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# MONITORING AND EVALUATION OF VIBRATION ON END MILLING OPERATIONS

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***Abstract.*** *Due to the characteristics of its tools and cutting conditions, the milling process causes vibration – which importantly affects its results. Thus, it is intended to monitoring and evaluation of the vibration caused during the end milling of three workpiece materials (6013 aluminum, 1020 steel and FC 300 gray cast iron) submitted to symmetric and asymmetric up milling with the high-speed steel tool. The monitoring of vibration behavior was achieved through the acquisition of the dynamic components of machining force signals (orthogonal axes) captured by a piezoelectric dynamometer fixed on the table of a vertical machining center. The cutting parameters, i.e., tool diameter, depth of cut and feed rate per tooth were kept constants. The acquired signal were graphically processed and analyzed according to the proposed goals, they allowed the characterization of the vibration profile on the process. Through the generated graphics, it was possible to observe the influence of symmetric and asymmetric up milling on the generated vibration signals. On the symmetric milling, the resultant cutting force presents a restricted oscillatory range, but with higher average power. The variation of the workpiece materials showed the characteristics of each material type: ductile materials are more difficult to machine due to adherence on the cutting edges.*

***Keywords:*** *end milling, dynamic cutting forces, vibration*

## 1. INTRODUCTION

The milling process is defined as a metal cutting technology in which a multi-edged tool removes material while travelling along various axes with respect to the workpiece. During milling, the tool performs the cutting motion (rotation), whereas the workpiece (that is, the milling machine table on which the workpiece is mounted) executes the feed motion (longitudinal, transversal or combined in relation to this axis). The milling techniques are defined according to the tool axis position relative to the workpiece and according to the tool denomination (Ferraresi, 1977; Tschätsch, 2009).

The engagement of each tooth with the workpiece is discontinuous in the milling process different to the turning process. As a tooth engages the workpiece, it receives a shock followed by a varying cutting force. The cyclic shock and variation of the cutting force induces vibrations between the tool and workpiece. It can also provide the necessary energy to excite a natural mode of vibration in any part of the machining system. These vibrations should be minimized because they can, and frequently do, degrade machining accuracy and surface finish. Moreover, under unfavorable conditions they may become unstable, leading to chatter, which can cause accelerated tool wear and breakage, accelerated machine wear, and even damage to the machine and part (Liu, 2009).

As it has influence on share of the output parameters and it is influenced by the process input parameters, the vibration is a very complex study area and little known. The milling operations are essentially a vibratory mechanical system, since the own geometry of the cutting tool always results in an oscillatory dynamic force.

Other parameter that influences this phenomenon is the feed rate of the cutting tool, which can amplify the system oscillation. There is still the piece material to be machined as an important variable, because the static cutting force depends of the material mechanical properties of the machined part, as rupture stress, hardness and tenacity.

The principal vibration influence is the finishing surface of the milling parts. The cutting force variation incites different deflections in the tool, which has constant rigidity, generating imperfections in the surface. This effect can be understood by the equation from classic mechanical, which relates the force directly proportional to the rigidity and the cutting tool deflection (Maia, 2009; Andersson *et al.*, 2011).

The objective of this paper is to accomplish the monitoring of the vibration generated in face milling process. Thus, different tests will be conducted, for which will be used a piezoelectric dynamometer to capture the force variation signals. From on the data acquired, will be made a proposal of analyze method, which will be used to generate standard graphics. These graphics will be the base to the debates about as the cut type, tool geometry and the workpiece material, influence the vibration of the face milling process.

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### 1.1. End Milling

End mills perform a combination of peripheral as well as face milling operations simultaneously. It has got cutting edges on the bottom face as well as on its periphery. End mills are extremely useful and are used for machining edges, shoulders, grooves, slots and keyway pockets. They are also widely used for die-sinking and generation of sculpted surfaces. A solid high-speed steel (HSS) end mill and its applications in slot milling (Tab. 1a) and side/face milling (Fig. 1b) are shown in Fig. (1). End mills have a taper shank which fits into a taper sleeve provided in the spindle of a vertical milling machine (Gupta *et al*., 2009).

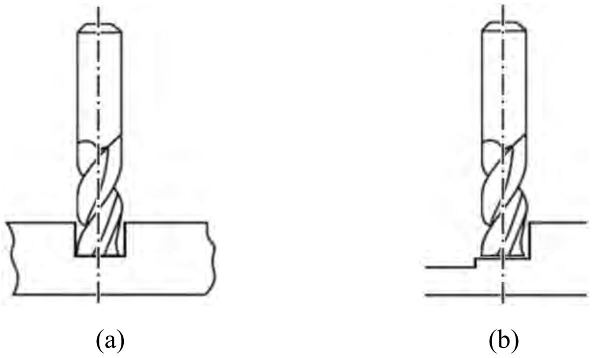


Figure 1. End milling: (a) slot milling; (b) side and face milling

During the face milling, down and up milling procedures are carried out alternately. At the beginning of the cutting procedure, the direction of rotation is opposite to the feed direction of the workpiece. However, starting from the middle of the workpiece (Fig. 2), the procedure merges into down milling. Alternate metal cutting by down and up milling is able to compensate as much as possible for deviations of the cutting force and thus to relieve the cutting edges of load. Consequently face milling allows for high metal removal rates (Tschätsch, 2009).

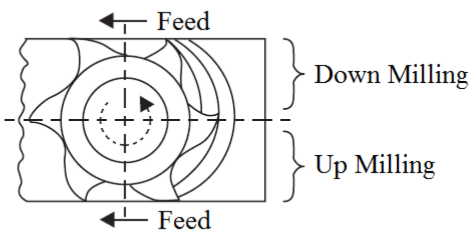


Figure 2. Down and up cut in face milling (adapted from Gupta *et al*., 2009)

In face milling, the position of the cutter with respect to the workpiece is of considerable significance. Three possibilities are there. Either the cutter may be symmetrically placed on the work piece or it may be asymmetrically placed, offset slightly towards the entry side or it may be asymmetric, offset slightly towards the exit side. All three positions are shown in Fig. (3) (Gupta *et al*., 2009).

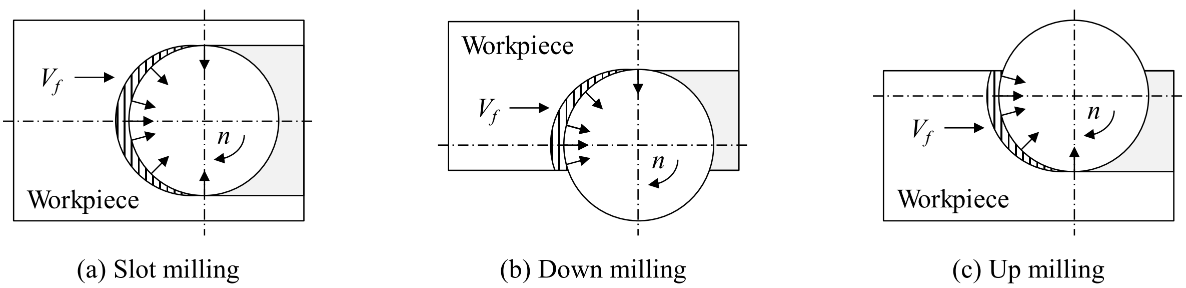


Figure 3. Symmetrical (a) *vs.* asymmetrical (b and c) milling

Asymmetric milling with larger chip thickness at entry and smaller chip thickness at exit (Fig. 3b) is ideal and should be adopted.

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## 2. MATERIALS AND METHODS

The experiment were conducted with the intention to monitor and to evaluate the vibration signal generated during the end milling process using two high-speed steel (HSS) end mills type N with diameter of 10 mm – one with two cutting edges (Fig. 4a) and other with four cutting edges (Fig. 4b). For the operation, both end mills were fixed in a headstock tool holder using tweezers with a distance of 35 mm between the headstock and the free extremity of the tool.

(a) Type 2 (b) Type 4

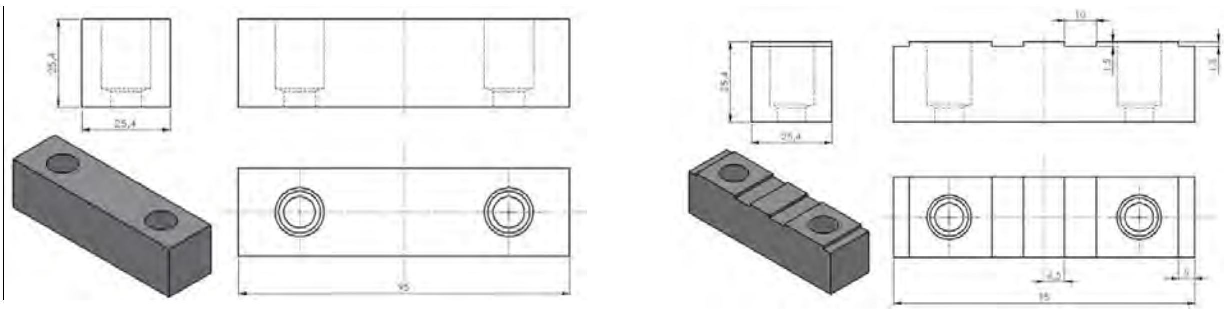
Figure 4. End mills (a) two cutting edges; (b) four cutting edges

Different materials were used in the workpieces because part of the goal of this study is to evaluate the effect of the material in the vibration. Table (1) shows a qualitative comparison among the mechanical properties of these materials.

Table 1. Comparison between the materials

| Material | Alloy | Rupture Stress | Ductility | Hardness |
|---|---|---|---|---|
| Aluminum | Aluminum Alloy 6013 | Low | High | Low |
| Steel | Steel SAE 1020 | Medium | Medium | Medium |
| Gray Cast Iron | Gray Cast Iron Series 300 | Medium | Low | High |

The workpieces were prepared to be fixed in the piezoelectric dynamometer. Figure (5a) presents the drawing of the workpiece and it dimensions and Fig. (5b) shows the drawing of the machined part.



(a) (b)

Figure 5. Standard drawings: (a) workpiece; (b) machined part

The end milling operations were performed on a 3-axis vertical CNC machining center ROMI model Discovery 308 with 5.5 kW of power in the spindle motor and a maximum speed rotation of 4,000 rpm (Fig. 6).

The speed rotation ($n$) is calculated from tabulated values of cutting speed. These tables are provided by manufacturers, since they are values generally estimated empirically. The cutting speed ($v_c$) is set based on the operation type, the tool material and geometry, and the workpiece material. The revolution time ($t_r$) is calculate from the Eq. (1) using the inverse of the tool rotation frequency, but as each material has different cutting velocities, consequently each material will had a different rotation and period. The results are shown in the Tab. (2).

$$t_r = \frac{60}{n} \tag{1}$$

Table 2. Results of the tool spindle for each material

| Parameter | Material | | |
|---|---|---|---|
| | Aluminum | Steel | Gray Cast Iron |
| Cutting Speed $v_c$ [m/min] | 40 | 24 | 16 |
| Speed Rotation $n$ [rpm] | 1273 | 764 | 509 |
| Revolution time $t_r$ [s] | 0.05 | 0.08 | 0.12 |

Figure 6. Machining Center ROMI Discovery 308

Feed rate ($v_f$) is defined in function of the product between feed per revolution ($f$) and spindle speed ($n$). However, the feed per revolution is the product between feed per tooth ($f_z$) and number of cutter's teeth ($z$). The $f_z$ was kept constant for the two cutting tools (two and four cutting edges). According the Eq. (2), the feed rate per tooth depends on the surface roughness average ($R_a$) expected and the nose radius ($r_\varepsilon$) of the cutting tool (Machado *et al*., 2009).

$$\frac{f_z^2}{4} = r_\varepsilon^2 - \left( r_\varepsilon - \frac{R_a}{500} \right)^2 \qquad (2)$$

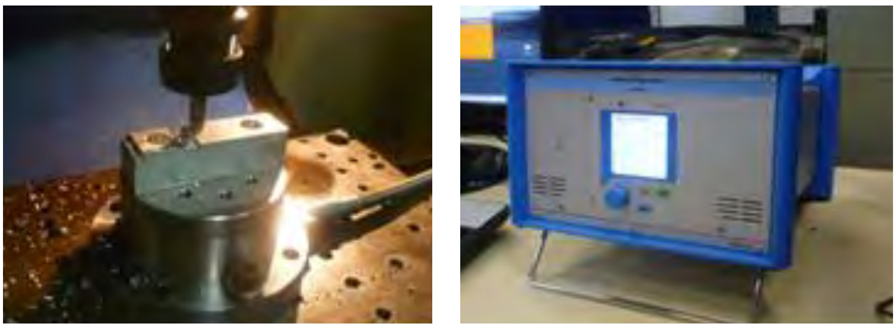
For an expected roughness of $R_a$ = 1.2 µm and tool nose radius $r_\varepsilon$ = 0.1 mm the feed per tooth is $f_z$ = 0.04 mm/rev. So, the feeds per revolution of the end mills are $f$ = 0.08 mm/rev ($z$ = 2) and $f$ = 0.16 mm/rev ($z$ = 4). Therefore, the results feed rates for the used workpiece materials and end mills are shown in the Tab. (3).

Table 3. Results of the feed rate for each material

| | Material | | |
|---|---|---|---|
| | Aluminum | Steel | Gray Cast Iron |
| $v_f$ Type 2 [mm/min] | 111 | 67 | 44 |
| $v_f$ Type 4 [mm/min] | 222 | 133 | 89 |

Other input parameters were still used for the realization of experiments. These were chosen to not to harm the cutting tool performance. As it was not objective this study to evaluate the influence of the following parameters, they were estimated to not generate a significant tool wear and fracture. The axial depth of cut was set in $a_p$ = 1.5 mm for the two cutting types. The radial depth of cut was set in $a_e$ = 10 mm for the slot milling and $a_e$ = 5 mm for the asymmetrical up milling (vide Fig. 5b), (Huang and Wang, 2011).

A Kistler 9272 stationary piezoelectric dynamometer 4 – component (Fig. 7a), a Kistler 5070A10100 charge amplifier (Fig. 7b), a Measurement Computer PCIM-DAS 1602/16 analogical/digital data acquisition board and a VI LabView software were used for three axis cutting force ($F_x$, $F_y$, $F_z$) and torque ($M_z$) measurements.



(a) (b)

Figure 7: Kistler force and torque monitoring system: (a) piezoelectric dynamometer 9272
(b) charge amplifier 5070A10100

The measurement was made with an acquisition rate of 25,000 samples per second in 10 seconds, totaling 250,000 points in each test.

According to Li *et al.* (2006), a method of comparison between different cutting passes is the plotting of the maximum, minimum and mean cutting force. However, in this paper it wasn't chosen, because it not represent the objective as well the method below.

The analysis method used was the calculus of the resultant cutting force ($Fc_R$), which considers the values of the $F_x$ and $F_y$ in each time instant which the signal was acquired. Thus, it was generated the graphical to this force $Fc_R$ during the time interval correspondent to a period of the tool, i.e. to the time interval that the tool needs to complete a rotation. Figure (8) represents the scheme used to understanding of the physic meaning of the $Fc_R$ calculus.

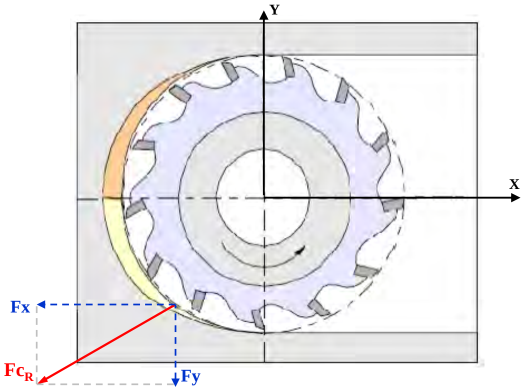



Figure 8. $F_{CR}$ representation scheme

Equation (3) was used to the calculus of the $Fc_R$ in each time instant.

$$Fc_R = \sqrt{F_x^2 + F_y^2} \tag{3}$$

This analysis method was chosen because the influence of the negatives values can be disregarded, since the intention of this work is to evaluate the force amplitude variation. Thus, there are the positives values ranging around of an average what is consistent with the process nature. The $Fc_R$ average represents the static force, while the variation around this average characterizes the dynamic force (Kovacic *et al.*, 2004).

The utilization of the forces $F_x$ and $F_y$ occurred due to the milling process to be performed by the combined action of the forces in this direction. The tool rotation makes the cutting tooth to rotate keeping contact with the part. The $F_x$ and $F_y$ vary of positives values to negatives values, depending of the contact angle ($\varphi$), which varies of 0º to 180º to the slot cutting and of 0º to 90º to the asymmetric up cutting.

The tests were performed according to Tab. (4).

Table 4. Tests distribution and characterization

| Test | Test | Material | Cutting Type | Tool | *n* [rpm] | $v_f$ [mm/min] |
|---|---|---|---|---|---|---|
| 1 | 1 | Aluminum | Asymmetrical up milling | Type 2 | 1273 | 111 |
| 2 | 2 | Aluminum | Slot milling | Type 2 | 1273 | 111 |
| 3 | 4 | Aluminum | Asymmetrical up milling | Type 4 | 1273 | 111 |
| 4 | 3 | Aluminum | Slot milling | Type 4 | 1273 | 111 |
| 5 | 9 | Steel | Asymmetrical up milling | Type 2 | 764 | 67 |
| 6 | 10 | Steel | Slot milling | Type 2 | 764 | 67 |
| 7 | 11 | Steel | Asymmetrical up milling | Type 4 | 764 | 133 |
| 8 | 12 | Steel | Slot milling | Type 4 | 764 | 133 |
| 9 | 7 | Gray Cast Iron | Asymmetrical up milling | Type 2 | 509 | 44 |
| 10 | 8 | Gray Cast Iron | Slot milling | Type 2 | 509 | 44 |
| 11 | 5 | Gray Cast Iron | Asymmetrical up milling | Type 4 | 509 | 89 |
| 12 | 6 | Gray Cast Iron | Slot milling | Type 4 | 509 | 89 |
| 13 | 13 | Aluminum | Asymmetrical up milling | Type 4 | 1273 | 222 |
| 14 | 14 | Aluminum | Slot milling | Type 4 | 1273 | 222 |

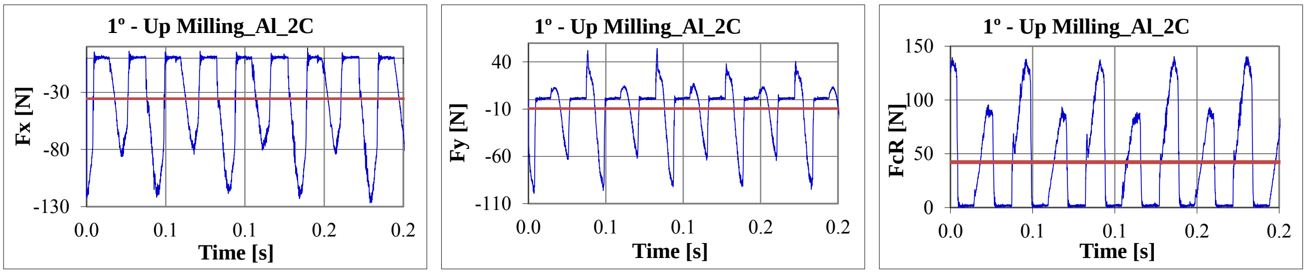
## 3. RESULTS AND DISCUSSIONS

14 milling practice tests were performed according to the Tab. (4). The machined surfaces roughness is a parameter that allows visualizing the effect of the vibration in the milling process. Figure (9) shows the three workpieces during the machining.

(a) (b) (c)

Figure 9. Workpieces during the end milling: (a) aluminum, (b) steel, (c) gray cast iron

Figure (10) shows the graphics of the $F_x$, $F_y$ and $Fc_R$ forces generated in the asymmetrical up milling of the aluminum with end mill type 2 (Test No. 1). $F_x$ and $F_y$ will not be discussed because the analysis method will be based on the $Fc_R$. The forces will be shown in complete rotation period (revolution time $t_r$) of the cutting tool for each material to facility the visualization on the desirable effects that are to evaluate.




(a) (b) (c)

Figure 10. Forces in up milling of aluminum with end mill type 2: (a) $F_x$, (b) $F_y$, (c) $Fc_R$

### 3.1. Cutting type analysis

The influence of the end milling cutting type (slot or asymmetric up milling) in the collected force signal $Fc_R$ during the tests will be analyzed in a comparative way. Figure (11) shows the graphics for some tests.

Figures (11a, 11b, 11c) show that there are two small time intervals during which the $Fc_R$ oscillates around of the zero independently of the material machined. During these instants the tool is not in contact with the workpiece. These intervals are the two infinitesimals instants during the exit of a tooth and the entry of the other. During a quarter of period, the tool is in contact with the workpiece, but after it keeps a quarter of period without contact with the workpiece and thus consecutively, generating signals intermittent.

Figures (11d, 11e, 11f) show that there are two small times intervals during which the $Fc_R$ modulus trends to zero. However, differently to asymmetric up milling, the intervals show in the form of pointed ends valleys that approximate to zero. The contact angle (φ) between tool tooth and workpiece varies from 0º to 180º. Therefore, then φ achieves the value of 180º for a tooth, the other tooth is entry in the workpiece, i.e., it has φ equal to 0º, since the tool has two cutting edges disposed symmetrically. In practice, during this infinitesimal time in that the tool is in this position, the two edges have the smaller contact area with the workpiece, and these corners are aligned with the feed rate, making the forces in X-axis of each tooth to converge for a same value, but with inverted signals, zeroing the $Fx$ resultant collected by the dynamometer. In this case, there is a force $F_x$ in each tooth with same intensity and direction, but inverted way. As in this infinitesimal time the $v_c$, in the contact point, is in the X-axis, together with the $v_f$, thus it trends to there is not force in the Y-axis. The combination these two effects of the $F_x$ and $F_y$ makes the $Fc_R$ trend to zero.

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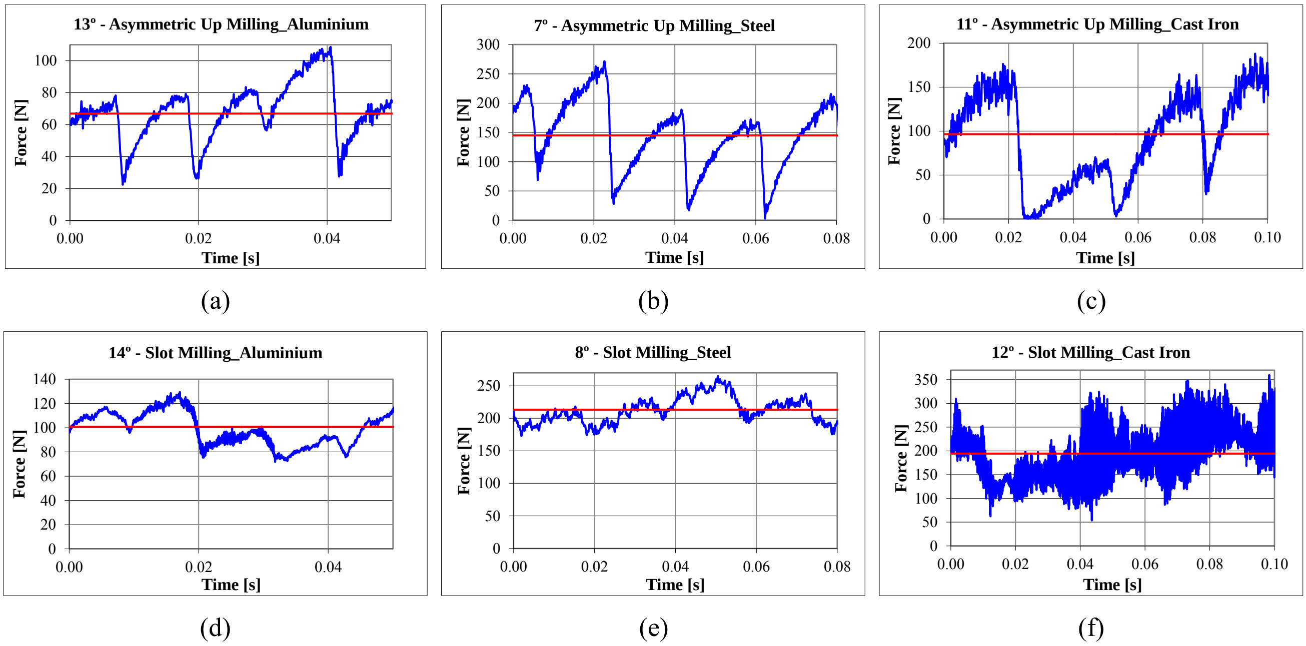



Figure 11. $Fc_R$ in end milling with end mill type 2: asymmetric up milling of (a) aluminum, (b) steel, (c) gray cast iron; slot milling of (d) aluminum, (e) steel, (f) gray cast iron

### 3.2. Number of the tool cutting edges analysis

The influence of the number of the tool cutting edges in end milling of aluminum in the collected force signal $Fc_R$ during the tests will be analyzed in a comparative way. Figure (12) shows the graphics for some tests.

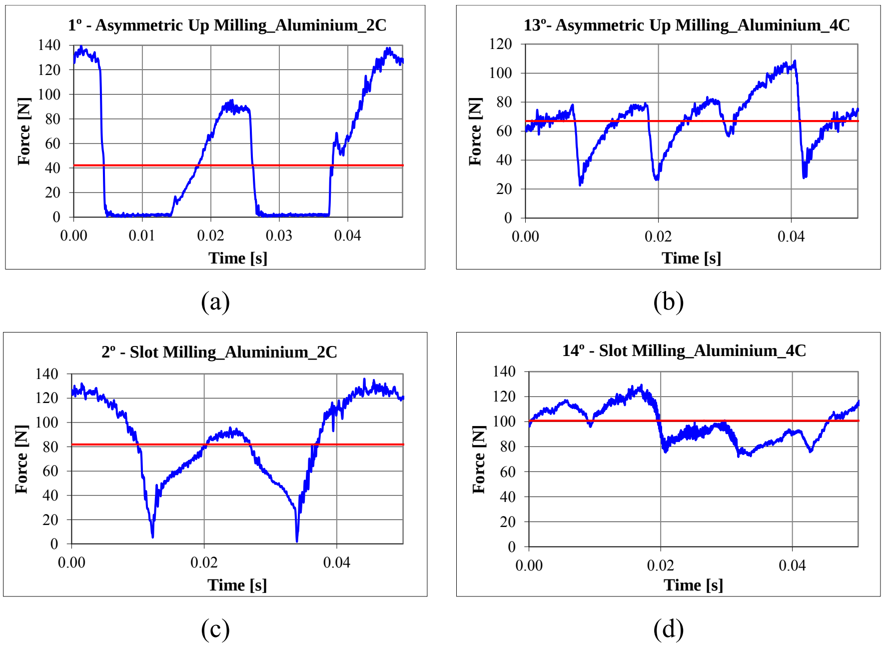


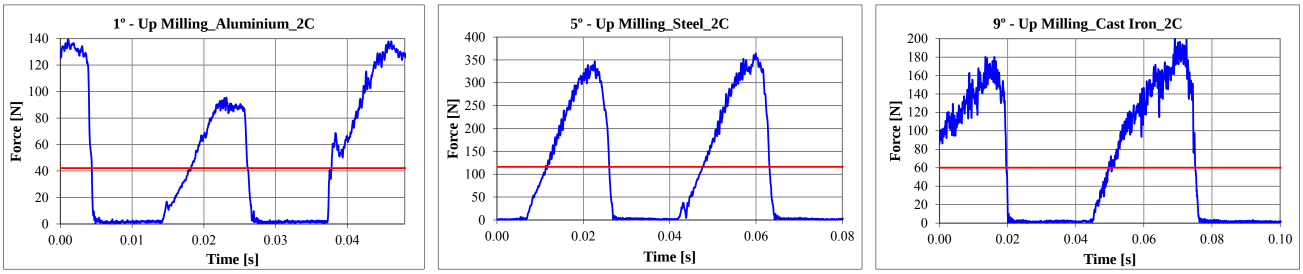

Figure 12. $Fc_R$ of the aluminium with end mill in asymmetric up milling (a) type 2, (b) type 4; and in slot milling with end mill: (c) type 2, (d) type 4

Figures (12a) and (12c) show two time intervals which the $Fc_R$ is or trends to zero. However, the Fig. (12b) and (12d) show four pointed ends valleys below of the average, but they don't reach the zero. It can be perceived that the variation of the $Fc_R$ amplitude in Fig. (12b) and (12d) is smaller than the Fig. (12a) and (12c), but the vibration frequency is superior. It is expected, since for the tool with two teeth there are two cutting edges executing the milling of the material intermittently for each end mill rotation. While for the tool with four teeth there are four cutting edges executing this milling. Thus, the vibration frequency will be directly proportional to number of the tool cutting edges.

The reduction in the force variation amplitude is associated to the fact that always there is a tooth in contact with the material. To each a quarter of rotation period the cutting force will be minimal and an eighth of the rotation period after it will be maximal. The maximum values of $Fc_R$ are spaced of the minimum values by an eighth period. Whereas the maximum values are spaced of the others maximum by a quarter of rotation and the same occur to minimum values.

### 3.3. Material analysis

The influence of the workpiece in asymmetric up milling with end mill type 2 in the collected force signal $Fc_R$ during the tests will be analyzed in a comparative way. Figure (13) shows the graphics for some tests.




(a) (b) (c)

Figure 13. Forces in asymmetric up milling with end mill type 2 in: (a) aluminum, (b) steel, (c) gray cast iron

The Figure (13) shows that the principal difference between each machined material is in the vibration amplitude. The steel (Fig. 13b) has higher cutting specific pressure, thus it is necessary higher force to machine it. The gray cast iron (Fig. 13c) has cutting specific pressure intermediary between the steel and the aluminum (Fig. 13a), so the cutting force necessary is intermediary too.

The aluminium has the smaller cutting force, but is the worst material to machining with an end mill of the type N. After the process there was an accumulation of aluminium adhered to the cutting edges generated by the use of low cutting speeds combined with the higher ductility this material. In the Fig. (13a), it can be perceived that one of the pointed ends has higher amplitude than other because the effects of aluminum adherence to the mill tooth.

The gray cast iron has ductility smaller to the aluminium, because it has higher hardness and is a fragile material. In spite of it has mechanical properties that would difficult the machining, but the existence of the free carbon in the graphite form in round the material grains gets better the machining properties. The graphite is a type of solid lubricant, and it has higher tenacity, that it absorbers a parcel of the materials vibrations. In the Fig. (13c) this material has vibrations of higher frequency along the cut because the gray cast iron presents a quick and fragile rupture, generating a small chip. Thus, there is the force variation provided by the tool teeth impact in the workpiece. There is the effect of the chip formation, that to be deformed locally it enlarges the $Fc_R$, and after it rupture the cut is facilitated again.

### 3.4. Surface roughness analysis

Table (5) shows the obtained results for the average roughness ($R_a$) of the machined surfaces.

Table 5. Results for the average roughness

| Test | Material | Cutting Type | Tool | *Ra* [μm] |
|---|---|---|---|---|
| 1 | Aluminum | Asymmetrical up milling | Type 2 | 0.28 |
| 2 | Aluminum | Slot milling | Type 2 | 0.62 |
| 3 | Aluminum | Asymmetrical up milling | Type 4 | 0.54 |
| 4 | Aluminum | Slot milling | Type 4 | 0.56 |
| 5 | Steel | Asymmetrical up milling | Type 2 | 1.52 |
| 6 | Steel | Slot milling | Type 2 | 1.64 |
| 7 | Steel | Asymmetrical up milling | Type 4 | 1.62 |
| 8 | Steel | Slot milling | Type 4 | 1.90 |
| 9 | Gray Cast Iron | Asymmetrical up milling | Type 2 | 2.92 |
| 10 | Gray Cast Iron | Slot milling | Type 2 | 3.49 |

Table 5. Results for the average roughness (cont.)

| Test | Material | Cutting Type | Tool | *Ra* [μm] |
|---|---|---|---|---|
| 11 | Gray Cast Iron | Asymmetrical up milling | Type 4 | 3.15 |
| 12 | Gray Cast Iron | Slot milling | Type 4 | 4.63 |
| 13 | Aluminum | Asymmetrical up milling | Type 4 | 1.38 |
| 14 | Aluminum | Slot milling | Type 4 | 1.24 |

The calculus of the feed rate per tooth was performed using a value of expected roughness equal to 1.2 μm. However, most of the results do not approximate of this expected value. The average roughness of the Tests No. 13 and 14 are the ones that most closely match of the initial value.

Equation (2) was used to connect the feed rate with the roughness, but it does not depend directly of important factors as material and tool type, which have great influence in the finishing surface.

## 4. CONCLUSIONS

The cutting type has very influence in the finishing surfaces, because it can be observed that the slot milling always has a roughness larger than the asymmetric up milling considering the same parameters, because the material removal rate in the slot milling is superior and resulting more localized strain in the material.

As regards the cutting tool type, the vibration amplitude of the cutting force will be lower as higher the tool teeth number. However, the frequency will be directly proportional to the cutting edges number.

The machined workpiece material is a parameter of very importance to the vibration. For aluminum there may be chip adherence in the cutting edges, resulting in increase of the cutting force. For gray cast iron, there is facility in the cutting and uniformity in the force variation. In this case, there is a vibration characterized for a noise, i.e., the formation of the short and fragile chip generates localized fluctuations in the cutting force. Thus, there are two vibration frequencies: one larger generates by tool rotation with the cutting edges impact in the workpiece, which is multiplied by the teeth number; and other smaller, generating oscillations along of the other, which is generated by the chip formation.

## 5. ACKNOWLEDGEMENTS

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## 7. RESPONSIBILITY NOTICE

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