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INFLUENCE OF TILT ANGLE AND FEED DIRECTION ON SURFACE ROUGHNESS AND CUTTING FORCES IN HIGH SPEED MILLING OF HARDENED TOOL STEEL

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Abstract. *In this work surface roughness, tool wear and cutting forces are analyzed in high speed milling process of hardened tool steel AISI D6 utilized in moulds and dies manufacturing. High speed milling enables the increase of productivity and decrease of costs and production time as other processes, EDM and polishing, can be substituted successfully by finishing in one machine and one workpiece fixation. However, it requires appropriate cutting strategies. The vicinity of the center of a ball nose end mill (typical tool used in this kind of process) has a low cutting speed which leads to plastic deformation in the workpiece, situation avoided by inclining the tool towards feed and/or cross feed directions (lead and tilt angle respectively) in order to make the tool axis not perpendicular to the workpiece). The tool path strategy, ascendant cut or descendent cut (which influences the lead angle variation along the cutting), is very important for a good surface finish and tight geometric tolerances. This work analyses a four axis milling having as input variables the tilt angle (with small values of tilt angle in such a way to avoid the contact of the tool tip with the AISI D6 steel workpiece and without tilt angle) and feed direction (in order to have ascendant and descendant cutting in the milling of a circular surface). A 12 mm diameter ball nose end mill with ultra-fine grain size and TiAlN coating was used in the milling experiments. Roughness values evolution and flank wear evolution and cutting forces were investigated according each tool path strategy. The main conclusion is that the chosen strategy (ascendant or descendant cutting) is, among the tested variables, the main variable of influence on surface finish, improving or worsening them.*

Keywords: *high speed milling, tilt angle, hardened steel, surface roughness, cutting forces, tool path strategy.*

1. INTRODUCTION

Machining hardened materials, although usual, is difficult because of their low machinability and consequent short tool life, which make the costs to increase. Usually, the harder the workpiece material, the lower cutting speed and feed rate must be. Moreover the tool must have an adequate design to direct chip flow out of the cutting zone and must be made of a high heat resistant material (ASM, 1975). The most machined hardened steels are the tool steel types. The cold work tool steel type D has microstructure rich in carbides which leads to a low machinability even in the annealed state.

The increase in investments in the CNC machining centers and associated technology, especially after 1980 decade, enabled improvements in milling process (Childs et al, 2004). The machining centers became faster and more rigid. The different workpiece sizes and tool machine applications lead to different structure of the rotary axis. In small machining centers, the fourth and the fifth axis movements occur by rotary table and in higher machining center, the fourth and fith axis movements occur by rotary spindle movements (Lacalle and Lamikiz, 2009 and Arnone, 1998). The five axis machining centers allows complex surfaces to be milled resulting in better surface finish and tighter geometric tolerances, reduced cycle time and reduced costs, as demonstrated in Altintas et al (2014).

In high speed machining concept the spindle rotation surpass 10,000 rpm generally and the depths of cut, radial and axial, are low. In such conditions, the cut would generate high temperatures, but the low depth of cut values makes the contact angle between cutting edge and workpiece in each tool rotation to be small, what harms the temperature increase. Therefore, it is recommended to avoid refrigerant the use of cutting fluids, because of the thermal damages to the tool caused by stress from the high variation of temperature. The cutting process in HSM has a low chip removal rate comparing to the conventional cutting process, although it is higher than grinding and EDM processes (Lacalle and Lamikiz, 2009 and Sandvik, 2000). Sandvik (2000) recommends not exceeding the axial depth of cut a_p 8% of tool diameter in roughing process, 4% of tool diameter in semi-finishing process and 0.2 mm in finishing process. The radial depth of cut a_e shall not exceeding 40% of tool diameter in roughing and semi-finishing process and 0.2 mm in finishing process.

The cutter material development expanded the grade of materials and specific applications. The submicron coated cemented carbide is recommended to milling hardened steels because of the wear resistance, toughness and chemical stability (Sandvik, 2015b). The tool coating evolution allowed the cutting speed increase. The tool coating is harder than tool substrate what makes its wear and thermal resistance also higher causing increase in tool life. There are many types of tool coatings, with different compositions and also coating with superimposed multilayers, each one adequate to a specific machining condition. The most common tool coatings in high speed machining are TiAlN and its stoichiometric variation AlTiN, but in some application other coating may be preferred, like AlCrN (Beak and Fox-Rabinovich, 2014 and Urbanski et al, 2000).

Milling steel cavities in the hardened state avoids the necessity of geometric restoration caused by distortions in heat treatment and low values of roughness and tolerances can be reached. Therefore, high speed machining may substitute successfully EDM process in finishing and super finishing process (Sandvik, 2000). The chosen path strategy may lead the roughness and machining time to low values and minimizing time for a following operation, like polishing (Souza et al, 2014).

The ball nose end mill is used in finish machining of profiles, but when the tool axis is perpendicular to the workpiece, the roughness, cutting force and tool life can be affected by the zero and low cutting speeds in the center and vicinity of tool. This insufficient cutting speed causes plastic deformation instead of chip formation close to the workpiece region in contact with the tool tip and its vicinity, which results in and poor surface finish. To avoid this undesirable cutting condition, it is recommended the use of tool inclination (Arnone, 1998, Sandvik, 2015 a. and Sandvik, 2015 c). If it is possible, the use of adequate wall inclination may avoid the contact of the tool center and cut area (Arnone, 1998 and Oliveira, 2007).

Tilt angle and lead angle, shown in figure 1, utilization may improve tool life and change force and vibration behavior, which enables reduced costs and can avoid chatter occurrence or minimize its effects (Koshy et al, 2002; Ozturk et al, 2009).

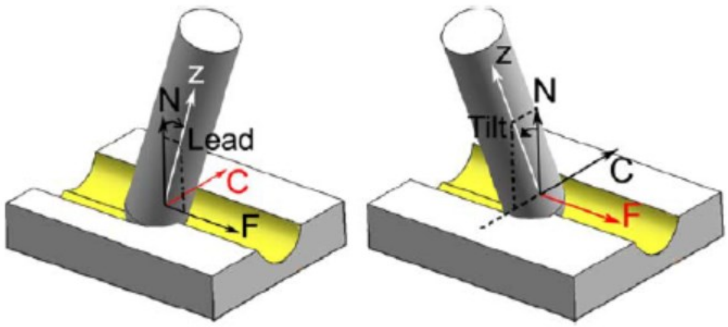


Figure 1: Lead angle and tilt angle scheme (Ozturk et al, 2009)

This paper aims to analyze the influence of tilt angle and path strategy effects in five axis machining of a quarter circle workpiece in roughness and forces.

2. EXPERIMENTAL PROCEDURES

A hardened at 60 HRC tool steel D6, whose composition is listed in table 1, was machined in a five axis center milling DMG DMU 40 Evo, maximum spindle speed 42,000 rpm, CNC software Heidenhain iTNC-530. The chosen tool had a carbide holder (ISO code R216F-12A16C-085) with a 12 mm diameter insert, ISO code R216F - 1230E-L GC1010 , TiAlN coated sub micrometric carbide in a HSK-A63 fixation system. The workpiece roughness was measured by a rugosimeter Mitutoyo SurfTest SJ-201 Ver3.10 in the cross feed direction. Force components were measured by dynamometer Kistler type 5019, sampling rate 30,000 Hz, scale 200 N/V, 7500 samples per channel and buffer size 1000.

Table 1: Chemical composition of tool steel D6 (Costa e Silva and Mei, 2013).

% C	% Cr	% V	% Nb	% W
2.00	12.5	0,07	0.15	1.00

The sample is designed to enable the cut of the quarter circle, with radius of 27 mm, and fixation on the top of the dynamometer. The milling process changes from peripheral milling and face milling as the tool travels along the radius or the inverse, depending if the cutting is downward or upward. Lead angle changes from 0° to 90° in downward cut and from 90° to 0° in upward cut. Figure 2 shows the workpiece design.

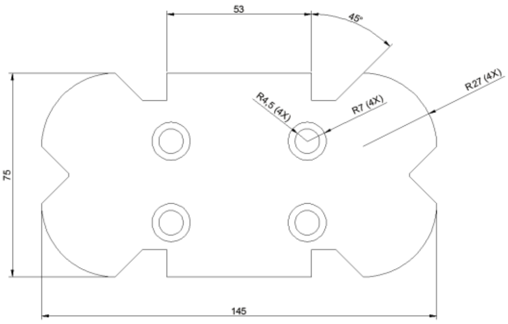


Figure 2: Sample design

The spindle speed used in tests was 11,075 rpm, the radial depth of cut (a_e) is 0.3 mm and constant stock value of 0.2 mm (a_p). The feed rate is 0.1 mm/tooth. To avoid the contact between the tool tip and the workpiece, the tilt angle θ_{tilt} must have a minimum value, calculated by tool radius and axial depth of cut (see figure 4b), which may be determined by equation 1.

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

where:
a_p = axial depth of cut
R = tool radius

For the a_p and R values used in this work, the calculated minimum tilt angle is 14,835°, but, for a safety margin, the chosen tilt angle value is 16° in positive and negative inclinations. The neutral inclination, tilt angle 0°, was tested for comparison.

Lead angle and path strategy may influence in effective diameter, whereas the lead angle, represented by θ_{lead} (see figure 3), changes as the tool moves along its circular trajectory. The different lead angle values result in different effective radius. Figure 3 shows this influence in the component of effective radius R_{lead}. Upward cut leads to higher values of R_{lead} than downward cut.

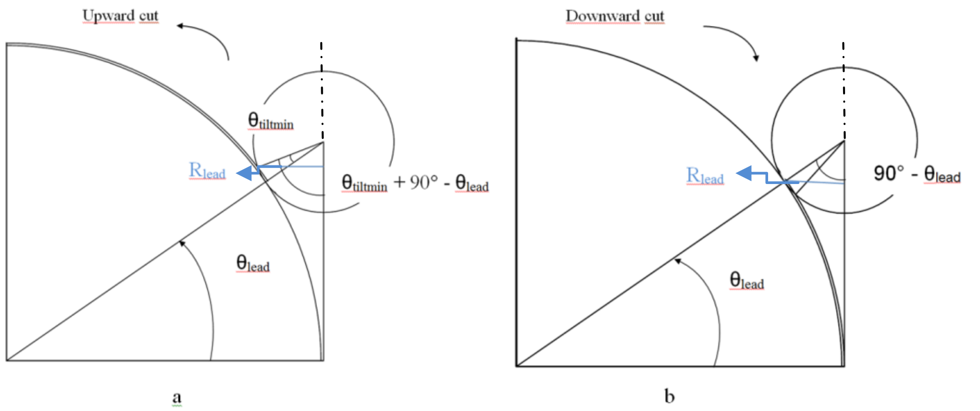


Figure 3: Schemes of lead angle influence in radius component R_{lead} for a) upward cut and b) downward cut.

For upward cut, R_{lead} may be calculated by equation 2 for lead angle 5° and by equation 3 for the other lead angle values:

$$R_{lead5°} = R * \sin(90°) \quad (2)$$

$$R_{lead} = R * \sin(90° - \theta_{lead} + \theta_{tilt\ min}) \quad (3)$$

where R_{lead} is the maximum tool radius in contact with the workpiece and θ_{lead} is shown in figure 3.

For downward cut, R_{lead} may be calculated by equation 4:

$$R_{lead} = R * \sin(90° - \theta_{lead}) \tag{4}$$

Tool inclination, θ_{tilt}, results in different effective diameter of cut according to resultant component of radius R_{tilt}. Figure 4 presents the influence of tilt angle in radius R_{tilt}.

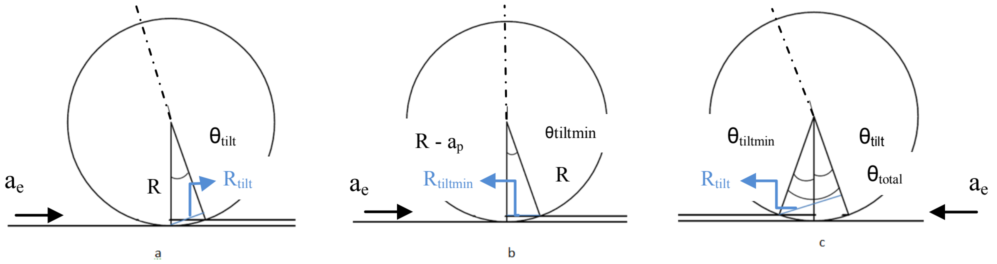


Figure 4: Influence of tilt angle in radius R_{tilt} for a) +16° inclination, b) 0° inclination and b) -16° inclination

For positive inclination, the component of effective radius R_{tilt} may be calculated by equation 5:

$$R_{tilt} = R * \sin(\theta_{tilt}) \tag{5}$$

For neutral inclination, in which geometry equation 1 is based, R_{tilt} may be calculated by equation 6:

$$R_{tilt} = R * \sin(\theta_{tilt\,min}) \tag{6}$$

For negative inclination, R_{tilt} may be calculated by equation 7:

$$R_{tilt} = R * \sin(-\theta_{tilt} + \theta_{tilt\,min}) \tag{7}$$

The effective diameter may be calculated by equation 8 for positive tilt angle in lead angle 5° and 45°:

$$D_{effective} = 2 * \sqrt[2]{R_{lead}^2 + R_{tilt}^2 - 2 * R_{lead} * R_{tilt} * \cos(90° - \theta_{tilt} - \theta_{lead})} \tag{8}$$

The effective diameter may be calculated by equation 9 for positive, neutral and negative tilt angles in lead angle 85°:

$$D_{effective} = 2 * \sqrt[2]{R_{lead}^2 + R_{tilt}^2} \tag{9}$$

The effective diameter may be calculated by equation 10 for neutral tilt angle in lead angle 5° and 45°:

$$D_{effective} = 2 * \sqrt[2]{R_{lead}^2 + R_{tilt}^2 - 2 * R_{lead} * R_{tilt} * \cos(90° - \theta_{tiltmin} - \theta_{lead})} \tag{10}$$

The effective diameter may be calculated by equation 11 for negative tilt angle in lead angle 5°:

$$D_{effective} = 2 * \sqrt[2]{R_{lead}^2 + R_{tilt}^2 - 2 * R_{lead} * R_{tilt} * \cos(90° + \theta_{tilt} - \theta_{lead})} \tag{11}$$

The effective diameter may be calculated by equation 12 for negative tilt angle in lead angle 45°:

$$D_{effective} = 2 * \sqrt[2]{R_{lead}^2 + R_{tilt}^2 - 2 * R_{lead} * R_{tilt} * \cos(90° - \theta_{tilt} - \theta_{lead})} \tag{12}$$

The effective diameter and cut speed, consequently, change according to process evolves. The resultant contact arc is parabolic and changes according to lead and tilt angle interaction along the cutting movement. It is expected to lead to different values of roughness and forces for different lead angles. They are measured for surfaces orthogonal to lead values of 5°, 45° and 85° in cross feed direction.

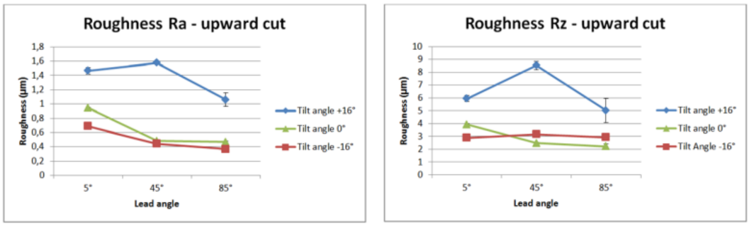
Table 2 shows the calculated effective diameters.

Table 2: Calculated effective diameters.

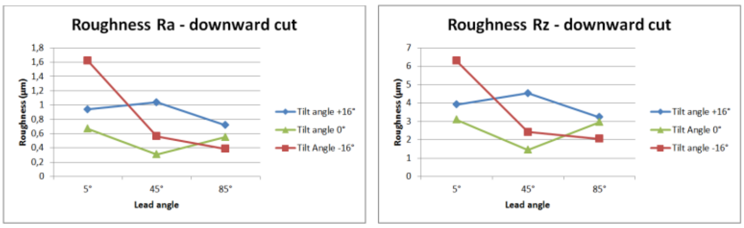
		Upward cut	Downward cut
Lead angle (°)	Tilt Angle (°)	D_{eff} (mm)	D_{eff} (mm)
5	16	11.25	11.20
45	16	7.65	5.82
85	16	5.25	3.47
5	0	11.33	11.29
45	0	7.87	6.03
85	0	5.10	3.24
5	-16	11.35	11.32
45	-16	9.14	7.70
85	-16	7.38	6.24

3. RESULTS AND DISCUSSION

Tool inclination, tilt angle and chosen strategy have a great influence in surface finish. Figure 5 shows roughness R_a and R_z results for tilt angle variation and both chosen strategies in cross feed direction.



a



b

Figure 5: Roughness evolution for a) R_a end b) R_z for lead angle and tilt angle.

Tilt angle has influenced in roughness values and behavior. Roughness R_a and R_z have similar behavior for the same strategy, upward cut or downward cut. In upward cut, tilt angle 16° provides the higher values of roughness for R_a and R_z. For the same feed direction, tilt angles 0° and -16° provide similar values of roughness, but tilt angle -16° has the best roughness values in general behavior. In downward cut, tilt angle 16° and 0° have the roughness values in a similar behavior of upward cut, but the values are lower. Tilt angle -16° has a high roughness value for lead angle 5° and higher values for the other lead angles than upward cut has for R_a and R_z. These roughness behaviors suggest vibration influence. Before going on the analysis of force variation, it is important to state that, aiming to obtain a good surface roughness in the cutting with circular trajectory of the tool, the tilt angle of 16° must be avoided (in all experiments it presented high surface roughness). The best strategies to mill the circular surfaces are upward cut with tilt angle of -16^{0} or downward cut with zero tilt angle. Both presented almost homogeneous roughness values along the trajectory (with different lead angles) and always below Ra value of 0.7 µm.

For analyses about vibration influence in roughness values, figures 6, 7 and 8 present the graphs of force components for the entire pass of the tool on the workpiece for the conditions which resulted in best roughness behavior, tilt angle -16° in upward cut and tilt angle 0°in downward cut, and the conditions which resulted in worst roughness values, tilt angle +16° in upward cut and tilt angle +16° in downward cut, for the force components: F_a, axial force; F_f, feed direction force and F_{cf}, cross feed direction force. Figure 6 presents F_a component graphs.

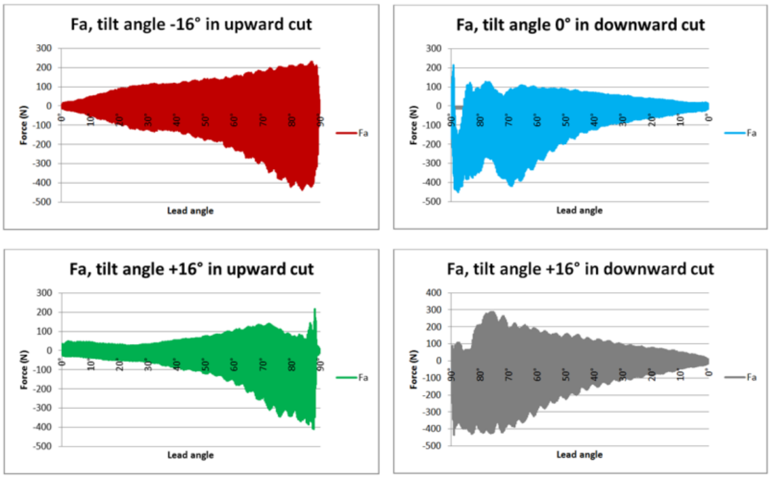


Figure 6: F_a graphs for the conditions with best and worst roughness behavior.

The F_a graphs for tilt angle -16° in upward cut (figure 6a) presented a behavior very close to what was expected in an upward cut, i.e., low values when lead angle is small and the effective diameter is high and high values when lead angle is high and effective diameter is small. In this last position, due to the small effective diameter a lot of plastic deformation occurs which generates high axial force. When tilt angle 0° and downward cut (figure 6b) was used, there are severe disturbances in F_a values from the beginning of the cut (lead angle 90°) up to lead angle 65°. These variations may be related to the engagement of the tool tip in the cut. After lead angle 65^0 the tool tip does not have any contact with the cut anymore and, consequently, the force variations stop. After that the force values decrease until the cut finish in lead angle 0°. For tilt angle + 16° in upward cut (figure 6c), the F_a graph presents an unexpected force value stabilization from lead angle 0° until lead angle 30° and then it increases, with considerable disturbance in force values from lead angle about 73° until cut end. For tilt angle +16° in downward cut (figure 6d), F_a graph presents severe disturbance from lead angle 90° until about lead angle 76° and the force values decreases until lead angle 0°, end of cut. The profiles of the curves indicate presence of vibration in all conditions, although this vibration occurs in the stiffest direction of the tool and may not influence roughness behavior. Figure 7 presents feed force components (F_f) also in the tests which obtained the best roughness values (tilt angle -16° in upward cut and tilt angle 0°in downward cut) and which obtained the worst roughness values (tilt angle +16° in upward cut and tilt angle +16° in downward cut).

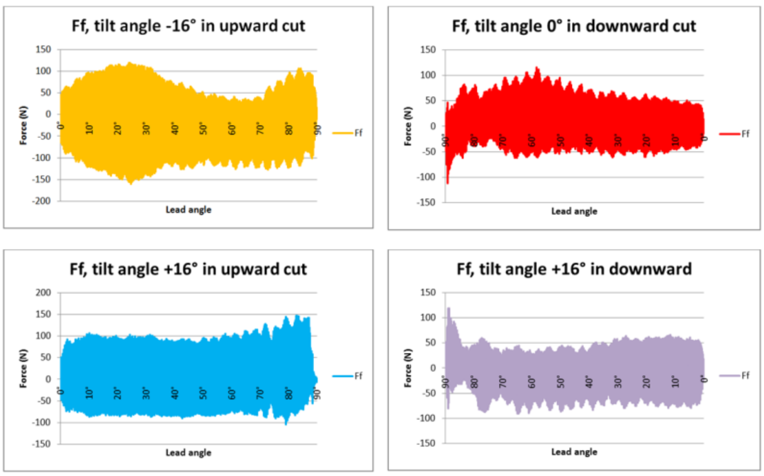


Figure 7: F_f graphs for the conditions with best and worst roughness behavior.

It can be seen in figure 7a that for tilt angle -16° in upward cut F_f the presence of vibration during the cut, since the peak values vary in a period of 3^0 of lead angle. The F_f graph for tilt angle 0° in downward cut (figure 7b) also presents the same vibration profile. In the experiment with tilt angle +16° in upward cut (figure 7c) F_f presents a regular behavior of until about lead angle 72° and some disturbance from this lead angle value until cut end. In the experiment with tilt angle +16° in downward cut (figure 7d) F_f also presents the vibration profilewith disturbance in force values along cut process. Therefore, it could be seen that vibration in this direction was not the reason for the different behavior of surface roughness, since both, the best and the worst conditions for surface roughness, presented similar variation in the values of Ff. However, the vibration in the feed direction may not affect the measured roughness values, since roughness was measured in cross feed direction. Figure 8 presents the component of the force in the cross feed direction (F_{cf}).

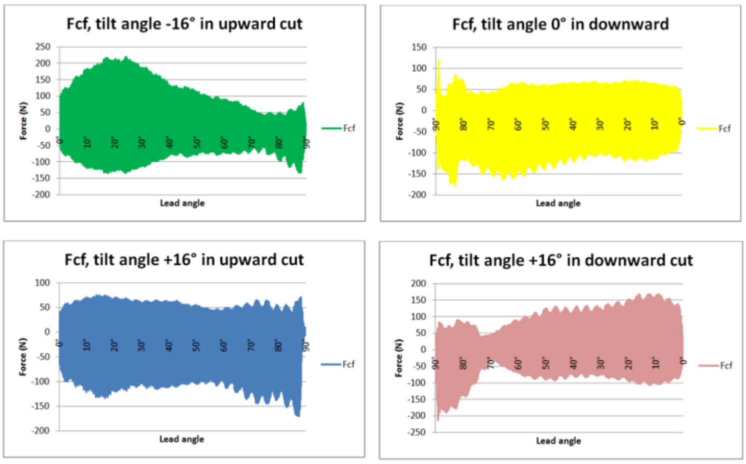


Figure 8: F_{cf} graphs for the conditions with best and worst roughness behavior.

It can be seen in this figure that the condition where the surface roughness values were low (figures 8a and 8b), in spite of variation of the force in different positions of the workpiece (different lead angles) mainly for the experiment with tilt angle -16^0 upward cut, the variation between subsequent peaks were smaller for the best conditions (figures 8a and 8b) than for the worst conditions (figures 8c and 8d). Figure 9 presents and amplified view of these variations. It can be seen in this figure that, for the worst conditions (figures 9c and 9d) not just the variation between peaks were high, but also variation of force occurred when different positions of the workpiece are compared (see the steep decrease of force in figure 9d for lead angle around 70^0). The distance between peaks in the figures is something around 3^0 of lead angle. To cut a portion of workpiece correspondent to 3^0, the tool rotates 7 times . That means that, for some reason, at each 7 tool rotations, the tool moves in the cross direction in order to vary the amount of chip removed and to cause the variation of the cross feed force component shown in figures 8 and 9. The higher variation of the cross feed component of the force caused the worst surface roughness in the cross feed direction obtained in the conditions tilt angle +16° in upward cut and tilt angle +16° in downward cut.

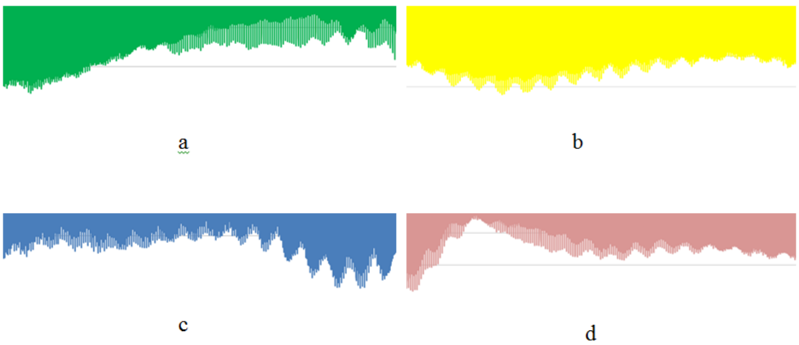


Figure 9: Detail of F_{cf} behavior between leads angle 20° and lead angle 80° for a) tilt angle -16° in upward cut, b) tilt angle 0° in downward cut, c) tilt angle +16° in upward cut and d) tilt angle +16° in downward cut.

4. CONCLUSIONS

This study concludes:

- The tested conditions which generated the best roughness values and behavior in the workpiece surface are upward cut in tilt angle -16° and downward cut in tilt angle 0°.
- The worst conditions for surface roughness occurred when the tilt angle was 16^0.
- The variation of the cross feed direction force component was the responsible for the unsuitable roughness values when 16^0 tilt angle was used..

5. ACKNOWLEDGEMENTS

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