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VIBRATIONS ANALYSIS IN THE BALL-END MILLING PROCESS

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Abstract. *Molds and dies are employed to impart a desired shape to an product to manufactured. In finishing milling the tool geometry and cutting parameters are chosen in such way to attempt the project requirements related to surface finish and dimensional precision. Ball-end mills are recommended for finishing of tapered and free form surfaces. This process is characterized by high interruptions during the cut. The time the tool spend cutting is just a fraction of one tool rotation period. The phenomena related to the process dynamic are different from those found in roughing operations. This paper presents the analysis of the vibrations in ball-end milling of a tapered surface considering different cutting paths. The evaluation of the stability is based on the surface roughness and audio signals captured by a microphone. The horizontal downward down milling strategies presented better results. In all vertical cuts, there was a strong influence of the amplitude of the tooth passing frequency. It was verified proportionality between this amplitude and the surface roughness values.*

Keywords: *Ball-end milling; vibration; tool path; cutting strategy;*

1. INTRODUCTION

Molds and dies are employed in several productive sectors such as the automotive industry, aircraft manufacturing and consumer goods manufacturing (de Souza et al., 2014). This represents a high influence on the cost of manufacturing components (Altan et al., 2001). In the fabrication of this tooling, materials of difficult machinability are employed, and the machining process by milling complex shapes is one of the most used (Kull Neto; Diniz; Pederiva, 2016). In this operation ball-end mills are used, and during machining, due to the cutting dynamics, constant changes occur in the contact with the machined surface, and the tool tip engagement may occur in some cutting stages (Scandiffio; Diniz; de Souza, 2016). Furthermore, in this process, long tools are used for milling deep cavities and this tends to increase the vibration amplitudes (Diniz; Castanhera, 2016).

These vibrations can come from two sources: forced vibrations, periodic excitation by the tpassage of teeth, and self-excited vibrations or chatter, caused by regenerative effect and mode coupling (Huang; Wang, 2010). Chatter is undesirable for two reasons. First, corrugated marks, process characteristics, are left on the surface of the part, which results in poor surface quality and loss in accuracy, and secondly, it has detrimental effect not only on tool life, but also on machine tool, more specifically without machine spindle (Toh, 2004a).

Recently, Kull Neto *et al.* (2016b) analysed the machining of free-form geometry in upward / downward vertical tool path, and they found no correlation between tooth passing frequency, surface roughness and cutting forces. In contrast, Polli (2005), using the same depth of cut values, but in downward horizontal machining, in ramp at 45 degrees, verified higher surface roughness when the harmonics of frequency of passage of the teeth coincided with 1/2 and 1/3 of the natural frequency, characterizing as forced vibrations.

In addition to the inherent vibration aspects, the choice of cutting path strategies is crucial for obtaining good results from machined surfaces, and if an appropriate cutting path is not considered, considering appropriate cutting parameters, the result can be the catastrophic failure of the cutter, in addition, can lead to unnecessary losses of time, cost and surface quality (Toh, 2006a). Toh (2004b, 2006b) concluded that the most favorable tool path, at 75° ramp machining in hardened steels is a simple vertical upward raster, on the other hand, Nicola, Missell and Zeilmann (2010) in 60 ° inclined surface machining found better results in a vertical direction, however downward. Wojciechowski, Twardowski and Pelic, (2014) obtained lower shear modulus modules in vertical ascending machining at the highest of the three ramp inclinations - 0; 30 and 60°. Furthermore, Ng et al. (2000) infers that, in the downward horizontal strategy, the forces are smaller on ramps at 45°.

Many researches have been carried out in order to verify the influence of cutting path strategies on vibrations and surface finishing, however, most of the research has been performed only for down milling cuts. Therefore, the objective of this work is to verify the influence of the vibrations in the finishing process with ball-end mill, in the machining of surfaces in ramp of 15 degrees, in down milling and up milling cutting, upward and downward, vertical and horizontal directions.

2. METODOLOGY

Tests were carried out in a machining center three axes Romi D600, with installed power of 16,5 kW, maximum rotation of 10000 rpm and maximum advance of the work table of 30 m / min, being possible work with up to 20 tools. A ball-end mill with two flutes, 12 mm, KDMB12R130A12SN, steel body, fixed to the machine with the aid BT40 ISO cone, using spring collet, with ratio length diameter (L/D) equal to 8. This tool was used with a single interchangeable insert, with coverage obtained by PVD technique, of TiAlN, class KC505M. Test specimens, considered rigid, with dimensions 40 x 40 x 40mm, SAE 8620 steel, was used in the machining tests, and the useful machining region was 40 x 10 mm. These were fixed to the machine with the aid of a hydraulic vise clamp precision. All tests were conducted dry and with the same values of radial and axial depth of cut, respectively $a_p = a_e = 0.2$ mm, and feed per tooth of $f_z = 0.1$ mm and spindle rotation 8000 rpm.

A Behringer ECM800 microphone was used and positioned at 155 mm of the cutting region. According to Delio, Tlusty and Smith (1992), the use of a microphone as a sensor has adequate bandwidth and is capable of detecting signals of vibration coming from the sources: tool, workpiece and machine tool.

The surface roughness was used as a relative parameter of the process stability. Stable machining was characterized by good surface finish, and, in unstable processes, results in deteriorated surface finish. The surface roughness parameters selected were R_a and R_z, which were obtained with the aid of a Mitutoyo Surf Test SJ 210, using a cut-off of 0.8 mm for all comparisons. Each surface was measured three times, after obtaining its respective mean.

The frequency response functions for the tool were obtained by attaching an accelerometer to the end of the tool, striking the tool in the direction of the accelerometer with an instrumented hammer and recording the signals simultaneously by using a signal analyzer.

Finishing ball-end milling in a inclined surface of 15 degrees was used in eight different cutting path orientation, composed of horizontal/vertical, upward/downward and up milling/down milling tool path, shown in Tab. 1.

Table 1. Description of cutter path orientation employed on machining in inclined plane with ball-end mill

Cutter path orientation	
HUD	Horizontal Upward Down milling
HUU	Horizontal Upward Up milling
HDD	Horizontal Downward Down milling
HDU	Horizontal Downward Up milling
VUD	Vertical Upward Down milling
VUU	Vertical Upward Up milling
VDD	Vertical Downward Down milling
VDU	Vertical Downward Up milling

The eight cutter path orientation employed in this work are best demonstrated in Fig. 1, where it is possible to verify the trajectory of the tool, beginning of the cut, direction of the tool immersions in the workpiece, as well as repositioning of the tool for the next pass.

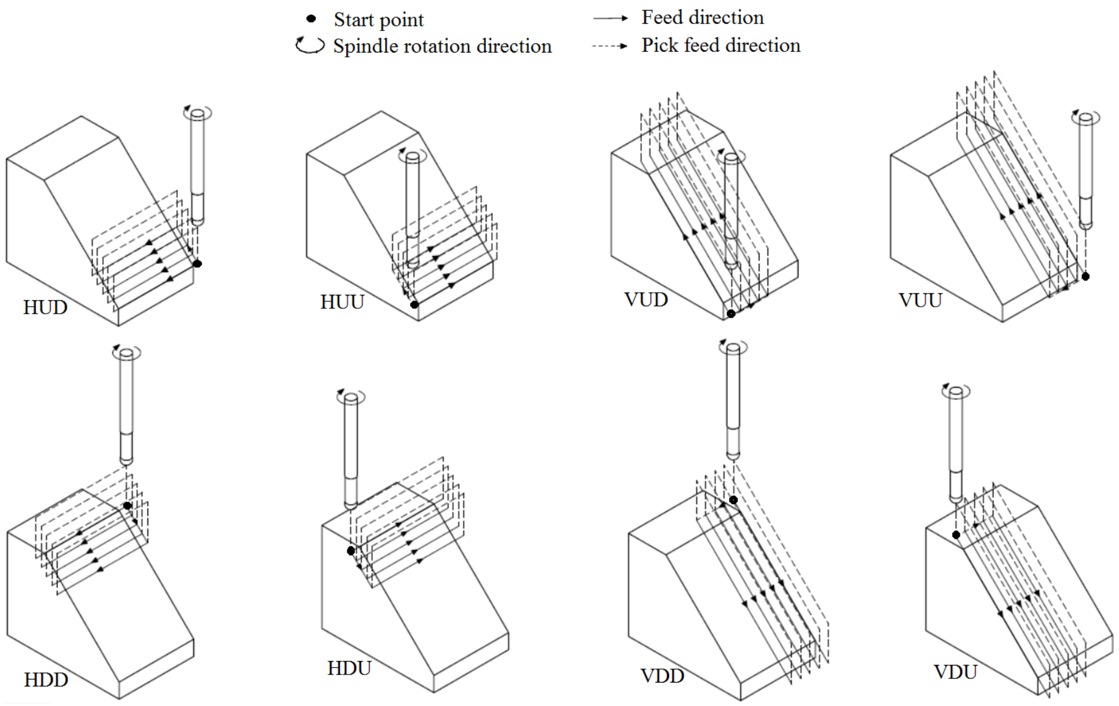

Figure 1. Cutter path orientation employed in this work on inclined plane.

3. RESULTS AND DISCUSSION

3.1 Natural frequency modes

The graph of Fig. 2 shows the natural vibration frequency modes of the tool (L/D = 8), with a higher peak of 795 Hz. In addition, two other modes, one with 720 Hz and another with to 940 Hz can be noticed.

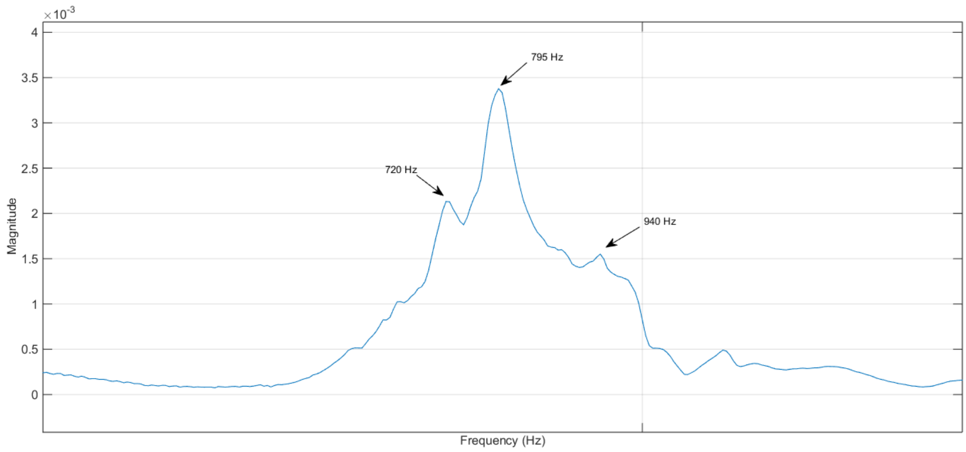

Figure 2. Natural vibration frequency modes of the tool.

3.2 Influence of cutter path orientation

Figure 3 shows the workpiece surface roughness for different cutter path orientations. The amplitude at the tooth passing frequency in the audio spectrum for each condition is also shown. In the vertical downward condition, there was a greater engagement of the tool tip in the cut, resulting in poor surface finish due to the impaired removal mechanism. Moreover, the effective diameter of the tool acting in the cutting region is only half of the value compared to the upward condition, as can be seen in Fig. 4. This result in a greater tendency of material removal by ploughing. In vertical cuts the surface roughness was directly proportional to the amplitude at the tooth passing frequency. It is noteworthy that in the VUD and VDU conditions there were inadequate cuts, resulting in a deteriorated surface.

The horizontal cuts resulted in lower surface roughness, however HDD and HDU conditions presented greater amplitude of the audio signal in the tooth passing frequency. This is probably due to the large tool tip engagement, as can be seen in Fig. 4 (b). In addition, the effective cutting diameter for downward cuts (3.2 mm) is about the half of the effective diameter for upward cuts (6 mm). Horizontal upward cuts (HUD and HUU) resulted in low surface roughness and relative low amplitude of the audio signal in the tooth passing frequency.

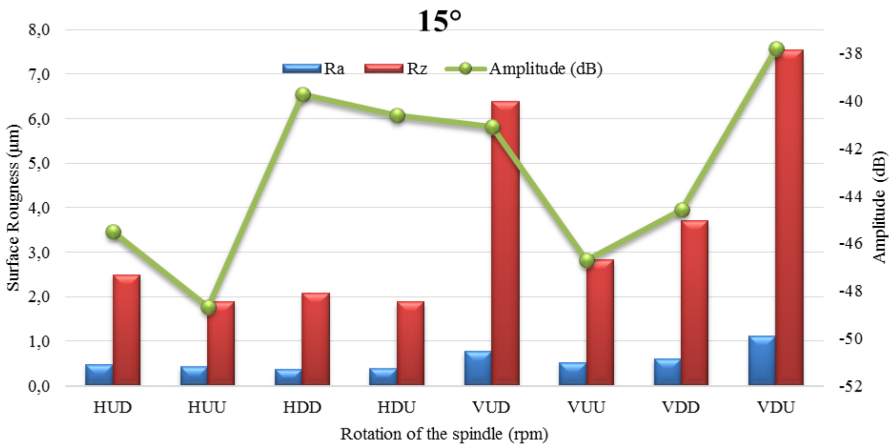

Figure 3. Surface roughness and amplitude at the tooth passing frequency for different cutter path orientation.

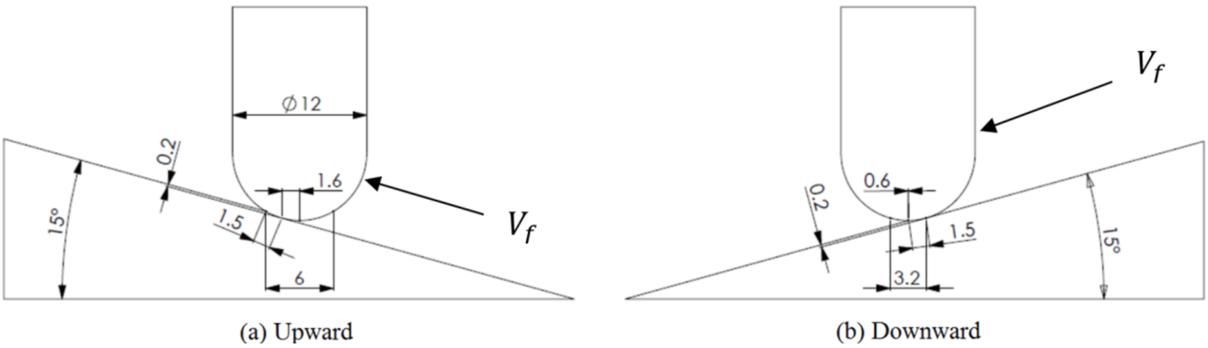

Figure 4. Cutter path orientation Upward (a) and Downward (b) with nominal and effective tool diameter.

Figure 5 shows the audio signal spectra for an unstable condition (VDD) and for a stable one (HDU). In the unstable condition, the amplitude at a harmonic of the tooth passing frequency (940 Hz) became prominent. This is due to its proximity to one of the natural vibration modes of the tool, causing visible undulations on the surface of the workpiece. For the stable condition, the highest peaks are related to the spindle rotation and the tooth passing frequency.

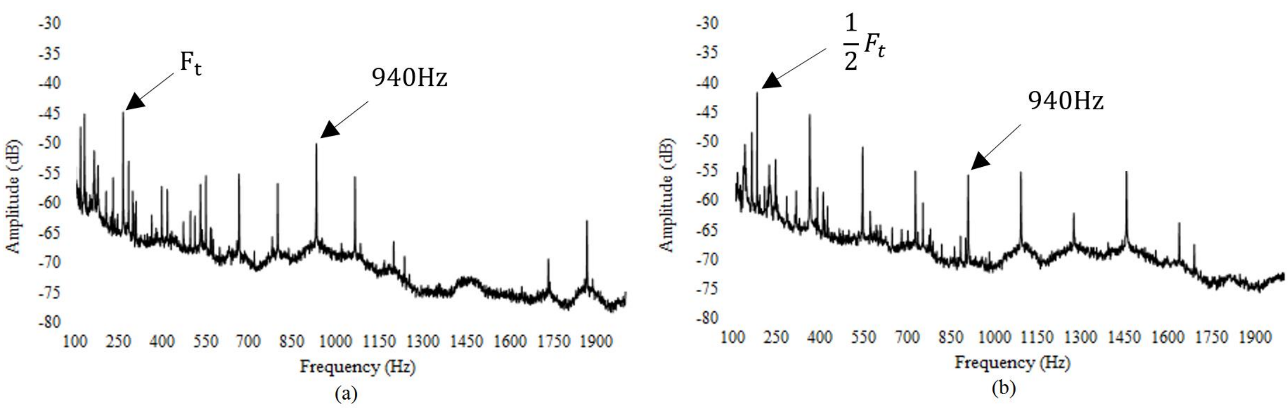

Figure 5. Spectra of the unstable condition - VDD (a), and stable condition - HDU (b).

The surface roughness profiles of the unstable and stable conditions are shown in Fig.6. It can be noticed that the stable process results in greater uniformity in the peaks and valleys of the profile and the distance between the ridges is approximately equal to the feed per revolution of the tool. The surface roughness profile for the unstable cut presents no regularity in the peaks and valleys, resulting in higher values of R_a e R_z.

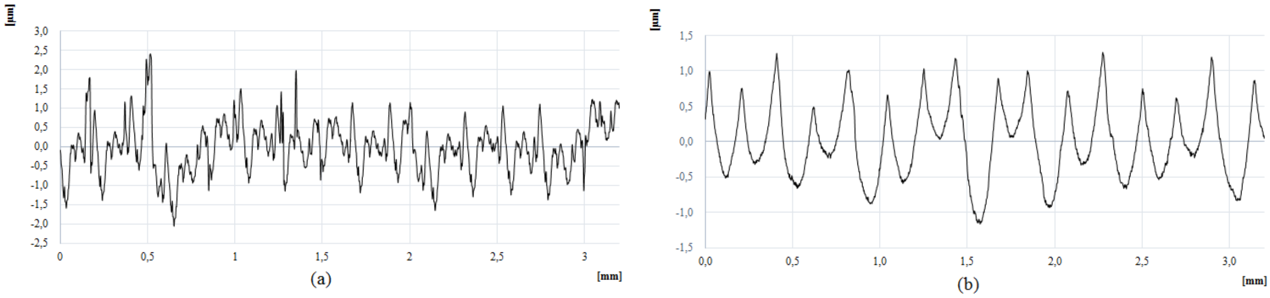

Figure 6. Surface roughness profile of unstable condition - VDD (a), and stable condition – HDD (b)

4. CONCLUSIONS

In the finishing operation with ball-end mill, the forced vibration by tooth passing frequency is predominant in the process. For horizontal downward cuts, the higher the amplitude of this frequency, the better the surface finish. On the other hand, for horizontal upward milling, the surface roughness is proportional to the amplitude of the tooth passing frequency. In horizontal cuts, the best results were found for the up milling condition.

In all cutter path orientation in vertical milling, there was a strong influence of the amplitude of the tooth passing frequency. It was verified proportionality between this amplitude and the surface roughness values. Moreover, there was greater tendency of material removal by plowing in this condition. In the unstable condition, the amplitude at a harmonic of the tooth passing frequency (940 Hz) became more prominent, due to its proximity to one of the natural vibration mode of the tool.

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6. REFERENCES

Altan, T. et al., 2001. Manufacturing of Dies and Molds. *CIRP Annals - Manufacturing Technology*, Vol. 50, p.404–422.

Delio, T., Tlusty, J. and Smith, S., 1992. Use of audio signals for chatter detection and control. *Journal of Engineering for Industry Transactions of the ASME*, Vol. 114, p.146–157.

Eduardo Diniz, A. and da Costa Castanhera, I., 2016. High Speed Milling of Hardened Steel Convex. *Procedia Manufacturing*, Vol. 5, p.220–231.

Huang, C.Y. and Junz Wang, J.J., 2010. A pole/zero cancellation approach to reducing forced vibration in end milling. *International Journal of Machine Tools and Manufacture*, Vol. 50, p.601–610.

Kull Neto, H., Diniz, A.E. and Pederiva, R., 2016a. Influence of tooth passinging frequency, feed direction, and tool overhang on the surface roughness of curved surfaces of hardened steel. *International Journal of Advanced Manufacturing Technology*, Vol. 82, p.753–764.

Kull Neto, H., Diniz, A.E. and Pederiva, R., 2016b. The influence of cutting forces on surface roughness in the milling of curved hardened steel surfaces. *International Journal of Advanced Manufacturing Technology*, Vol. 84, p.1209–1218.

Ng, E.G. et al., 2000. Experimental evaluation of cutter orientation when ball nose end milling inconel 718. *Journal of Manufacturing Processes*, Vol 2, p.108–115.

Nicola, G.L., Missell, F.P. and Zeilmann, R.P., 2010. Surface quality in milling of hardened H13 steel. *International Journal of Advanced Manufacturing Technology*, Vol. 49, p.53–62.

Polli, M.L., 2005. *Analysys of the dynamic stability of high speed finishing end miling and ball-end milling*. In Proceedings of the 18th International Congress of Mechanical Engineering - COBEM2005. Ouro Preto, Brazil.

Scandiffio, I., Diniz, A.E. and de Souza, A.F., 2016. Evaluating surface roughness, tool life, and machining force when milling free-form shapes on hardened AISI D6 steel. *International Journal of Advanced Manufacturing Technology*, Vol. 82, p.2075–2086.

De Souza, A.F. et al., 2014. Investigating the cutting phenomena in free-form milling using a ball-end cutting tool for die and mold manufacturing. *International Journal of Advanced Manufacturing Technology*, Vol. 71, p.1565–1577.

Toh, C.K., 2006a. Cutter path orientations when high-speed finish milling inclined hardened steel. *International Journal of Advanced Manufacturing Technology*, Vol. 27, p.473–480.

Toh, C.K., 2006b. Cutter path strategies in high speed rough milling of hardened steel. *Materials and Design*, Vol. 27, p.107–114.

Toh, C.K., 2004a. Surface topography analysis in high speed finish milling inclined hardened steel. *Precision Engineering*, Vol. 28, p.386–398.

Toh, C.K., 2004b. Vibration analysis in high speed rough and finish milling hardened steel. *Journal of Sound and Vibration*, Vol. 278, p.101–115.

Wojciechowski, S., Twardowski, P. and Pelic, M., 2014. Cutting forces and vibrations during ball end milling of inclined surfaces. *Procedia CIRP*, Vol. 14, p.113–118.

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