THE INFLUENCE OF SOME CUTTING PARAMETERS IN FINISHING MILLING OF HARDENED STEEL USING A BALL NOSE TOOL

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***Abstract**: The application of the HSC technology, together with CAM system programming, seem highly attractive, mainly in the dies and mould industries. Due to the importance of technological knowledge about all parameters involved into this process, the main result is not, in most of the cases, which one desired. Thus, without the domain of this technological knowledge occur a decrease of the productivity and an increase of the costs, mainly the costs related with the cutting tools. This paper investigates the finishing milling operation on flat surfaces of a WNr 1.2367 tool steel, hardened to 50-52 HRc. A High Speed Machining Center was used for the experimental tests. A 6 mm diameter ball nose end milling cutter was used. Three levels of feed per flute (fz) and three radial depth of cut (ae) was evaluated, both input parameters for the CAM systems, which directly affect the productivity and the surface finishing. The milling strategy used was the offset. The tests were carried out in two stages. The first stage, tests were performed in downcut direction. In the second stage experimental tests were performed in upcut direction. The roughness in all regions was evaluated. The tests were performed in a such way that the wear of the tool was very limited. Looking for the best set of cutting data, the results bring out the relationships between the cutting parameters for surface finishing. The increase on feed per flute showed direct increase of surface roughness, but the increase of radial depth of cut showed a larger influence. This shows a possibility to reduce a cut time raising only the feed per flute at same radial depth of cut. In all cases, however, the upcut direction showed better results than downcut for surface roughness.*

***Keywords**: roughness; high speed cutting; mold and dies.*

1. Introduction

The High Speed Cutting is considered as the state-of-art in the manufacturing industries, after some years of uncertainly about its application. The production with reduced times, short life cycle for the products and also the search for a high quality is evident in these manufacturing industries. Therefore, the development of the HSC technology becomes essential. This technology brings a development of drivers, spindles, control systems, cutting tools, CAM softwares, etc. All this development shows the feasibility and the advantages that this new technology has created mainly in die and mould industry. There are many advantages on using the HSC, for example a lead-time reduction, the elimination or reduction on process steps, the possibility of milling hardened materials as the tool steels for instance, higher chip remove rates, reduction of cutting forces and the good roughness reached (Abele, 2003; Schulz, 2001; Toh, 2004 And Fallböhmer et. al., 1996).

These technologies applied in milling processes raise the chips removal rates, although the reduction of the tool life looks to be a barrier for the economic use of this technology (Schulz, 2001). Thus, to dominate this technology has how objective to offer good quality at costs low, these are essential conditions for the industries which intend to keep themselves in the competitive die mould market.

The old machining concepts are not valid in HSC, the cut parameters and the materials behavior in HSC are not still totally known. Thus is necessary to highlight the main differences between the costs of the cuttings tools for HSC and the use of the conventional milling, evaluating the viability and the limitations of this process. The development of the strategies optimization is still slow, for the selection of the economic cut conditions in the process planning since a century ago Taylor has already recognized the importance of the maximum material removal (Feng, 2000; Wang, 1998). The selection of the cutting conditions and strategies continues being established based on the experience, indications and recommendations of manuals. Cutting tools are the main variables affecting the cutting performance. The knowledge of the parameters is necessary since each parameter has several ways of influencing tool life (Gomes, 2001 and Silva et al., 2002).

The increase of the cutting speed by using HSC technology provides, among others benefit, an improvement on the surface finishing. On the other hand, the increase in tool wear and the alterations in tool wear behavior had demonstrated that this question must be seen in a holistic form, what shows that HSC technology is a challenge for researches (Schulz, 2001). Usually, the manufacture of die and mould demands long lead times and has great difficulties to ensure accuracy and the required surface quality in manufacturing of mould and dies. This occur because the surface roughness of dies and moulds after the cutting process is not satisfactory to be used directly in the production. In this case, some stages of the finishing process needs to performed by hand (Boujelbene, et. al. 2004), hence leading to inferior dimensional and geometric precisions of parts compared to those obtained normally with CNC tool machines.

It well known that the superficial texture (Calil and Boehs, 2004) can significantly affects various properties such as friction, wear, heat transmission, mechanical resistance, fatigue and fluid flow. Specifically, for die and moulds these properties are closely related to their performance in service. Hence, the surface texture on dies and moulds is extremely important and must be evaluated by their external parameters, as well as by their surface integrity. In HSC processes the final result can vary because the intrinsic process phenomena are not totally known.

According to Silva Filho et. al. (2000), after the cutting process the surface texture may look like those shown in Figure 1, with some peaks and valleys. The use of the end mills on flat surfaces produces low roughness values, although this operation proportion in recess profile. The recess profile is difficult to remove by burnishing, spend a long time and bring down the precision. To obtain the same roughness using a ball nose the cut time rise a lot, but proportion a projection profile. The projection profile is easy to remove by burnishing and it does not adversely affect the dimensional accuracy. The ball nose was used in this work because of the fact of great applications in the die and mold finishing, which have rounded corners in almost cases.

Figure 1. Roughness value for the different profiles
(a) recess profile (b) projection profile

Burnishing operations are necessary to obtain the desired superficial finishing; however these operations can correspond up to 80% of the total cut time (Tsao and Chen, 1996). The present work is focused on evaluating the influence of the parameters a_e (stepover), f_z (feed per flute) and the cutting strategy on surface finishing on flat regions of dies and moulds. In such cases, the contact tool/workpiece is critical, since the cutting speed is zero at the center of ball nose end mill and the impossibility to change the tool contact angle in the 3 axes milling. The zero cutting speed at the center leads to a poor surface qualities and a rapid tool wear (Chen et. al., 2005).

From the literature, the feed per flute was always known as the variable that most influences the surface quality. For the flat surfaces, the radial depth of cut (a_e) affects the size of the scallop-1 assuming that the geometry remains as showing in the Fig. 2. This knowledge can help the die and mould industries to reduce this long time of burnishing and obtain the best results in milling operations.According to Chen et. al. (2005), the chip formation is much more complicated to analyse in ball end milling operation than in other processes. "When the ball nose milling proceeds along a cutting path, the orientation of cutting edge is dynamically and periodically changed during the spindle rotation". The cutting is not only in rotation movement, but it is also in translation movement. Translation movement what is responsible for generation of a flat finish surface geometry.

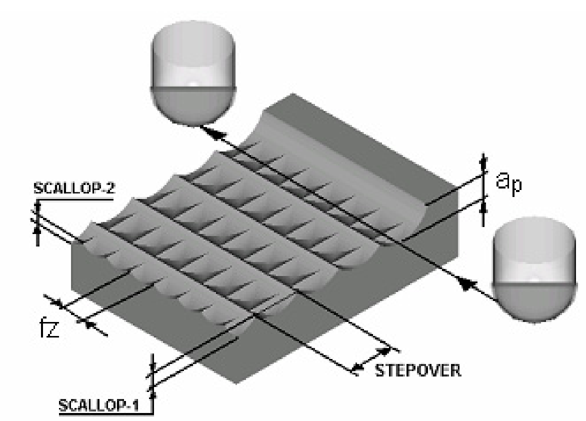


Figure 2. Parameters fz and stepover affecting scallop-1 and scallop-2 in the 3D surface

When using a ball nose for a flat surface finishing there are not only that forms shown in Fig. 1. Basically, two theoretical forms exist, the first form was named as scallop-1 and the second kind is named as scallop-2, as shown in the Fig. 2. The scallop-2 is formed from a residual material left in the spaces between successive spins of the flutes during the feed motion. The roughness is affected by both scallop-1 and scallop-2 sizes, and is so necessary accepted that the finished surface is three-dimensional geometry and its roughness is a relationship between scallop-1 and scallop-2 values. Then the feed per flute parameter value and the stepover parameter value affect directly the roughness as show in the Fig. 2.

However, the most CAM softwares offer the possibility to set up the scallop-1 and for flat surfaces use it to calculate a stepover value. But this does not consider that can affect the feed per flute value in the roughness. The CAM software let for the users the obligation to choice the right value of feed per flute. Often the choice of feed per flute is focused on reducing the cut time but, raising the feed and brings down the surface quality. As shown in the Fig. 3, Chen et. al. (2005) propose theoretical models to calculate the contact point "**C**" of cut edge during a dynamic motion of an end ball cutter partly immersed in the material. Chen et. al. (2005) employed a computer simulation program to affirm that is possible to predict the finishing surface texture profile. These consider both, the influence of feed per flute and the stepover, in the roughness result. This work is uneasy to show the influence of these parameters in the roughness by an evaluation of some values.

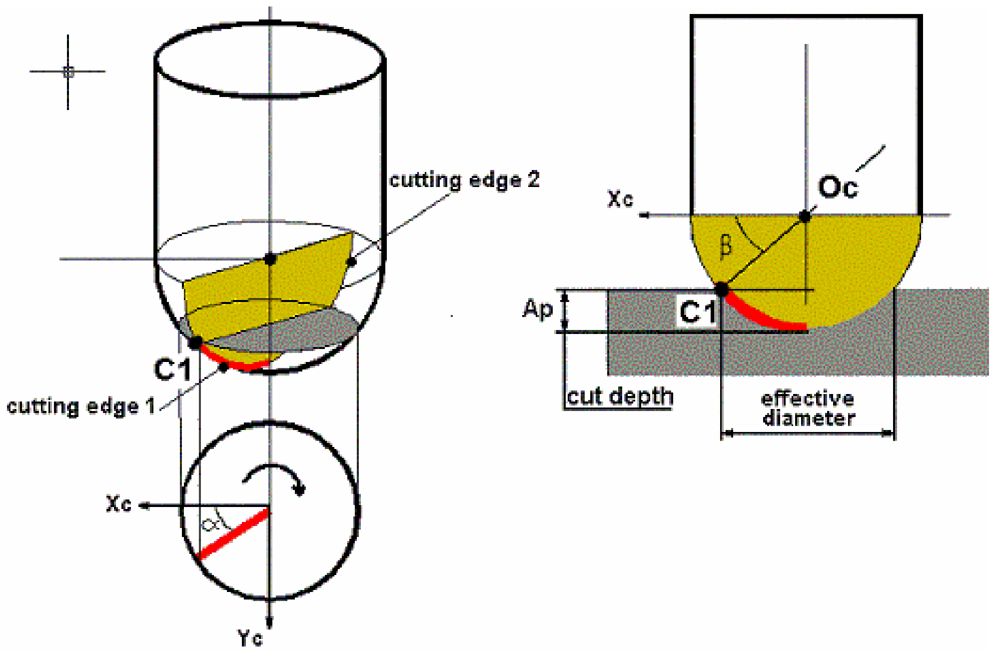


Figure 3. Geometry of cutting edge using a ball nose tool immersed on material (Chen et. al., 2005)

2. Experimental work

The experimental tests were carried out using a high speed 3 axis vertical milling center HERMLE model C800U with 18 kW and 24.000 rpm. The workpiece used was a block of steel WNr 1,2367 with chemical composition and hardness shown in Tab. 1. The workpiece has the following dimension: 100 mm X 80 mm X 30 mm.

Table 1. Chemical composition and hardness of the workpiece.

C	Cr	Mo	V	Hardness
0.38%	5%	3%	0.6%	52 HRc

The end ball mill was a 6mm diameter with (TiAl)N coating. It was used a hydro-mechanical tool holding system (CoroGrip model 92828), keeping the tool with 30 mm out in balance. The axial depth of cut, a_p= 0,2 mm, was kept constant, resulting in an effective cutting diameter d_e=2,15mm, calculated by the expression $de = 2 * \sqrt{ap * (D - ap)}$. The cutting speed recommend by tool supplier was 200m/min, however, 162m/min was used due to the maximum limit of the machine. The sequence of tests and the variables used can be seen in the Tab. 2.

Table 2. The sets of conditions and parameters for roughness tests.

	test number	scallop-1 (mm)	ae (mm)	fz (mm/tooth)	Va (mm/minute)
downcut orientation	1	0,001	0,155	0,05	2400
	2	0,001	0,155	0,1	4800
	3	0,001	0,155	0,15	7200
	4	0,003	0,268	0,05	2400
	5	0,003	0,268	0,1	4800
	6	0,003	0,268	0,15	7200
	7	0,005	0,346	0,05	2400
	8	0,005	0,346	0,1	4800
	9	0,005	0,346	0,15	7200
upcut orientation	10	0,001	0,155	0,05	2400
	11	0,001	0,155	0,1	4800
	12	0,001	0,155	0,15	7200
	13	0,003	0,268	0,05	2400
	14	0,003	0,268	0,1	4800
	15	0,003	0,268	0,15	7200
	16	0,005	0,346	0,05	2400
	17	0,005	0,346	0,1	4800
	18	0,005	0,346	0,15	7200

Figure 4 shows that the scallop-1 must be understood as the height of the ball nose tip to the peak of material, observed in the milling of a flat surface, as showed in Fig. 3. The radial depth of cut, or the stepover (a_e) in the tests was calculated as a function of the desired scallop-1, as occurs in the majority of CAM softwares (Baptista, 1999). For a flat surface milling the expression shown in Fig. 4 was used: where "**c**" is the value desired for scallop-1 and "**r**" the radius of the ball nose. It is possible to set this scallop-1 value in some CAD/CAM NC systems, not only for flat surfaces, but for all kind. For a desired scallop-1 value, the stepover value can be calculated by the expression shown in the Fig 4.

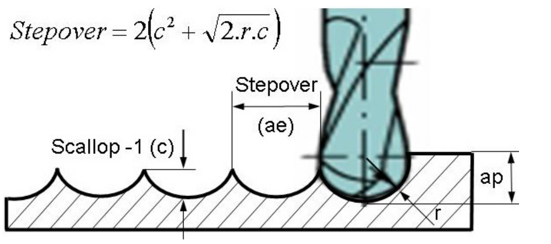


Figure 4. Parameters in flat surface milling using a ball nose tool

The offset strategy for finishing processes using a ball nose consists of successive and parallel cutting paths separated by a stepover. Each area of milling test was 12mm x 15mm, in a total of 18 tests on the workpiece, 9 tests using a downcut direction and 9 tests using upcut, Fig. 5. The stepover calculated values are function of a desire scallop-1 value. This scallop-1 value is showed on the Tab 1.

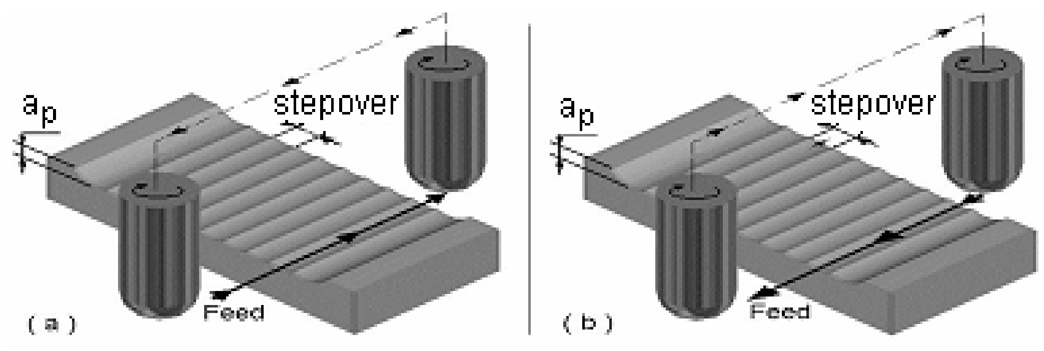


Figure 5. a) Downcut milling b) Upcut milling

Surface roughness values were recorded with profilometer surftest model Mitutoyo SJ201. The roughness values showed in Fig. 6 and 7 are average of three measurements reading taken in both feed and transverse directions. The roughness Ra was measured in the same direction of cut and also at the transverse direction. The Rz roughness was measured only in the transverse direction of cut. According Camargo (2002), for known periodic profiles, the Rz parameter is most indicated. The Rz parameter shows the absolute values of the points of bigger removal, above and below of an existing average line inside the cut-off. Therefore, it supplies complementary information to the Ra parameter, which eliminates the influence of the values of peaks and valleys. The value of cut-off used was 0,8 mm, specified for periodic profiles with known distance and a stepover rates between 0,1mm to 0,32mm. The Optical Microscopy Axiotech Zeiss, equipped with digital colour camera AxioCam MRc, was used to examine the machined surface texture and tool wear.

3. Results and discussion

The Rz value informs the average distribution of the vertical surface, which shows a closer view towards the texture of the surface. Therefore, it has been able to approximate scallop-1 values, which is the focus of this study, comparing the programmed and the measured value. In the central area of the cutter a perfect cut doesn't exist, but a crushing phenomenon. The cutting edge in the center of the cutter doesn't produce a perfect shear plane, in this way an incomplete shear of the material is generated in this area increasing the roughness values. Fig. 6 shows that the measured Rz values of scallop-1 are greater than the estimated and the measured values, especially in downcut direction. The measured values of the scallop-1 are greater than the theoretical values due to the crushing phenomenon in the central area of the tool. The roughness value measured by 0,155 and 0,268 stepover range is not so significant. The result was almost the same in all tests. The 0,268 mm value is the best choice by save the cutting time and reduces the tool wear.

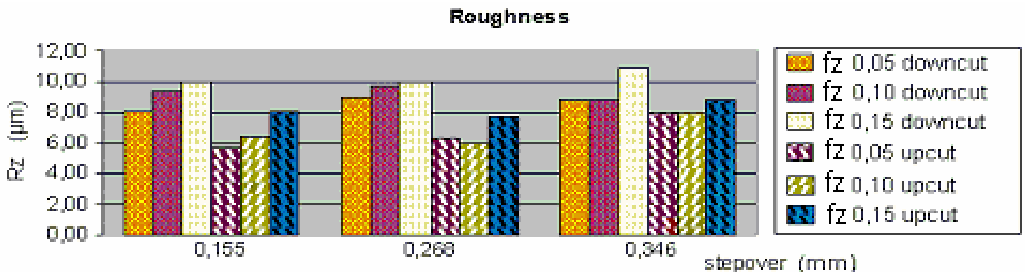
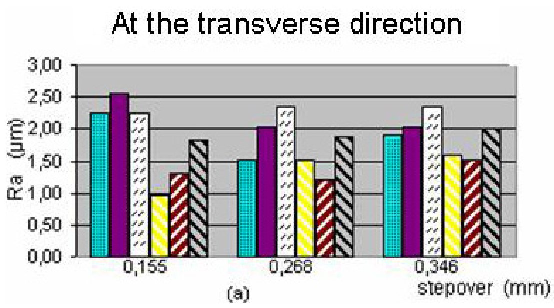


Figure 6. Roughness measured in Rz parameter at the transverse direction

Figure 7 shows a comparison between Ra values at the feed direction and at transverse direction. Fig. 7(a) shows that great variations don't exist in the value of the roughness Ra when the stepover varies from 0,155 to 0,346 mm. However, small variations exist in function of the feed per flute and of the cutting direction. The increase of feed per flute has influence in the roughness by affect the scallop-2, which can be seen by comparing the values measured at Fig. 7(b). Fig. 7(b) shows that an increase of the roughness exists when the stepover varies from 0,155 to 0,346 at the feed direction. The values of roughness Ra don't vary in function of the cutting direction into the intervals of stepover used.

The Ra roughness values are the same independent of the measured direction, when using 0,346 mm of stepover. The 0,15 feed per flute show a high influence in the Ra roughness measured at the feed direction. But the difference in the Ra roughness for 0,05 and 0,10 feed per flute is not so significant. This show that the crushing phenomenon doesn't occurs only by zero cutting speed in the ball nose center, but because of the high feed rate too. The Ra parameter is not enough to shows a true texture of the surface, but can be used as a guideline for selecting the cutting parameters.



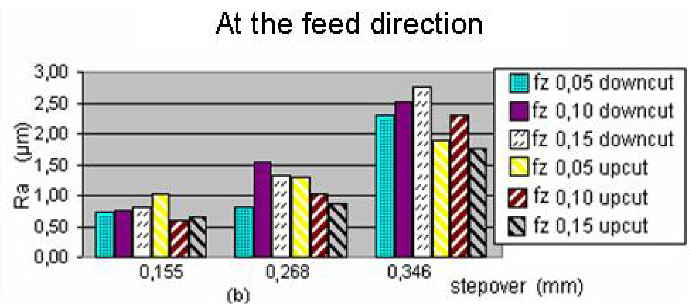


Figure 7. Roughness measured in Ra parameter
a) At the transverse direction b) At the feed direction

Figures 8(a) and 8(b) show translation rotation phenomenon. When this phenomenon occurs can be observed that the feed rate is high Fig. 8(b), the tip of the cutting tool rubs over the material and the twist of the next flute does not reach the residual material. This added with a crushing phenomenon makes the material “increases” against the flank cutter, Fig. 8(c).

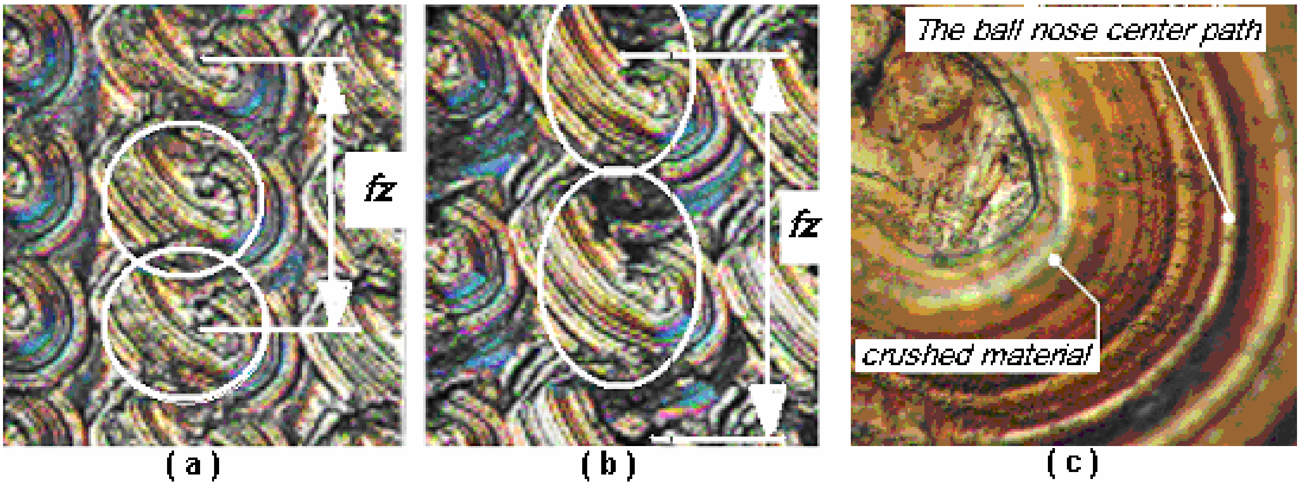


Figure 8. The microscopy of milling surface
(a), (b) Feed influence with 100X zoom; (c) Ball nose path with 500X zoom

Fig. 8(c) shows a cyclical phenomenon of crushing in the workpiece at central region of the ball nose pathway. This added to the crushing phenomenon increases deposition of more material on the flank surface of tool. The Figure 9 shows the surface texture in all milling tests (zoom at 25x). Tests 3, 6, 9, 12, 15, 18 show an overlapped texture in the cutting path caused by a high feed per flute.

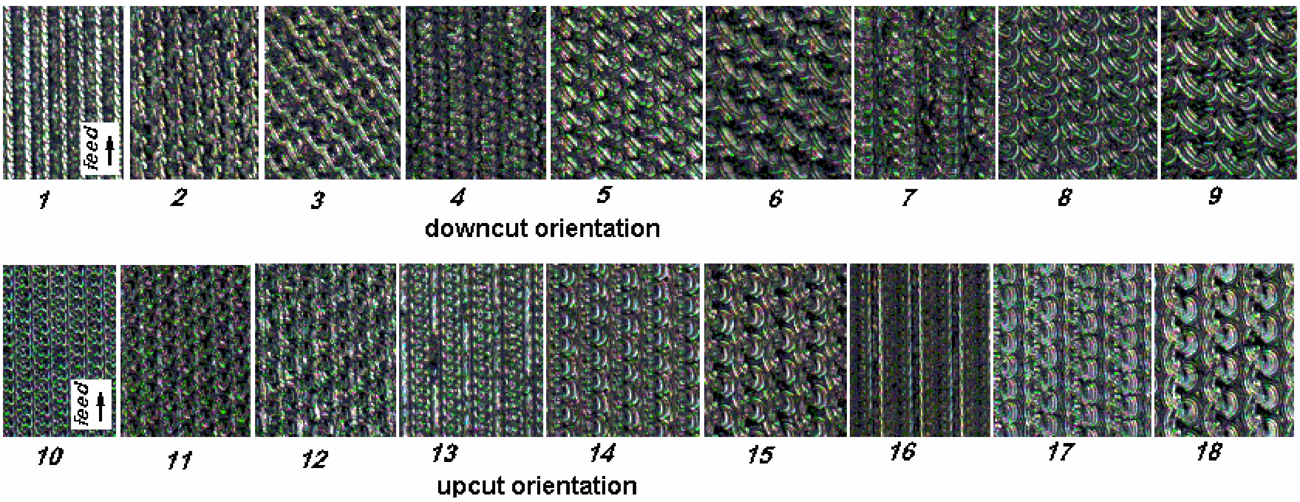


Figure 9. Surface texture in all milling tests (zoom at 25X)

4. Conclusions

This paper presents an experimental study of the influence of feed rate, and stepover and downcut/upcut direction in the roughness surface. We can be ended that:

Applying a downcut orientation strategy, in all tests a higher roughness occurs, independent of the feed per flute value or stepover values.

The difference in the Ra roughness for 0,05 and 0,10 feed per flute is not so significant. This show that the crushing phenomenon doesn’t occurs only by zero cutting speed in the ball nose center, but because of the high feed rate too.

The roughness Ra measured by 0,155 and 0,346 stepover range is not so significant at transverse direction, the result was almost the same in all tests. The 0,268 mm value is the best choice by save the cutting time and reduces the tool wear.

The increase of the rugosidade Ra measured at the feed direction was significant for the interval of stepover values among 0,155 to 0,346. However, inside of each stepover value, the variation of the feed per flute was not significant for the increase of the rugosidade Ra.

The results show that in the flat surface milling using a ball nose, to set only the scallop-1 value in the most CAM systems is not enough to leave a desired condition of roughness. The optimization of tool path, feed rate and determining the optimum cutter feed direction results in save machining time and satisfactory machining quality.

In all tests the programmed scallop was not reached. These conclusions shown that is necessary the application of news methods for predict the true result of roughness surface, including theoretical models.

The enhancement of the current generation of CNC pathway programs must based in best cutting conditions. This work shows that the cutting parameters should be based on the knowledge and in the *best practices* storages in a CAM data bank. However, this can improve the automatic programming to reach the desire true result. This shows that the best choice is 0,10 feed per flute using the upcutting direction of cut and 0,268 stepover for all tests.

5. Acknowledgements

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