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Three and five axes milling of sculptured surfaces

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Abstract

The aim of this work is the analysis of the influence of the milling parameters on the surface finish. This work is of interest to both science and industry. On one hand, it tries to reduce the manual polishing time, which represents a high percentage of the production time of moulds. On the other hand, while the literature mainly refers to steel moulds, this work was carried out on aluminium because of its advantages for machining and its suitability for moulds. In small batch production the manufacturers are interested in the production of aluminium moulds. A 5 axis CNC milling machine was used for the surface finishing of several parts, previously 3 axis machined, within equal cutting conditions. Different machining conditions on 3 and 5 axes finishing operations were tested. The comparison of the results allows to conclude that a better surface finish is achieved with 5 axis milling using an end mill inclined in the feed instead of the traditional 3 axis milling with a ball nose cutter. The application of the Design of Experiments technique together with multiple linear regression enables the establishment of a mathematical model of the process that gives the process parameter values that lead to the minimum machining time in order to achieve a certain roughness.

Keywords: Three and five axes milling; Tool type and orientation; Surface finish and machining time

1. Introduction

The development of the aeronautic and automobile industries brought new technological challenges, related to the growing complexity of the products and the new geometries modelled in CAD systems. These more complex geometries impose new challenging manufacturing situations for the milling of moulds and stamping tools. This is an important reason for the development of new milling technology, namely 5 axis milling.

The study of these new milling technique is very important in order to identify in what conditions each one of these techniques can give the best result.

Manual polishing of sculptured surfaces is almost necessary to obtain the desired surface roughness. This kind of operation is a consequence of the inability of the milling process to achieve economically the required surface quality and in our days is more and more affected by the decreasing number of qualified workers. The 5 axis milling is, now, one of the techniques that can give enormous advantages in machining operations, potential for significant reduction of the required manual finish.

In this paper, the roughness (Ra) of the machining surface is related to the operating parameters, appealing to a mathematical-statistic model.

The part geometry was selected in order to represent, in a block of small dimensions, all the different geometries that can be found in moulds and stamping tools.

The equations relating the roughness level to the machining conditions (feed per tooth and stepover), on particular part area, were determined. As expected, the developed mathematical model expresses adequately the experimental results and enables the utilisation of an optimisation criterion, machining time in this case. This fact emphasises the importance of the mathematical models to establish the machining parameters aiming the optimal use of the resources.

The experimental work planning and the analysis of the results were done according to the ''Design of Experiments'' method.

2. Experimental work

This work targets a specific industrial problem — *the finishing of sculptured surface by milling operation*. The

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work carried out consisted on the comparison of the performance of 5 axis milling comparative to the 3 axis milling of sculptured surfaces. All of the process variables have been identified and the most relevant ones were selected for study. The final objective is to quantify their values in order to obtain the minimum machining time for a fixed roughness.

2.1. Identification and selection of process variables

The process parameters selected for the experimental work were the stepover, the feed per tooth, the feed direction and the 3 and the 5 axes milling technology.

As the milling machine had a low rotation limit of 4.200 rpm, and the tool could work in higher speed, it was decided to keep the cutting speed constant. Also, the tool diameter was kept constant and a small diameter of 10 and 12 mm, such as occurs with industrial practice, were chosen in order to avoid geometrical interference between the tool and the part. The cutting depth was also maintained constant not only to reduce the number of variables but also because in finishing operations the depth is always small.

2.2. Equipment

The milling operations were performed on a 5 axis CNC milling machine (Hermle UWF 1202 H) equipped with an Heidenhain TNC 425 CNC controller.

MasterCam version 5.54 was used to create the CNC part programs. *Multisurf* module for 3 axis and *Flowline* module for 5 axis, were used.

3. Experimental set-up

The experimental work was divided into two phases. The first phase was the 3 axis milling analysis, with a ball nose mill. The second phase was the 5 axis milling, with two kinds of tools, a ball nose and an end mill.

The control parameters considered were the surface roughness, dimensional accuracy and shape of the part geometry, and machining time.

The part's geometry has four different shapes: a convex shape, a concave shape, an horizontal plane shape and an inclined plane shape (Fig. 1).

Although this study is about 5 axis milling, the part had a curvature only in one direction (the double curvature will bring only more complexity, and this model can also be applied in that case). So, it was decided to involve only one rotation axis (A axis — rotation over the linear X axis).

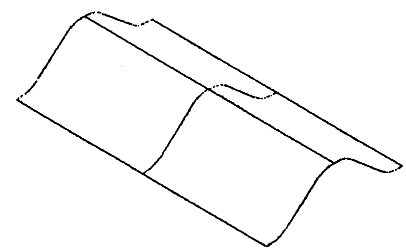

Fig. 1. Surface part.

The part's material was an aluminium alloy of the 7.000 series, used in the manufacturing of plastics injection moulds for small and medium series production.

3.1. Three axis milling

Initially, the importance of the stepover and the feed per tooth parameters on finishing operations were investigated by three axis milling.

After this initial study, the feed direction importance was analysed. This parameter was studied considering three different directions: (a) the direction of 0°; (b) the direction of 45°; (c) the direction of 90° ("*contouring*") (Fig. 2).

As the next picture prints out, one of the characteristics in 3 axis milling operations is that the lead/lag angle is not constant. This angle is defined between the tool axis and the surface normal.

On 3 axis milling operations it is possible to identify three different cutting types: the *downward cutting*, the *plane cutting*, and the *upward cutting*, Fig. 3 [1].

The cutting speed is not constant along the machining path. Fig. 3 also shows that the cutting speed distribution in the tool edge is different for each one of the three cutting types.

3.2. Five axis milling

On the finishing operations by 5 axis milling the lead (β_f>0)/lag (β_f<0) angle importance (with different positive values) to the quality of the machined surface was analysed. The results of a ball nose mill in opposition to an end mill were also compared.

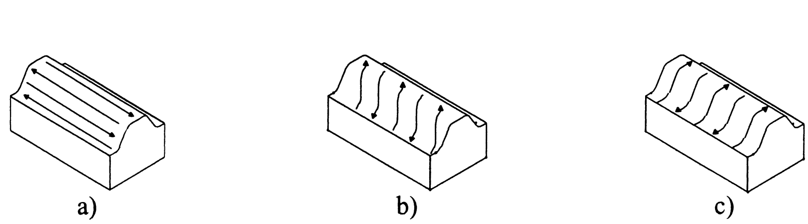

Fig. 2. Feed direction.

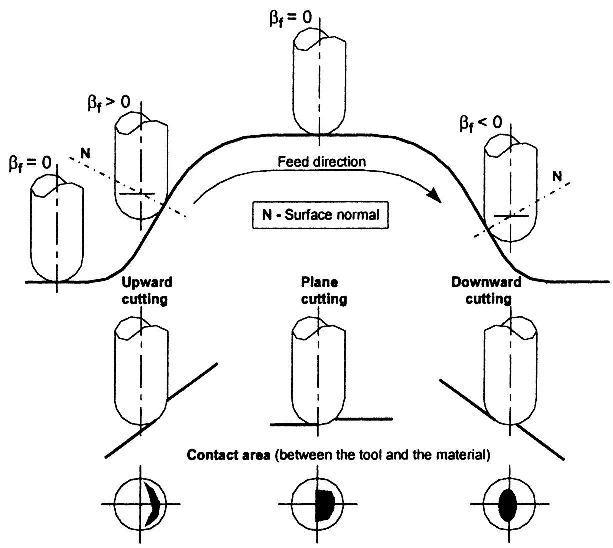

Fig. 3. Lead/lag angle (β_f).

The CAD/CAM system used creates the 5 axis CNC part programs, with the tool axis perpendicular to the surface (Fig. 4).

Usually, on milling operations with ball nose mill, the maximum roughness value occurs along a direction perpendicular to the feed direction. So, replacing the ball nose mill by an end mill inclined in the feed direction, it will be possible to reduce the scallop dimension, and that is directly related to the surface roughness (Fig. 5).

In the 5 axis milling experiments, the lead/lag angle (β_f) values were chosen taking into account the values recommended in the literature (the ball nose mill, with $+15^\circ$; the end mill, with $+4^\circ$) (Fig. 6) [1].

4. Experimental work and analysis of results

First some experiments were carried out in order to define the best range of values for the process parameters to be investigated.

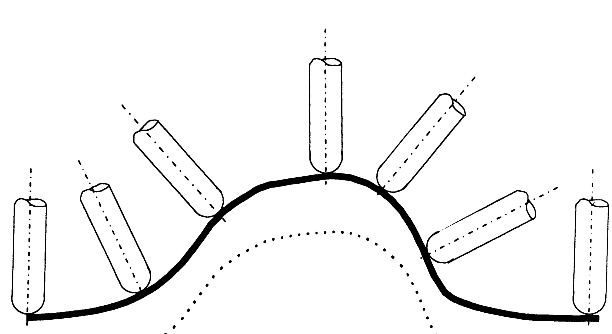

Fig. 4. 5 Axis milling operation.

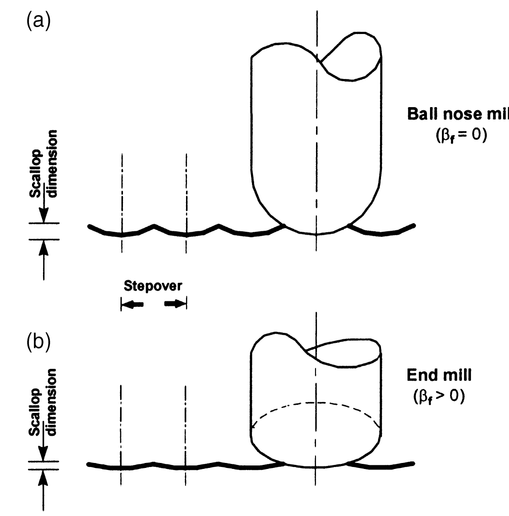

Fig. 5. (a) Ball nose mill (β_f=0); (b) End mill (β_f>0) (The tools has the same diameter and stepover.)

4.1. Preliminary experiments — 3 axis milling

Initially, the stepover and the feed per tooth values were selected from the tool catalogue. However, the roughness results were not satisfactory because they were not industrially acceptable for finishing operation.

4.1.1. Stepover and feed per tooth

Another group of experiments (the results are shown in Tables 1 and 2 for the inclined plane shape, Fig. 1) with different values for stepover and feed per tooth were defined later.

The results (feed per tooth and stepover, respectively) for the machining time and the roughness represented in Figs. 7 and 8 show more clearly that

- until 1 μm roughness there is no important aggravation of the machining time;

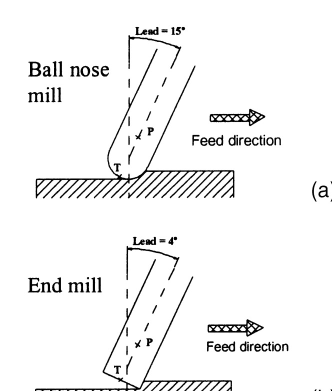

Fig. 6. (a) Inclination of the ball nose mill (β_f=+15°); (b) inclination of the end mill (β_f=+4°).

Table 1
Average roughness, Ra (μm)

Stepover (mm)	Feed per tooth (mm/tooth)							
	0.030	0.040	0.050	0.060	0.080	0.132	0.139	0.170
0.063	0.29				0.55			
0.100		0.46				1.15		
0.155	0.47						1.36	
0.200	0.63		0.70	0.75				1.63
0.250	0.85		0.85	0.90		1.42		
0.275			0.98			1.43		
0.300	1.08			1.11				
0.325						1.48		
0.350	1.27							
0.375						1.64		
0.440	1.55		1.63		1.71			
0.500				1.94				
0.600				2.27				
0.700				3.10				

Table 2
Machining time (s)

Stepover (mm)	Feed per tooth (mm/tooth)							
	0.030	0.040	0.050	0.060	0.080	0.132	0.139	0.170
0.063	1.560				625			
0.100		740				239		
0.155	675						147	
0.200	482		305	250				93
0.250	390		254	208		96		
0.275			223			88		
0.300	325			172				
0.325						75		
0.350	280							
0.375						65		
0.440	225		134		86			
0.500				104				
0.600				87				
0.700				74				

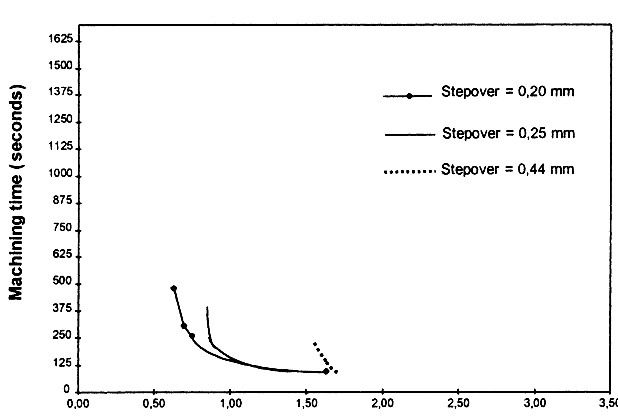

Fig. 7. Stepover (mm).

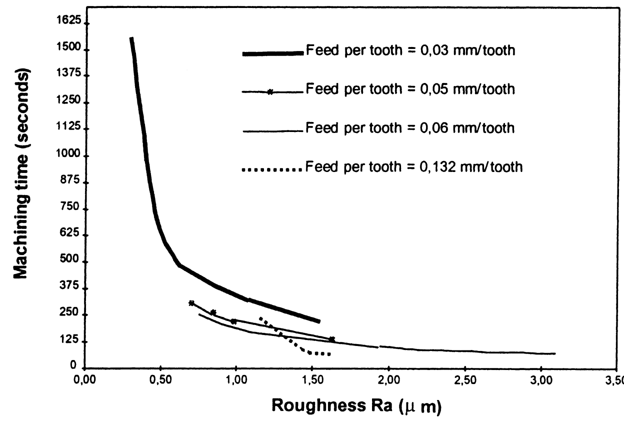

Fig. 8. Feed per tooth (mm/tooth).

- there are different values of stepover and feed per tooth leading to the same roughness value, but with different machining time;
- for the stepover and feed per tooth parameters, there is a lower limit where a dramatic aggravation on the machining time begins.

Process model. With the last results for the inclined plane shape a process model was developed.

$$\text{Roughness (Ra)} = -0.781 - \frac{0.4676}{\log(\text{Stepover})} - \frac{1.2436}{\log(\text{Feed per tooth})} \quad (1)$$

Eq. (1) relates the roughness with the stepover and the feed per tooth. This equation was obtained by a multiple linear regression (the logarithmic approach displayed the best results).

$$\text{Machining time} = \frac{(921.94/\text{Stepover}) + 74.98}{(\text{Feed per tooth}) \times 310.8} \quad (2)$$

Eq. (2) relates the machining time to the stepover and feed per tooth. It is an application of the uniform movement equation.

After the definition of the required roughness value, in this case a 1 μm roughness was chosen, the process variables for the minimum machining time were optimised (Eq. (3), Fig. 9).

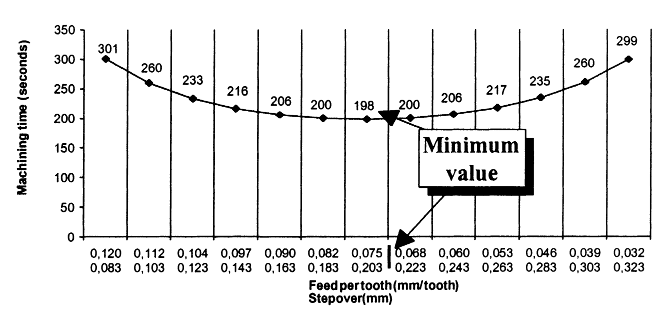

Fig. 9. Minimum machining time.

Table 3
Finishing levels

Roughness, Ra (μm)	Finish levels
≈0.5	Roughness surface equivalent to manual polish
≈1.0	Roughness surface acceptable in finishing operations (implies manual polishing)
≈1.8	Roughness surface still acceptable (with lower machining time, but implies large manual polishing)

$$\text{Machining time} = (921.94/\text{Stepover}) + 74.98 \times \left(10^{\{[-0.376/\log(\text{Stepover})]-1.4321\}} - 1 \times (310.8)\right)^{-1} \quad (3)$$

These studies were made for the inclined plane shape but they can be developed for any other shape.

4.1.2. Feed direction

The analysis of the feed direction was focused for three different roughness levels (Table 3). The roughness results were obtained in the inclined plane shape of the part.

The values in Table 4 show that in the range of values analysed:

- roughness is not affected by the feed direction;
- file dimension is much greater for the directions of 45° and 90°;
- machining time is lower in the direction of 0° and higher in the direction of 90°.

Table 4
Feed direction importance

Feed direction (°)	Stepover (mm)	Feed per tooth (mm/tooth)	Roughness, Ra (μm)	Machining time (s)	File dimension (bytes)
0	0.1	0.04	0.46	744	24.359
45			0.49	837	540.690
90			0.47	858	554.065
0	0.2	0.075	1.09	215	12.179
45			0.98	244	262.436
90			1.04	259	280.507
0	0.44	0.132	1.79	67	5.777
45			1.80	85	137.033
90			1.77	98	145.107

4.2. Final experiments — 5 axis milling

Based on the results of the preliminary experiments, a plan for the final experiments was established. These experiments were developed for four different surface types: (a) horizontal plane shape; (b) inclined plane shape; (c) convex shape; (d) concave shape.

In all these surfaces, four different experiments (3 axis milling with a ball nose mill and with an end mill, 5 axis milling with a ball nose mill/β_f=+15° and with an end mill/β_f=+4°) were carried out.

The surface roughness (Ra) was measured in three different directions (feed direction, 45° relative to the feed direction, and perpendicular to the feed direction; Fig. 10).

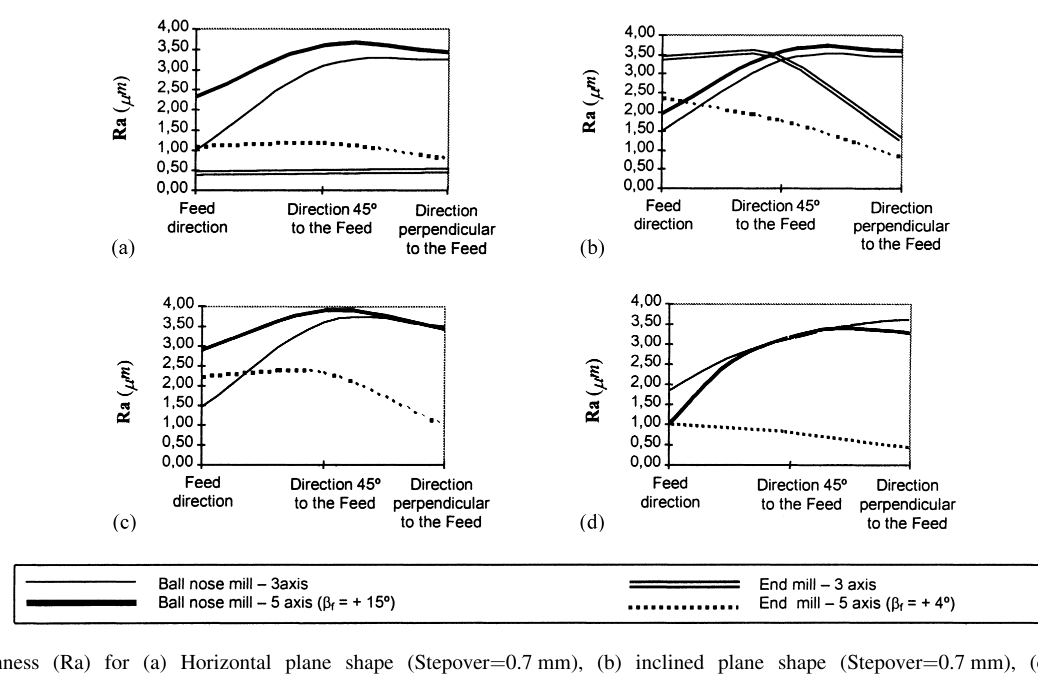

Fig. 10. Roughness (Ra) for (a) Horizontal plane shape (Stepover=0.7 mm), (b) inclined plane shape (Stepover=0.7 mm), (c)* convex shape (Stepover=0.7 mm) and (d)* concave shape (Stepover=0.7 mm) (* Values not represented for the end mill — 3 axis once the lead/lag angle varies along the surface. The measured roughness values lie between the values measured for the plane and the inclined surfaces.)

As expected, in the horizontal plane surface, the 3 axis milling with an end mill gives the best results (lower roughness).

In the range of values considered for the milling operation with a ball nose mill, 3 or 5 axes, the maximum roughness value occurs in a direction perpendicular to the tool movement, while for the 5 axis milling with an end mill, the maximum roughness value occurs in the direction of the tool movement.

In the last experiments, except in the horizontal plane surface, the best results (lower roughness) were achieved in the 5 axis milling with an end mill.

5. Conclusions and future developments

Based on this work and on the experimental results, it is possible to conclude the following for this aluminium alloy of the 7.000 series, for the ball nose mill (10 mm) and the end mill (12 mm), and for the machining conditions used:

- the stepover and the feed per tooth are important parameters in terms of which direction, feed or transverse, and maximum roughness (Ra) occur;
- the feed direction has no relevant influence on the surface roughness (Ra), but it is very important in the machining time and in the dimension of the CNC program;
- in finishing operations of sculptured surfaces by milling with 5 axis machines it is possible to achieve a better surface finish (roughness) and a lower machining time replacing the traditional ball nose mill by an end mill, inclined in the feed direction.

In terms of future developments, it will be important

- to develop a theoretical model that relates the roughness of the machined sculptured surface and the operating parameters;
- to analyse the cutting forces and the tool wear in order to obtain a more global knowledge of the milling process;
- to make experiments in double curvature surface to confirm that the 4 axis can include all the 5 axis technological variables;
- to study the combination between the 5 axis milling and the high speed machining (HSM), because it is the actual tendency in the industry and this work evidences the interest.

References

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