed that the model gives a good result at higher feed rate which supports his assumption that feed per tooth to tool radius is larger in micro end milling than in the conventional end milling operation.

Zaman et al. [13] established a new concept to estimate the cutting force in micro end milling by estimating the theoretical chip area instead of undeformed chip thickness.

Pérez et al. [14] developed a new model for the estimation of cutting forces in micromilling based on specific cutting pressure. The proposed model includes three parameters which allow to control the entry of the cutter in the workpiece and which consider also the errors in the radial position of the cutting edges of the tool. The new mechanistic force model determines the instantaneous cutting force coefficients using experimental data processed for one cutter revolution. The model has been validated through experimental tests over a wide range of cutting conditions. The re-

sults obtained show good agreement between the predicted and measured cutting forces.

Rodriguez e Labarga [15] developed a new cutting force prediction model in micromilling operations for application on machining monitoring systems, considering the most influents factors of the process, like tool deflection, runout, scale effect and . Experiments carried out on Aluminum 7075 and AISI 1045 steel presented a good concordance with simulated results.

Kang et al. [16] developed a mechanistic model to predict the cutting force in micro milling and its influence on tool wear and superficial roughness of Al 7075 alloy. Experimental results showed good concordance and the raise of the feed per tooth indicated a raise of the cutting force values.

This article compares mechanistic models for micro milling process considering homogeneous grain properties. It is not taken into account dynamic behavior of tool and interactions between tool-workpiece due to stiffness or grain variation. Experimental data is used to calculate specific pressure in different approaches and compare results between models.

CUTTING FORCE MODELLING

The knowledge of cutting forces is fundamental for tool optimization and it is very important to avoid tool breakage and instability. In micro milling, those factors are even more relevant due to the high cost of tools, that breaks very easily. Meso and micromilling models are presented.

A. CHIP LOAD CUTTING MODEL

Elemental normal and frictional forces are required to the determination of cutting forces for a given geometry. The mechanistic modeling approach is a combination of analytical and empirical methods in which the forces are proportional to the chip load [17].

The specific cutting pressure, K_n , K_f and K_z , have been shown as a function of chip thickness t_c in mesoscale milling process and it is used for calculation of dF_n , dF_f and dF_z on each angular position θ of the discretized cutting edge, proportional to the chip load area dA as shown in (1).

$$\begin{aligned} dF_t(\theta) &= K_t dA(\theta) \\ dF_r(\theta) &= m_1 K_t dA(\theta) \\ dF_z(\theta) &= m_2 K_t dA(\theta) \end{aligned} \quad (1)$$

Using a semi empirical modeling as [12], relating specific cutting pressures by empiric factors m_1 and m_2 .

Chip area is calculated based on uncut chip thickness $t_c(\theta)$, that is called Martellotti equation:

$$t_c(\theta) = f_t \sin(\theta) \quad (2)$$

The specific cutting pressure is calculated as:

$$\ln K_t = a_0 + a_1 \ln t_c + a_2 \ln V_c + a_3 \ln t_c \ln V_c \quad (3)$$

The coefficients a_0 , a_1 , a_2 and a_3 are called specific cutting energy coefficients. They are dependent on the tool and workpiece materials and also on the cutting speed and the chip thickness. They are determined from calibration tests for a given tool work piece combination and for a given range of cutting conditions.

B. CHIP LOAD AND CUTTING EDGE MODEL

The differential tangential, radial and axial cutting forces can be separated in cutting area dependent part and cutting edge part, as in (3) [14].

$$\begin{aligned} dF_t(\theta) &= K_{tc} t_c(\theta) db + K_{te} db \\ dF_r(\theta) &= m_1 K_{rc} t_c(\theta) db + K_{re} db \\ dF_z(\theta) &= m_2 K_{zc} t_c(\theta) db + K_{ze} db \end{aligned} \quad (4)$$

C. CHIP THICKNESS CORRECTION IN MICRO CUTTING MODEL

Bao [1] developed a more precise expression then Martelotti calculation for uncut chip thickness $t_c(\theta)$ used by Newby et al. [18] to calculate average uncut thickness.

$$t_c(\theta) = f_t \sin(\theta) - \frac{z}{2\pi r} f_t^2 \sin(\theta) \cos(\theta) + \frac{f_t^2}{2f} \cos^2(\theta) \quad (5)$$

D. SIZE EFFECT BY PLOUGHING

Ploughing effect under minimum uncut chip thickness, which was modeled by different approaches. Liu et al. [19] modeled considering analytical model using slip line theory and Johnson-Cook model. Malekian et al. [6] presented an article on micromilling of aluminium, which is used in this article based on the edge radius r_e and on a critical or stagnant angle, φ_m .

$$t_{cm} = r_e (1 - \cos(\varphi_m)) \quad (6)$$

The stagnant angle is considered equal to the friction angle between the material and the rake face, regardless of the other parameters involved in the process.

EXPERIMENTAL SETUP

In order to analyze micro milling forces and compare to modeled results, experiments were performed.

E. MATERIAL, TOOLS AND EXPERIMENTS

The workpiece material selected for the experiments is an aluminum alloy (Al 6351-T6), which is an AlMgSi alloy usually applied in the automotive, construction engineering and shipbuilding industries. The overall workpiece dimensions are 47x50x15 mm, in which a small area is faced to be subjected to the experimental machining.

It was used a carbide micro-milling tool, very often applied in medical, aerospace and electronic areas, with 0.381 mm diameter and 1.143 mm flute length, as showed in Figure 1 based in manufacturer information.

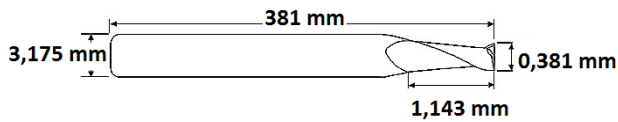


Figure 1: Tool Dimensions

The cutting tool was measured in SME microscopy. As the cutting edge radius has strong influence on the cutting force model chosen, the images presented on Figure 2 were taken. Using those SEM images, the helix angle, point radius and cutting edge radius is measured. The tool has point tip radius of 2,5 μ m, cutting edge radius of 0,5 μ m and $\beta=30^\circ$ helix angle.

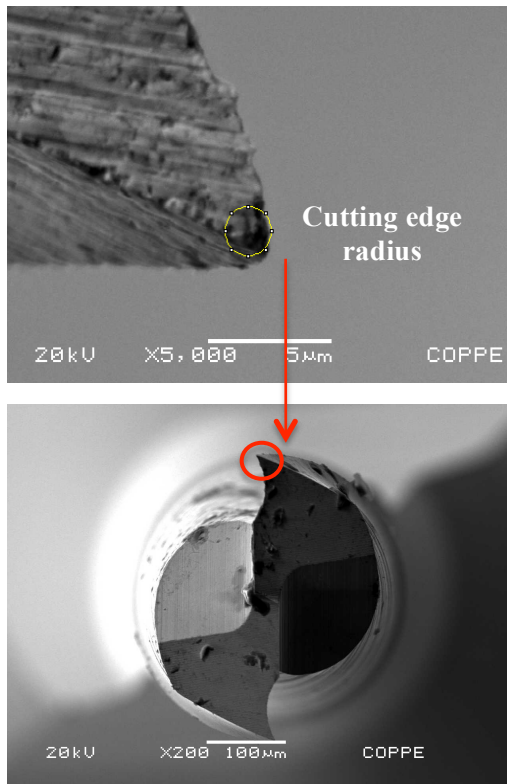
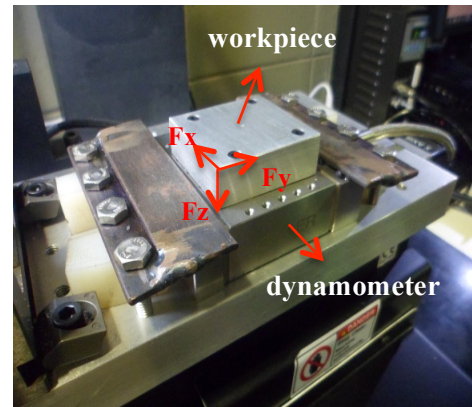


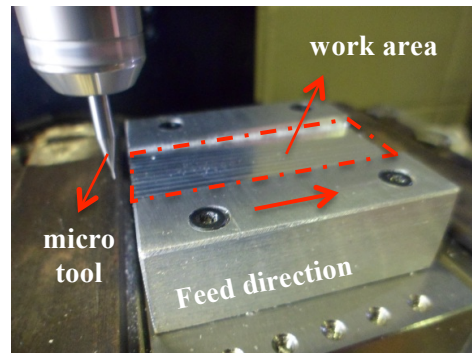
Figure 2: SEM Microscopy of the cutting tool presenting the cutting edge radius (r_e)

The micro machine used on the experiments was the CNC Mini Mill/GX from *Minitech Machinery Corporation*. The machine uses NSK 60K RPM Precision Spindle with 3 Axis Controller. Its standard resolution is 0.00078125mm using dual linear ball bearing slides on each axis, sealed for the table mechanism (THK linear slides - RSR15 series, Caged-ball technology). The drive mechanism THK Ball Screw actuator - preloaded and sealed, achieves low torque fluctuation and no backlash.

A mini-dynamometer is used for cutting force measurement. The MiniDyn KISTLER 9256C2 used cable 1697A5, as shown in Figure 3. The cutting force components are presented in the Figure. It was used a charge amplifier 5070A10100 and a data acquisition board NI USB 6251. Table 1 summarizes the equipment used on the set-up.



(a) MiniDyn and Force Components



(b) Feed Direction

Figure 3: Experimental Set-up

Table 1: Equipment Specifications

| Equipment | Specification |
|------------------|------------------|
| Micro Mill | CNC Mini-Mill GX |
| Charge Amplifier | 5070A10100 |
| Oscilloscope | NI USB 6251 |
| Dynamometer | Mini Dyn_9256C2 |
| SEM | ZEISS DSM 940 |

F. EXPERIMENTAL PROCEDURE

Before micro milling experiments, a workpiece surface of 50 x 20 mm was faced using a 3mm milling tool, 18m/min cutting velocity and feed rate equals to 200 mm/min.

The micro milling tool performed a surface trajectory before each pass to guarantee the axial depth of cut designed. The axial depth of cut chosen is 20 times higher then the point radius, 100 μ m. That is why the main cutting edge has more significance impact on the cutting model. The secondary cutting edge was neglected.

Considering the cutting edge radius of 0,5 μ m, three feed per tooth (f_t) values were planned for running tests from 1-5 μ m, almost 10 times higher then the radius. This choice was made in order to use cutting models that does not considers ploughing as the main component of the cutting force. Two replicates were run for each level of feed per tooth and 20 revolutions of the signal were taken.

Table 2 presents the cutting parameters used on the experiments.

Table 2: Cutting Parameters

| | |
|--------------------|---|
| Spindle revolution | 20,000 rpm – clockwise |
| Cutting Velocity | 18 m/min |
| Feed per tooth | 2, 4 and 5 μ m/tooth (Three Levels) |
| Axial depth of cut | 100 μ m |
| Width of cut | 381 μ m (full immersion) |
| Length of cut | 15 mm |
| Workpiece material | Al 6351 T6 |

RESULTS AND DISCUSSION

In this section it is presented the experimental data, the simulated curves and a basic specific cutting pressure is calculated.

G. EXPERIMENTAL RESULTS

The experimental data was averaged using 20 revolutions for each test. Is is presented on Figure 4, 5 and 6 three representative curves for the experiments using 0,002 mm/th, 0,004mm/th and 0,005 mm/th respectively. The force components presented (F_x and F_y) represents the components on the plane normal to the spindle, as presented on Figure 3a. No filter is applied and 2N/V amplification is used in the charge amplifier, the maximum rate.

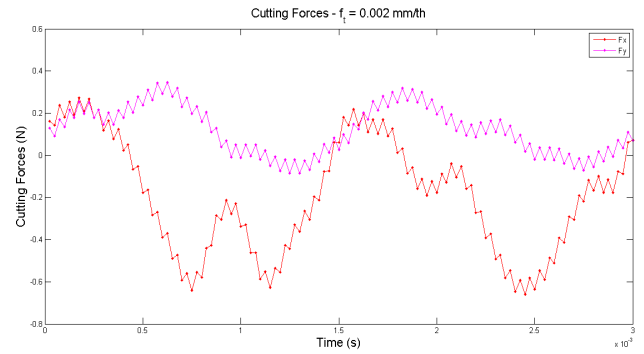


Figure 4: Experimental Cutting Components F_x and F_y using $f_t=0,002$ mm/th.

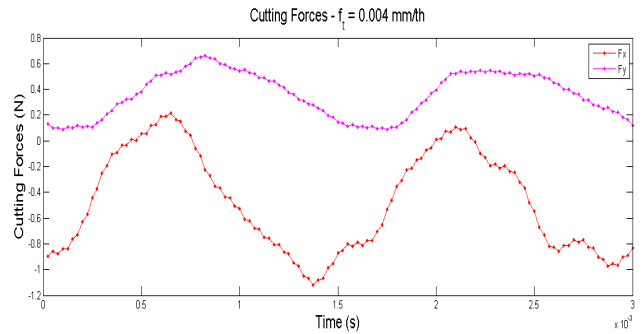


Figure 5: Experimental Cutting Components F_x and F_y using $f_t=0,004$ mm/th.

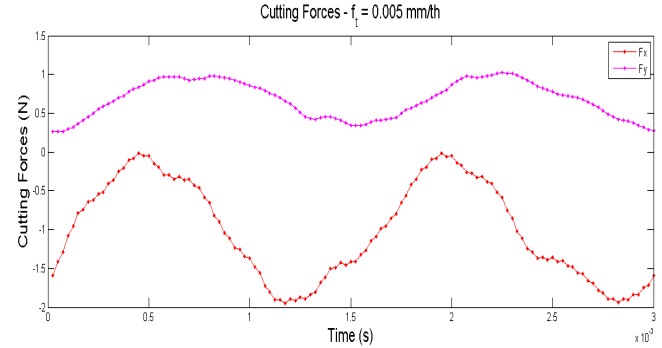


Figure 6: Experimental Cutting Components F_x and F_y using $f_t=0,005$ mm/th.

Using all experiments, the resultant force is calculated and the higher value is taken on each revolution. All results are taken into account to produce the graphic presented on Figure 7. This figure shows that the maximum resultant force remains linearly distributed if the feed is increased. Although when the feed is doubled, the force does not increase in this same rate.

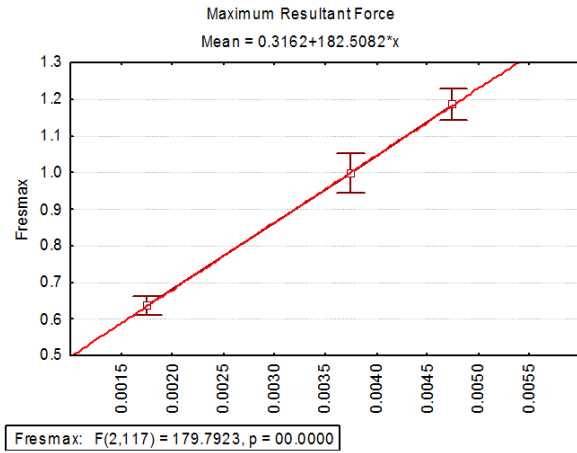


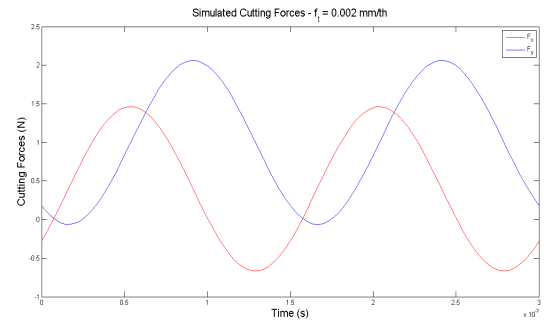
Figure 7: Effect of feed per tooth on Resultant Forces

H. SIMULATION RESULTS

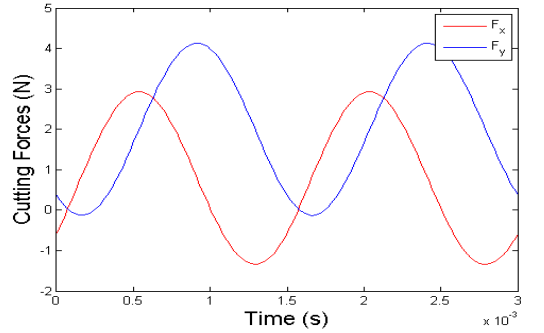
For comparison purposes, simulations were performed using the cutting data presented on Table 2. Specific pressure K_t is considered as 5000N/mm^2 using the value taken from [14]. The radial specific pressure is considered as 40% of K_t .

Figure 8 presents the results calculated for the three levels of feed rate used on experiments. Figure 8a uses $f_t=0,002\text{mm/th}$, Figure 8b uses $f_t=0,004\text{mm/th}$ and $f_t=0,005$ is used on Figure 8c.

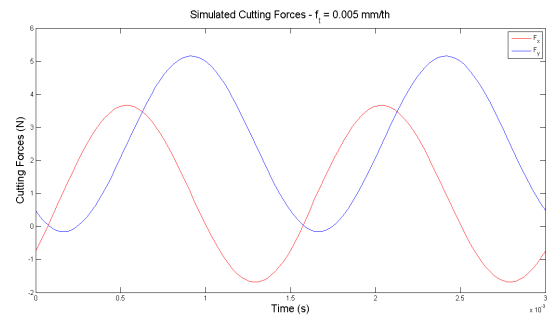
Figure 9 shows the three resultant forces, one for each case. In the model, the force is proportional to the area and it is not considered tool run-out, as the experiments did not shown strong differences between the two cutting flutes.



(a) $f_t=0,002\text{ mm/th}$



(b) $f_t=0,004\text{ mm/th}$



(c) $f_t=0,005\text{ mm/th}$

Figure 8: Simulated Cutting Components F_x and F_y

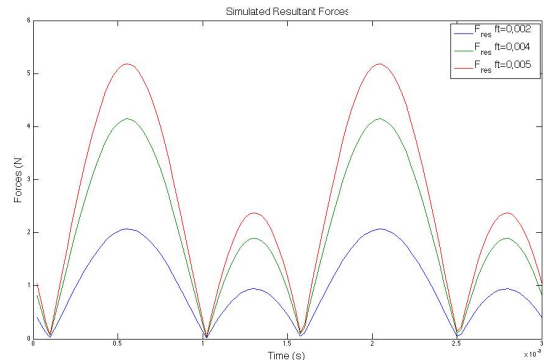


Figure 9: Simulated Cutting Force

I. SPECIFIC CUTTING FORCE

Specific pressure K_t considered for aluminium in the simulation is over estimated. Using experimental data and considering only the maximum resultant force, the specific cutting pressure calculated is four times less the simulated one. The value of 1000 N/mm^2 is nearer the meso scale specific force for aluminium.

CONCLUSIONS

This article deals with micro milling of an aluminium alloy using three levels of feed rate and constant cutting velocity, axial depth of cut and same tool. First effort on experimental cutting force is challenged in our laboratory. Experimental and simulated forces are qualitatively compared. The specific pressure considered based on previous articles is over estimated, as values around 1 kN/mm^2 is calculated from experiments.

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