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SIMULTANEOUS 5-AXES AND 3-AXES MILLING COMPARISON APPLIED ON A AUTOMOTIVE COMPONENT

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Abstract. *The appliance of simultaneous 5-axes milling leads to significant costs and lead times reduction through an optimization of the tool-piece contact, that allows fine complex surfaces contour suitability by the tool. This paper presents a comparison between simultaneous 5-axes and 3-axes milling applied on a automotive component. Surface roughness and machining times were measured, and real time acquire of machine axes positioning and feed speed data was performed. The results showed a time reduction of 99% for this case without penalizing of surface roughness levels. However design for simultaneous 5-axes milling knowledge constituted a crucial demand for accomplishing the tasks.*

Keywords*: 5-axes milling, 3-axes milling, complex surfaces*

1. Introduction

Free form surfaces are widely used in the design of complex products with intricate features. This kind of feature is often produced by 3-axes CNC machine tools using ball-end mill cutters. However, the machining with 5-axes machines offers many advantages over 3-axes machining, including drastic reduced setup times, lower costs per part, more accurate machining, and improved part quality. For certain applications, particularly in aerospace industry, 5-axes machining helps manufacturers enhance productivity with far fewer setups on a smaller number of machines, and increased stiffness (Altmüller, 2001). Automotive manufacturers also can realize substantial payoffs from 5-axes machining, especially because costs for the latest 5-axes equipment has declined. The reasons for going with five-axes equipment vary, but the benefits of deploying multi-axes machines center lie on improved productivity, higher machining accuracy, reduced in-process inventory, and improved operator and machine usage.

The problems with 5-axes machining are based on development of effective algorithms that allows the use of alternative tool path generation, once these always bump into the mathematical complexity (Jun, 2003 and Choi, 1997). The CAM programming, free form surfaces and the post processing are critical points in 5-axes machining, because of the whole complexity of this processes. That is the biggest reason for finding several papers concerning this subject, and suggesting methods and improvements to tool path generating and post processing for 5-axes machining of free form surfaces (Chen, 2001).

In theory, the 5-axes machining can be classified into face milling and cylindrical milling (or periferal milling) (Liu, 1995). In general the first one, using flat-end cutter, is suitable for the machining of large surfaces, like blades of hydraulic turbine, whose binding relations among surfaces are very simple, and the second one, using cylindrical cutter, has wide applications for the milling of small and middle dimension surfaces, whose binding relations among them are of a higher complexity level, such as the milling of turbines BLISK's. In this paper, 3-axes machining strategies are compared to 5-axes machining strategies to manufacture complex surfaces using the best characteristics of contact between tool and workpiece. In this study productivity, surface roughness and kinematics behaviour of the machine tool were analyzed.

2. Experimental equipment, materials and procedure

As this work involves only finishing operations and because the equipments availability and facilities for the experiments performing, the comparison among 3- and 5-axes milling were based in time and surface roughness measurement, apart from real time acquisition of machine axes positioning and feed speed data.

The machining operations were carried out in a 5-axes machining center, Hermle C 600 U, that is equipped with a Siemens Sinumerik 840D CNC, and whose translational movements are executed by the spindle, and the rotational motions, A and C axes in this case, are accomplished by the table. The tool paths were generated and post-processed in the UGS PLM Solutions' CAD/CAM system Unigraphics NX3.

2.1. Test-piece definition

Automotive CVT's cam pair was taken for test-pieces. That is because the similarity among the pairs makes them suited for the comparison in present work. Figure 1 presents the CAD model of both final workpieces and drawing of the rough piece, which is made of SAE 1040 steel.

Figure 1. CAD models of the test pieces 1(left), and 2 (right). The top surfaces are those that will be finished with the 3 and 5-axes operations.

Piece 1, left, was made by 3-axes milling, whereas piece 2, right, was manufactured through the other way. The top surfaces were chosen as comparison medium due to their proper characteriscs for the simultaneous 5-axes milling. Both pieces are made of SAE 140 steel.

2.2. 3-axes milling definition

The 3-axes milling definition was carried out concerning workpiece geometry, process safety, and productivity. Hence, a ball-end cutter was chosen, because of its fine complex surfaces contour suitability, and due to the fact that surface roughness in the feed direction is less sensitive to f_z variations (Gomes, 2002). The tool diameter had to be restricted to 4 mm, according to the smallest concave radius of the part. Table 1 presents a brief description of this tool.

Table 1. Tool description.

Tool End	Ball Nose
Diameter	4 mm
Shank Diameter	6 mm
Material	Fine-grained carbide
Coating	TiAlN
z	2

As machining strategy, the spiral milling was chosen (Fig. 2). In this drive method, the cutter follows the surface silhouette along Z axis, as long as describe a Archimedes' spiral over XY plan. The effectiveness of this strategy as well as the surface quality are benefited by the circular profile of the piece geometry when faced from the top, once that blank cut motions, and tool transitions marks are avoided. The side step, a_e, is taken progressively during the spiral, thus purging intermediates engages and retracts, or orthogonal increments.

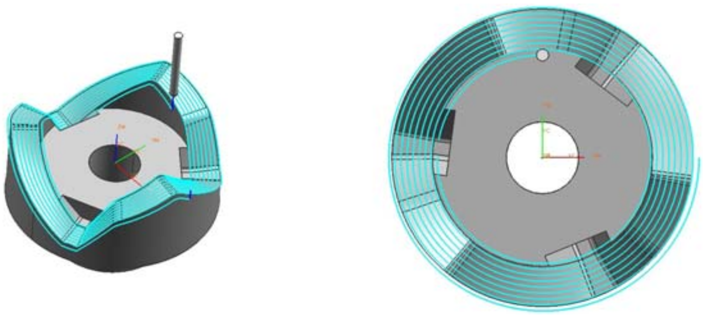

Figure 2. 3-axes milling spiral strategy.

The cut parameters for this operation are shown in the Tab. 2. The theoretical surface roughness, determined as 5 μm, was crucial when choosing the f_z and a_e choice.

Table 2. Cut parameters.

v_c (m/min)	201
f_z (mm)	0,07
a_e (mm)	0,1
a_p (mm)	0,07

2.3. 5-axes milling definition

Unlike for the roughing operations, there is an considerable amount of tool path generation methods proposed when the task is finish a surface, however among the available CAM systems, these methods are always the same: the Sturz Method, or inclined tool method, in which a constant tilt angle between the tool axis and surface normal is set by the user; a similar to that method, but with only the position of the tool being determined by the machining surface, while the orientation come along with a drive surface; or a method in which the orientation is defined by a line or point, to which the tool axis must be ever attached

The test-piece has an ideally suited geometry for the implementation of a sort of the Sturz Method, the Swarf Milling (Fig. 3). In this type of simultaneous 5-axes milling, free form surfaces, generally ruled surfaces, are generated with the tool periphery of a flat-end mill, what brings a sharp decrease of the machining steps, relative to 3-axes milling with ball-nose tools.

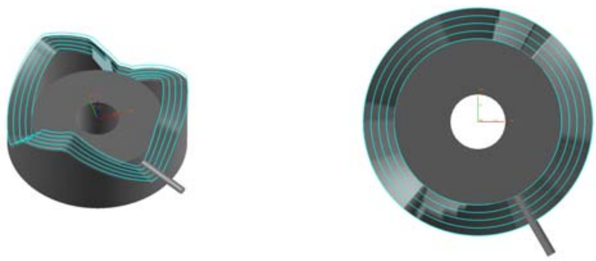

Figure 3. Swarf milling.

Swarf Milling operations are ordinarily performed with flat-end tools, due to theirs larger cut length (a_{pmax}) and that's the reason for the selection of a mill with that geometry. One more time the smallest concave radius of the surface was the motive for the tool diameter choice. A brief tool description of the cutter used for this machining is displayed in the Tab. 3.

Table 3. Tool description.

Tool End	Flat end
Diameter	4 mm
Material	K Grade Carbide
Coating	TiAlN
z	2

Table 4 shows the programmed cut parameters. Yet, the theoretical surface roughness determined only the f_z, and the depth of cut was set considering the mill stiffness.

Table 4. Cut parameters.

v_c (m/min)	201
f_z (mm)	0,07
a_e (mm)	0,05
a_p (mm)	2,4

2.4. Comparison methods

The comparison methods, next described and detailed, were defined by the primal aims of the finishing operations, dimensional accuracy and surface roughness. Furthermore the execution times of the machining programs were measured taking into account the productivity.

2.4.1. Axes positioning and speeds

Concerning the machine kinematics analysis, a real time acquisition of the tool positioning and feed speed data was executed during the milling of the test-pieces. To accomplish this task a personal computer was equipped with a Siemens' network adapter, SIMATIC NET CP 5611 module, which has a PROFIBUS interface, providing a direct link between the computer and the machine-tool PLC's. The mentioned PC posses a 1,7 GHz processor and a RAM memory of 256 MB. As computational tool for data analysis and acquiring the software that was used was Labview. Figure 4 shows pictures of the PC and machine tool connections, as well as the CP5611 module.

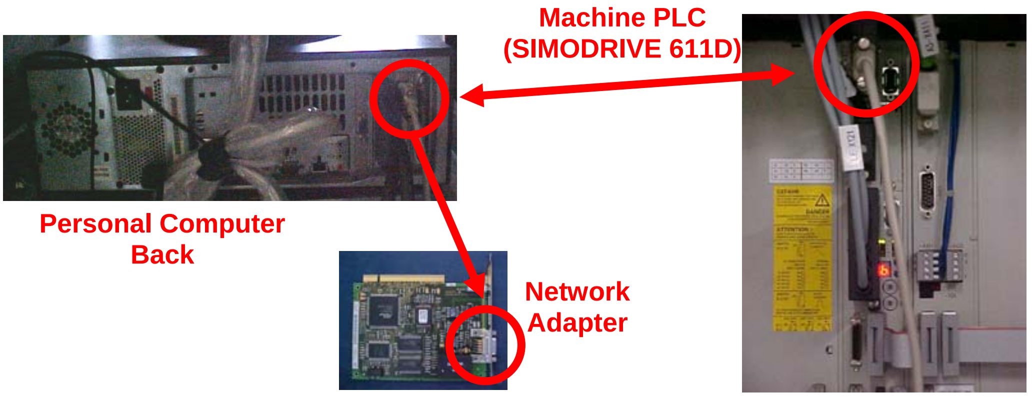

Figure 4. Schematic connection between the personal computer, network adapter and machine PLC's.

In both operations the data were acquired only in a strict period of time. For the conventional 3-axes finishing this period comprises a few cycles, while for the simultaneous 5-axes milling, the acquisition time comprises only one cutting pass. Once selected machining strategies results in a tool path that follows a defined pattern, these periods can be considered as representative.

2.4.2. Surface roughness

Surface roughness was another evaluated result. A Mitutoyo's SJ-201P surface roughness tester was the applied device here. Three measures were performed in each one of three surface locations pointed out in the Fig. 5. For piece 2 these measures were only executed orthogonal to feed direction, because that's the critical circumstance for the surface quality in this situation, once the surface roughness is mainly defined by the f_z. Nevertheless, for the other test-piece the measures were maid not only in the direction mentioned above, but also in the feed direction.

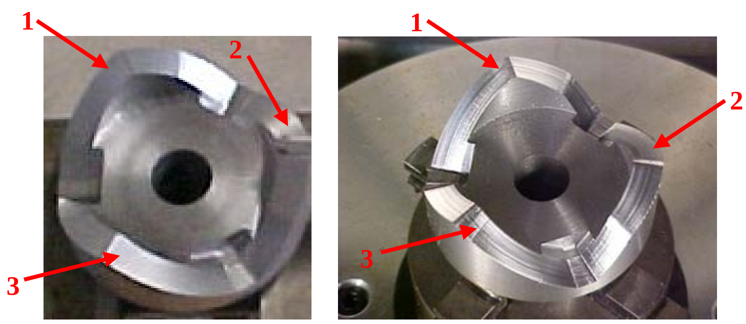

Figure 5. Locations of the surface roughness measures, for the 3-axes milled piece (left),
and the 5-axes milled piece (right).

The pieces were left in the table fixture after the machining and inclined with a tilt angle similar to the helix angle of the cam's ramp. The tester were mounted in a device that permits the detector to touch the surface, as shown in Fig. 6, left and center. In the orthogonal to feed direction orientation, for the 3-axes milled test-piece, the last was mounted in a rotary vice, and inclined in the same way described, however, the surface roughness was oriented as can be seen in Fig. 6 right.

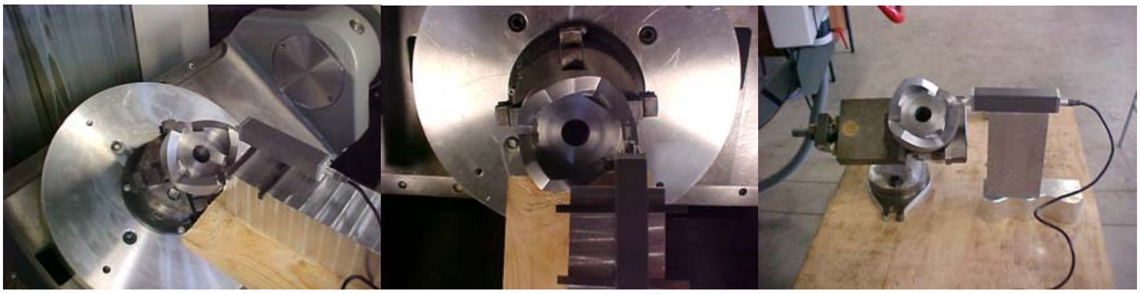

Figure 6. Surface roughness measure device, and its positioning.

Surface roughness R_a and R_z were colleted following the ISO 11652. According to this norm sampling length and evaluation length must be set in 2,5 mm and 12,5 mm respectively, for the range of R_a e R_z that comprises the measured values. The chosen filter was the Gaussian filter PC50. Nevertheless, due to lack of feasible space for measurements, the evaluation length had to be diminished, and a new value of 7,5 mm was adopted.

3. Results analysis

In the following sub-sections, analysis and comments about the experimental results are performed.

3.1. Machine axes positioning and feed speeds

Figure 7 denotes a similar behavior between X and Y axes, a sinusoidal curve, however with a phase angle difference of 90º, assenting to the XY plan circular profile of the piece. The lesser amplitude and the three times higher frequency of the Z axis curve also reflects the surface geometry, corresponding to its three identical relieves.

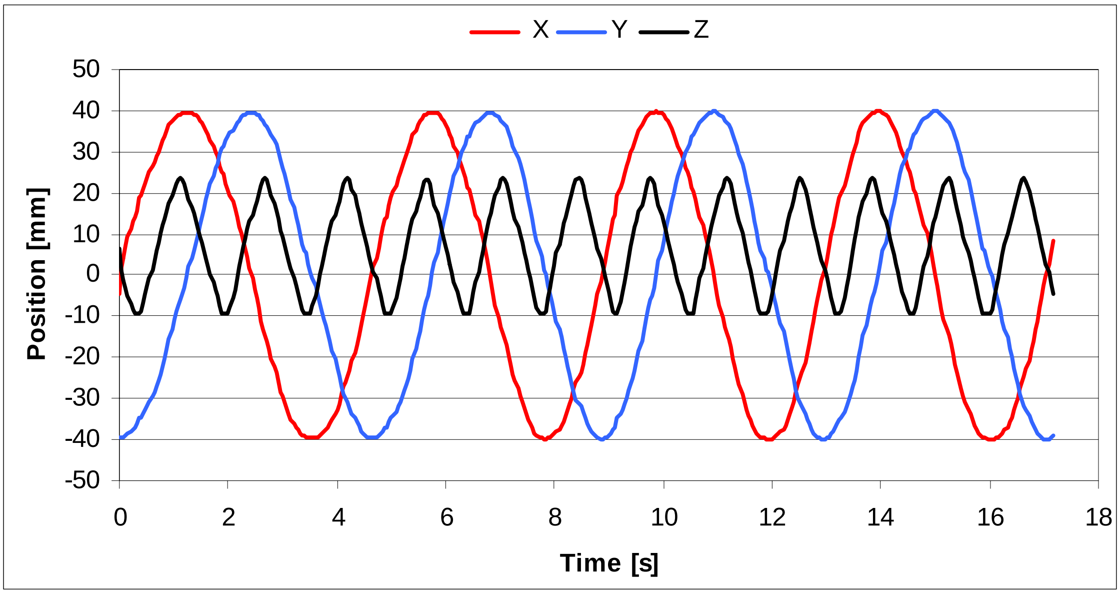

Figure 7. Position of the translational axes along a strict period during the 3-axes machining.

In Fig. 8, it can be seen that the speed curves are marked by a relative constancy, only interrupted by a cyclic decelerate for the X and Y axes and for the effective feed speed, noticeable by the alternated single and double peaks.

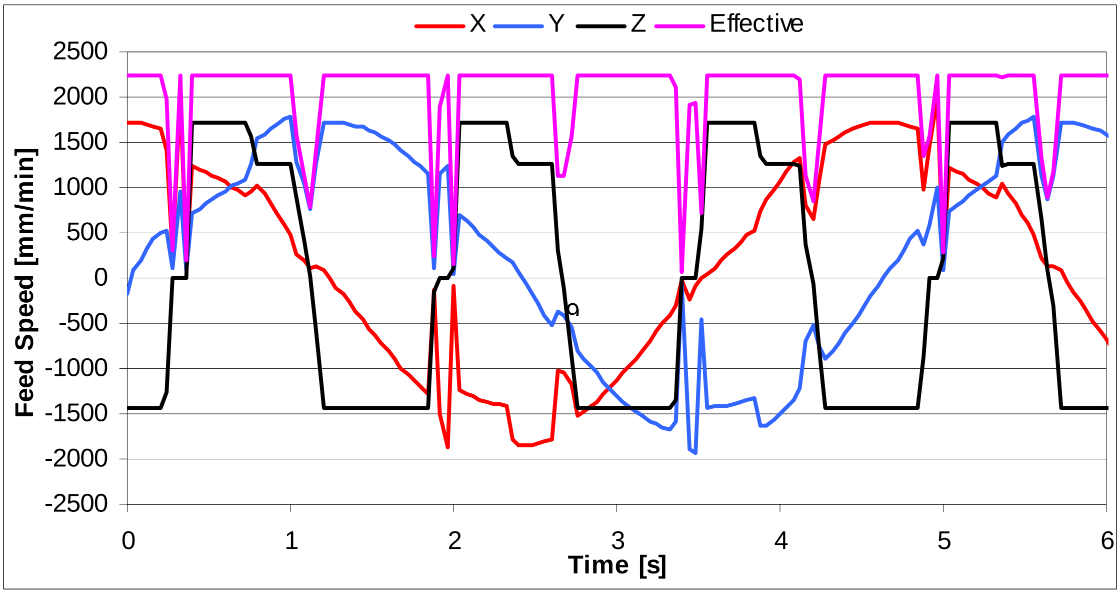

Figure 8. Feed speed of the translational axes along a strict period of time during the 3-axes machining.

When these last curves are plotted over the Z axis positioning, Fig. 9, becomes possible to see that these decelerations occur in the peaks and valleys of the three ramps, where a motion inversion happens.

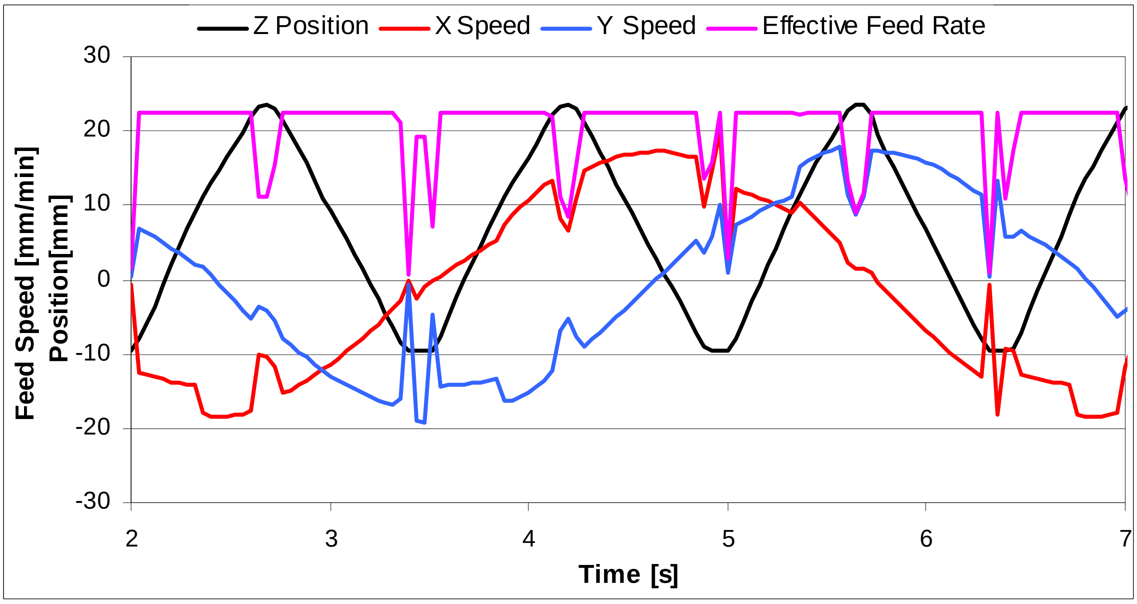

Figure 9. Position of the translation axes along a strict period of time during the 3-axes machining.

Figure 10 presents the tool positioning during the time for the three translational axes in the workpiece coordinate system, and for the two rotary axes. The machine CNC has a command for the multi-axes milling, TRAORI, that changes dynamically the workpiece coordinate system, making it and the tool follow the rotations and translations of the piece. Hence, the plotted translational axes doesn't correspond to the Cartesian axes, and that's the reason why they receive the ' notation in the next figures.

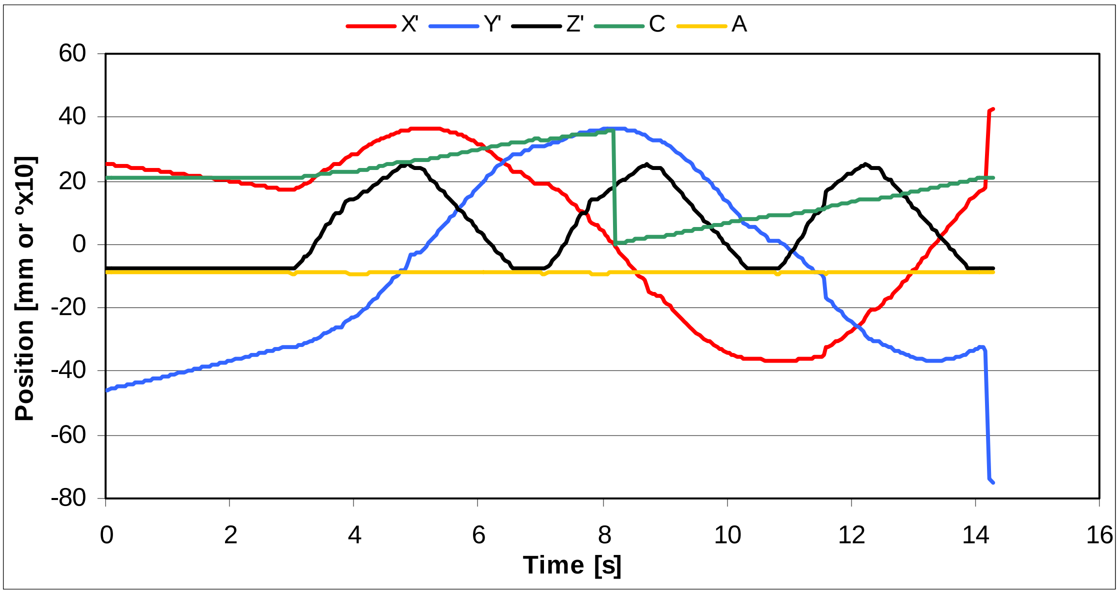

Figure 10. Position of the translational and rotational axes along a strict period during the 5-axes machining.

It is seen that X', Y' e Z' axes behaviors hold a likeness regarding the behavior of the translational axes of the previous machining, as can be noted in Fig.10. However also can be seen some disturbance in the curves, denoting less smoothie motions, just alike was perceived at the moment of the milling, which has been marked by frequent interruptions. These problems occur due to the kinematics and dynamic complexity involved in this process.

Figure 11 endorse these assertions with the exposure of the constantly variable speeds. In this figure, it can be verified too that effective feed rate never reaches the programmed feed rate, which would be of 2240 mm/min. It is supposed that this is owned to a rotary axes speed limitation imposed by the machine manufacturer.

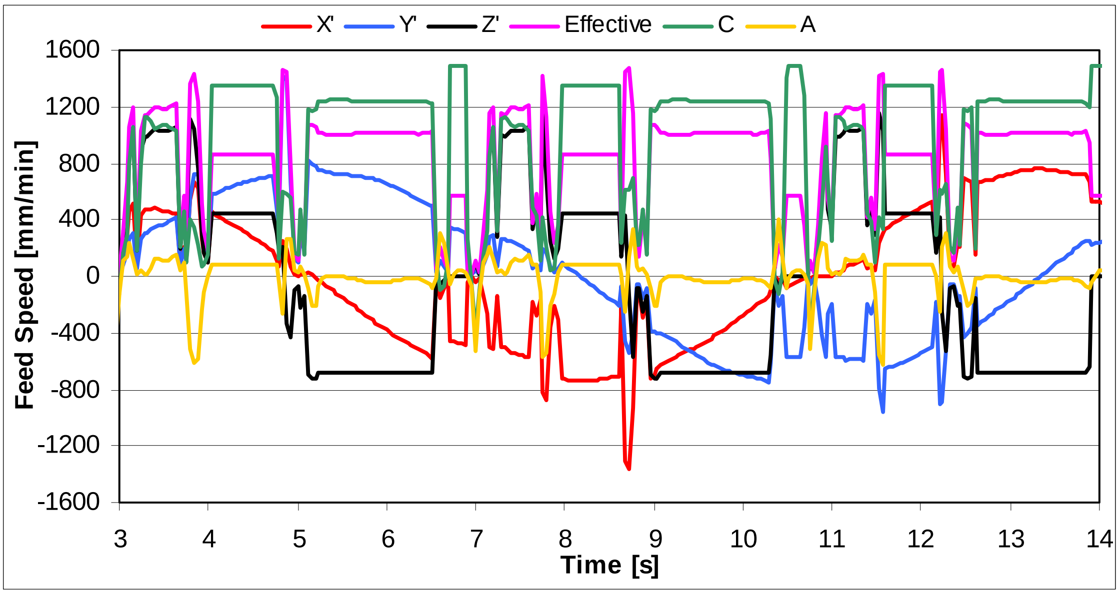

Figure 11. Feed speed of the translational and rotational axes along a strict period during the 5-axes machining.

3.2. Surface Roughness

The obtained surface roughness values for test-piece 1 are exhibited in Tab. 5, for both directions of measure. This table also shows arithmetic averages for each measurement points, and a global average.

Table 5. Surface roughness, R_a and R_z, in µm, for the piece 1.

	Parallel						Orthogonal					
Points	1		2		3		1		2		3	
Measures	Ra	Rz	Ra	Rz	Ra	Rz	Ra	Rz	Ra	Rz	Ra	Rz
1	2,72	16,85	3,18	22,08	3,46	20,52	2,17	13,61	2,47	14,84	2,13	12,99
2	2,60	16,49	2,21	15,26	2,22	15,24	3,11	17,00	2,22	13,34	3,02	14,41
3	3,02	17,66	2,76	17,86	2,60	16,12	2,73	14,91	2,96	15,94	2,57	14,89
Average	**2,78**	**17,00**	**2,72**	**18,40**	**2,76**	**17,29**	**2,67**	**15,17**	**2,55**	**14,71**	**2,57**	**14,10**
Global	Ra	Rz					**Global**		Ra	Rz		
Average	**2,75**	**17,56**					**Average**		**2,60**	**14,66**		

Table 6 exposes the values for these parameters founded in test-piece 2. In both cases it can be perceived that, although the surface roughnesses differ from one piece to another, all values stay under the imposed surface roughness limitation of 5 µm.

Table 6. Surface roughness, R_a and R_z, in µm, for the piece 2.

	Orthogonal					
Points	1		2		3	
Measures	Ra	Rz	Ra	Rz	Ra	Rz
1	3,95	20,48	4,84	25,19	4,15	20,13
2	4,40	24,49	5,08	26,69	3,76	19,48
3	4,26	22,45	3,75	20,36	4,31	18,13
Average	**4,20**	**22,47**	**4,56**	**24,08**	**4,07**	**19,25**
Global	Ra	Rz				
Average	**4,28**	**21,93**				

4. Conclusions

Inside the modern manufacturing context, simultaneous 5-axes milling posses feasible potential for cycle times reduction. That could be noticed in this case study, where the required times for finishing surfaces that are so much alike, was of 27 minutes for the 3-axes milling, whereas for the simultaneous 5-axes milling the time was of only 1 minute and 20 seconds, which means a significant time reduction, and maintaining the surface roughness under the restriction.

However, the improved process complexity demands increased modeling and CAM programming times, due to de need of specially designed surfaces generation for the simultaneous 5-axes milling, and also due to deeper knowledge regarding the specific CAM strategy parameters requirements. Not to mention kinematics and dynamics problems, as could be seen previously in this paper, in which the programmed feed rate was constrained by the rotary axes speed.

5. Acknowledgements

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6. References

Altmüller, S., "Fünf-achs-fräsen von freiformflächen aus titan", 2001. Aachen: dissertation RWTH Aachen. 198p.

Choi, B.K., Kim D.H. and Jerard R.B., 1997, "C-space approach to tool-path generation for die and mold machining", Computer Aided Design, Vol. 29, No.9, pp. 657-669.

Chen, S.L. and Wang W.T., 2001, "Computer aided manufacturing technologies for centrifugal compressor impellers", Journal of Materials Processing Technology, Vol. 115, No. 3, pp. 284-293.

Gomes, J.O., 2001, "Fabricação de superfícies de forma livre por fresamento no aço temperado DIN 1.2083, na liga de alumínio (AMP8000) e na liga de cobre (CuBe)", Florianópolis: Universidade Federal de Santa Catarina. 150 p.

Jun, C-S., Cha, K., Lee, Y-S., 2003, "Optimizing tool orientations for 5-axis machining by configuration-space search method", Computer-Aided Design, Elsevier, Vol. 35, pp. 549-566.

Liu, X.W., 1995, "Five-axis NC cylindrical milling of sculptured surfaces", Computer Aided Design, Vol. 27, No. 12, pp. 887-894.

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