COBEM 2023 27TH INTERNATIONAL CONGRESS OF MECHANICAL ENGENEERING

ABCM Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-2364
ANALYSIS OF THE MACHINING FORCES AND VIBRATIONS IN TURNING WITH GROOVING TOOLS

Amarildo Alves Dias
Milton Luiz Polli
Bruno Edson Klipstein
Federal University of Technology - Paraná, Graduate Program in Mechanical Engineering and Materials – PPGEM. Deputado Heitor Alencar Furtado Street, 5000 –CIC, Curitiba – PR, 81208-340.
amarildodiasmec@gmail.com
polli@utfpr.edu.br
klipstein@alunos.utfpr.edu.br

Abstract. *Among current manufacturing processes, machining stands out as one of the main means of production. The turning process is extremely important in the manufacturing of various parts. Vibration, or the phenomenon of self-excited vibrations that occur mainly due to the low dynamic rigidity of the cutting tool or the workpiece, compromises surface finish, dimensional accuracy, and tool life. Wide-channel turning with groove tools offers a significant time gain compared to the use of right or left cutting geometries. However, research addressing the occurrence of regenerative vibrations in this type of process is scarce. This study analyzed the dynamic stability in the turning process with groove tools. Experimental tests were conducted on a CNC lathe, with variations in cutting parameters and workpiece overhang. The material used in the tests was 1045 steel. Machining was performed without cutting fluid using the N123G2-0300-0004-TM 1125 insert. Stability evaluation was based on the analysis of the audio signal and machining forces. The results showed that the lateral deflection of the tool, with the increase in machining forces and feed rate, improves the stability of the process. It was also evident that the reduction in the workpiece overhang contributes to a more stable operation.*
Keywords: *Channel turning, regenerative vibrations, grooving tool, chatter, machining stability.*

1. INTRODUCTION

Due to its flexibility of use, high production capacity combined with great dimensional and geometric precision, machining, along with its sub-processes, is present in the production chain of most industrialized products. It also provides high-quality surface finishes for a wide range of geometries with a good cost-benefit ratio (Kikukawa et al., 2019; Lauro et al., 2014). Machine tools and cutting tools have evolved considerably in recent years. Regarding machine tools, they have become more powerful, precise, rigid, and with a higher level of automation. However, some problems persist in this process, like vibrations, which at certain levels can increase production costs, reduce productivity, waste raw materials, and contribute to increased noise in the environment (Yan et al., 2023; Altintas et al., 2020; Munoa et al., 2016).

The vibratory system in typical machining operations is dynamic and complex (Kounta, 2023). While free and forced vibrations are easily identifiable and have trivial solutions, in regenerative (self-excited or chatter) vibrations, control is complex due to the variety of components that can affect the stability of the system during machining (Siddhpura and Paurobally, 2012; Quintana and Ciurana, 2011). The forces that contribute to the occurrence of this type of vibration do not originate from factors external to the cutting process, but from resulting forces generated during it (Pires, 2011).

According to Altintas (2012) the self-excitation mechanism occurs when one of the structural modes of the machine-tool-part system is initially excited by the cutting forces. The regenerative effect is caused by the superimposition of successive cuts, when the tool passes over an undulating surface on the workpiece with a phase change between successive undulations. The lack of synchronism between the passes (Figure 1) causes the chip thickness to vary exponentially with consequent variation of the cutting forces, exciting the structure which may have its amplitude of vibration increased if the excitation frequency is close to a dominant structural mode of the system (Lara, 2017). Such vibrations result in deteriorations of the finished surfaces and tool damages (Atsuta et al., 2023).

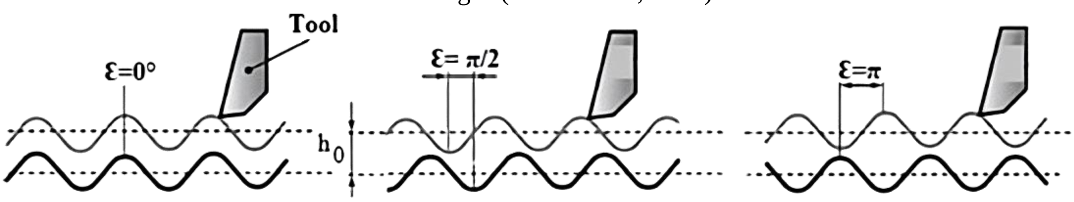

Figure 1. Self-excitation mechanism (Altintas, 2012).

In turning operations, regarding process instability, studies mainly focus on internal machining due to the fragility of the tool holder. Studies on vibration control methods have also been conducted for radial cutting with a lathe tool.

In wide channel machining, the use of interchangeable carbide insert lathe tools represents a viable alternative since this tool can machine in both directions (right and left) and also avoids the need to change the tool for removing the remaining material on one side of the channel, as in the case of a conventional turning tool (Figure 2).

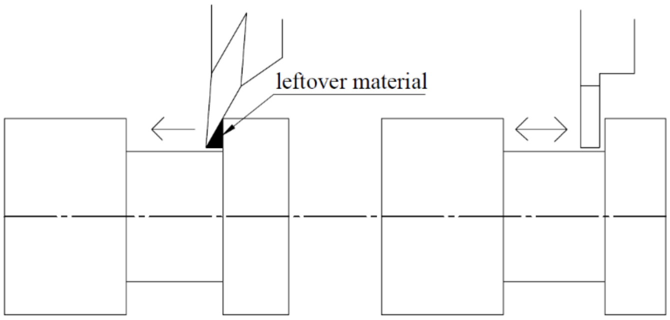

Figure 2. Machining comparison with a turning tool and a left-hand tool.

This work aims to gain a better understanding of the phenomena associated with the dynamics of the channel turning process with a lathe tool and how cutting parameters influence the dynamic stability of the process.

2. EXPERIMENTAL PROCEDURE

The analysis of the dynamic stability of the studied process consisted of practical and systematic tests in a machining laboratory. In order to obtain input data for future computer simulations, tests were conducted to measure the components of machining force, thus obtaining the cutting coefficients for the tool-workpiece pair at this stage. In the analysis of process stability, audio signals were recorded during the experiments using a conveniently positioned smartphone to minimize interference from other sound sources. The data obtained by varying the test conditions (workpiece rigidity and cutting parameters) were analyzed using specific software.

2.1 Materials and Equipment

The measurement of machining forces was carried out using a Kistler piezoelectric dynamometer (model 9265B) and a signal amplifier (model 5070A), along with a National Instruments data acquisition board and a personal computer running LabView software. The sensitivity adjustment of the signal amplifier was set for forces up to 1.5 kN. The LabVIEW programming was designed so that the input voltage values (V) were displayed in force units (N).

Tests were conducted to measure the components of machining force on both a conventional lathe (Romi, Model ID-20) and a CNC lathe (Romi, Model GL-240) for result comparison. The same cutting parameters were used in both tests. For measuring the forces on the CNC machine, two fixtures were fabricated, one for attaching the dynamometer to the tool turret of the lathe, and another for securing the tool to the dynamometer (Figure 3).

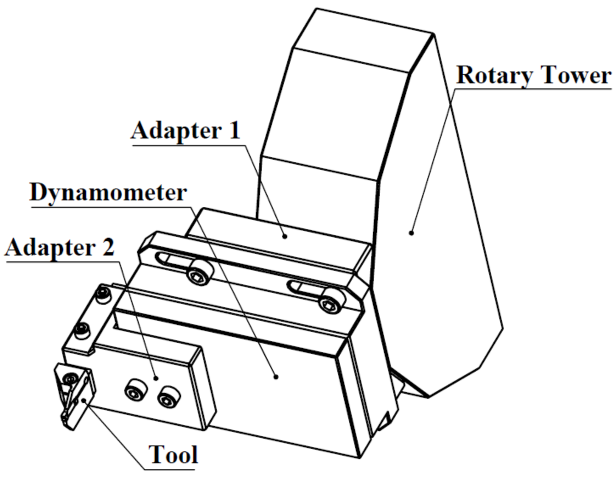

Figure 3. Detail of the dynamometer attachment on the CNC lathe.

The cutting tool used in this study is specific for axial cutting operations with lateral feed and has the TM cutting geometry from the manufacturer Sandvik. The manufacturer also provides tools with CM profile for radial cuts. Figure 4 shows the details of the tool geometry, as well as the main angles and cutting data for the ISO P material class (steels) provided by the manufacturer.

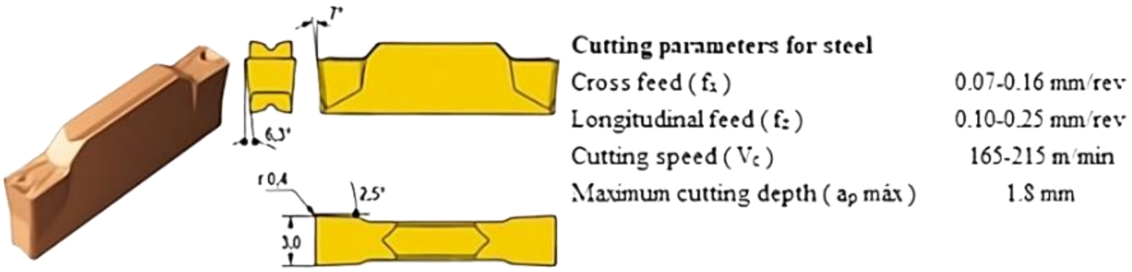

Figure 4. Geometry and parameters of the insert - N123G2-0300-0004-TM 1125 (Adapted from Sandvik, 2020).

Regarding the tool holder, considering that the maximum depth is the characteristic that supposedly has the most influence on the rigidity of the tool holder, a commonly used holder for turning operations was chosen to avoid extremes in this regard. Thus, the tool holder used was the RF123G20-2020B, designed for a maximum depth of 20 mm, providing a moderate rigidity based on this aspect and suitable for the purpose of this work. The tool holder is also from Sandvik.

The raw material used in the tests was the ArcelorMittal's round drawn SAE 1045 steel, with dimensions illustrated in Figure 5. According to conducted tests, the samples used comply with the manufacturer's specifications, both in terms of chemical composition and physical.

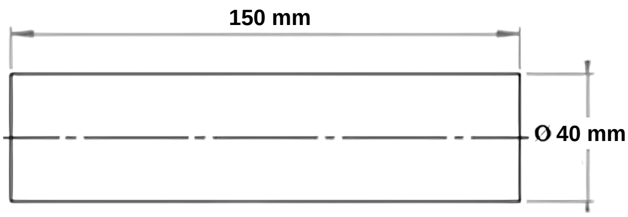

Figure 5. Raw material used in the tests.

The dimensions of the material used were determined based on preliminary machining tests. This ensures a secure fixation, appropriate free length (overhang), and sufficient rigidity for the test conditions and objectives of this research.

For audio signal acquisition, a dedicated smartphone Samsung model SM A310M/DS was used. During the experiments, in order to achieve better sound capture, the machine door was kept open. Two softwares (Matlab R2023a and Audacity 3.3.3) were used for data analysis. Audacity was used to define the periods of stable and unstable cutting, while Matlab was utilized to determine the frequencies at peak and to obtain the RMS value during the analyzed period.

2.2 Test Method

To measure the components of machining force (cutting force F_c, feed force F_f, and passive force F_p), the workpiece was fixed with a small overhang and the values of depth of cut (a_p) and cutting speed (V_c) were set to 1.25 mm and 50 m/min, respectively. The values of feedrate ranged from 0.1 to 0.25 mm/rev. Three tests were made for each condition and the average values were considered in the analysis. The workpiece geometry was prepared according to Figure 6.

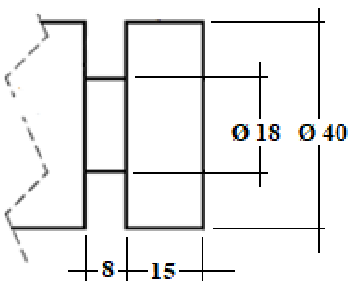

Figure 6. Workpiece geometry for measuring machining forces.

For all the tests the workpiece was fixed using a 3-jaw Autoblock chuck, model 150 BH, with hydraulic actuation. For the stability tests, the workpiece overhang (free length of the workpiece) was three times the diameter of the workpiece, without the use of a tailstock for support at the free end. The clamping pressure was set at 15 bar (1500 kPa). Figures 7 illustrates the proposed method for turning operations using a tool bit. To preserve the cutting edge of the tool under analysis and not influence the results, finishing passes were applied to all machined diameters using a "V" profile tool with a 0.4 mm corner radius, reducing the diameter by 0.5 mm.

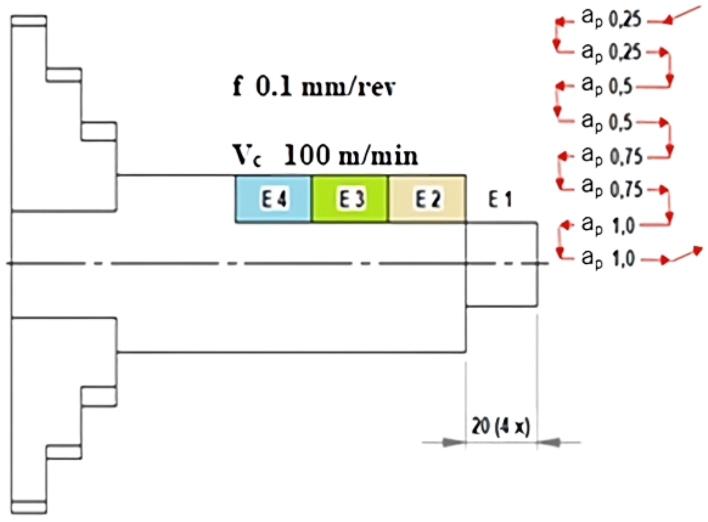

Figure 7. Test with variation in depth of cut.

3. RESULTS AND DISCUSSIONS

3.1 Machining Forces

Among the cutting parameters, cutting speed is the one that most influences tool wear. Therefore, at this stage, values below those recommended by the manufacturer were chosen in order to preserve the cutting edge. However, care was taken to prevent the formation of built-up edge (BUE), which, according to Reis (2000), occurs due to significant frictional forces between the chip and the cutting tool under certain machining conditions, especially at low cutting speeds.

Figures 8 to 11 show examples of force measurement with variation in feedrate, which were used to determine the force coefficients. The values of depth of cut and cutting speed were 1.25 mm and 50 m/min, respectively.

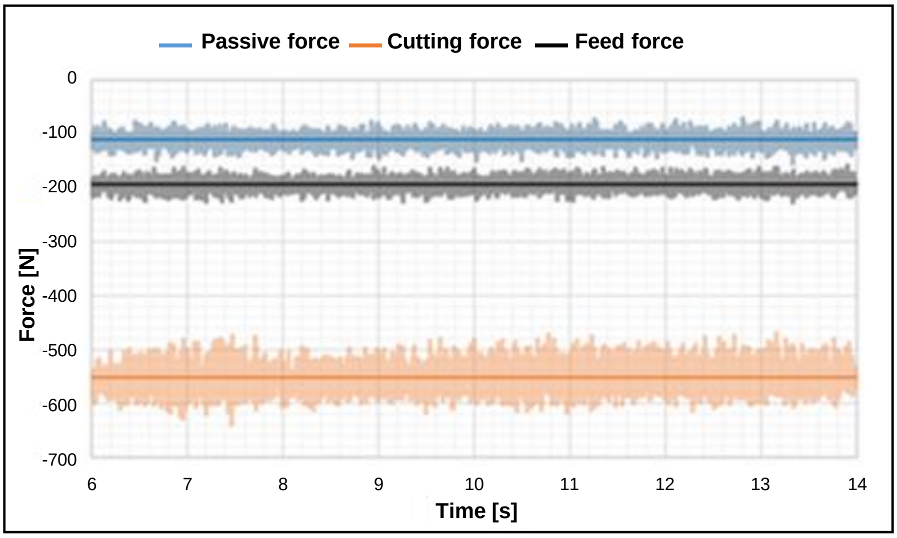

Figure 8. Average value of machining forces for f = 0.10 mm/rev.

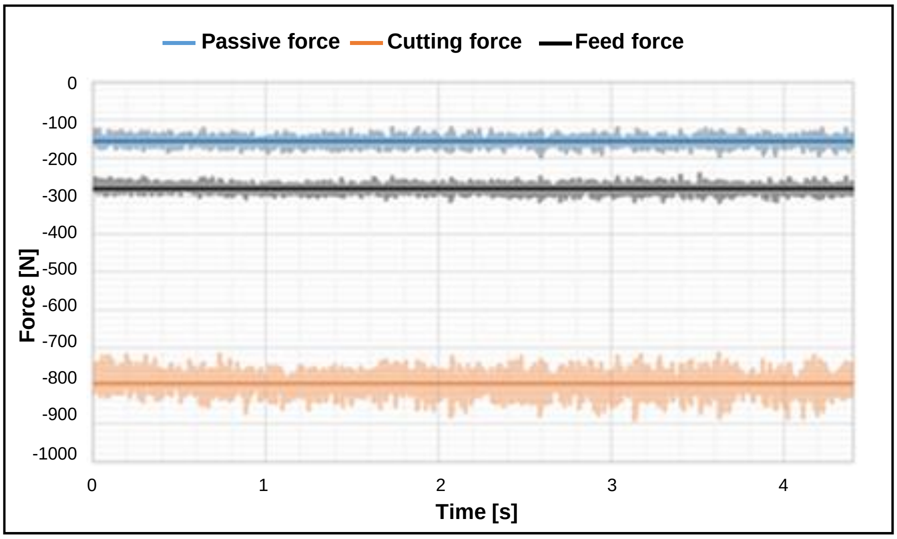

Figure 9. Machining forces for f = 0.15 mm/rev.

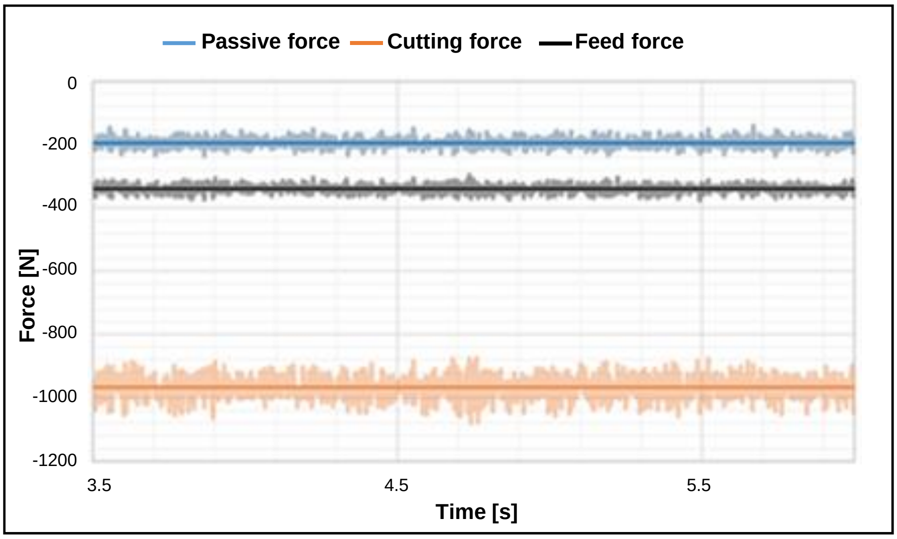

Figure 10. Machining forces for f = 0.20 mm/rev.

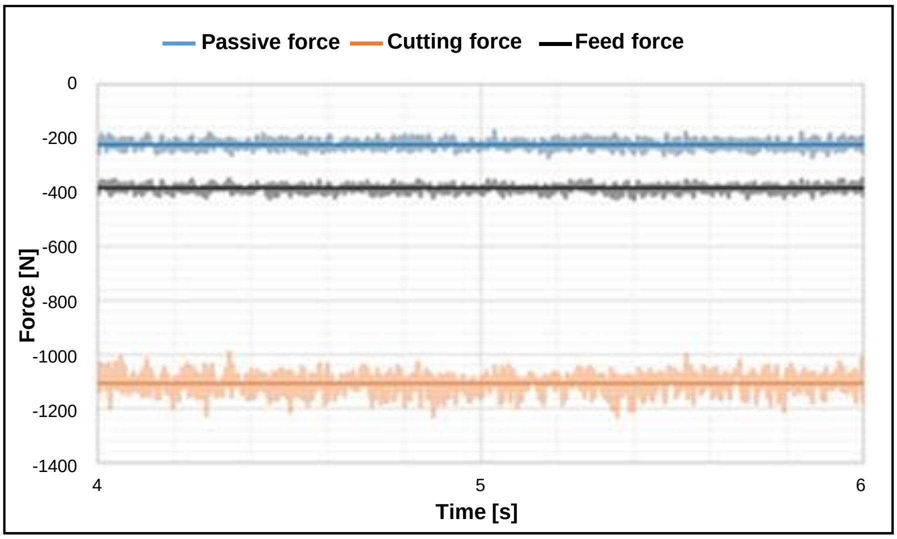

Figure 11. Machining forces for f = 0.25 mm/rev.

The same cutting condition was tested in both right and left feed directions, extracting the most stable intervals for force recording. In all the experiments, the period of greater stability coincided with the right feed direction, which can be justified by the slight inclination of the cutting edge of the tool, approximately 0.1 mm over a length of 8 mm. This reduced the contact area with the workpiece, leading to increased stability in the machining forces.

The negative values in the results may be due to the orientation of the applied load, which can be opposite to the orientation of the piezoelectric sensor of the dynamometer. Therefore, the negative signal was ignored, and the absolute value of the average forces was considered.

The forces obtained for all tested parameters showed consistent values. According to Altintas (2012), in the composition of the cutting force (F_c) and feed force (F_f), additional forces due to tertiary deformation, friction, and chip compression effect are also included. Unlike the mechanistic mathematical model that uses the Kienzle equation to obtain the components of the machining force (F_u), Altintas' model considers that the cutting and feed forces are composed of shear forces (F_{cc} and F_{fc}) and forces at the cutting edges (F_{ce} and F_{fe}). Therefore, it is necessary to determine the shear and edge cutting coefficients. Figure 12 shows the evolution of the mean forces and the linear regression with the characteristic equation of each component of F_u, where the slope and intercept correspond to the shear forces and forces at the cutting edge, respectively.

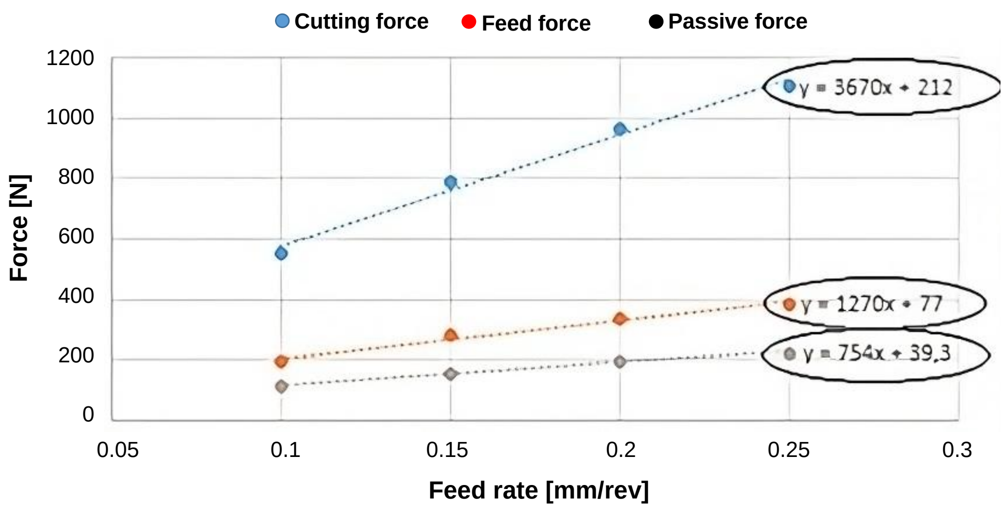

Figure 12. Evolution of machining forces in function of the feedrate (a_p = 1.25 mm; V_c = 50 m/min).

Table 1 shows results obtained in the measurements of machining forces with variation of feedrate. The cutting coefficients and forces at the cutting edge were obtained based on the characteristic equations obtained from the linear regression shown in Figure 12.

Table 1. Results of machining force measurements.

Feed rate (mm/rev)	F_c (N)	F_f (N)	F_p (N)	K_{cc} (N/mm^2)	K_{fc} (N/mm^2)	K_{ce} (N/mm)	K_{fe} (N/mm)	F_{ce} (N)	F_{fe} (N)
0,10	552	193	111	2936	1016	169,6	61,6	212	77
0,15	793	280	156	2936	1016	169,6	61,6	212	77
0,20	966	339	194	2936	1016	169,6	61,6	212	77
0,25	1106	385	224	2936	1016	169,6	61,6	212	77

K_{cc} - Shear cutting force coefficient; K_{fc} - Shear feed force coefficient; K_{ce} - Edge cutting force coefficient; K_{fe} - Edge feed force coefficient.

3.2 Process Stability Analysis

For stability tests, the insert was aligned. In the 8 mm length, a maximum misalignment of 0.01 mm was observed. To verify the cutting edge height, the workpiece was faced with it. The absence of remaining material in the center of the workpiece indicated that the tool height was correct in relation to the center of the machine.

The instability in the machining process can be observed through the increase in audio signal amplitude and also by the appearance of the machined surface. The frequencies during moments of instability were recorded for future comparisons with the natural frequencies of the tool and the workpiece. In this study, the criterion used for stability analysis was the sound amplitude, obtained based in the RMS (Root Mean Square) value, which represents the effective amplitude of the audio signal. The amplitude was obtained considering the entire machining period, as shown in Figure 13. Therefore, the recorded intensity was more affected by the instability duration rather than the sound amplitude itself.

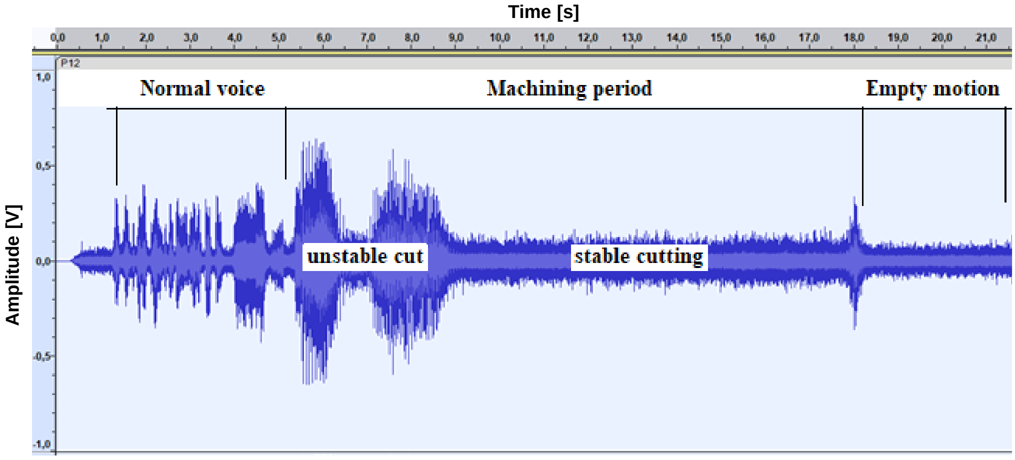

Figure 13. Audio signal in turning with grooving tool

Table 2 presents the RMS values and frequency at instability peaks for each of the four workpiece overhang values.

Table 2. Results of stability tests with variation in cutting depth.

Overhang (E)	Depth (mm)	Value RMS	Frequency (Hz)	Overhang (E)	Depth (mm)	Value RMS	Frequency (Hz)
E1	**0.25a**	**0.29**	**758**	E3	**0.25a**	**0.26**	**747**
	0.25b	**0.10**	**690**		**0.25b**	**0.05**	**788**
	0.50a	**0.28**	**759**		**0.50a**	**0.25**	**876**
	0.50b	**0.30**	**697**		**0.50b**	**0.09**	**800**
	0.75a	**0.26**	**752**		**0.75a**	**0.11**	**783**
	0.75b	**0.17**	**759**		**0.75b**	**0.10**	**793**
	1.00a	**0.29**	**692**		**1.00a**	**0.13**	**781**
	1.00b	**0.31**	**692**		**1.00b**	**0.14**	**787**
	1.25a	**0.20**	**671**		**1.25a**	**0.15**	**1001**
	1.25b	**0.29**	**695**		**1.25b**	**0.16**	**990**
E2	**0.25a**	**0.28**	**759**	E4	**0.25a**	**0.26**	**869**
	0.25b	**0.05**	**761**		**0.25b**	**0.05**	**773**
	0.50a	**0.26**	**703**		**0.50a**	**0.08**	**876**
	0.50b	**0.15**	**726**		**0.50b**	**0.08**	**787**
	0.75a	**0.12**	**752**		**0.75a**	**0.08**	**783**
	0.75b	**0.13**	**761**		**0.75b**	**0.09**	**777**
	1.00a	**0.20**	**760**		**1.00a**	**0.11**	**780**
	1.00b	**0.19**	**760**		**1.00b**	**0.12**	**750**
	1.25a	**0.18**	**755**		**1.25a**	**0.13**	**1030**
	1.25b	**0.21**	**756**		**1.25b**	**0.13**	**1005**

(yellow)	Unstable	(orange)	Little Unstable	(light blue)	Stable

The results were obtained from the tests with variation in depth of cut. The letters (a) and (b) next to the depth values represent the left and right feed rates, respectively.

The unit of measurement for the RMS value obtained in the tests depends on the unit of the original signal, which, being collected by a smartphone, does not have a clearly defined physical unit. Therefore, the value found represents a relative measure of the energy level for each test. For moments of stability in the cutting process, the RMS value remained below 0.15, while for RMS values above 0.25, vibrations occurred during machining. Intermediate values showed little instability.

In comparison between the results in E1 and E4, the tests showed a significant improvement in machining stability with the reduction of workpiece overhang. However, for the number of tests conducted, the cutting depth did not have a significant influence on the cutting process. Regarding the frequency at moments of maximum sound amplitude, there was some variation with changes in the workpiece geometry and overhang. The frequency of the oscillation ranged from 671 Hz to 1030 Hz.

4. CONCLUSIONS

In this research, the stability analysis was carried out in turning of 1045 steel with a specific grooving tool. The results showed that the machining forces increase linearly with the feedrate. The cutting force is almost three times greater than the feed force, which in turn is 70% higher than the passive force. It was possible to determine the shear force constants and edge coefficients for this particular combination of cutting tool and workpiece.

Regarding the stability of the process, based on the number of tests conducted, there is a clear improvement in stability with the reduction of the workpiece overhang during machining. The alignment of the insert balanced the moments of instability in both cutting directions. There was no evidence of increased instability with greater depth of cut, which can be justified by the higher cutting force and consequently greater lateral deflection of the tool. Another factor to consider in the tests is the reduction in the diameter of the workpiece, as smaller radii of curvature increase the clearance between the tool and the workpiece, resulting in less friction and a greater tendency for vibrations.

It is necessary to perform modal analysis of the components to determine whether vibrations occurred in the cutting due to the tool or the workpiece flexibility. The variation in moments of instability throughout the tests, as the workpiece geometry changed, suggests that the natural frequencies of the workpiece are close to the recorded peak frequencies.

5. REFERENCES

Altintas, Y. et al., 2020. "Chatter Stability of Machining Operations". *Journal of Manufacturing Science and Engineering,* Vol. 142 (11): 110801.

Altintas, Y., 2012. *Manufacturing automation, Metal Cutting Mechanics, Machine Tool Vibrations and CNC Design*. Cambridge Press, Cambridge.

Atsuta, T., et al., 2023. "Control of chatter vibration in double inserts turning with phase difference of modulations". *Precision Engineering,* Vol. 82, p. 106-115.

Kikukawa, J. K. *et al.*, 2019. "Analysis of the Turning Process in Relation to the Surface Roughness of SAE 1010 Steel". *UniToledo Engineering in Action Magazine*, Vol. 04, n. 2, p. 96-113.

Kounta, C. A. K. A. et al., 2023. "Deep Learning for the detection of machining vibration chatter". *Advances in Engineering Software,* Vol. 180, n.10, p. 34-45.

Lara, A. P., 2017. *"Analysis of Vibrations in the Internal Turning Process of 6351-T6 Aluminum Alloy" (in Portuguese).* Master's thesis, Graduate Program in Mechanical Engineering, UTFPR, Curitiba, Brazil.

Lauro, C.H. *et al*., 2014. "Monitoring and processing signal applied in machining processes. A review". *Measurement: Journal of the International Measurement Confederation*, Vol. 58, p. 73–86.

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

Pires, B.J., 2011. *Study of forces, vibrations and tool wear in titanium alloy milling (in Portuguese)*. Master's thesis, Graduate Program in Mechanical Engineering, UNICAMP, Campinas, Brazil.

Quintana, G.; Ciurana, J., 2011. "Chatter in machining processes: A review". *International Journal of Machine Tools & Manufacture*, Vol. 51, n. 5, p. 363-376.

Sandvik, 2023. *External grooving*, https://www.sandvik.coromant.com/en-us/knowledge/parting-and-grooving/external-grooving. Accessed 15 May 2023.

Siddhpura, M. Paurobally, R., 2012. "A review of chatter vibration research in turning". *International Journal of Machine Tools & Manufacture,* Vol. 61, p. 27-47.

Reis, A. M., 2000. *Influence of the secondary position angle of the tool, nose radius and lubrication when machining in the presence of a cutting edge (in Portuguese)*. Master's thesis, Graduate Program in Mechanical Engineering - Federal University of Uberlândia, Uberlândia, Brazil.

Yan, X. et al., 2023. "A digital apprentice for chatter detection in machining via human-machine interaction". *Journal of Intelligent Manufacturing.* Vol. 34, p. 3039-3052.

6. RESPONSIBILITY NOTICE