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VIBRATION ANALYSIS OF FINISHING BALL-END MILLING INCLINED SURFACE OF HARDENED STEEL

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Abstract. *Molds and dies are commonly employed in the industry in order to obtain a wide variety of products. The materials used are difficult to machine due to the characteristics they present to resist to the environment they are exposed. Ball-end mill is widely used in the process of milling complex surfaces of molds and dies. There are variations in the contact of the cutting edge and the machining surface during the tool paths. This paper presents an analysis of the dynamic stability of the ball-end milling process of inclined surfaces of 45º. A ball-end milling, diameter of 12 mm was used to finish an inclined surface of AISI D6 hardened steel. A horizontal downward down milling tool path orientation was employed with depth of cut of 0.3 mm at different cutting speeds. The evaluation of the stability of the process was performed analyzing the surface texture parameters, with the aid of a 3D surface roughness tester, and vibration signals captured by microphone and accelerometer. The results showed that the condition, which the tooth-passing frequency reaches one third of the prevailing vibration mode of the system is detrimental to the quality of the machined surface due to high amplitude forced vibrations.*

Keywords: *vibration analysis; ball-end milling; inclined surface*

1. INTRODUCTION

Molds and dies are employed in the industry to obtain a wide variety of products. Due to its capability in high strength retention and wear resistance at elevated temperatures, hardened steels are used in manufacture of molds and dies, however they are difficult to machining (Toh, 2006). Ball-end mill is widely used in the process of milling complex surfaces of molds and dies. (Wojciechowski et al., 2015).

During milling, due to the cutting dynamics, constant changes occur in the contact with the machined surface and tool tip engagement may occur in some cutting stages (Scandiffio; Diniz; de Souza, 2016). When this machining involves surfaces with small angles, there is a tendency of the engagement of regions near the center of the tool in the cut. In addition, the cutting speed tends to zero at the center point of the tool, the removal mechanism changes from shear to plastic deformation (De Souza et al., 2014).

Furthermore, long tools are used for milling deep cavities and this tends to increase the incidence of vibrations (Diniz; Castanhera, 2016). These vibrations can come from different sources: forced vibrations (periodic excitation at the tooth passing frequency), and self-excited vibrations or chatter caused by regeneration of the chip thickness or mode coupling (Huang; Wang, 2010). Two are the reasons that make this phenomenon undesirable in machining processes: firstly, chatter marks are left on the workpiece surfaces, which results in poor surface finish and loss of dimensional accuracy. Secondly, it has detrimental effect not only on the life of the tool, but also on the machine tool, more specifically in the machine spindle (Toh, 2004).

Researchers have been engaged in the investigation of the milling process using ball-end milling. De Souza et al. (2014) carried out investigations on the milling phenomenon of freeform surfaces using ball-end mill in the manufacture of molds and dies and concluded that engagement of the tool center causes undesirable cutting effects, such as increased cutting force and surface roughness, as well as instability in the cutting process. On the other hand, Scandiffio et al. (2016) obtained favorable results when there was engagement of the tool center in the cut in machining of hardened materials, such as increased cutting stability and reduction of surface roughness. With regard to vibration phenomenon, by using of depths of cut of 0.2 mm, in the machining of freeform geometry in upward / downward vertical tool path, Kull Neto et al. (2016) did not find correlation between tooth-passing frequency with surface roughness and cutting forces. In contrast, Polli (2005) using the same depth values, but in downward horizontal machining at inclined surface (45º), observed that higher peaks of surface roughness occurs when the tooth-passing frequency coincides with 1/2 and 1/3 of the natural frequency, characterizing the forced vibrations.

This paper presents an analysis of the dynamic stability of the ball-end milling process of inclined surfaces of 45º of AISI D6 hardened steel. A horizontal downward down milling tool path orientation was employed at different cutting speeds. The evaluation of the stability of the process was performed analyzing the surface texture parameters with the aid of a 3D surface roughness tester, and vibration signals captured by microphone and accelerometer.

2. METODOLOGY

Tests were carried out in a Romi D600 machining center, with 16.5 kW and maximum spindle speed of 10000 rpm. A ball-end mill (KDMB12R130A12SN) with two flutes, 12 mm diameter and 96 mm overhang with interchangeable insert with TiAlN coating (KC505M grade) was used for the experiments. Test specimen of AISI D6 hardened steel (60 HRC) with 40 mm x 50 mm x 135 mm in dimensions was fixed in a vise. Its chemical composition is shown in Tab. 1. The hardness of the specimen was measured by using a Mitutoyo durometer model 963-101. All tests were conducted at dry condition and with radial and axial depth of cut of 0.2 mm and 0.3 mm, respectively. The feed per tooth was 0.1 mm/rev. For each spindle speed, a 4 mm x 40 mm area was machined, resulting in 20 tool passes. Surface roughness and surface topography were obtained by using an optical 3D profiler (Talysurf CCI, Taylor Hobson Precision). Machining tests were performed employing the horizontal downward down milling tool path orientation (HDD) as shown in Fig. 1.

Table 1. Chemical composition of AISI D6 steel.

Element	Amount (%)
C	2.00 – 2.25
Si	0.20 – 0.40
Mn	0.30 – 0.60
Cr	11.00 – 13.00
W	0.60 – 1.25

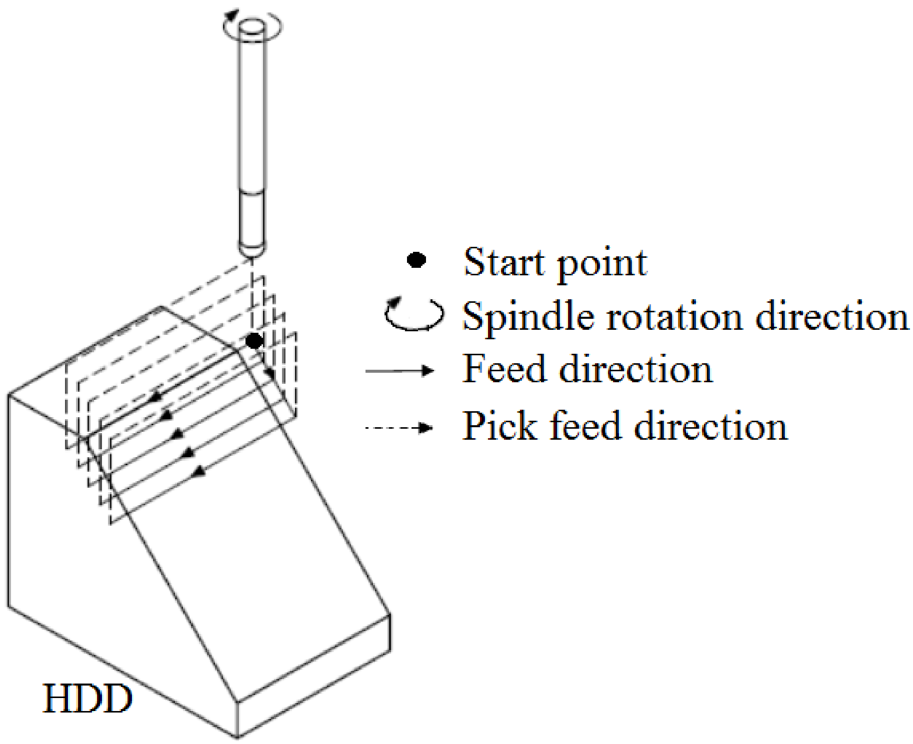

Figure 1. Horizontal downward down milling (HDD) cutter path orientation on inclined plane.

Figure 2 shows the experimental set up for obtain the frequency response of the system by impact testing. In this test, the relationship between the imposed excitation (force input) and the system vibratory response (displacement output) results in the system frequency response to impulsive excitation. The excitation was performed by using a hammer instrumented with a piezoelectric force transducer (PCB 086C03), and the displacement was captured by an accelerometer (PCB 352C65) attached to the tool mounted on the machine spindle. The signals were amplified by two signal conditioners connected to the data acquisition board, which converted them to digital form to the PC. Subsequently the system frequency response was obtained by using the software Matlab® and ITA-Toolbox developed by the Institute of Technical Acoustics of the RWTH University, Aachen - Germany.

The objective of the impact test is to excite a range of frequencies that contain the natural modes of the spindle/tool holder/tool system. Figure 3 shows the obtained system frequency response to impulsive excitation at tool tip. The highest peak occurs at 795 Hz and corresponds to the natural frequency of the system. There are other two peaks with lower magnitudes at 720 Hz and 940 Hz.

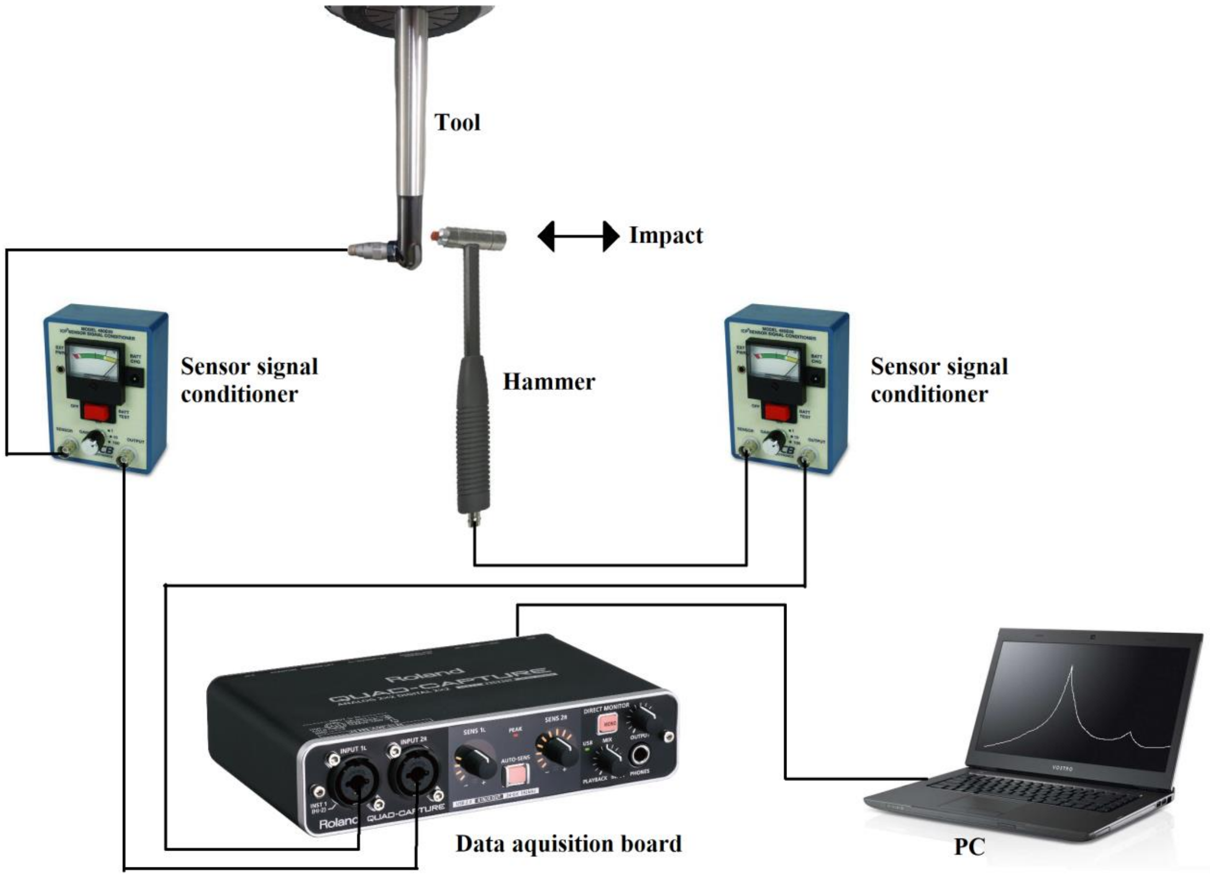

Figure 2. Experimental set up for obtain the frequency response of the system by impact test.

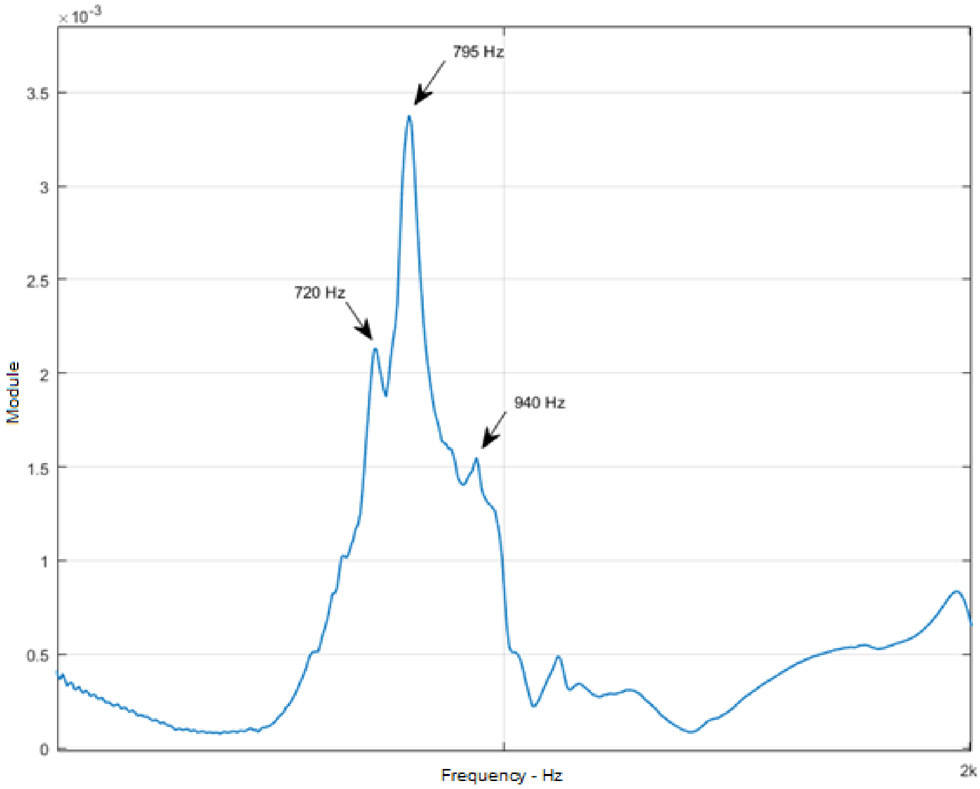

Figure 3. System frequency response to impulsive excitation at tool tip.

Fifteen spindle speeds were used during the experiments in order to verify the influence of the tooth passing frequency on the vibration signals during the milling process. Table 2 shows the spindle speeds, the respective frequencies, as well as the ratio between the tooth passing frequencies and the frequencies with higher magnitude in the frequency response function of the system (F_t/F_n).

Table 2. Experimental parameters in machining for L / D = 8.

Nº	Spindle speed (rpm)	Frequency (Hz)	F_t (Hz)	F_t/F_n
1	5400	90.00	180.00	1/4 – 720 Hz
2	5962	99.37	198.73	1/4 – 795 Hz
3	6000	100.00	200.00	–
4	6500	108.33	216.67	–
5	7000	116.67	233.33	–
6	7050	117.50	235.00	1/4 – 940 Hz
7	7200	120.00	240.00	1/3 – 720 Hz
8	7500	125.00	250.00	–
9	7950	132.50	265.00	1/3 – 795 Hz
10	8000	133.33	266.67	–
11	8500	141.67	283.33	–
12	9000	150.00	300.00	–
13	9400	156.67	313.33	1/3 – 940 Hz
14	9500	158.33	316.67	–
15	10000	166.67	333.33	–

A condenser microphone (Behringer ECM8000) was positioned close to the tool and connected to a Behringer UPHORIA UMC22 audio interface in order to capture the audio signals. An accelerometer ICP 603C01 was magnetically attached to the spindle housing of the machine to capture the vibration signals. Both sensors, microphone and accelerometer, were connected to a digital vibration analysis equipment (SDAV-2, Teknikao). A high-passband filtering (120 Hz) was used to remove noise not related to the machining process. A spectrum analysis of the vibration signals was further performed. Figure 4 depicts the experimental setup for the vibration signals measurement used during the experiments

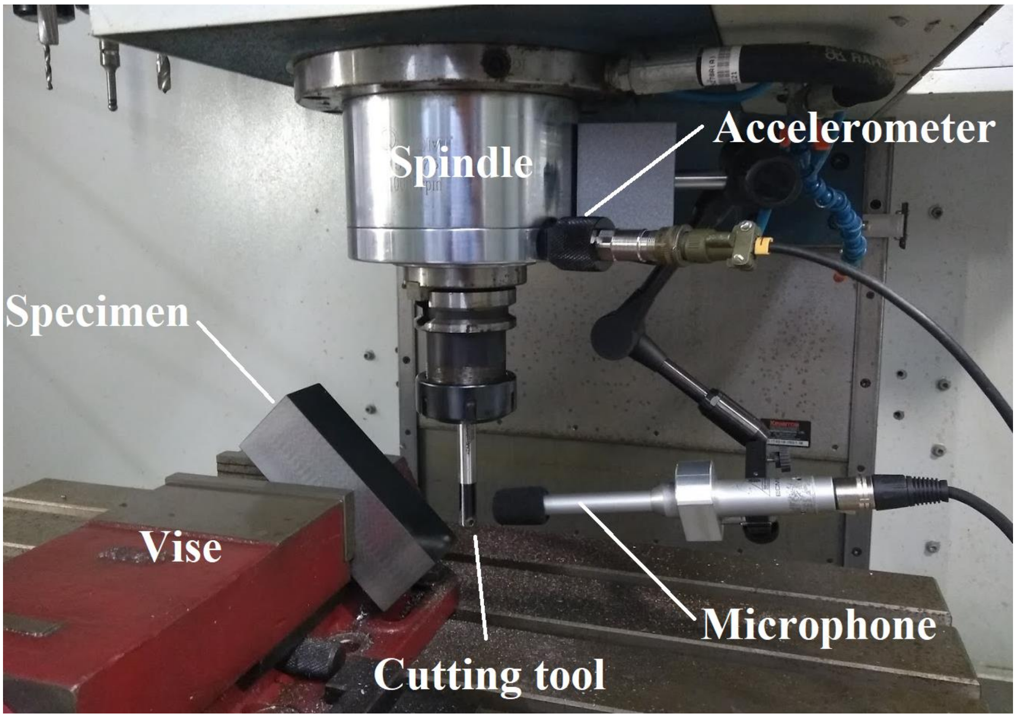

Figure 4. Experimental setup for vibration signals measurement.

3. RESULTS AND DISCUSSIONS

Figure 5 provides the surface roughness values, parameters R_a and R_z, measured in the tool cutting feed direction, and global vibration values (RMS) captured with microphone (a) and accelerometer (b) during the machining process for different spindle speeds. The surface roughness values were relative low for all the tested spindle speeds with the exception of spindle speeds of 7950 and 8000 rpm. For these spindle speeds there was an evident deterioration of the surface finish resulting from unstable cuts. The predominant vibration mode of the system was 795 Hz and for these spindle speeds the tooth-passing frequency was nearly one third of the natural frequency. In this case, the third harmonic of the tooth-passing frequency had sufficient energy to excite the system at natural frequency. Therefore high amplitude forced vibrations occurred during the process.

In addition, it can be observed that the microphone provided a superior signal that can be utilized to identify the tool vibrations when compared to the accelerometer. As the accelerometer was mounted on the spindle housing, reduction in sensitivity results when sensing vibrations arising from the tool. However, the magnitude of the audio signal increased significantly above 8500 rpm and so did the acceleration signal above 9000 rpm. This fact might be related to another peak in the frequency response function of the system (940 Hz) probably related to the machining spindle. The spindle speed of 9400 rpm results in a tooth-passing frequency that is equivalent to one third of this frequency. Nevertheless, this condition did not lead to a poor surface finish.

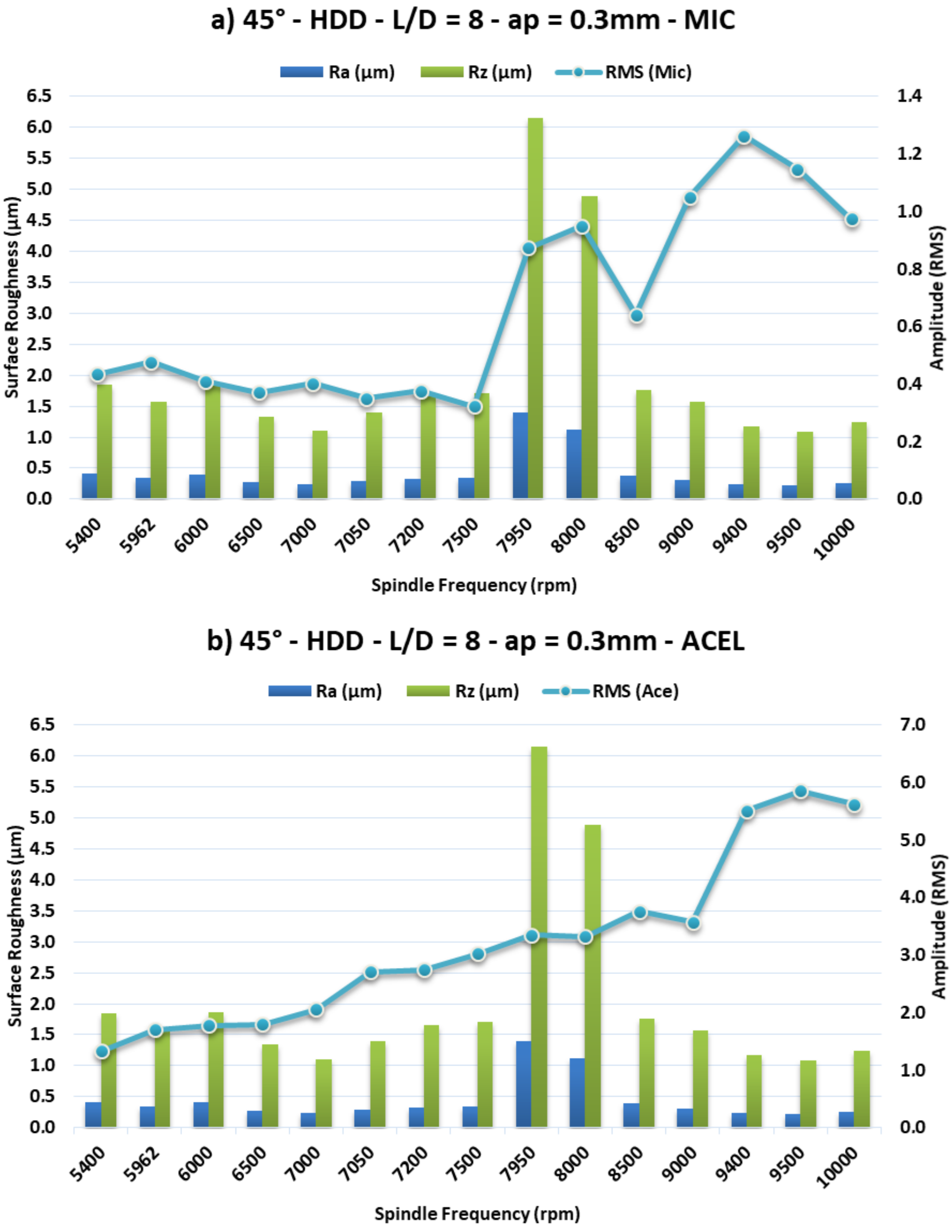

Figure 5. Influence of spindle frequency on surface texture - R_a e R_z - and vibrations (RMS) obtained with (a) microphone and (b) sensor accelerometer.

Figure 6 shows the original 3D topography of an (a) stable (n = 8500) and (b) unstable condition (n = 7950 rpm). The stable condition resulted in a more isotropic surface. The distance between the peaks measured in the pick feed direction corresponds to 0.2 mm, in agreement with the radial depth of cut. Moreover, the distance between the marks measured in the feed direction corresponds mainly to the feed per revolution due to tool runout. On the other hand, for the unstable condition, it can be noticed the presence of high peaks and deep valleys. The profile has a wavy aspect and the distance between the vibration marks (approximately 0.5 mm) are not consistent in size with the feed and the radial depth of cut. In this case, the marks of lower depth generated by one flute were removed by another one or even by the same flute during the next revolution due to high amplitude vibrations.

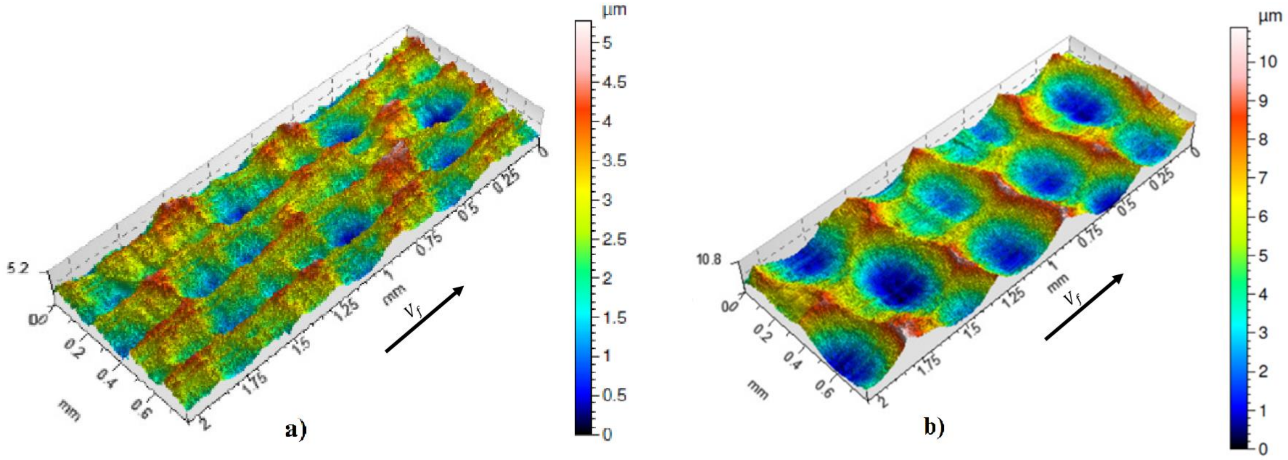

Figure 6. Original 3D topography of an (a) stable cut (n = 8500 rpm) and (b) unstable cut (n = 7950 rpm).

Figure 7 shows the spectra of the audio signal for stable (a) and unstable (b) machining. For the stable cut (n = 8500 rpm), there are peaks with high magnitude at the spindle speed (141.66 Hz) and at 850 Hz. There are other peaks with low magnitudes at harmonics of the spindle speed. For the unstable cut (n = 7950 rpm) there are peaks at the tooth-passing frequency (265 Hz), at the spindle speed and at 795 Hz. However, it is possible to observe some small peaks (indicated by the red arrows) that do not correspond to harmonics of the tooth-passing frequency, which is a reflection of the instability in the cut.

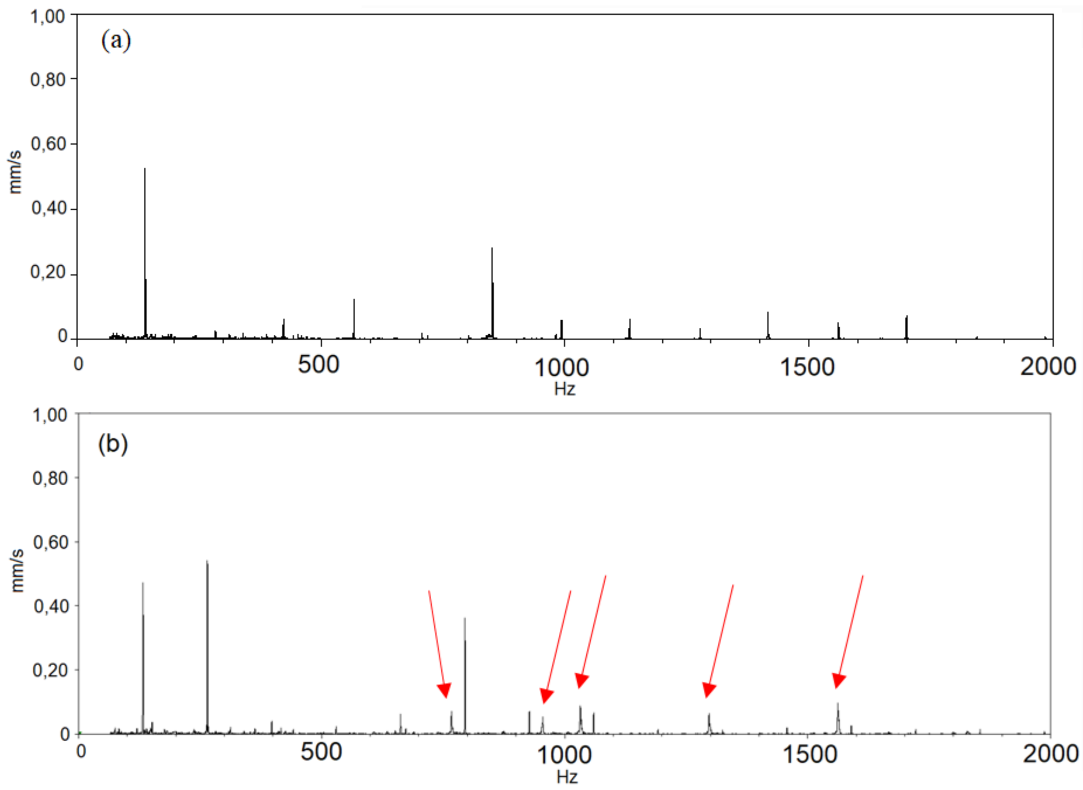

Figure 7. Spectra in frequency domain of the audio signal, for stable machining (a) at 8500 rpm, and unstable (b), at 7950 rpm.

4. CONCLUSIONS

The microphone provided a superior signal that can be utilized to identify the tool vibrations when compared to the accelerometer. As the accelerometer was mounted on the spindle housing, reduction in sensitivity resulted when sensing vibrations arising from the tool.

The stable conditions resulted in isotropic machined surfaces and relative low surface roughness values. There was an evident deterioration of the surface finish resulting from unstable cuts when the tooth-passing frequency was nearly one third of the natural frequency. In this case, the third harmonic of the tooth-passing frequency had sufficient energy to excite the system at natural frequency. Therefore high amplitude forced vibrations occurred during the process. The surface topography presented high peaks and deep valleys. The profile showed a wavy aspect and the distance between the vibration marks were not consistent in size with the feed and the radial depth of cut.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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