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High Speed Milling of Hardened Steel Convex Surface

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Abstract
This paper presents a contribution to hardened tool steel milling studies. High speed milling is largely utilized to substitute some EDM and polishing operations, mainly in hardened tool steel finishing. Tool path strategy may either enable good surface finish or contributes to generate high roughness values and poor surface finish. Tool inclination (angle between tool axis and workpiece surface) influences the system response to vibration. In this work, several milling experiments were performed in a circular convex AISI D6 hardened steel workpiece, having as input variables feed direction (upward and downward the circle) and tilt angle (tool inclination). The main results indicate that upward tool path presented mostly high roughness values which were also influenced by tool inclination. Downward tool path presented low roughness values and was less influenced by tool inclination. Upward tool path and positive tool inclination should be avoided because they presented roughness values incompatible to EDM process substitution.

Keywords: High speed milling, Hardened steel, Tool path, High speed machining, Cutting force, Vibration

1 Introduction

High speed milling of hardened materials enables the use of milling instead of EDM and polishing processes in finish machining of molds and dies, when the substitution is possible, mainly in complex surfaces in four or five axis machining centers (Altintas et al, 2014; Arnone, 1998; Childs et al, 2004). In this process, the contact angle between cutting edge and the material, the radial depth and the axial depth of cut are low and spindle rotation is high, which leads to high values of cutting speed. Chip removal rate in high speed milling is low compared to conventional milling, but it is higher than EDM chip removal rate. Low chip thickness increases the specific cutting force (K_s) and should be avoided by the use of the highest possible feed rate, which reduces time production. On the other hand, high values of feed per tooth increases workpiece surface roughness (Diniz et al, 2010; Sandvik, 2015a; Sandvik, 2015b; Sandvik, 2000; Souza et al, 2014).

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Vibration in high speed milling process influences workpiece surface roughness and tool life and must be controlled for operator, machine and process safety. However, this process is very prone to tool vibration, since the tool, several times, must be long, to cut deep cavities of the molds and dies, and with small diameter, in order to copy the typical small diameters of the corners of these components. Among the several ways to reduce vibration in this process, as the use of sensors, analytical and finite elements models, lobe diagrams construction and analysis, it can be cited the choice of different values of cutting parameters and cutting strategies. In milling process, vibration occurs due to the chip formation and to the variation of cutting force caused the chip thickness variation. Milling process might also present chatter or self-excited vibration. Chatter may produce very poor surface finish in workpiece, reduced tool life, tool damage and breakage, damage of the machining center structure and risks to operator security. Chatter occurrence in conventional milling process is rare due to the low spindle speed used, but in HSM it is important, because high spindle speed is able to reach frequencies similar to those where chatter occurs (Altintas et al, 2014; Arnone, 1998; Beak and Fox-Rabinovich, 2014; Koshy et al, 2002; Lacalle and Lamikiz, 2009; Sandvik, 2015a; Sandvik; 2015b; Sandvik, 2000; Urbanski et al, 2000).

Cutting strategies are important factors to reduce vibration and workpiece surface roughness and to decrease production time. To choose a cutting strategy means to choose the tool path direction and trajectroy and tool axis inclination related to the milled surface. The choice of a suitable tool path strategy is able to reduce tool vibration and to produce good surface finish, suitable to be used in dies and moulds, resulting in lower process costs (Souza et al, 2014). The angles which define tool inclination are tilt angle and lead angle. Tilt angle is the angle between cross feed direction and tool axis and lead angle is the angle between feed direction and tool axis (Ozturk et al, 2009; Sandvik, 2015a; Sandvik, 2015b; Sandvik, 2000).

Souza et al (2014) analyzed tool path strategies for convex semi sphere milling made of AISI P20. The utilized tool was a 6 mm diameter ball nose coated with TiAlN carbide mill. The authors tested five spiral strategies: i) radial contour from the material base to top; ii) radial contour from the top to the material base; iii) parallel contour from the material base to the top; iv) parallel contour from the top to the material base; v) the tool followed the convex semi-circle, with parallel passes. They concluded that the real process time was longer than estimated process time, according to software simulation, mainly for the non-spiral strategies. The roughness values were the lowest and adequate for EDM process substitution, for the radial tool path from base of material to top.

Cutting strategies may minimize chatter effect. Kull Neto et all. (2016a) performed high speed milling tests in a convex quarter of cylinder of 27 mm radius made of hardened AISI D6 steel. The tool trajectory used was linear following the cylinder axis. The input variables were the spindle rotation (to produce different tool edge entrance frequencies), the direction of the tool passes (downward and upward) and the tool overhang (97 and 112 mm). The tool used was a 12mm ball nose carbide tool coated with TiAlN. They concluded that cutting strategy was more influent than tool edge entrance frequency, even when this frequency was a resonance frequency of the system. Downward cut (when the tool pass goes down in the cylinder in the subsequent passes) produced lower vibration and lower roughness values than the ones produced by upward cut, regardless the tool overhang used.

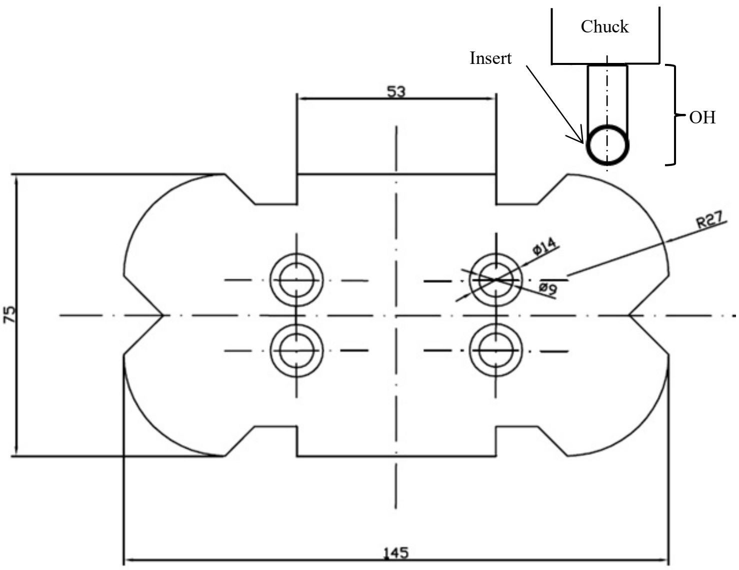
Kull Neto et al (2016b) analyzed the milling of the same quarter of cylinder used in the previous work, but now the tool trajectory was linear. The subsequent tool passes followed the workpiece radius. The input variables were the tool inclination (called tilt angle -16°, 0° and 16°) and feed direction (downward and upward). Radial force values observed with tilt angle 16° and downward cut were higher than other cutting conditions tested and which made the roughness values in this condition to be the highest among all the tests. The condition which produced the lowest roughness values, tilt angle 0° in upward cut, produced low values of radial force.

The main objective of this analysis is to find the influence of tool inclination tilt angle and tool feed direction in the surface finish of a quarter circle convex surface of a hardened AISI D6 steel workpiece, milled using HSM technique, with the tool describing a quarter of circle in each tool path.

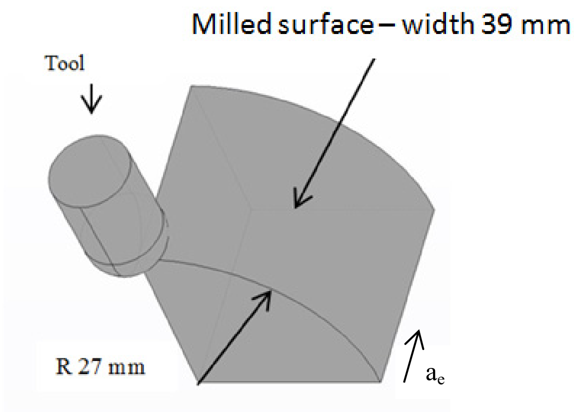
This kind of surface is typical of moulds and dies and the knowledge of how to mill it is fundamental for the companies which machine this kind of parts.

2 Experimental Procedures

Hardened AISI D6 steel is a typical material for cold work molds (Costa e Silva and Mei, 2013). The sample used in the milling experiments, presented in figure 1, was quenched and tempered to the hardness of 60 HRC. The milled surface was the 27 mm radius quarter of circles shown in figure 1.



a) Sample design and tool position.



b) Milled surface**.**

Figure 1: Schemes of the workpiece used in the experiments, without scale.

A five axis CNC machining center with maximum spindle speed of 42,000 rpm was used in the experiments. The tool was a two cutting edges 12 mm ball nose cutter, whose ISO code is R216F-12A16C-085. The tool material was a sub micrometric grain size cemented carbide with TiAlN coating.

Tool overhang (distance between the tool tip and the chuck, “OH” in figure 1a) was 112 mm. The roughness measurement was accomplished by a portable roughness meter and the force values were taken by a piezoelectric dynamometer, with sampling rate of 30,000 Hz. The tests parameters were feed rate of 0.1 mm/tooth, constant stock of 0.2 mm (material removed uniformly along sample radius of 27 mm - see figure 2) and radial depth of cut (a_e) of 0.3 mm, in the same direction of cross feed direction. The milled surface had width of 39 mm, which results in 130 tool paths with a_e = 0.3 mm in each quarter of circle, or approximately 5.5 m in equivalent linear cut.

Two tool feed directions were used in the experiments: upward path and downward path. The tool inclination movement was done before the cutting and did not change along it.

Figure 2 presents the tool movements, upward path and downward path.

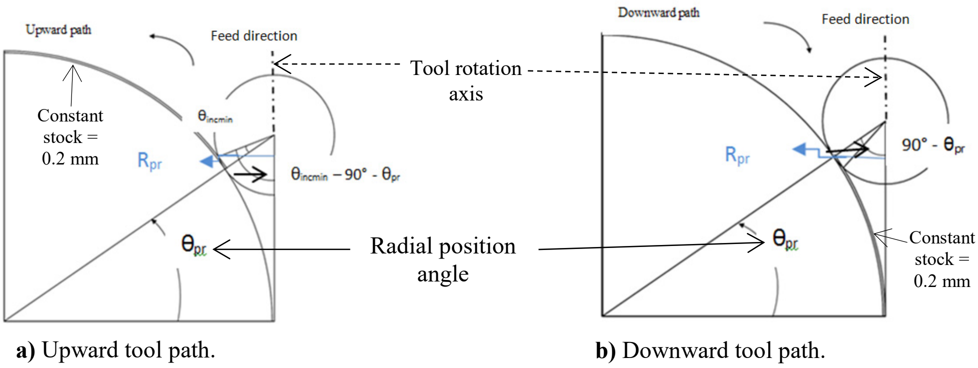


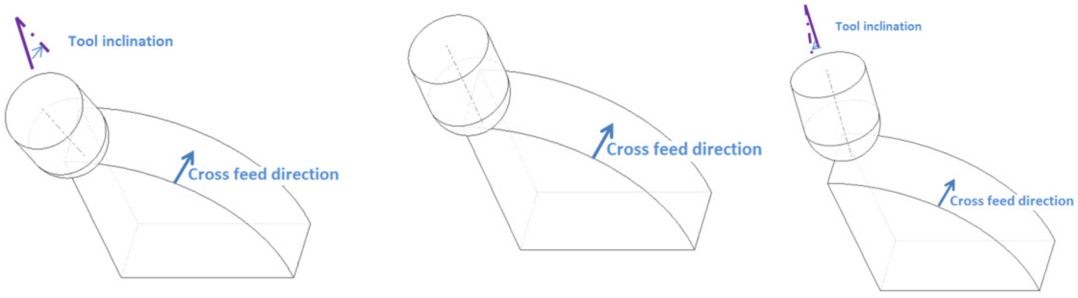
Figure 2: Tool paths.

In upward cut, tool path was from the radial position angle, θ_{pr}, 0° to 90° and the effective cutting speed decreased, because the effective diameter started from maximum value and finished in minimum value. In the downward cut, the tool path was from the radial position angle, θ_{pr}, 90° to 0° and the effective cutting speed increased, because the effective diameter started from the minimum value and finished in maximum value. Radial position angle (θ_{pr} - see figure 2) is, in this work, equivalent to lead angle as defined by Ozturk et al. (2009).

Tool inclination tilt angles (figure 3) used in the experiments were calculated using equation 1, where a_p is the axial depth of cut at θ_{pr} 90°, and R is the tool radius. This equation provides the minimum tilt angle which does not allow the engagement of the tool center into the cut, which would cause cutting speed to be zero.

$$\theta_{tilt\ min} = \cos^{-1}\left(\frac{R - a_p}{R}\right) \quad (1)$$

The value of the minimum tilt angle obtained by equation 1 was 14.83° and, for security, the chosen tilt angle used in the experiments was 16°. Negative tilt angle was the inclination in which the angle between tool axis and a_e direction is less than 90°. Positive tilt angle was the inclination in which the angle between tool axis and a_e direction is higher than 90° and neutral tilt angle was the inclination in which the angle between tool axis and a_e direction was 90°, when tool was at θ_{pr} 90°, and did not change along the tool path. It is the opposite sign criterion utilized by Kull Neto et al (2016b). Figure 3 presents tool inclination.



a) Positive inclination, tilt angle +16°.

b) Neutral inclination, tilt angle 0°.

c) Negative inclination, tilt angle -16°.

Figure 3: Tool inclinations.

Milled surface had the roughness measured at the cross feed direction after 260 tool paths (removal of two layers of material), approximately 11 m of linear cutting, to avoid a possible influence of the surface generated by the cleaning tool in the sample surface preparation. Measurements were taken in the regions of θ_{pr} = 5°, θ_{pr} = 45° and θ_{pr} = 85°. The cutoff length used was 0.8 mm. Roughness values equal or lower than 0.7 µm are considered adequate roughness values for HSM in this work.

In order to avoid chatter occurrence the cutting edge passing frequency (RPM x number of tool cutting edges/60) was set as a fraction of the first peak frequency in the function response frequency. In order to determine spindle rotation, the function response frequency (FRF) of the tool was experimentally built using an instrumented hammer and accelerometers stuck close to the tool tip. Tool spindle rotation was calculated in such a way to make the tool tooth passing frequency to be half of the first response peak frequency. Since this first peak was at 738.30 Hz, the tooth passing frequency was 369.15 Hz and, since the tool had 2 tooth, the spindle frequency was 184.5 Hz and the spindle speed was 11,075 rpm. Figure 4 presents the tool FRF curve.

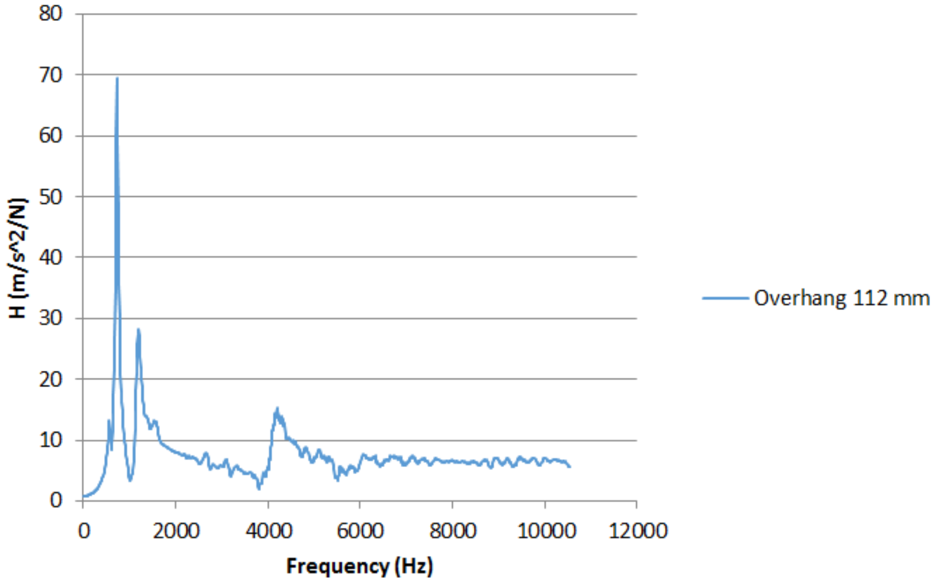


Figure 4: Tool frequency response function curve.

3 Results and Discussion

Figure 5 presents Ra roughness values for the radial position angles 5°, 45° and 85° in upward and downward tool path and tilt angle (t. a.) +16°, 0° and -16°.

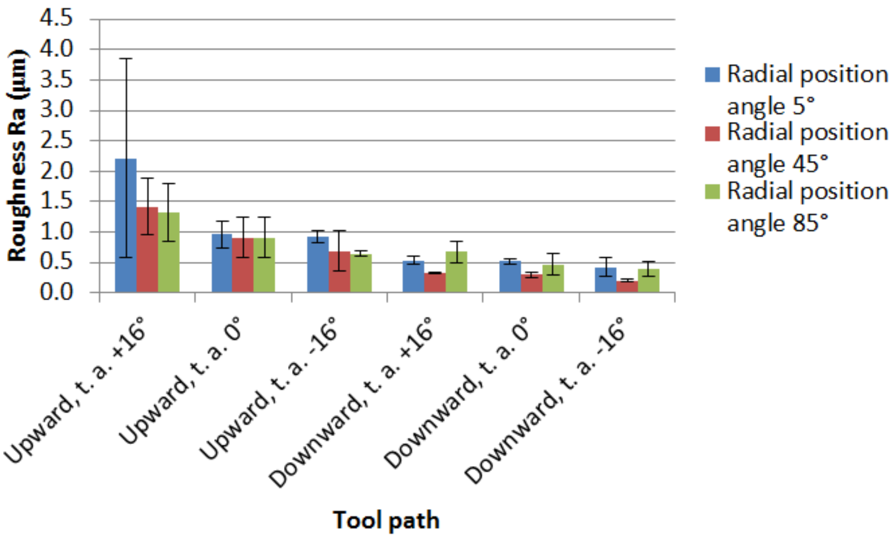


Figure 5: Roughness Ra for tested tilt angle values

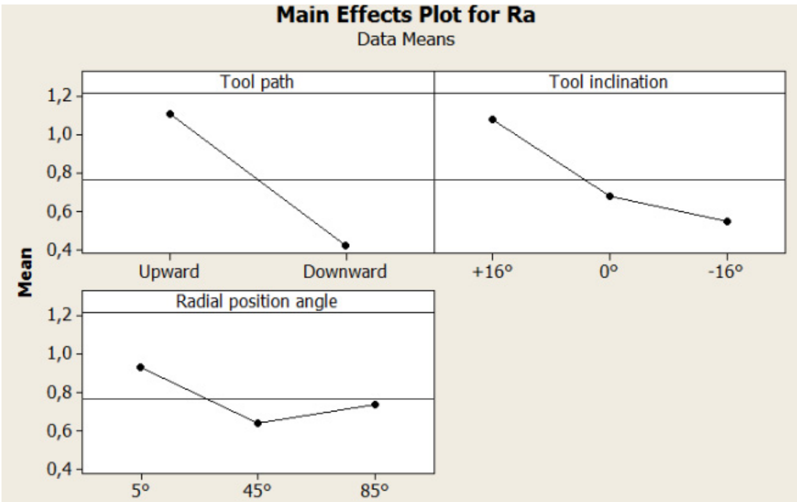
Figure 6 presents the main effects of tool path, tilt angle and radial position angle on surface roughness based on ANOVA analysis.

Analysis of Variance for Ra, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tool path	1	2,12730	2,12730	2,12730	54,74	0,002
Tool inclination	2	0,92768	0,92768	0,46384	11,94	0,021
Radial position angle	2	0,26089	0,26089	0,13044	3,36	0,139
Tool path*Tool inclination	2	0,47295	0,47295	0,23647	6,08	0,061
Tool path*Radial position angle	2	0,14026	0,14026	0,07013	1,80	0,276
Tool inclination* Radial position angle	4	0,08484	0,08484	0,02121	0,55	0,714
Error	4	0,15545	0,15545	0,03886		
Total	17	4,16936				

S = 0,197135   R-Sq = 96,27%   R-Sq(adj) = 84,15%

a) ANOVA table results.



b) ANOVA figure.

Figure 6: ANOVA analysis of roughness.

Some points must be discussed about the results shown in these figures:

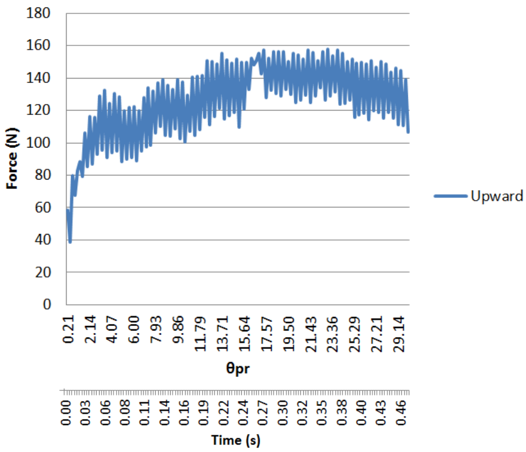
I) As it can be observed in figure 5 and confirmed in figure 6, the tool path strategy is the main factor of influence on surface roughness and downward strategy proved to be much more efficient in terms of generating low values of surface roughness when tool path describes the circle quarter - two factors must be analyzed to explain this result - i) in downward strategy the effective tool radius is a little lower than in upward strategy (Souza et al, 2014), what should have resulted in higher roughness values for the first strategy, since the geometric contribution of the tool diameter to the roughness is such that roughness should increase as the tool diameter decreases. Similar to Scandiffio et al (2016) results, upward tool path strategy resulted in higher roughness values than downward tool path strategy. Therefore, the geometric contribution of the tool diameter was not predominant in the generation of surface roughness; ii) in the upward strategy the tool started the cutting with its highest effective diameter (θ_{pr} = 0°), which means that it started the cutting with the maximum value of the radial component of the force and the minimum value of the axial component. Since the radial direction of the tool is not rigid (it bends the tool), the tool starts the cutting vibrating. This vibration, which will be shown later in figure 7, continues at least up to the point where θ_{pr} reached 60°, what damaged the surface roughness of the workpiece. On the other hand, in downward cutting, the tool started the cutting with its smallest value of effective diameter and, consequently, with the radial component of the force in its minimum value and the axial component in its maximum value. Therefore, the tool started the cutting without so much vibration and could go along the cutting producing a good surface finish. So, it can be concluded that tool vibration was the main factor which made surface roughness obtained with upward cutting much higher than that obtained with downward cutting. ANOVA graphs confirm the tendency of high roughness values for θ_{pr} = 5° and low roughness values for θ_{pr} = 45°. It also shows the tool inclination tilt angle influence, resulting in higher values of roughness for tilt angle +16° and lower values of roughness for tilt angle -16°. ANOVA table confirms tool path as the most influent factor in roughness values.

II) Surface roughness values were higher when the radial position angle was 5°, mainly when upward strategy was used - it must be remembered here that, when upward strategy was used, the tool started the cutting with the maximum effective diameter (θ_{pr} = 0°) and the maximum value of the radial component, which caused tool vibration and, consequently, high values of surface roughness. This result also means that the factors that could cause surface roughness to be high when θ_{pr} was 85° (low value of effective diameter and consequent high value of geometric surface roughness, low cutting speed and, consequently, high plastic deformation in the volume of workpiece material in the vicinity of the chip formed) were not as influent on surface roughness as tool vibration, since surface roughness in this position was smaller than when θ_{pr} was closer to zero. Surface roughness when θ_{pr} was 45° was lower than when θ_{pr} = 85° for downward strategy and in the same level when upward strategy was used. For downward strategy, when the cutting occurred close to the top of the workpiece circle (close to θ_{pr} = 85°), the tool effective diameter was very small (even zero very close to the top), what made the plastic deformation of the workpiece and the geometric roughness very high. This factor made the roughness generated in this portion of the workpiece not higher than when the tool radial position was 5° due to the high vibration in this region, but higher than when θ_{pr} was 45°, which is a portion with intermediary contributions for the surface roughness from both, plastic deformation and geometric roughness of one side, and vibration of another side.

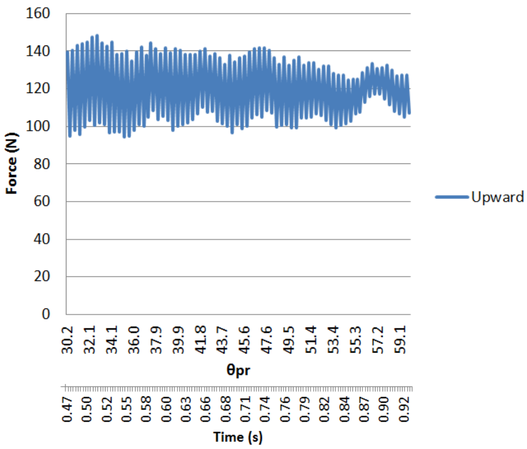
III) Surface roughness increased as tilt angle also increased again mainly for upward strategy - Ozturk et all. (2009) affirms that if the tool axis is bent towards the next pass of the tool (tilt angle considered positive in this work) the cutting tool can deflect into the workpiece surface (generating what is called "over cutting" by these authors) for a clockwise rotating tool, harming the surface roughness. This is the reason to explain the high roughness values when tilt angle of +16° was used, mainly in upward strategy, where the values of cutting force were higher.

Figure 7 presents graphs of the force peaks (highest value of force in each cutting edge engagement with the workpiece) in radial direction for the two experiments which presented the extreme values of surface roughness: a) upward strategy with tilt angle +16° (figure 7a, 7b and 7c) which presented the highest values of surface roughness; b) downward strategy with tilt angle -16° (figure 7d, 7e and 7f), which presented the lowest values of surface roughness.

Upward tool path, tilt angle +16°

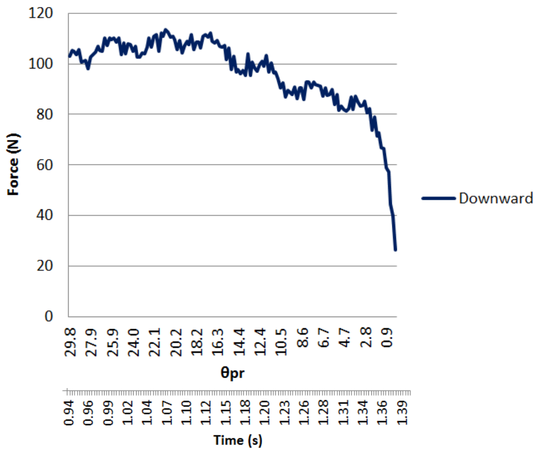


a) From θ_{pr} 0° to 30° (beginning of cut).

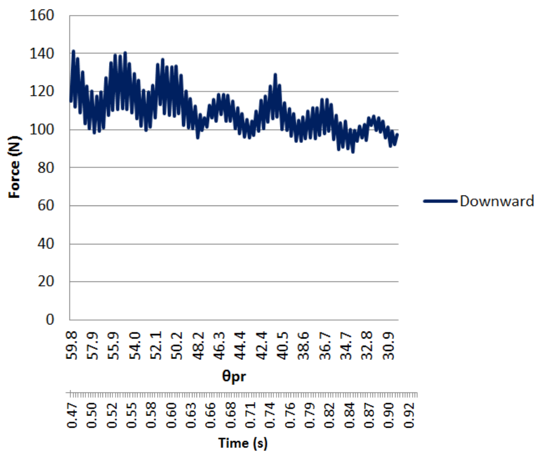


b) From θ_{pr} 30° to 60°.

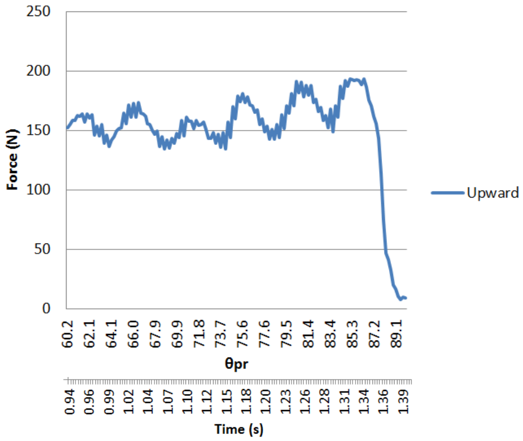
Downward tool path, tilt angle -16°



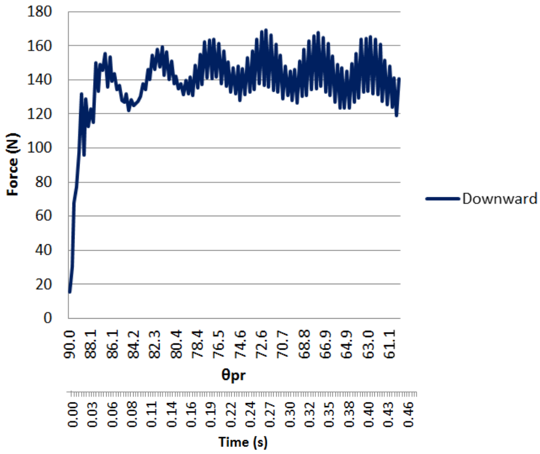
d) From θ_{pr} 30° to 0° (end of cut).



e) From θ_{pr} 60° to 30°.



c) From θ_{pr} 60° to 90° (end of cut).



f) From θ_{pr} 90° to 60° (beginning of cut).

Figure 7: Radial force peaks of tilt angle +16° in upward tool path and tilt angle -16° in downward tool path.

Some points can be seen in this figure: a) the comparison between the radial force results of these two experiments when θ_{pr} was in the range of 0 to 30° shows that the upward strategy (figure 7a) generated higher values of peak forces and higher variation of force between two consecutive peaks (therefore, between two consecutive cutting edge engagements). Of course, this pattern of force variation in the upward strategy was harmful for the workpiece surface roughness, as was seen in the analysis of figure 5 (surface roughness in this workpiece position was higher than 2 µm for upward strategy and lower than 0.5 µm for downward strategy); b) comparing the force values for θ_{pr} from 30° to 60°, it can be seen that the values of the forces in upward strategy (figure 7b) were a little higher than the values obtained in downward strategy (figure 7e), and the variation of the values between two consecutive values were much higher for the upward strategy, about 50 N in some curve regions. Consequently, the roughness values were close to 1.5 µm for the upward strategy and close to 0.25 µm to the downward strategy; c) it can be seen in figures 7c and 7f that for upward strategy in the workpiece radial position from 60° to 90° the radial peak forces presented a different behavior - it did not vary so much between two consecutive peaks, but presented the highest value of force among all force measurements, getting close to 200 N in some points, and a large variation comparing different portions of the workpiece. For example, in the portion where θ_{pr} was in the range from 84.1° to 86.4°, force was close to 200 N and in the portion where θ_{pr} was between 76.9° and 78.4°, force was close 140 N. In other words, the radial force did not vary from one cutting edge engagement to the next, but from the cutting of one portion of the workpiece and the next. This force behavior indicates that, in a certain portion of the workpiece, the actual depth of cut was high and in the other portion the actual depth of cut was small. It seems that this is the reason for the high value of surface roughness obtained in this portion of the workpiece for the upward strategy (around 1.3 µm).

4 Conclusions

Based on the results obtained in this work, it can be concluded that, for the high speed milling of convex circle of hardened steel performed in conditions similar to those used here:

- A high speed milling process in which tool path describes a quarter circle in each tool path is able to produce adequate roughness values for molds and dies made of hardened tool steel AISI D6.

- The tool path strategy is the main influence on surface roughness – upward tool path strategy obtained roughness much higher than downward strategy. This was the main contribution of this work to the molds and dies industries;
- The increase of the tilt angle caused increase of surface roughness mainly when upward strategy was used;
- The roughness obtained in the central portion of the circle (radial position angle around 45°) was smaller than in the portions of this kind of workpiece, mainly in the downward cutting;
- Among the factors which influence surface roughness (tool vibration, geometric roughness determined by the tool effective diameter and radial depth of cut and plastic deformation of the volume of workpiece material in the vicinity of the chip formed) tool vibration was predominant caused by the variation of the components of the cutting force, especially the radial component, which is in the less rigid direction of the tool.

For future studies, a tool life investigation should be executed, because the vibration behavior might increase or decrease tool life, affecting wear and enabling tool damages. Frequencies in which system is vibrating analysis should be made for a deep investigation about tilt angle influence in vibration.

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Responsibility Notice

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