SURFACE TEXTURE IN FINAL MILLING OF INCLINED HARDENED STEEL

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Abstract. *In the final milling process of free form surfaces, commonly employed in the production of molds and dies, a knowledge of the cutting conditions and a strategy for choosing adequate processing routes can provide a significant reduction in the manufacturing times. The best cutting path orientations for a specific condition and the surface texture achieved are of great value for the programmers when defining the processing route. The milling of hardened materials at the finishing stage offers advantages, providing the mold and die cavities with superior surface quality and dimensional control. The objective of this work is to evaluate quantitatively and qualitatively, the roughness behavior, the surface formation and the regularity in the feed-interval and path-interval scallops. The analysis was carried out for a workpiece inclined at an angle of 60° and for different cutting path orientations. The milled surfaces of hardened AISI H13 tool steel were verified and measured in order to compare the strategies and the obtained surface textures. Four different cutting path strategies were employed in these experiments, with horizontal and vertical single direction rastering, both upward and downward. The conclusion is that, in the vertical upward strategy, the surface texture display greater surface roughness and an irregularity with regard to plastic deformation. The other strategies showed lower roughness and similar regularity.*

Keywords*: Cutting path, Surface texture, Roughness, Hardened steel, Ball-end milling*

1. INTRODUCTION

Progress and advancement in technologies such as the design of molds and die cavities, cutting tools, machine tool design and computational systems for design and manufacture (Computer Aided Design/Computer Aided Manufacturing - CAD/CAM) have made possible the machining of hardened materials. A practical result is that it offers advantages in the processing and in the final machined product, providing good surface quality and dimensional control (Wang *et al*., 2003).

In the final milling process of free surfaces with complex geometries, a knowledge of the cutting conditions and the choice of adequate processing may provide a significant reduction in the manufacture times. Machines equipped with Computer Numerical Control (CNC) have the movements of their axes and trajectories defined by a programmer. A knowledge of the recommended machining strategy for a specific condition, as well as the finishing of the surface obtained can be of great value for the programmers in the defining phase of the process.

Although the machining of hardened steels presents difficulties during machining, it offers advantages in the process and the final machined product, providing improvement in surface quality and dimensional control (Wang *et al*., 2003). A final machining after the thermal treatment, with the material already at the final work hardness, prevents recurrent problems related to the hardness, such as possible workpiece distortion and dimensional variation.

One of the more basic and predominant geometric forms in the manufacture of molds and die cavities is the inclined plane. To simulate a finishing condition, a geometry of low complexity was adopted, defined as an inclined surface, in one workpiece of definite and reduced dimensions. The main doubt in the machining of this geometry is to know what is the best strategy, defined as the tool trajectory. This includes the workpiece inclination, defined as the angle formed between the tool and a plane normal to the axis of the tool. We consider the ball-nose end mill which is the type of tool most appropriate for finishing processes on surfaces with complex forms.

In the literature, studies of the machining of inclined planes are restricted mainly to evaluating the life of the tool and varying the cutting conditions (feeds and speeds). A smaller number of papers go beyond this and consider the cutting strategies, comparing them with the obtained surface quality. The strategies are defined by the feed and cutting directions, being vertical or horizontal with respect to the plane, and with a direction that can be ascending (upward) or descending (downward).

Chen *et al.* (2005) presented a new model that describes the path-interval and feed-interval scallops generated in the ball-end milling processes. They claimed that the scallop height was continuously reduced by increasing the tool-axis inclination angle. An inclination angle up to 10 degrees is, however, good enough for most tool diameters from the surface roughness viewpoint.

Kang *et al*. (2001) carried out a comparative study, evaluating the characteristics of machined steel with a hardness of 28 HRc in a workpiece of plain geometry, varying the angle of inclination to 15, 30 and 45 degrees, using four possible cutting strategies. They used a solid carbide ball nose end mill coated with TiAlN, having a diameter of 10 mm and two cutting edges. They presented a qualitative and quantitative analysis of the surfaces obtained, showing images of the surface texture and graphs of roughness for each condition. The texture obtained for each condition shows the influence of the cutting strategy employed. In conclusion, they reported that the strategies employing an ascending cut, with the tool executing the cut from the base of the inclined plane and going up, presented lower values of surface roughness and a more homogeneous texture, when compared with the descending strategies.

Toh (2004) carried out an analysis of the topography of surfaces machined on AISI H13 with hardness 52 HRc. The analysis evaluated different cutting strategies and cutting path orientations, using a plane geometry, inclined 75°, simulating a finishing process. They used a solid tungsten carbide ball nose end mill, with TiAlN coating, with a diameter of 10mm and 6 cutting edges. The objective was to understand the surface texture generated by certain cutting path orientations in a material of difficult machinability. An analysis of the topography resulted in three-dimensional graphs of the roughness profile and allowed a determination of the best orientation for obtaining texture of better quality. In conclusion, Toh reported that the strategy envolving an ascending vertical cut provided the best results.

Machining strategies can be generated with the aid of CAD/CAM systems, where the geometric information of the part is converted into machine language, generating CNC programs that transmit to the machine-tool the coordinates that define the strategies of the tool cut as well as the cutting speeds and advance. The programmer has the freedom and flexibility necessary to define the machining strategies and the cutting speeds and advance for each situation. Defining the strategy, the programmer is determining the form and the orientation of the tool movements that will be generated on the part. The CAM programming requires a certain knowledge of machining and also of the available software resources. The operator of CAD/CAM systems must be an experienced professional and duly trained, therefore the machining process depends strong on the ability of this professional (Ramos, 2003).

The surface of a machined piece is composed of many texture components, which are generated during the manufacturing process. The milling process produces a pattern of regular and repetitive ridges, with a clearly visible preferential direction defined by these ridges (Bet, 1999).

According to Tabenkin (1999), the finishing or texture can be described in terms of the number and direction of the valleys and peaks that compose a surface. The analysis of the surface, in practical terms, can be made in terms of three basic components: roughness, undulation and form. Generally the three exist simultaneously, overlapping, although in many situations, it is desirable to examine each condition independently. In general, it can be said that the roughness has a shorter wave length than the undulation which, in turn, has a shorter wave length than the form shunting line.

In the milling process, the cutting edges of the tool have a motion which is a combination of translation and rotation. The periodic variation of the cutting edge orientation during spindle rotation results in two kinds of scallops being generated on the machined surface: the pick-interval scallop and the feed-interval scallop (Chen, 2005).

The objective of this study is to analyze the surface finish produced on a hardened hot worked die steel AISI H13 by the end milling process, using an inclined workpiece angle of 60 degrees in relation to the horizontal plane, with different cutter path orientations. For this present study, the ball-nose end mill was used with an indexable insert, as commonly used in the mold and die industry. This type of tool is frequently used in finishing processes, mainly because of the cost reduction obtained for the case of large surfaces.

2. EXPERIMENTAL WORK

2.1. Wokpiece and tool

Hardened AISI H13 hot worked tool steel with a chemical composition of 0.4% C, 0.94% Si, 0.36% Mn, 5.04% Cr, 1.22% Mo and 0.88% V, according to the quality certificate of Gerdau Aços Finos Piratini (2005), was used throughout the experimental work. This steel is frequently used in the manufacture of molds and die cavities. The workpiece was hardened and annealed to obtain a final hardness of 54 HRc. The workpiece material was machined into blocks with dimensions of 50 mm x 50 mm x 25 mm.

The tool used in these experiments was an indexable insert tungsten carbide, ball nose end mill, ISO H10 class, with TiAlN PVD coating, indicated for final milling of hard steel. The cutter has a nominal diameter of 16 mm and two cutting edges (z). The cylindrical tool shank is made up of steel, fixed in a Weldon holder tolling system.

2.2. Experimental equipments

All machining experiments were performed on a Dyna DM 4500 vertical Machining Centre, with maximum rotation of 6.000 rpm and power of 7.5 KW.

For the roughness measurements of the machined surfaces, a Veeco Dektak 6M Bench-Top Surface Profiler was used, with Dektak 6M software and a high resolution 0,7 µm radius sub-micron stylus, located at the Division of Materials Metrology of INMETRO. Using a 2D surface stylus instrument, the parameters which characterize surface roughness can be easily determined and quantified.

For the visualization of the surface texture, a FEI Quanta 200 Scanning Electron Microscope (SEM) was used at the Division of Materials Metrology of INMETRO. The main advantage of using the SEM is that real life surface characterization can be performed more reliably.

2.3. Experimental procedure

The effect of employing different cutting path orientations, when machining hardened AISI H13, was investigated in relation to workpiece surface roughness. Figure 1 illustrates the cutting path orientations employed in this work. Four cutting strategies were considered, as defined by the trajectory of the tool, with climb cut only, upward and downward, in the horizontal and vertical directions. For the climbing direction, the cutter moves in parallel lines scanning across the area to be machined. The cutter mills across the machined surface, steps over a fixed amount, moves back to the original position through air before milling across another line.

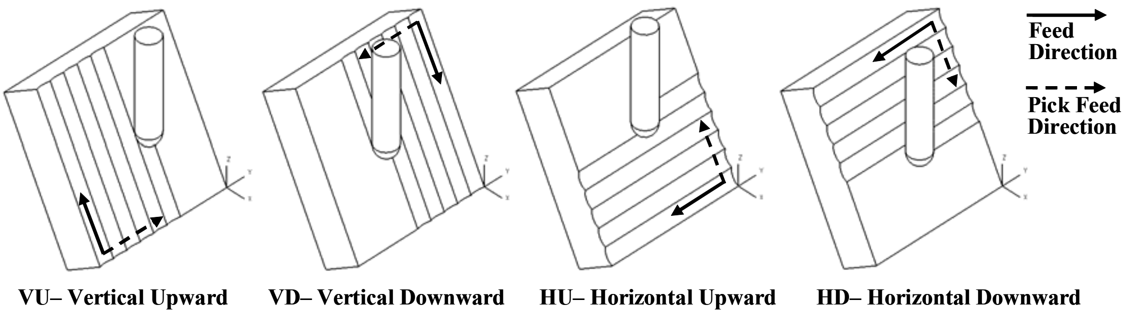

Figure 1. Considered cutter path orientations

The strategies implemented and the CNC cutting paths were defined using Unigraphics NX4 CAM software. For each strategy, the machined area was limited to 20 x 50 mm on the workpiece face. The machined region, the initial machining point for each strategy and the cutting path orientations for the pick feed direction (a_e) and the feed direction (F) are illustrated in Fig. 2.

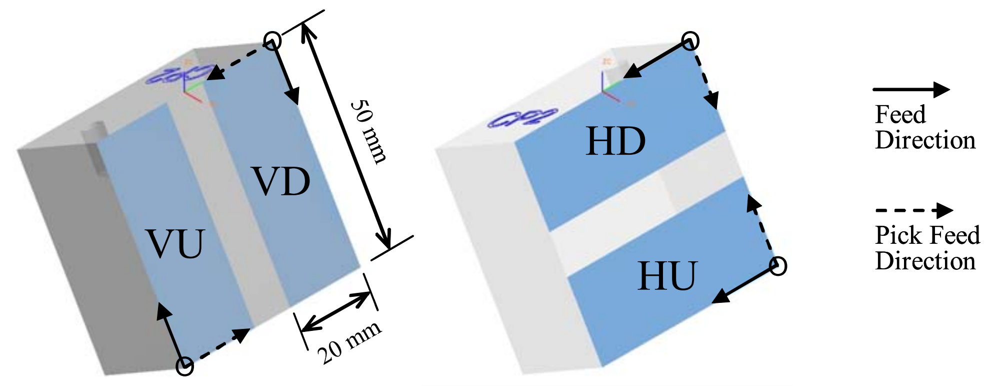

Figure 2. Workpiece machined regions and the cutter path orientations

For each test one new cutting edge was used after having been previously checked. All machining tests were conducted dry. In addition, a blast of compressed air was delivered through a nozzle to the tool to facilitate the chip removal. The workpiece was fixed on a device with an inclination of 60 degrees in relation to the horizontal plane, as illustrated in Fig. 3.

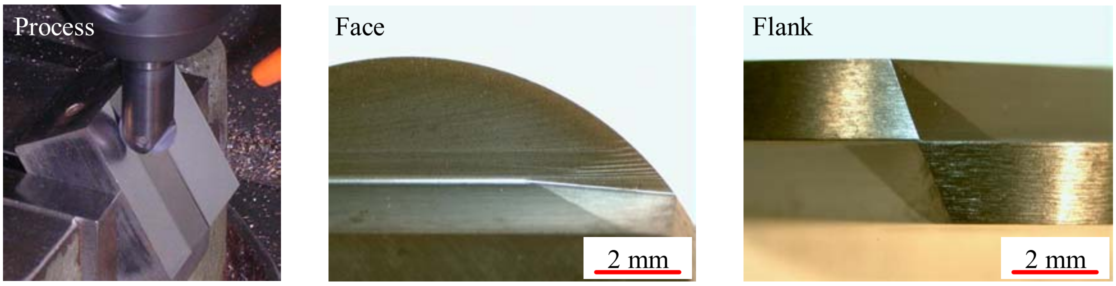

Figure 3. Images of the test and the insert details

For this experiment, the same cutting speed (v_c) and feed per tooth (f_z) were used for all the strategies considered, as shown in Tab. 1. The average value of the effective cutting diameter was adopted and calculated for the upward and downward strategies. The tool overhand, defined for the length of tool until the tool holder, was kept the same for all the tests, being fixed at 2.5 times the value of the nominal diameter of the tool.

Table 1. Cutting parameters employed

Tool effective diameter average (mm)	13.51
Tool overhand length (mm)	40
Cutting speed - v_c (m/min)	150
Axial depth of cut - a_p (mm)	0.2
Peck feed - a_e (mm)	0.2
Feed per tooth - f_z (mm)	0.1
Spindle revolution - n (rpm)	3534
Feed rate - F (mm/min)	707
Cutting edges - z	2
Machined time (min.)	11.5

3. RESULTS AND DISCUSSIONS

The workpiece surface roughness was measured using a roughness tester (contact stylus) moved across the feed direction (f) and the pick feed direction (a_e). The average parameters R_a and R_{z_DIN} were adopted to characterize the workpiece surface roughness, where R_a is the arithmetic average in the measured segment and R_{z_DIN} represents the average of the maximum roughness over 5 measurement intervals. A sampling length of 2.0 mm and a cut-off length of 0.4 mm were employed. The average roughness values are given in Tab. 2. For measurement the stylus was positioned onto the initial track of the tool, parallel to the feed and pick feed directions.

Table 2. Measured surface roughness

Direction	Surface roughness (µm)							
	Vertical Upward VU		Vertical Downward VD		Horizontal Upward HU		Horizontal Downward HD	
	R_a	$R_{z\ DIN}$	R_a	$R_{z\ DIN}$	R_a	$R_{z\ DIN}$	R_a	$R_{z\ DIN}$
Feed	0.500	2.823	0.244	0.911	0.227	0.934	0.193	0.584
Pick Feed	0.687	3.617	0.173	0.636	0.308	1.616	0.311	1.500

In Figures 4 and 5, graphs of surface roughness are shown which had been generated from data obtained with the VEECO Dektak 6M software. The graphs represent the roughness in the feed direction (f) and the pick feed direction (a_e), on the same measurement scale.

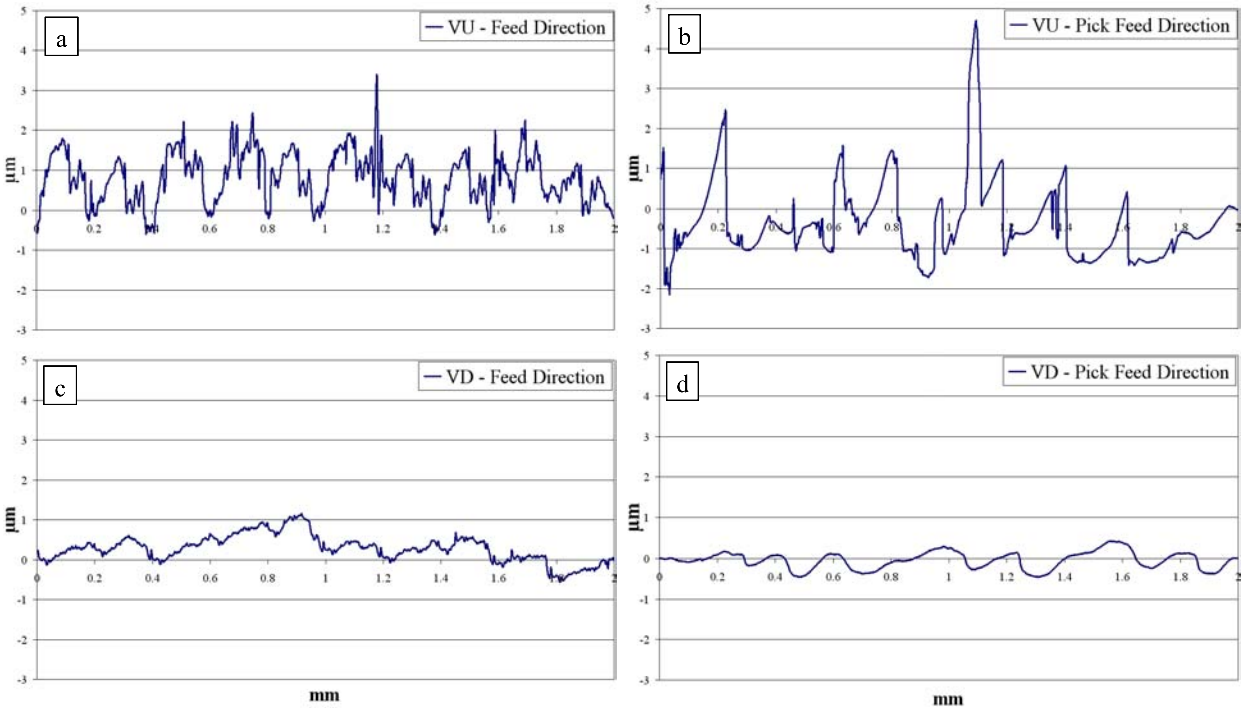

Figure 4. Roughness graphics for vertical upward (4a, 4b) and vertical downward (4c, 4d)

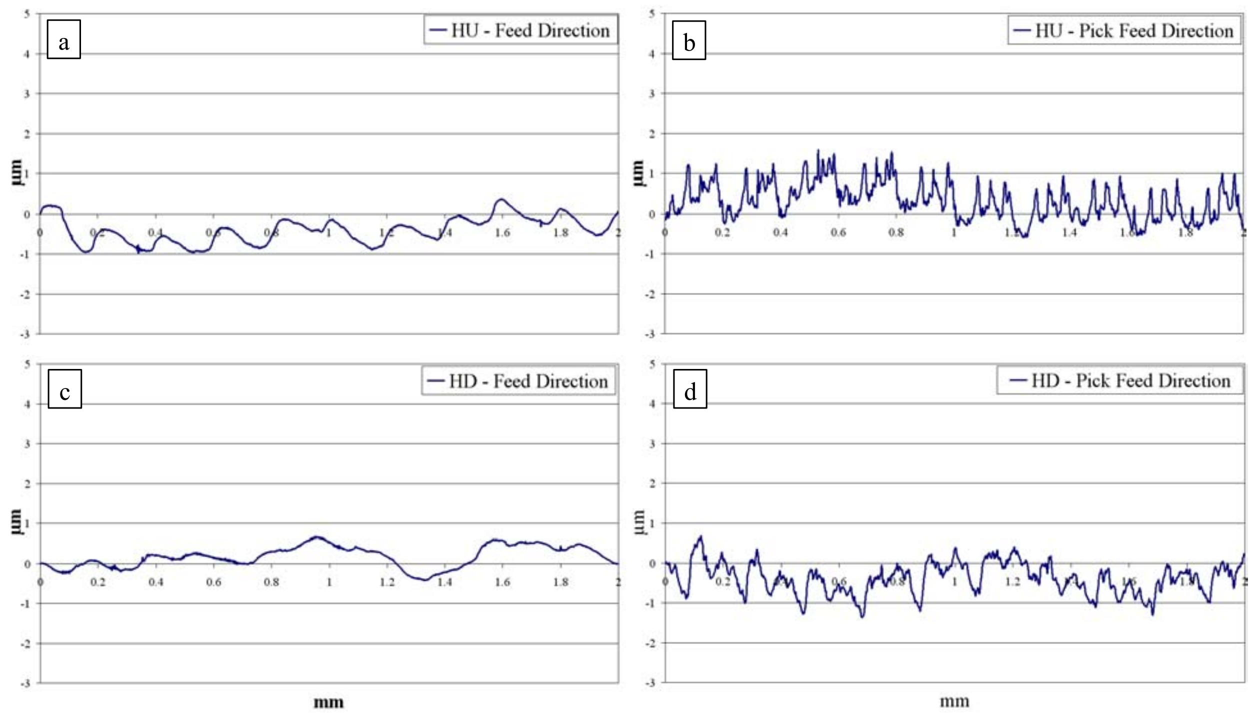

Figure 5. Roughness graphics for horizontal upward (5a, 5b) and horizontal downward (5c, 5d)

The machined surface obtained from the vertical upward strategy (VU) presented the largest roughness values in both directions evaluated. This effect occurred for all repetitions with the same strategy. The tool wear after the tests was not significant. That does indicate the results haven influence from the instability of the edge and from the cutting mechanical differences.

Figures 6 to 9 show secondary electron SEM images of the textures obtained, with magnifications varying from 50x up to 500x. The surface roughness can be easily visualized with SEM and it is possible to see clearly that the textures which result from surface machining show the influence of the cutting strategy employed. Figure 6 shows surface texture resulting from the vertical upward strategy (VU), where an irregular texture is verified, which the marks and scallops generated in machining had not clearly revealed. For this condition the worst surface texture is observed, especially for higher magnifications (Fig. 6 with magnification of 500x), clearly showing material adhesion on the machined surface. This was the main contribution towards a substantial increase in the roughness. From the work of Toh (2004), the vertical upward orientation gave the best workpiece surface texture. But, they used a solid tungsten carbide ball nose end mill, with TiAlN coating, diameter of 10 mm and 6 cutting edges, especially made for his experiment.

For the texture resulting from the VD strategy, shown in the Fig. 7, square forms appear with tracks and the scallops resulting from the tool in the feed direction (f) and the pick feed direction (a_e) being clearly identified. The marks and scallops are repetitive being able to be observed and to be quantified in the roughness graphs (Fig. 4c and 4d).

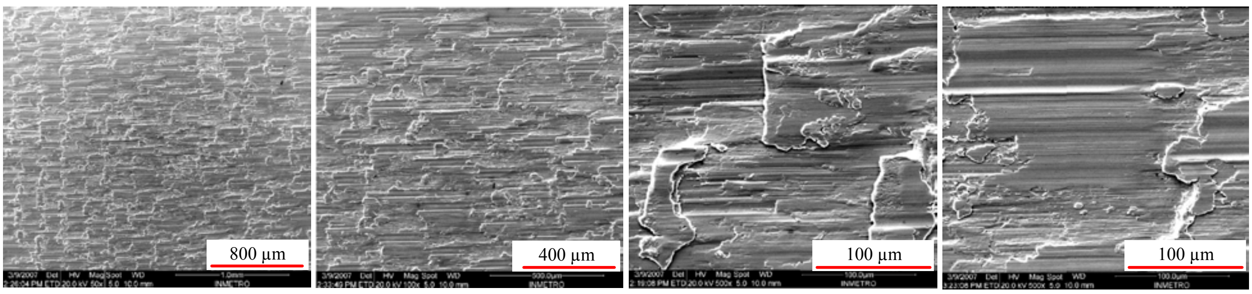

Figure 6. Images of SEM (secondary electrons), strategy VU with magnification of 50x, 100x, 500x and 500x

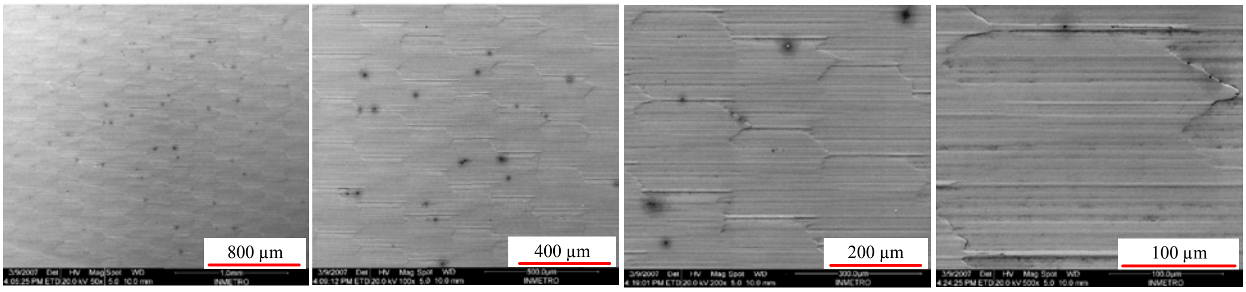

Figure 7. Images of SEM (secondary electrons), strategy VD with magnification of 50x, 100x, 200x and 500x

Figure 8 shows the surface texture resulting from the HU strategy, where marks and scallops from the tool in the feed direction (f) and the pick feed direction (a_e) are clearly identified. The marks and scallops are repetitive and distinct for the feed and pick feed directions, being able to be observed and quantified in the roughness graphs (Fig. 5a and 5b). Marks of the tracks are clearly verified in the feed direction. A little material adhesion on the machined surface deposited alongside the feed marks was observed. How for the VU strategy, the upward direction may have a higher linear speed of cutting than the downward direction. Differences in cutting characteristics also occur where the contact point of the ball-end mill changes, as on inclined plane, because the effective tool diameter changes.

In the texture resulting from strategy HD, shown in Fig. 9, well-defined marks from the tracks are seen and are clearly verified in the feed direction (f). For this strategy, material adhesion side flow was not observed.

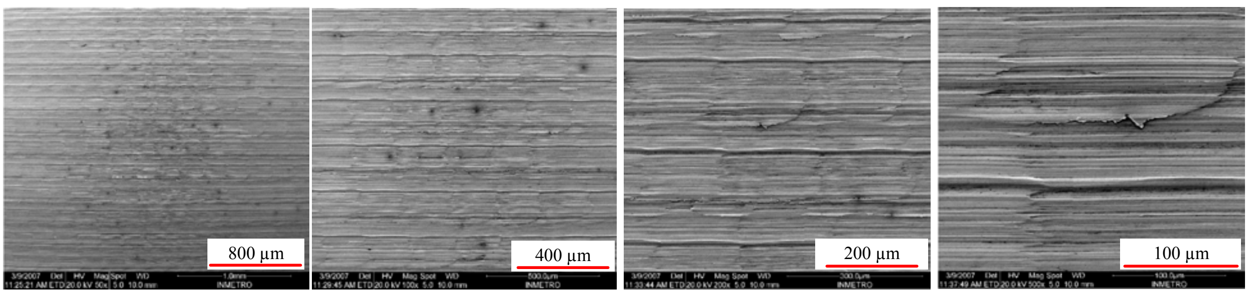

Figure 8. Images of SEM (secondary electrons), strategy HU with magnification of 50x, 100x, 200x and 500x

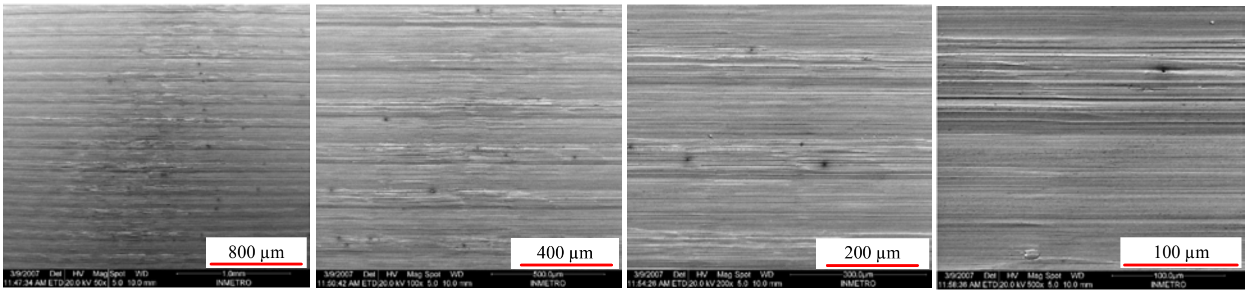

Figure 9. Images of SEM (secondary electrons), strategy HD with magnification of 50x, 100x, 200x and 500x

4. CONCLUSIONS

Our results clearly illustrate that using a vertical upward cutting path orientation (VU) gave the highest surface roughness. This machined surface presents the worst surface finish as well as an irregular texture with material side flow.

The vertical downward cutting path orientation (VD) gave the lowest surface roughness and best workpiece surface texture. This strategy gave raise to a well defined surface with regular cutter marks. This machined surface texture seems to be relatively isotropic.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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