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ANALYSIS OF VIBRATIONS IN THE INTERNAL TURNING PROCESS OF ALUMINUM ALLOY 6351-T6

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Abstract. *Tools with high overhang are susceptible to regenerative vibrations during machining, altering the dynamic stability of the process and generating an undesirable surface finish. This paper aims to analyze the vibrations in the internal turning process using a tool holder with a high length/diameter ratio. The proposal was to analyze the influence of machining parameters such as rotation and depth of cut on the dynamic stability of the internal turning process of the 6351-T6 aluminum alloy. For this, the data generated in the elaboration of stability lobe diagram of the process was used. Simulations were carried out in the Matlab software using a pre-set model and comparing with the experimental results obtained. Low spindle rotations, therefore low cutting speeds provide stable cuts even at high depths of cut due to the damping effect. According to the models in the literature, for a sufficiently small value of depth of cut the process would be always stable. However, there were discrepancies between the values resulting from the simulations and the experimental ones. The model used in the simulations does not consider the instabilities due to the use of very small depths of cut. Very small cutting depths can cause instability in internal turning. In this case the area of the chip is influenced by the tool nose radius of the tool and presents a curved aspect with regions of small section.*

Keywords: *chatter, regenerative vibrations, internal turning process, aluminum alloy.*

1. INTRODUCTION

In an internal turning process, three different types of mechanical vibrations are present due to the lack of dynamic stiffness of the machine tool system comprising the tool, the tool holder, the part and the machine tool. These vibrations can be free, forced and regenerative. Free vibrations are induced by shocks and forced vibrations are due to an imbalance effect in the machine tool, in the sets of gears, bearings and spindles. Free and forced vibrations can be easily identified and eliminated. But regenerative vibrations are not yet fully understood because of the complexity of their nature. They are more harmful to some machining processes including turning (Siddhpura and Paurobally, 2012).

When chatter vibrations occur, the amplitude of the vibrations increases continuously until the relative displacement between the tool and the workpiece becomes so large that the tool moves away from the workpiece for part of the time. This becomes a non-linear behavior, which limits the amplitude of the vibrations to a finite value. The magnitude of the vibrations depends on the characteristics of the shear forces, such as the magnitude and direction of the shear forces, and the frequency of the cutting edge in which a cutting edge always comes in contact with the part. The dynamic characteristics of the entire machining system in terms of natural frequencies, damping coefficients and rigidity of the machine tool structure also affect the magnitude of the vibrations (Saleh, 2013).

Since 1941 many publications have been carried out on techniques for the prevention and analysis of regenerative vibrations, experimental techniques for detecting regenerative vibrations, signal acquisition techniques, artificial intelligence techniques and techniques for controlling and eliminating regenerative vibrations (Siddhpura and Paurobally, 2012). However, the regenerative vibrations are still a very important topic in manufacturing research. This relevant persistence for many years can be explained by two main factors: the complexity of the phenomenon makes its study and its understanding not to be trivial: and negative effects of regenerative vibrations stimulate interest in solving the problem (Quintana and Ciurana, 2011).

Regarding the first factor, regenerative vibrations are a highly complex phenomenon due to the diversity of elements that can make up the dynamics of the system and its behavior: the cutting tool, the tool holder, the workpiece material, the machine structure Tool and cutting parameters. Predicting its occurrence is still the subject of much research, even the regenerative effect, the main cause of regenerative vibrations, has been identified and studied long before. In addition, regenerative vibrations can occur in different metal removal processes: milling, turning, drilling, boring, broaching and grinding (Quintana and Ciurana, 2011).

System vibrations can lead to time variation of relative positioning between tool and workpiece. Vibrations with excessive amplitudes can cause several disturbances in the machining process, such as the reduction of tool life or even its breakage, reduction of the surface quality of the part and, in extreme cases, damage the spindle of the machine- tool (Altintas, 2000).

The study of the machining process, as in any other manufacturing process, is justified by the marked need to ensure adequate process efficiency and, thus, reduce production costs and increase productivity (Peixoto, 2013). In order to obtain the optimum conditions for the process, it is possible to determine the optimum conditions for the process, considering the dynamics and mechanics of the cutting operation and, therefore, increase the rate of material removal (Mendes and Oliveira, 2008).

In structures with low dynamic stiffness, two major problems can occur: one is the decrease in surface quality and the increase of shape error due to forced vibrations. The other is instability during the machining process associated with regenerative vibrations (Altintas, 2000). If machining conditions are not properly selected several negative effects can occur (Quintana and Ciurana, 2011):

- Low surface quality.
- Unacceptable inaccuracy.
- Excessive noise.
- Disproportionate tool wear.
- Damage to the machine tool.
- Reduced material removal rate.
- Increased costs in terms of production time.
- Waste of materials.
- Waste of energy.
- Environmental impacts in terms of materials and energy.
- Costs of recycling, reprocessing or disposal.

For these reasons, avoiding regenerative vibrations is a topic of great interest. On the factory floor, machine tool operators generally select conservative cutting parameters to avoid regenerative vibrations, and in some cases, additional manual operations are required to clean the marks of the regenerative vibrations left on the workpiece surface. This common practice usually results in a decrease in productivity. In addition, this interest has stimulated a great challenge for research. Researchers have studied ways to detect, identify, prevent, prevent, reduce, control or eliminate regenerative vibrations. A review of the literature on the problem of regenerative vibrations leads to the classification of existing methods into two main groups. The first group consists of those methods that guarantee the stability of the machining process by selecting cutting parameters in combination with the stable zone of the stability chart. The second group includes those methods that avoid regenerative vibrations by changing the behavior of the system and modifying the stability boundaries (Quintana and Ciurana, 2011).

2. METODOLOGY

2.1 Determination of frequency response functions (FRF's)

By means of impact tests the frequency response functions were obtained at the tip of the tool for the different assemblies performed as shown in the figure 1. To this end, a PCB Piezotronics 352C68 SN77121 accelerometer was attached to the machine-mounted tool end and this was excited by a PCB Piezotronics ICP 086C03 impact instrumented hammer equipped with a piezoelectric force transducer type ICP 086C03 and 2 Piezotronics PCB signal conditioners. The collected signals passed through the software ITA-Toolbox dynamic signal analyzer that was developed by the Institute of Technical Acoustics of the RWTH University - Aachen in Germany, to work together with Matlab software.

In this way, the natural frequencies required for the interpretation of the experimental results and the modal parameters used in the computational simulations were identified.

2.2 Machine tool

For the tests was used the Hyundai-KIA CNC Turning Center SKT160A of the CNC Laboratory of the Sociesc Faculty of Curitiba.

2.3 Tools

The Iscar CCGT insert 09T304-AS IC20 with a tip radius of 0.4 mm and the tool holder Iscar S16QSCLCL-09 (diameter = 16 mm) with an overhang length of 96 mm (L / D = 6).

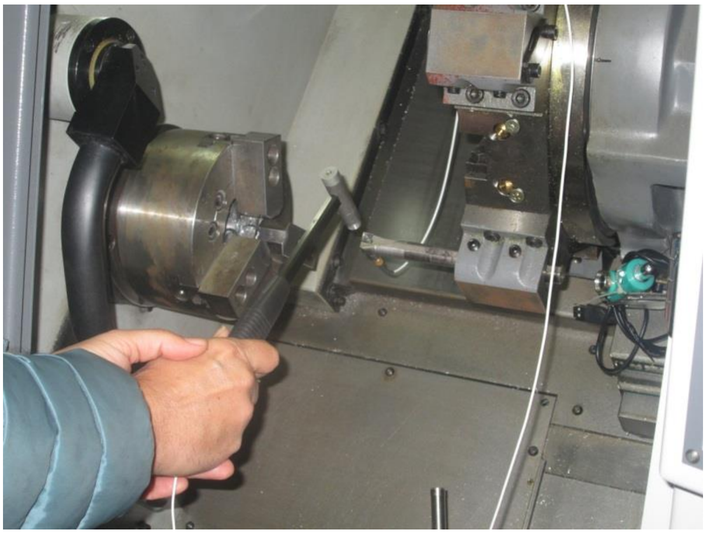

Figure 1. Experimental determination of FRF with instrumented impact hammer.

2.4 System dynamic characteristics

In general, machine tool and workpiece structures have complex geometries, and process dynamics are difficult to predict. In many machining situations, the system has multiple coupled modes of vibrations acting in different directions, or dominant modes of vibrations that can change from one position to another of the cut (Polli, 2005). In internal turning process, the cutting tool is usually the most flexible part in the system, since its length-to-diameter ratio (L / D) is high and therefore its geometric characteristics and mechanical properties have a direct influence on rigidity and resulting natural frequencies.

Considering the tool as a swing beam, the stiffness value (K) for the first vibration mode can be calculated by (Inman, 1996):

$$K = \frac{3EI}{L^3} \quad (1)$$

The tool set and tool holder can be considered as a thin and long circular bar in balance and therefore its moment of inertia can be calculated by Eq. (2).

$$I = \frac{\pi d^4}{64} \quad (2)$$

Where E is the modulus of elasticity, I is the moment of inertia, L is the overhang length of the tool and d is the diameter of the toolholder.

The resulting natural frequencies for the tool assemblies were used to calculate the modal masses. The damping ratio (ζ) was found by power half-band method.

The mechanical properties of the analyzed tool material are shown in the table 1.

Table 1 – Mechanical properties of the analyzed tool material.

Material Properties	High Strength Steel
Modulus of Elasticity(GPa)	200
Density (Kg/m^3)	7,850
Coefficient of Poisson	0.32

2.5 Material

The material that was used for the tests was the 6351-T6 aluminum alloy, the specimens were cylindrical with a diameter of 32 mm and a length of 20 mm with a central hole of 21 mm in diameter as shown in figure 2. This material was used because it has relatively good machinability and is soft without compromising the useful life of the tool during the tests and reducing the total cost of the experiments.

The specimens were dimensioned and fixed in the machine in such a way that they could be considered rigid and that the dynamic instabilities were restricted to the flexibility of the system composed by the tool and tool holder.

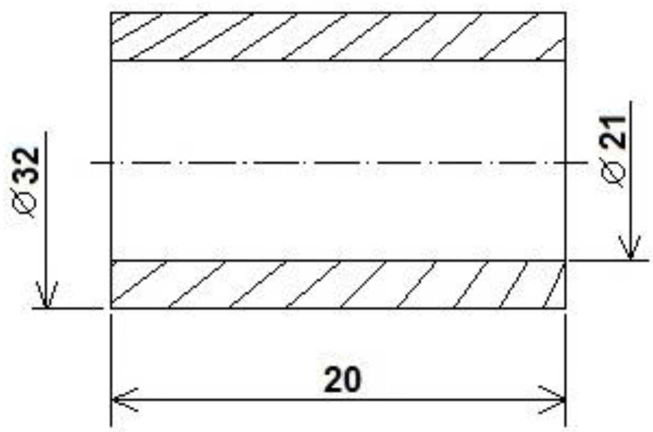

Figure 2. Sample drawing.

2.6 Test methodology

As previously specified, tests were performed by varying the spindle rotation, the depth of cut at the feed rate f = 0.104 mm/rev., in order to obtain a stability chart for the internal turning process. For the L / D = 6 ratio, several tests were performed as shown in figure 3, with a feed rate of 0.104 mm/rev., spindle rotation from 1,000 rpm to 5,000 rpm and depth of cut (a_p) ranging from 0.25 mm to 2 mm with increments of 0.25 mm as shown in the table 2.

Table 2 - Machining parameters used in the experiments for L / D = 6.

Spindle rotation (rpm)	Spindle rotation increment (rpm)	Depth of cut – a_p (mm)	Depth of cut increment (mm)
1,000 à 2,500	250	0.25 à 2.00	0.25
2,500 à 3,000	500		
3,000 à 5,000	1,000		

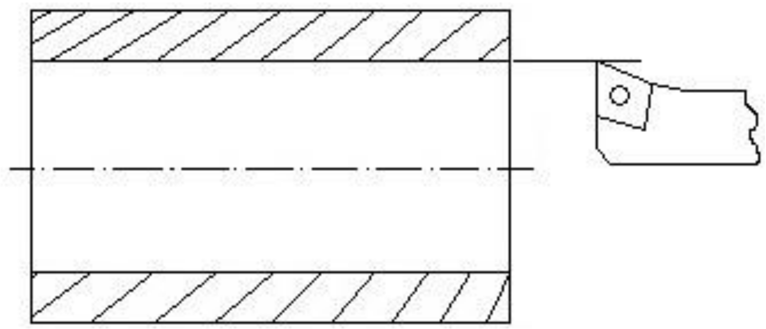

Figure 3. Machining condition used in the tests.

All experiments were performed in the dry (without lubricant-coolant).

After the tests and with the data generated, an individual analysis was performed for each parameter used. For all the tests, measurements in the time and frequency domain were analyzed in order to observe the differences between the stable and unstable processes, thus enabling the determination of the parameters that make up the stability chart and the comparison of the simulations with the results of the experiments.

3. RESULTS AND DISCUSSIONS

3.1 Frequency response function (FRF)

With a measuring hammer, an accelerometer attached to the tool and 2 Piezotronics PCB Signal Conditioners, impact tests were performed to determine the frequency response (FRF) function. From the FRF it was possible to determine the natural frequency of the tool holder, which was used in the simulations in Matlab and in the analysis of the experimental results. The graph of figure 4 shows the frequency response (FRF) function measured at the tool tip for the ratio L / D = 6. The peak magnitude occurs at the natural frequency (f_n) and corresponds to 969.9 Hz.

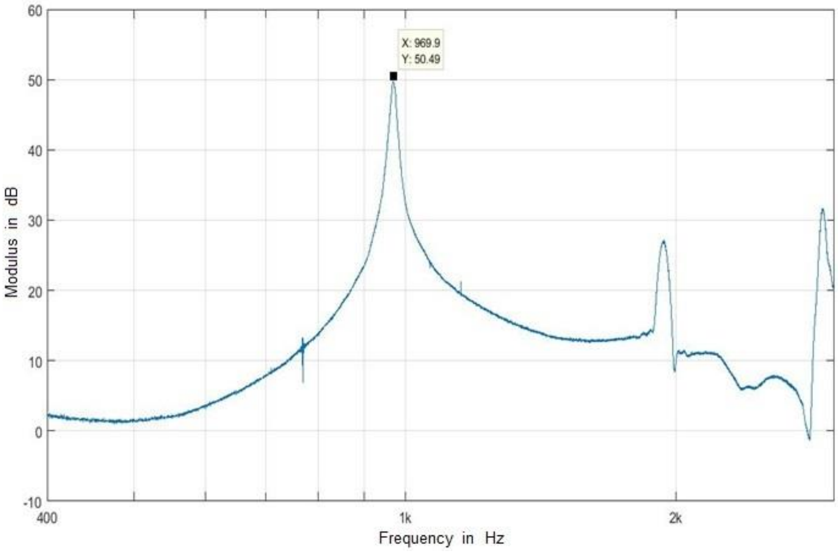

Figure 4. Frequency response function for L / D = 6.

3.2 Determination of the process damping coefficient

To determine the damping coefficient of the process, the three border points of the stability chart were taken. Simulations were performed in Matlab comparing with the experimental data until the approximate damping coefficient value that best fit the experimental data was obtained (Tyler, 2012).

3.3 Process Simulation

Based on a model of the process, simulations were carried out taking into account the parameters of table 3.

The cutting parameters adopted were the same as those used in the practical tests, with the value set at 0.104 mm/ rev. as feed rate and the tool overhang length of 96 mm. The depth of cut and spindle rotation varied for the purpose of mounting the stability chart.

Table 3. Data used in the process simulation.

Parameter	L/D = 6
Modal mass – m (Kg)	0.0617
Stiffness constant – K (kN/m)	2,290.74
Comprimento em balanço da ferramenta (mm)	96
Damping coefficient (c) – system (N.s/m)	4.108
System natural frequency (Hz)	969.9
Elasticity module – E (GPa)	200
Cutting specific pression (K_{tc}) – (N/mm^2)	624.44
Friction angle – β_a (°)	50.7
Output angle – α_r (°)	26
Part diameter (mm)	32
Tool-holder inertia moment (mm^4)	3,216.99
Tool-holder diameter (mm)	16
Damping coefficient (C) – machining (N/m)	26,848

The value of the modal mass (m) was calculated by Eq. (3) and the value of the stiffness constant (K) was found by Eq. (1). The values of Table 3 of modal mass (m), stiffness constant (K) and damping coefficient (c) were used in the model of Eq. (4) and Eq. (5) in the simulations performed in Matlab software.

$$w_n = \sqrt{\frac{K}{m}} \tag{3}$$

$$F_c = m\ddot{u} + c\dot{u} + Ku = F_u\, cos(\beta_a - \gamma_0) - \left(C\frac{b}{v_c}\, cos^2(\gamma_0)\right)\dot{u} \tag{4}$$

$$F_u = F_P + F_f + F_c \tag{5}$$

Where:

m - model mass;
$\ddot{u}$ - acceleration in damping direction;
c - model damping coefficient;
$\dot{u}$ - speed in damping direction;
K - model rigidity;
u - damping direction;
F_c - cutting force;
F_p - passive force;
F_f - feed force;
F_u - machining active force;
β_a - friction angle;
γ_0 - tool chip output angle;
C - machining damping coefficient;
b - cut width;
v_c- cutting speed.

In the time domain solution this equation is solved iteratively by the Euler method. The acceleration is calculated from the force and doubly integrated to reach the displacement of the tool.

The figure 5 shows the simulation results for L / D = 6 for a stable machining condition. It can be noticed that at the beginning of the process there is a variation in the values of force and displacement of the process, but soon afterwards the process stabilizes characterizing a stable condition.

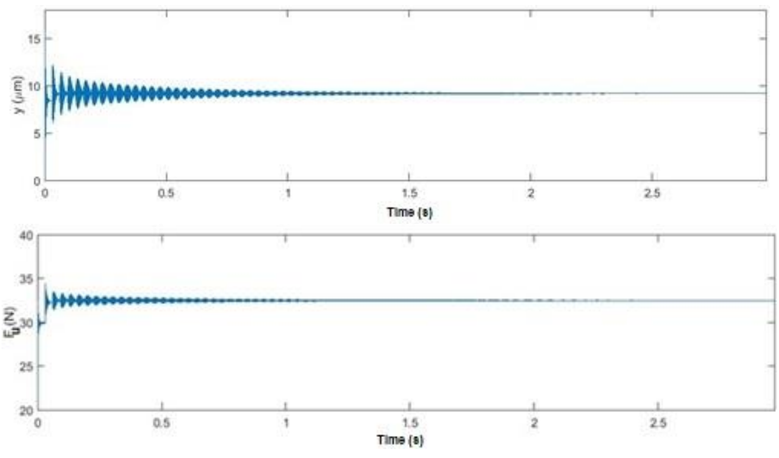

Figure 5. Simulation results with L / D = 6 for a_p = 0.5 mm and n = 2,000 rpm - stable condition.

The figure 6 shows the simulation results for an unstable machining condition. It can be noticed that at the beginning of the process there is no oscillation but soon after in the process there is an abrupt variation of the levels of force and displacement characterizing an unstable condition. Note that for high displacements, there are points where the force is zero. This corresponds to a process non-linearity due to loss of contact between the tool and the workpiece. If there were no such nonlinearity the force would increase infinitely.

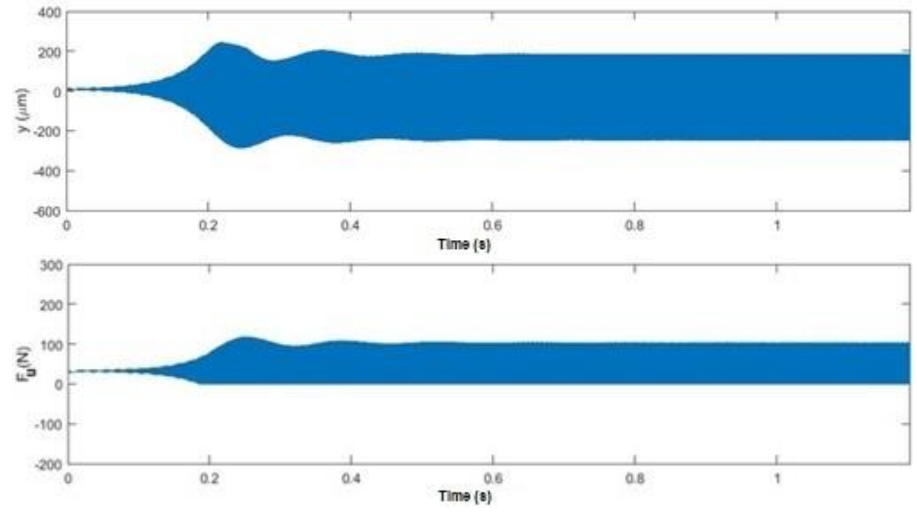

Figure 6. Simulation results with L / D = 6 for a_p = 0.5 mm and n = 5,000 rpm - unstable condition.

After implementing the equations and applying the proposed method, the points of the stability chart were obtained and plotted, as shown in figure 7. With the results of overlapping tests and simulation, discrepancies in the results are observed, especially for values of (a_p) near the tool nose radius (r_ε). For this condition the results of the simulation showed unstable cuts and in the experiments were shown as stable cuts, this is due to the fact that for cutting depths near or below the tool nose radius the model considered the cutting unstable.

At spindle rotations below n = 2,000 rpm there is a large stability region, this is due to the damping effect. In the algorithm implemented, this factor was considered, so the results are close to those obtained experimentally. There were discrepancies between some values resulting from the simulations and the experimental ones because the model does not consider the instabilities due to the use of very small depth of cuts.

As the spindle speed rises, the damping process ceases the existing and the effects of stability lobes begin to be visible. At higher rotational speeds, the diagram lobes become evident and the stability regions decrease.

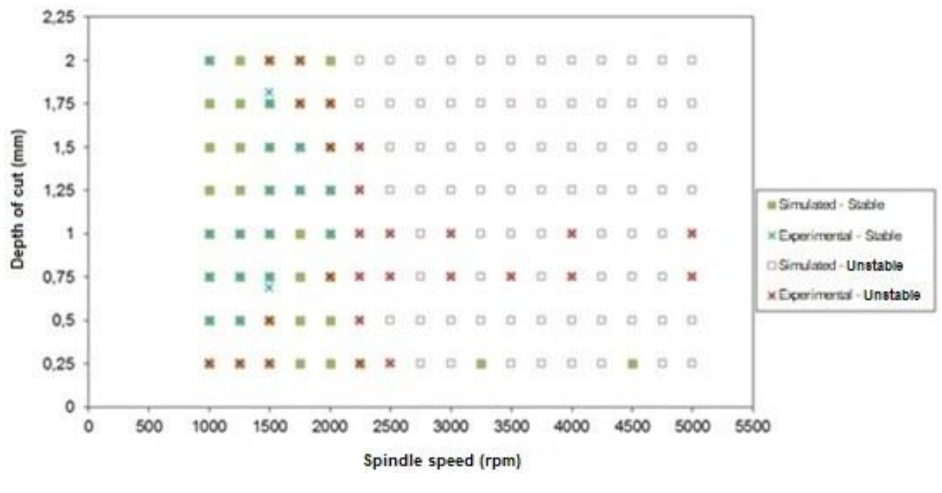

Figure 7. Stability chart for L / D = 6 obtained from Matlab and comparison between simulated and tests results.

4. CONCLUSIONS

Low spindle rotations, therefore low cutting speeds provide stable cuts even at high depths of cut due to the damping effect. According to the models in the literature, for a sufficiently small value of depth of cut the process would be always stable. However, there were discrepancies between the values resulting from the simulations and the experimental ones. The model used in the simulations does not consider the instabilities due to the use of very small depths of cut. Very small cutting depths can cause instability in internal turning. In this case the area of the chip is influenced by the tool nose radius of the tool and presents a curved aspect with regions of small section. Even small-amplitude vibrations, such as those caused by the impact at the beginning of the cut, can cause loss of tool contact with the part resulting in an unstable process. In addition, at small cutting depths smaller than the tool radius, there is a gradual increase in the passive (radial) force component, which contributes to the dynamic instability of the process in this machining condition. High cutting depths increase cutting efforts and according to general theory increase the self-excitation process of vibrations.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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