24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-0525
CUTTING SPEED: EFFECT ON CUTTING FORCES AND PROCESS DAMPING IN MILLING OF 7050 T7451 ALUMINUM

Rafael Borges Mundim
Anderson Vicente Borille
Instituto Tecnológico de Aeronáutica (ITA)
Centro de Competência em Manufatura (CCM)
Pç. Mal. do Ar Eduardo Gomes, 50, Vila das Acácias, 12228-970 São José dos Campos/SP - Brazil
mundim@ita.br
borille@ita.br

Abstract. *It is often found in literature that high speed cutting (HSC) offers benefits related to reduction in cutting forces. However, no data regarding the dynamic cutting behavior is provided, thus not allowing for assertive conclusions to be made on the actual benefits of reduction of cutting forces. This experimental study investigated the effect of cutting speed on cutting forces and damping in milling of an aluminum alloy (AA 7050 T7451) over a range that covers both conventional and HSC cutting speeds. For this, a typical setup adopted when milling these alloys was used, consisting of a 16000 RPM CNC machine tool and a cutter with a diameter large enough to allow for cutting speeds as high as 2500 m/min. Experimental data consisted of on-line force measurements, tap testing and subsequent chip type and form analysis. Findings indicate that the dynamic behavior of the fixture system may have a more significant effect on the cutting process than any reduction in cutting forces expected at high speeds. Additionally, results indicate that as long as the cutting process is dynamically stable, any influence of reduction of amplitude of cutting forces may be imperceptible under usual production scenarios.*

Keywords: *HSC, milling, aluminum, cutting stability, cutting forces*

1. INTRODUCTION

The evolution of cutting tool materials over the last 100 years alongside the higher speeds achievable by machine tool spindle units (Abele *et al*., 2010) have allowed cutting speeds to rise considerably (Fig. 1). This rise in cutting speed capability is partially responsible for the practical development of high speed cutting technology. High speed cutting (HSC) or high speed machining (HSM) is of special interest to industry due to proven advantages like larger material removal rates and better surface quality (Davim, 2012).

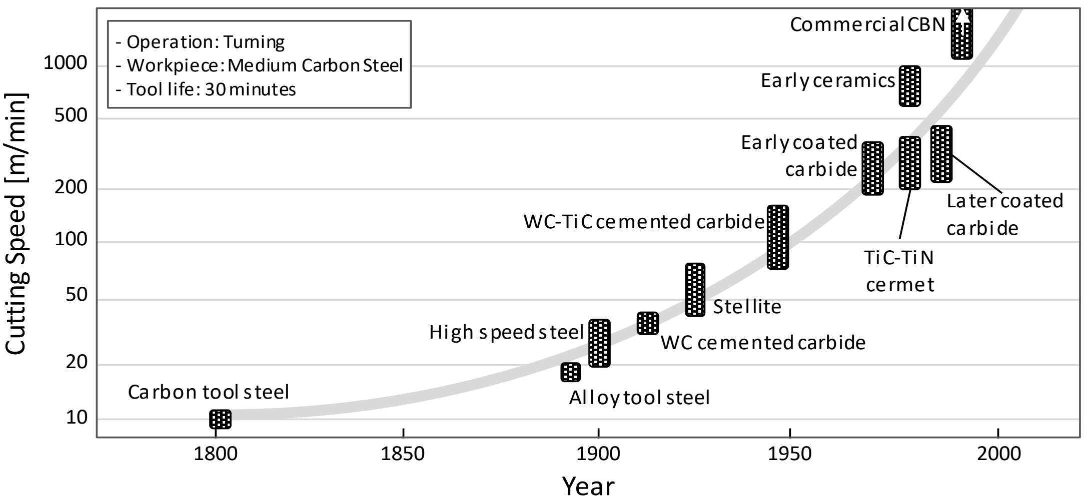


Figure 1. Evolution of cutting tool materials from the year 1800 to circa 2000. After Karino (1998) and Farhat (2003).

Grzesik (2008) points out that, despite HSC not having a unified definition, three main factors must be taken into account when characterizing machining as conventional or high speed. These factors are 1-cutting speed, 2-cutting mechanics, and 3-machining dynamics.

The first point of view that defines HSC uses a general cutting speed approach for specific materials and processes. That way, HSC ranges are described according to the process and material being machined, as shown in Fig. 2. Through this definition, machining of aluminum alloys at speeds over 500 m/min may be characterized as HSC, while Ni-based alloys reach HSC ranges at speeds as low as 60 m/min.

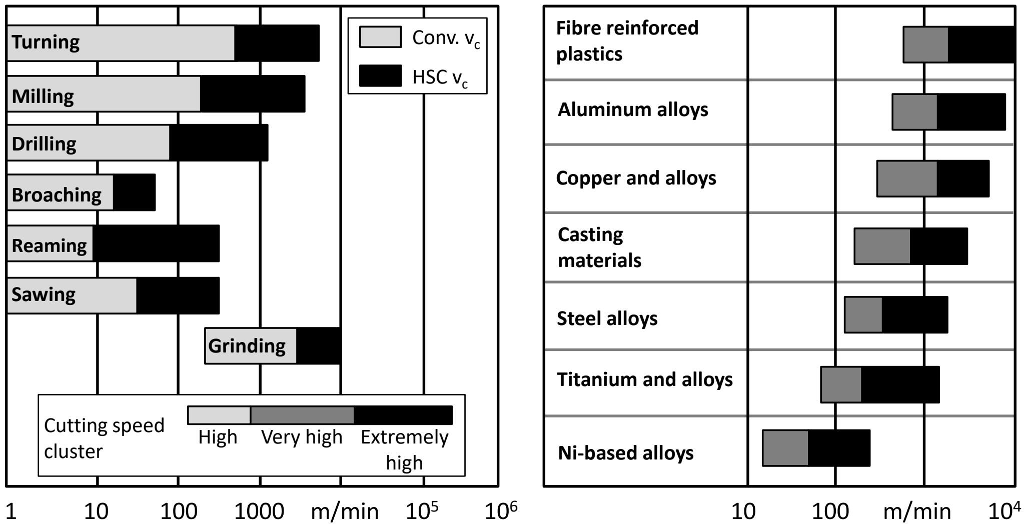


Figure 2. Cutting speed ranges depending on the type of machining operation and work material.
After Byrne, Dornfeld & Denkena (2003).

The second point of view used to define HSC is based on cutting mechanics (Schulz, 2001). This definition proposes that the HSC range begins when stabilization of friction and deformation force components is reached. Through this definition the author associates the material's ultimate tensile strength to the lower limit of high cutting speed (Fig. 3). By comparing this definition with the previous one, slight deviations are observed for similar materials. Additionally, Schulz (2001) notes that this definition should be taken into consideration only for ductile (long chip) materials.

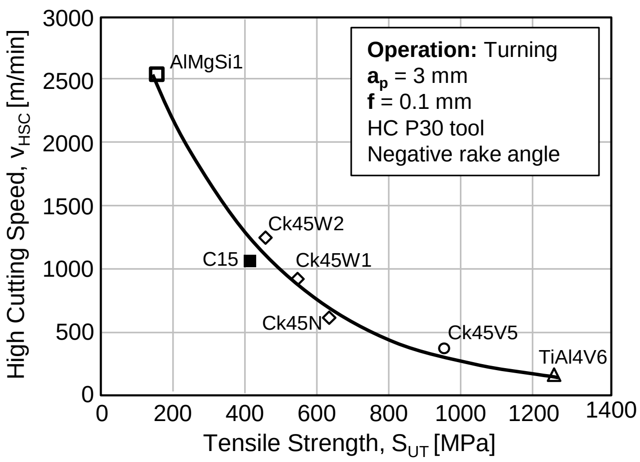


Figure 3. High cutting speed as a function of tensile strength for different materials. After Schulz (2001).

The third point of view defines HSC based on the dynamic stability. Under this aspect, HSC ranges are those at which the vibrational behavior of the system is affected by cutting speed change, as described by stability lobe theory (Tlusty and Polacek, 1963). This aspect is of great importance since higher material removal rates may be obtained by selecting adequate speeds at which stable cut is possible with maximized cutting depths.

Schulz (2001) lists several characteristics that are a consequence of HSC (Tab. 1). One of these characteristics is low cutting forces, which would benefit machining of flexible components such as thin walls and floors. Milling of these flexible structures is of great economic interest to improving product performance due to weight reduction of components (Munoa *et al.*, 2016).

Hoppe (2004) investigated chip formation and cutting force variation in turning of 7075 aluminum alloy for conventional and HSC speeds. His findings show a slight decrease in cutting forces at around 2000 m/min for a larger uncut chip section but this reduction is less noticeable for smaller sections. However, no statistical data regarding variability is presented and the encountered variations could, therefore, be insignificant.

Table 1. Characteristics of HSC and application examples. After Schulz (1999).

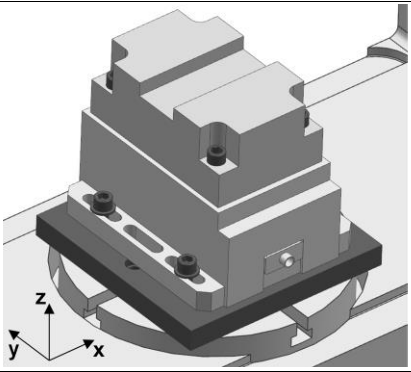
Characteristics	Application	Examples
High metal removal rate	▪ Light metals ▪ Steel and cast iron	▪ Aerospace ▪ Die and mold making
High surface quality	▪ Precision machining ▪ Special components	▪ Die and mold making ▪ Optics and precision mechanics
Low cutting forces	▪ Machining of thin-walled components	▪ Aerospace ▪ Automotive industry ▪ Household appliances
High excitation frequencies	▪ Vibration-free machining of difficult components	▪ Precision components ▪ Optical industry
Heat dissipation through chips	▪ Distortion-free machining ▪ Colder workpieces	▪ Precision components ▪ Magnesium alloys

Due to the relevance that force reduction may have on applications involving milling of very flexible parts, this study investigated the behavior of machining forces when cutting an aluminum alloy (AA 7050 T7451) at conventional and HSC speeds. In order to draw useful conclusions this investigation takes into account aspects such as chip formation and the dynamic behavior of the machining system.

2. EXPERIMENTAL PROCEDURE

It is often found in literature that reduction in cutting forces occurs at higher cutting speeds, as pointed out in the introductory section. Since the investigated alloy (AA 7050 T7451) is mainly used for milled structural aircraft parts at high cutting speeds, a typical machining center for such application with a maximum spindle speed of n = 16000 RPM was adopted to conduct tests (Hermle® C600U). A force acquisition system was used to acquire forces in the x-y-z directions at a sampling rate of up to 8 kHz, on which a presumably rigid workpiece was mounted (Tab. 2).

Table 2. Block-like aluminum workpiece used for cutting speed tests as mounted on the dynamometer (left), and force acquisition system specification (right).

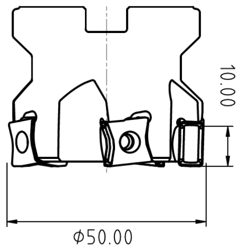


Dynamometer Kistler® 9265B	Range (kN): Fx, Fy (-15 +15), Fz (-10 +30) Natural frequency (kHz): x, y ~1.7, z ~2.7
Amplifier Kistler® 5070A	8 channels Acquisition Rate: 8000 Hz
Acquisition Board	PCIM-DAS1602/16 (PCI)
Adopted Measuring Range	1000 N for each of the 8 channels
Acquisition Software	DynoWare® 2825A

In order to verify the actual behavior of cutting forces due to varying cutting speed, experiments were conducted ranging from 200 m/min up to 2500 m/min (Tab. 3). The experimental runs consisted of 100% radial immersion (a_e) cuts with fixed feed (f_z) and axial cutting depth (a_p). Test conditions were determined considering the tool's geometry and the machine tool's speed range (n). A single cutting insert (N_t = 1) was used on a 5-tooth cutter in order to reduce the signal frequency, given by the tooth passing frequency (F_{pass} – Eq. 1) and its harmonics, while also eliminating the effect of tool run-out. The remaining 4 inserts had the active cutting edges ground and were also mounted as a way to minimize tool unbalance issues. Despite the high rigidity of the cutting tools and holders adopted, stability was evaluated by the force frequency spectra obtained by applying an FFT (Fast Fourier Transform) treatment to time signals.

$$F_{pass}[Hz]=\frac{N_t \cdot n[RPM]}{60} \tag{1}$$

Table 3. Test conditions for evaluating the effect of cutting speed on cutting force.

v_c [m/min]	n [RPM]	F_{pass} [Hz]	a_p [mm]	a_e [% D]	N_t	f_z [mm]	Cutter
200	1273	21.22	1	100	1	0.1	 ISCAR F90LN D050 / Positive Rake (27°)
600	3820	63.66					
1000	6366	106.10					
1250	7958	132.63					
1500	9549	159.15					
1750	11141	185.68					
2000	12732	212.21					
2250	14324	238.73					
2500	15915	265.26					

3. RESULTS AND DISCUSSION

All tests presented sufficiently stable cuts from a production environment point-of-view, as indicated by the obtained surfaces. However, at 1500 m/min and 2500 m/min slight disturbances were observed due to the structural behavior of both the machine tool spindle and workpiece fixture system. At 1500 m/min the tooth passing frequency excited one of the natural frequencies of the fixture system while at 2500 m/min a spindle disturbance was observed. Since the goal of this experiment was to evaluate the amplitude of cutting forces, these two runs were discarded from the analysis.

Although the workpiece used for testing is block-like, the fixture system is composed of several elastic elements such as nuts, bolts and washers (Fig. 4). These elastic elements influence the process in a way that leads to signal noise, as pointed out by Altintas *et al*. (2004). Instead of filtering these out, it was decided to maintain the original signal and evaluate the impact these would have on the milling forces.

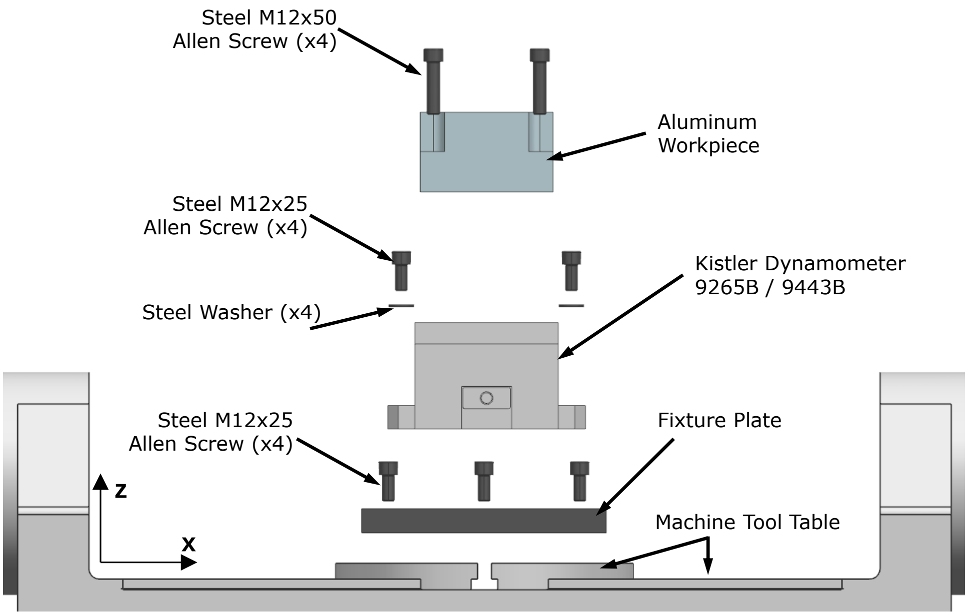


Figure 4. Exploded view of the fixture system used for the cutting speed experiments.

Due to the rapid force and frequency change as cutting speed was raised, an increasing oscillation of the measured force signals between successive tooth passes (non-cutting period) was observed. This effect is due to the reduced damping time between successive passes and consequent excitation of the workpiece-fixture system. Despite this effect, as shown through the cutting force profile projection in Fig. 5, a slight reduction in cutting forces was observed at around 1750 m/min. Reduction in cutting forces is in accordance with the work of Hoppe (2004) and an analysis of the process chips reveals that at around this speed a higher tendency for chip breakage occurred (Fig. 6).

Different chip forms can be associated to the increased temperature and consequent change of the chip formation mechanism, as pointed out in the introductory section. As explained by Hoppe (2004), strain hardening of the material is overcompensated by thermal softening at higher speeds causing the chip formation process to become unstable due to alternating shearing and compression mechanism. In turn, this mechanism will be responsible for creating lamellar structures that cause chips to be more prone to fracture than the chips observed at lower speeds. It should be noted, however, that dynamic effects might also play a role in increasing the tendency for chip breakage at this speed.

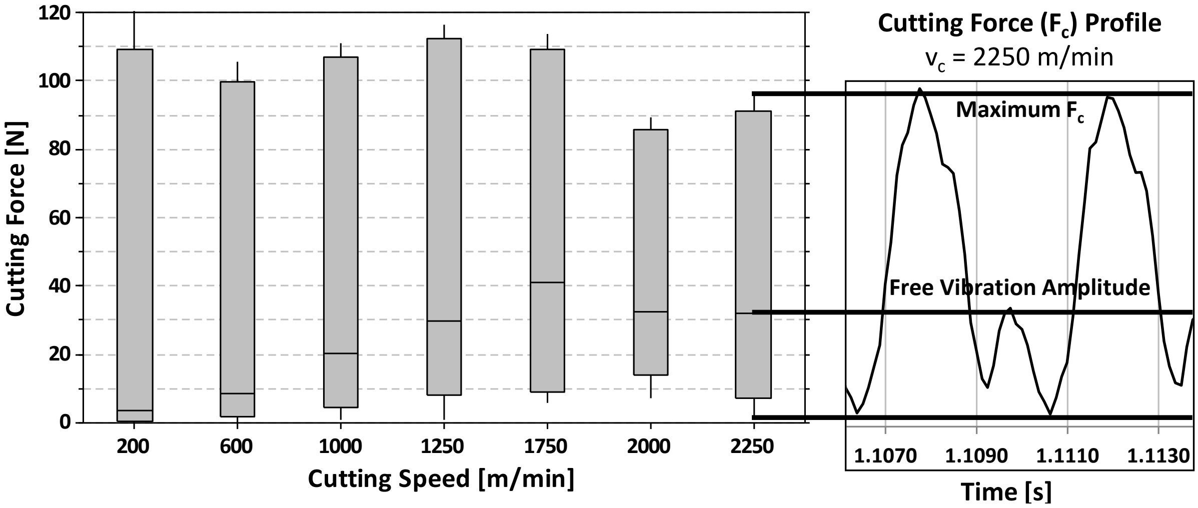


Figure 5. Boxplot of cutting force profiles indicating maximum cutting force observed and free vibration amplitude.

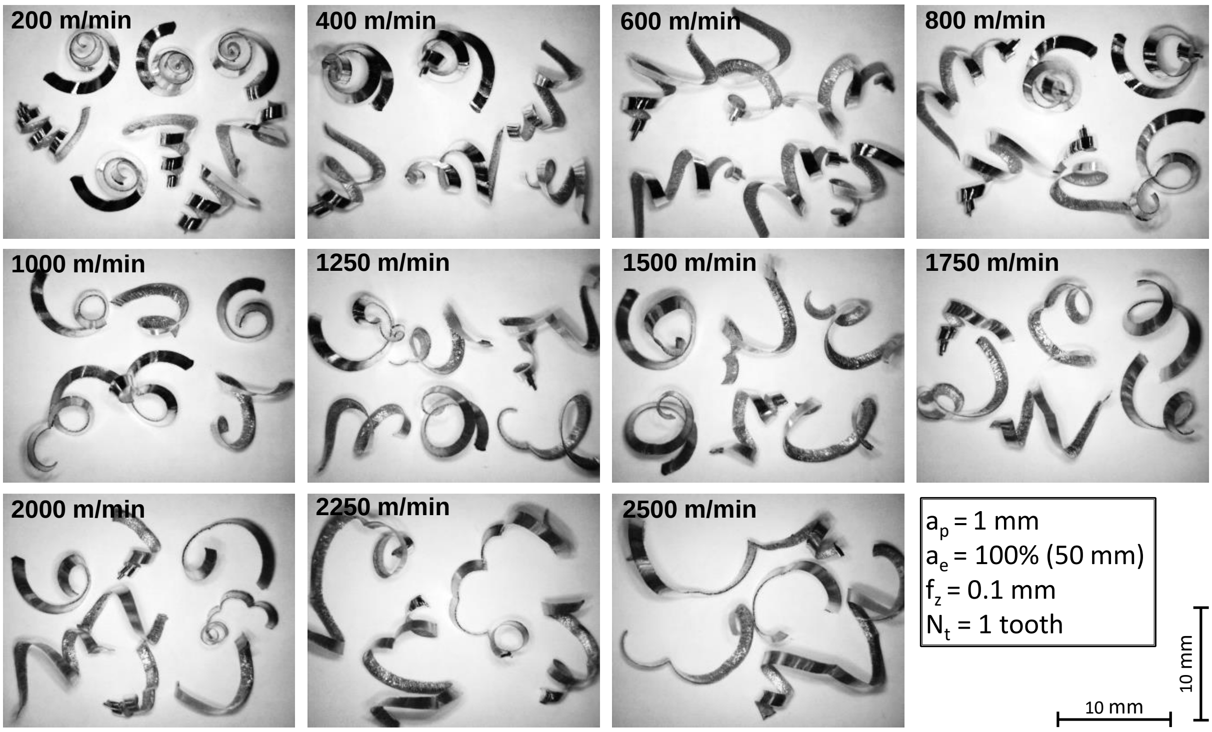


Figure 6. Chips produced by each cutting condition (200 – 2500 m/min).

The free vibration of the workpiece-fixture system during non-cutting time is depicted for different cutting speeds in Fig. 7. It can be noted that as cutting speed increases, the interval between successive teeth impact is reduced and the workpiece-fixture system does not come to rest before the next cutting period. So, as depicted in Fig. 7, at $v_c = 200$ m/min the underdamped behavior of the system is fully observed, in which the force amplitude falls to zero before the next tooth enters the cut. At $v_c = 600$ m/min the typical vibration peaks of the same underdamped system are also observed, but when the next cutting period starts the workpiece-fixture system is still oscillating. So, at this speed, not enough damping time is available for the structure to come to rest. As speed increases, damping time is reduced even more, as depicted in the third graph ($v_c = 1000$ m/min).

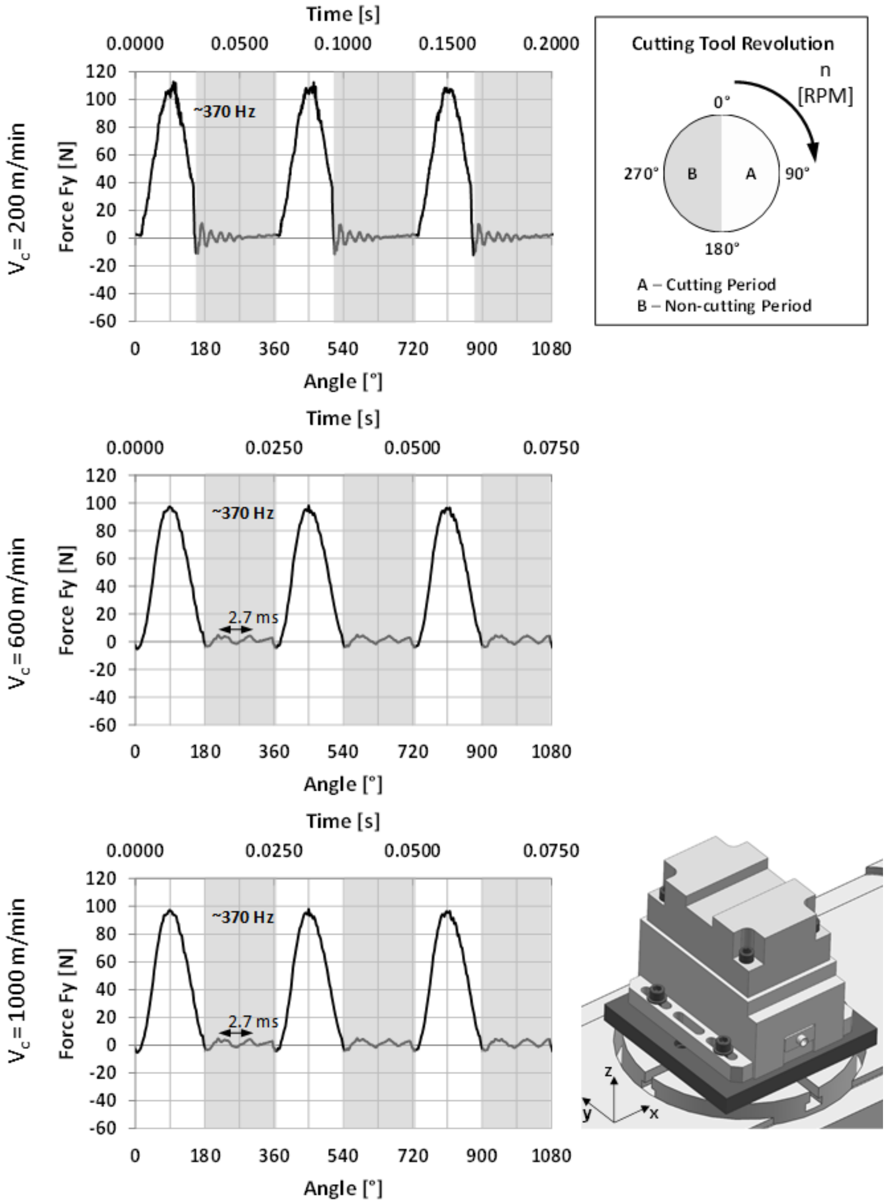


Figure 7. Force signal along the y-direction for three different cutting speeds. Three cutter revolutions shown.

In order to verify that the free vibrations observed through the dynamometer were in fact due to the workpiece fixture system, the obtained frequency domain data was confronted to dynamic response data obtained by tap-testing the structure (Fig. 8). A maximum difference of 3% was observed between the frequencies of the main vibration mode and the vibration signal observed during cutting, which led to the conclusion that the measured cutting force signal is modulated by the system’s dynamic behavior significantly around its natural frequencies. This finding indicates that even if a reduction of cutting force takes place due to a change in the chip formation mechanism, its effect can be considerably smaller than those of the dynamic response of the fixture system. This, in turn, may invalidate this literature-suggested characteristic in cases where the dynamic behavior of the machining system is not adequate.

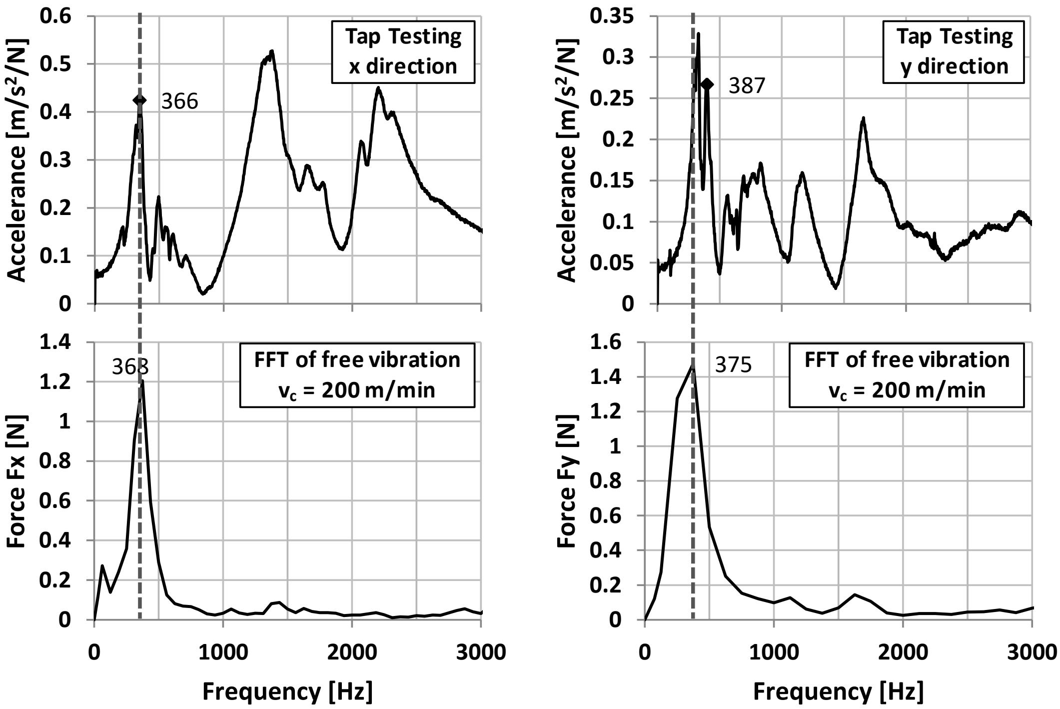


Figure 8. FFT of force signals (F_x and F_y) during non-cutting period at v_c = 200 m/min and frequency response functions (FRF) for respective directions.

4. CONCLUSIONS

For the investigated range (200 – 2500 m/min) and cutting tool - workpiece material combination, no reduction in cutting forces was observed that could be attributed conclusively to a change in the flow behavior of the material. A minor change was observed at around 2000 m/min. However, experimental modal analysis data could attribute this behavior to the dynamics of the machining system. At this same speed range a higher propensity to producing smaller chips was observed. This, in turn, is attributed not only to a transition of the material flow characteristics but it could also be a consequence of the workpiece-cutting tool vibrational behavior. This supports the statement that, even if a change of the chip formation mechanism takes place at higher speeds, it could be insignificant if compared to the effect of the dynamic behavior of the machining fixture as the tooth passing frequency varies.

The findings in this exploratory work imply that the dynamic behavior of the machining system must be taken into account when inferring about possible reductions in cutting forces. However, for the specific case of this work, the force amplitude of free vibration between successive teeth impact is considerably lower than that of the chip formation process. Therefore, as long as the cutting process is dynamically stable, any influence of free vibration in between excitations (tooth impact) may be ignored under usual production scenarios.

5. ACKNOWLEDGEMENTS

This work was supported by CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) and CNPq (National Counsel of Technological and Scientific Development – Brazil). Acknowledgements are also due to Embraer and Siemens PLM for providing technical and material support in this project.

6. REFERENCES

Abele, E.; Altintas, Y.; Brecher, C. Machine tool spindle units. *CIRP Annals - Manufacturing Technology*, v. 59, n. 2, p. 781–802, 2010.

Altintas, Y. *et al*. Sensors and signal analysis in high performance cutting. In: International Conference on High Performance Cutting (HPC), 2, 2004, Aachen. *Proceedings*... Aachen: CIRP, 2004. p. 117 - 136.

Byrne, G; Dornfeld, D.; Denkena, B. Advancing Cutting Technology. In: *CIRP Annals - Manufacturing Technology*, 2003. p. 483 - 507

Davim. J.P (Editor). *Machining of Complex Sculptured Surfaces*. London: Springer, 2012.

Farhat, Z. N. Wear mechanism of CBN cutting tool during high-speed machining of mold steel. *Materials Science and Engineering: A*, v. 361, n. 1–2, p. 100–110, 2003.

Hoppe, S. *Experimental and numerical analysis of chip formation in metal cutting.* 2004. 199 f. Thesis - Mechanical Engineering, RWTH Aachen University, Aachen, 2003.

Grzesik, W. *Advanced Machining Processes of Metallic Materials: Theory, Modelling and Applications.* [S.L.]: Elsevier Science, 2008. 472 p.

Karino, K. *Trouble Shooting for Cutting: Prediction Information to Improve Production Techniques.* [S.L.]: Mitsubishi Materials, 1998.

Munoa, J. *et al*. Chatter suppression techniques in metal cutting. *CIRP Annals – Manufacturing Technology*, v. 65, n. 2, p. 785–808, 2016.

Schulz, H. The History of High-Speed Machining. *Revista de Ciência & Tecnologia*, Piracicaba, v. 7, n. 13, p.9-18, jun. 1999.

Schulz, H. *Scientific Fundamentals of HSC.* Munich: Carl Hanser Verlag, 2001.

Tlusty, G.; Polacek, M. The stability of machine tools against self-excited vibrations in machining. Annals of the *International Research in Production Engineering Conference*. Pittsburgh: American Society of Mechanical Engineers, 1963

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.