23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

COMPLEX SURFACES ANALYSIS OBTAINED THROUGH THE MILLING PROCESS

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Abstract. *In the milling process, the finishing stage of a complex surface is usually performed by a ball nose end mill that does not present a constant contact area, creating a non-uniform roughness which hinders productivity. This work aims to evaluate the influence of milling direction and cutting direction using a ball nose end mill on roughness of complex surfaces obtained during milling of AISI P20 steel. For this purpose, a convex surface was analyzed in three different angles (85º, 45º and 5º) of the workpiece in order to verify the influence of the cutting effective diameter on the surface machined. Tests were carried out, changing the cutting speed (225, 250, 275 and 300 m/min), the milling direction (up milling and down milling) and the cutting direction (ascendant and descendant). The depth of cut, the feed per edge and the machining width were kept constant, 1.5 mm, 0.1 mm/edge and 0.3 mm, respectively. Increasing cutting speed presented little importance on machined surface roughness. However, the effective cutting diameter significantly influenced the roughness and characteristics of the surfaces obtained.*

Keywords: *complex surface, roughness, milling, AISI P20 steel.*

1. INTRODUCTION

Products manufactured by molds and dies presented major modifications in their projects from 1990, because of the plastics industries, automotive and aerospace, searching new designs and reduction of aerodynamic coefficient of friction, respectively. According to Lazoglu and Altintas (2002) the increase of the industrial design requirements, searching ever more forms for the presentation of a product lead to an intensification of products and objects containing free-form geometries.

In the manufacturing of molds and dies the quality of the final product is influenced by the finish left by the machining process being that one of the features that is increasingly required with product development. Even with the technological advances of the last decades, the manufacture of those tools with free-form surfaces, still presents a major challenge to ensure the quality and accuracy desired. The milling process is often used for these finishing operations because it can produce a pattern of regular and repetitive furrows with a preferred direction clearly observable and with well-defined grooves (Bet, 1999). Currently high-speed CNC machines and the development of new cutting tools, made possible the employment of small lateral increments (a_e), reducing the spacing between successive passes parallel of the tool, which allied to high cutting speeds and feed, allow the obtention of a better surface quality resulting in a texture of isotropic formation (Souza *et al.*, 2014).

However, the finishing step is usually performed by a ball nose end mill that during machining does not show a constant area with the workpiece surface thus modifying the forces during the process by generating a non-uniform surface roughness. In most cases, the region of contact between tool and workpiece varies from the center of the tool to a value that depends on the depth of cut and the inclination of the surface (Chiang *et al.* 1995; Souza *et al.*, 2013).

Figure 1 shows the dynamics of contact tool/workpiece during the machining of a semicircular surface with a ball nose end mill. It can be seen that when the tool is in position A, the contact with the workpiece occurs at its ball nose and at this point, the cutting speed is equal to zero. At B, the tool has a long contact with the workpiece which may include the tool nose. At C, the tool uses its periphery to perform cutting whose effective cutting diameter is maximum.

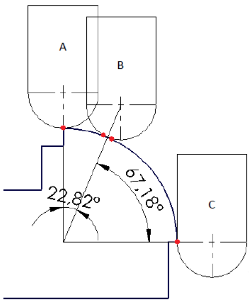


Figure 1. Points of contact of a ball nose end mill in a semicircular geometry.

According to König and Klocke (1997) the increasing of the cutting speed results in the increase of the temperature at the region of the cut, reducing the components of force machining due to the lower resistance of the machined material at higher temperatures, resulting in better finishes. In addition a surface generated with a ball nose end mill results in a wavy profile, and the radial cutting depth or lateral increment (a_e) apply a significant influence on the peaks height formation of the surface because of geometric feature tool nose (Oliveira, 2002). The smaller a_e, the smaller will be the heights of peaks and the theoretical roughness resulting in a smoother surface profile.

This article aims to evaluate the influence of cutting speed, cutting direction and milling direction using a ball nose end mill on the roughness of convex surfaces obtained during milling of AISI P20 steel. For this, the machined surfaces were analyzed in a scanning electron microscope (SEM) and in an white light interferometer optical at angles of 85º, 45º and 5º.

2. EXPERIMENTAL PROCEDURE

The machine tool used in the experiments was a 3 axis machining center, model MVC-955, manufactured by CHARLES Company, with spindle power of 7.5 kW and maximum rotation of 8000 rpm. The machine tool presents rapid feed of 30 m/min, as well as acceleration and deceleration of 8 m/s^2 on the axis X, Y and Z. The numerical control of machine tool is the Siemens Sinumerik 840D, and the maximum travel in axes X, Y and Z is 900, 550 and 530 mm, respectively.

The workpiece material used was AISI P20 steel (30 HRC) benefited and chemical composition as shown in Tab. 1 obtained by optical emission test. The AISI P20 steel is a low alloy steel used in manufacturing of plastic injection molds due its high polishability, that allows it to may obtain mirrored surfaces. The microstructure of the material consists of martensite characteristic of a high-temperature quenching material.

Table 1. Chemical composition of steel AISI P20.

Elements	C	Mn	Cr	Mo	Ni
(%)	0.37	1.48	1.78	0.18	0.74

The workpiece was designed with a semicircle, equivalent to a circle quadrant, to simulate machining of complex geometries. The workpiece was pre-machined on the dimensions of 160x54x40 mm with a convex semicircle of 30 mm radius as shown in Fig. 2a. The fixation of the workpiece was performed by 4 screws (Fig. 2a) on a grinded plate fixed on the machine tool table. The tool path on the convex surface of workpiece is shown in Fig. 2b. All tests were conducted with raster machining strategy in the software CAM PowerMill 9.0.0.03. All CAM configurations was performed using a tolerance of 0.01 mm, which used a post-processor that uses straight segments to define the tool path.

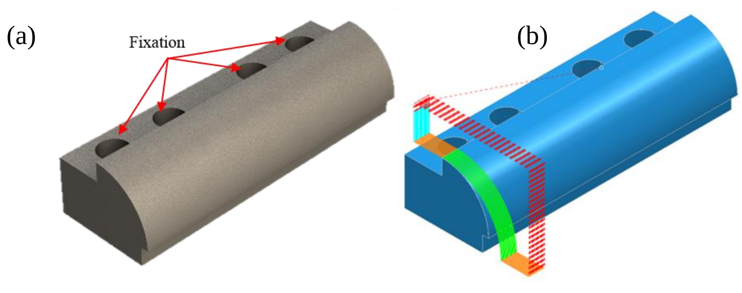


Figure 2. Workpiece geometry (a) and simulation of tool path (b).

The Table 2 shows the cutting parameters used in the tests. The experimental planning is composed with 8 tests down milling and 8 tests up milling, both without coolant, showing as variables direction and cutting speed. The radial and axial depth of cut, feed and the number of edges were parameters that did not have undergone modifications and their values are respectively a_e = 0.3 mm a_p = 1.5 mm, f_z = 0.1 mm/edge and 2 edges. The total machining width for each test was of 10 mm, a total of 33 passes of the cutting tool on the semicircle.

Table 2. Cutting parameters used in the tests.

Milling direction	Down Milling								Up Milling							
Cutting direction	Descendant				Ascendant				Descendant				Ascendant			
Tests	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI
v_c (m/min)	225	250	275	300	225	250	275	300	225	250	275	300	225	250	275	300

The inserts used in the tests were ball nose carbide (class P) with coating (Ti, Al)N applied by the PVD process, manufactured by the company Seco Tools (code 219.19-160P-M05 F17M) featuring 2 edges and diameter of 16 mm. The support of the inserts is also manufactured by the company Seco Tools, having as specification the code R219.19-1616.0-08-092. The support fixation was realized by a thermal shrinking chucks DIN 69871 40 SKIRN 16x80.E, with a height of 70 mm and beat of 4 µm.

After the realization of the tests, the machined surface texture was analyzed by a scanning electron microscope (SEM) HITACHI, model TM-3030 and an white light interferometer optical Zygo model Newview 7300. The analysis of the surfaces texture was performed in an area of 1 mm^2 in three different angles, being 85º, 45º and 5º (as shown in Fig. 3), in order to verify the influence of the variation of the effective cutting diameter on machined surface texture.

The data generated in the interferometer were analyzed in the software MountainsMap 7.0, in which the texture of the surfaces was analyzed by the standard ISO 25178. The form error of the surfaces was removed using a polynomial of degree 12. The roughness parameters obtained were S_a, S_v, S_z, S_p, S_{ku}, S_{sk}, S_q and Abbot curve. The results were statistically analyzed (with a confidence interval of 95%) according to Montgomery and Runger (2003) using Minitab 16 software.

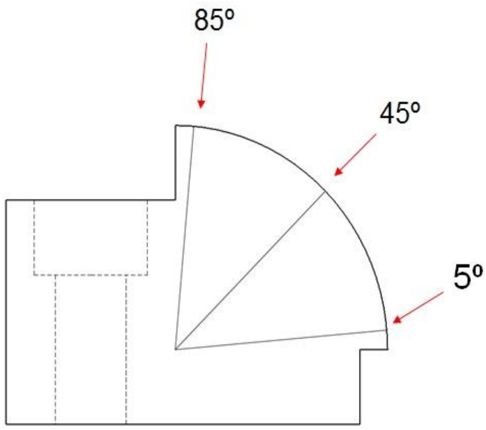


Figure 3. Angles where the surfaces texture was analyzed.

3. RESULTS

Figure 4 shows the images obtained with a magnification of 500 x for two tests in which the cutting speed and the cutting direction were kept in v_c = 250 m/min and ascendant, however varying in down (VI) and up milling (XIV) to three different angles, to 85°, 45° and 5°.

For the different tests, it can be seen that there was not much difference between the surfaces generated. In down milling, only at angle of 45° a small amount of material was adhered on machined surface (as indicated in Fig. 4). In the angles of 45° and 5°, there is a considerable presence of void for both directions, however, it cannot be clearly observed in the samples machined with 85° due to the high presence of deformed material on the surface. In the sample of 85° in down milling (VI) the overlapping of layers of material is clearer. This occurs due to a reduction in the effective cutting diameter, approaching the cutting speed to zero. In this region, a part of the material suffers cut and the other suffers deformation being pushed to the side. In the sample of up milling at the same angle, the layers of material are presented in a non-uniform look of ripped material and/or crushed. The remaining surfaces obtained by other tests that have not been shown here presented similar visual aspects to those shown in Fig. 4.

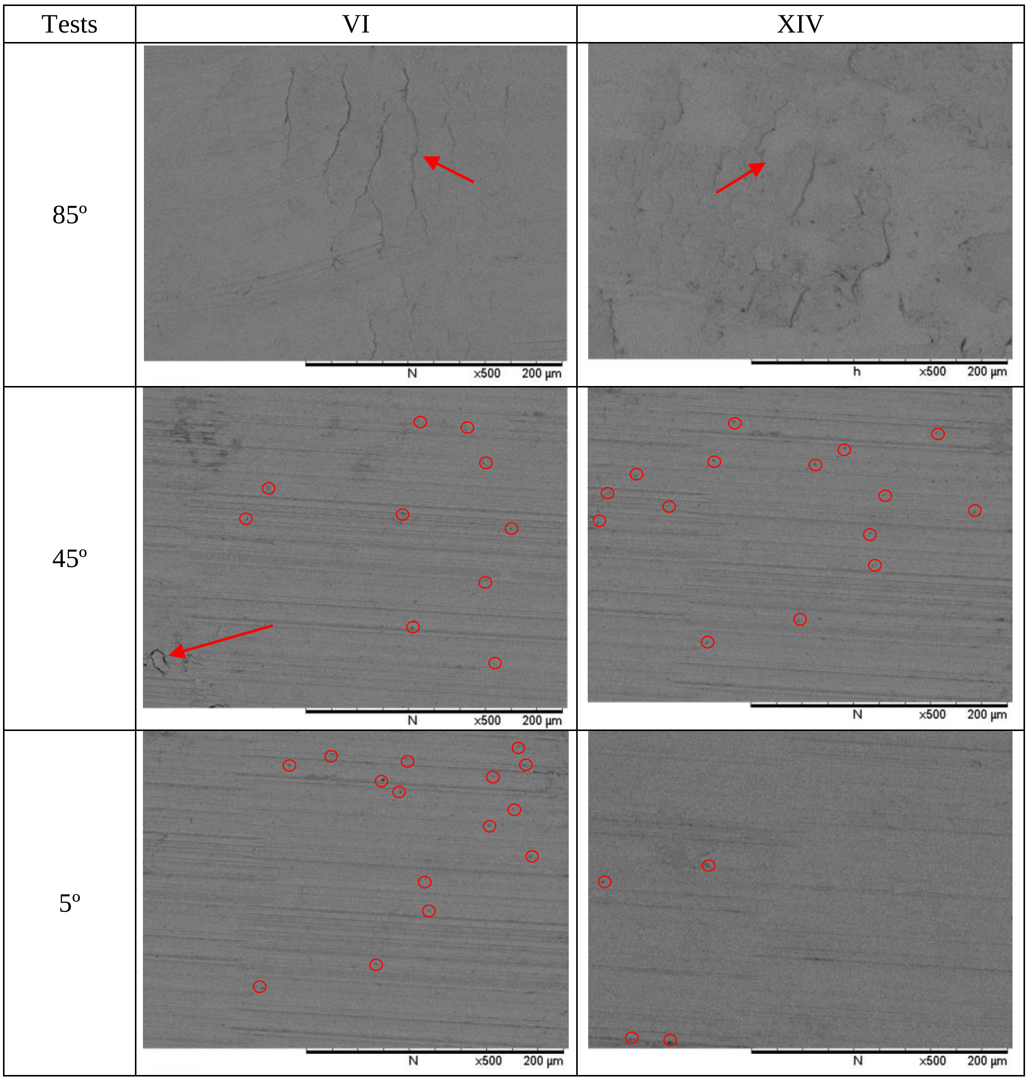


Figure 4. Images obtained by SEM in angles 85° 45° and 5° of tests surfaces VI (down milling ascendant and v_c=250 m/min) and XIV (up milling ascendant and v_c=250 m/min).

Figure 5 shows the images generated by optical interferometer after scanning the machined surfaces at 85°, 45° and 5°. The surface evaluated at 85° had the worst condition for the down milling descendant and up milling ascendant. This can be explained by the crushing of material surface, being that the experiment VI down milling ascendant and X up milling descendant one can see clearly the marks of a_e and the feed, generating surfaces close to isotropic although the relationship a_e/f_z not being equal to 1. But even the surface VI and X showing a better texture, an accumulation of material between the peaks can be seen, indicating that not all material was torn, i.e. a part was deformed and remained on the surface machined.

The surfaces at 45° were similar, besides the smallest heights of peaks about the other conditions. Chen *et al.* (2005) and Vakondios *et al.* (2012) showed that, running the milling with ball nose end mill using a slope at the milling cutter shaft at a certain angle let us to get lowest height of peaks. However, increasing the angle of inclination from a certain value, the heights of the marks does not get more reduction, i.e. remains stable for a certain radius "R" of the tool. What can be found in this case when at 45° obtained the lowest roughness to a same feed and a_e.

At 5°, the surfaces also kept the same look in terms of texture but they differed in terms of height of the peaks having the tests with ascendant direction with lower values compared to the descendants. The machining with ball nose end mill has the characteristic that the cutting speed is variable along the edge (König and Klocke, 1997). Depending on the shape and slope of the surface, each point of the edge of the mill in contact with the workpiece is subjected to different conditions of cut (Silva Filho, 2000; Souza *et al*., 2013; Souza *et al*., 2014). Thus, the effective cutting diameter is differentiated for the ascendants directions and descendants.

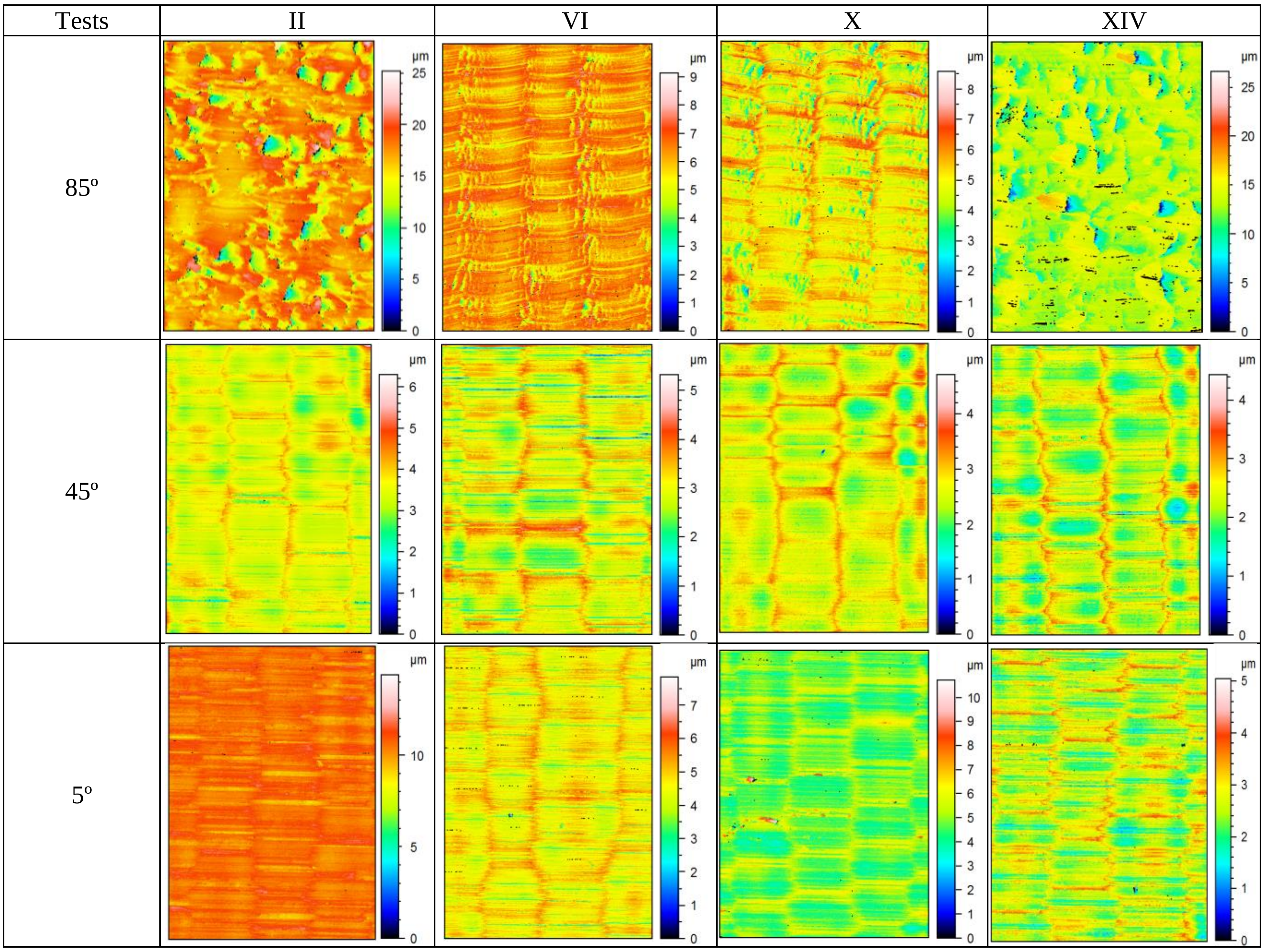


Figure 5. Images obtained with the white light interferometer optical for the samples II, VI, X and XIV in the angles 85º, 45º and 5º. Cutting parameters to all images (v_c=250 m/min); II – Down milling descendant; VI – Down milling ascendant; X – Up milling descendant; XIV – Up milling ascendant.

Through Fig. 6 the differences in the contact area of the cutting tool with the workpiece for the ascending and descending milling for a cutting depth constant ca be noted. Souza *et al.*, 2015, studied the influence of ball nose tool path along a free form surface in the forces acting during the milling process. The authors found that ascendant directions present smaller forces during machining in virtue that the ball nose of the mill participate less of cutting than in descendant direction, creating smaller vibrations. That said the ascendant direction of the tests of this work showed lower roughness of machined surfaces compared with surfaces obtained with the descendant direction.

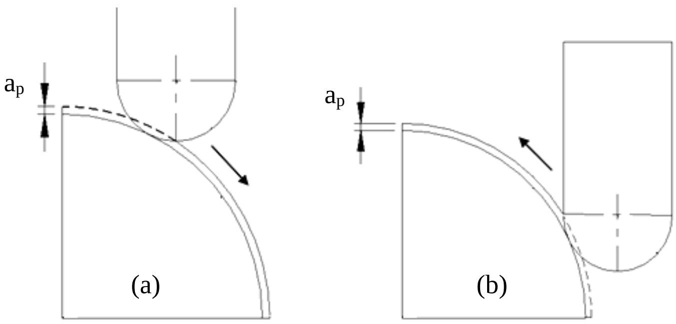


Figura 6. Cutting direction (a) descendant and (b) ascendant.

Figure 7 shows the interactions of the parameter S_q with varied parameters in the tests. The root mean square height or S_q parameter is defined as the root mean square value of the surface departures, z(x,y), within the sampling area

(Whitehouse, 1994; Leach, 2013). All roughness parameters analyzed showed a behavior similar to that presented in the Fig. 7 and therefore it was chosen to just display the values about S_q. From the interaction chart when both threads are parallel or nearly parallel the interaction between the factors involved does not exist or have little importance. When the segments intersect, the interaction between the factors involved exist.

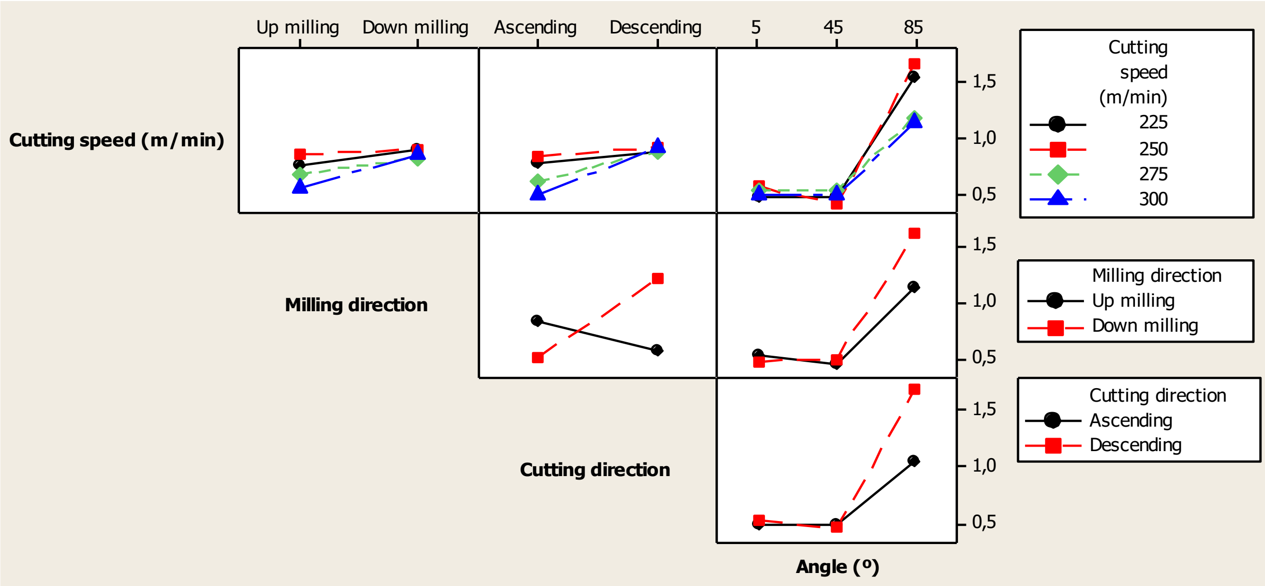


Figure 7. Interactions chart parameter S_q in the cutting conditions.

Therefore, it can be concluded that the only varying parameters that had interactions with the parameter S_q was the milling direction and the cutting direction. Through the chart it turns out that the angle analyzed 85° negatively influenced on machined surface roughness, being independent of interactions with the other varying parameters in the tests. Table 3 shows the values of P-value for the interactions, where we can verify that the angles analyzed in the workpiece, the milling direction and the cutting direction were the only ones that showed significant interactions in the machined surface roughness values (values less than 0.05).

Table 3. P-Value for interactions.

S_q * Milling direction	0,045
S_q * Cutting direction	0,034
S_q * Cutting speed	0,175
S_q * Angle	0,048

Figure 8 shows the parameters S_k, S_{pk} and S_{vk} for samples II (Down milling descendant and v_c = 250 m/min) and for sample XIV (Up milling ascendant and v_c = 250 m/min), for the different angles 85°, 45° and 5°. The parameter S_k in accordance with ISO 13565-2 (1996), is defined as the depth of roughness profile core. It characterizes the long term wear of the surface which will influence the operating performance of the surface (Whitehouse, 1994). Low values for this parameter indicate greater load capacity during contact operations. The parameter S_{pk} in accordance with ISO 13565-2 (1996), is defined as the average height of the peaks above of the roughness profile of the core. It represents the portion of the surface that will suffer premature wear. Processes that produce low values for this parameter are ideal where the geometry of the product should be maintained after the beginning of operation of the component. The parameter S_{vk}, in accordance with ISO 13565-2 (1996) is defined as the average depth of the profile valleys designed beyond roughness profile core. It characterizes the fluid retention capacity of the surface. High values indicate greater retention of fluid lubricants, that is, a surface of plateau type, for example, has low values of S_k and S_{pk} and high values of S_{vk} (Mummery, 1992; Whitehouse, 1994).

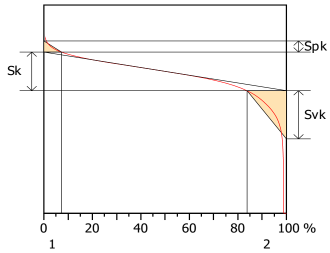
In Fig. 8 to 85° shows for both samples high values of S_{vk} which indicates that are good areas for fluid retention. But also high values of S_k which indicates low load capacity. The samples to 45° and 5° values are very close having low values of S_{pk} and S_{vk} and values close to 1 µm to S_k. This indicates that the surface have low capacity of fluid retention, little material for the initial wear and a good load capacity during contact operations.

In all analysis, the variation of the cutting speed showed no differences from the results analyzed, so we opted to present the characteristics only for a cutting speed. The remaining surfaces obtained by other tests presented similar characteristics to the surfaces shown in Fig. 8.

Tests: II, XIV

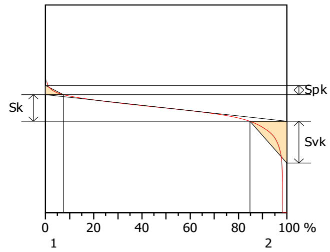
85º

II



Parameters	Value	Unit
Sk	4.66	µm
Spk	1.34	µm
Svk	5.83	µm
Sr1	7.28	%
Sr2	83.8	%

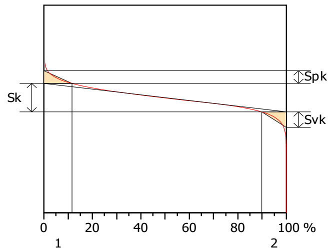
XIV



Parameters	Value	Unit
Sk	3.41	µm
Spk	1.18	µm
Svk	5.35	µm
Sr1	7.47	%
Sr2	84.7	%

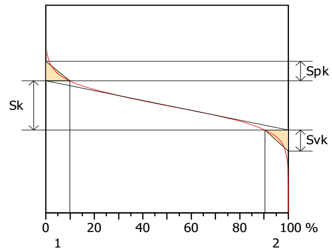
45º

II



Parameters	Value	Unit
Sk	0.861	µm
Spk	0.385	µm
Svk	0.472	µm
Sr1	11.6	%
Sr2	89.9	%

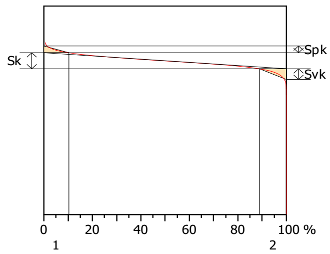
XIV



Parameters	Value	Unit
Sk	1.05	µm
Spk	0.416	µm
Svk	0.450	µm
Sr1	9.91	%
Sr2	90.4	%

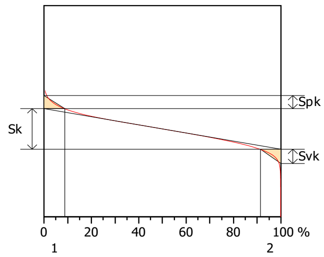
5º

II



Parameters	Value	Unit
Sk	1.11	µm
Spk	0.468	µm
Svk	0.733	µm
Sr1	10.3	%
Sr2	88.9	%

XIV



Parameters	Value	Unit
Sk	1.57	µm
Spk	0.508	µm
Svk	0.555	µm
Sr1	8.80	%
Sr2	91.4	%

Figure 8. Abbot curve for tests II and XIV in the angles 85º, 45º and 5º. Cutting parameters of the tests: II – Down milling descendant and v_c=250 m/min; XIV – Up milling ascendant and v_c=250 m/min.

4. CONCLUSION

The analysis on SEM showed that there was no major differences of the surface angles of 85º, 45º and 5º between the tests realized. However the visual aspect in the microscope showed a quantity of material deformed an the surface machined in the angle of 85º which is associated to the performance of the ball nose of tool at the time of the cut where the cutting speed is null.

With the images generated by optical interferometer it was observed that the smallest values of surface roughness were obtained in angles 45º and 5º, regardless of direction and cutting direction approaching the near isotropic surfaces.

Through the analysis of interactions, the cutting speed was the only variable examined that did not present significant interaction with the roughness of the surfaces obtained. However it was noticed that the angle proved to influence the roughness of machined surface acting as a parameter independent of other variables analyzed in the tests due to the variation of the effective cutting diameter along the machined surface.

Finally, it was found that the variation of the effective cutting diameter of a ball nose cutting tool influences not only on the values of the surfaces roughness but also on the characteristics of the surfaces. At the angle of 75º machined surfaces showed better surfaces for fluid retention and the surfaces obtained at 45º and 5º presented few material for the initial wear and with good load capacity being required for operations that present contact.

5. ACKNOWLEDGEMENTS

The authors are grateful to Federal University of Santa Catarina (UFSC) in particular the Program of Post Graduation in Mechanical Engineering (POSMEC); the Machining and Numerical Control Laboratory (USICON), Precision Engineering Laboratory (LMP), Ceramic & Composite Materials Research Laboratories (CERMAT) at UFSC and the National Council for Research and Development (CNPq).

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