SOME EFFECTS OF STOCK VARIATIONS DUE TO THE USE OF 2½ AXES STRATEGY ON ROUGHNING

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Abstract. *Milling moulds and dies using of 2½ axes strategy results in a surface with steps, in stairway form, particularly if the roughing tool is a flat end milling tool. The theoretical value of stock removal usually adopted by the CAM software for calculation does not account for that excess of material left by the roughing cut. In general, that significant variation of the stock material is commom and must be removed by the finishing cuts. The present work applied high speed cutting (HSC) strategies in a workpiece containing surfaces in different angles of inclination 75, 45 and 7°. Initially, the workpiece was rough cut with an end mill tool of 12 mm of diameter with sharp flat corner. Two ball nose end mills with of 12 and 6 mm diameters were tested with 75 mm and 45 mm in balance, out of holder . The finishing strategy was down milling in the upward and downward directions for the three inclinations. The roughness values were compared by considering the two tools and in-balance lengths, keeping constant all the other milling parameters. The worst values for roughness occurred with the largest in-balance length, independently on the surface inclination. Values of roughness found were slightly higher than would be expected in finishing operation, however, important comparisons could be made with the results. It was also verified that for some cases the downward cutting has produced smaller roughness being compared to the upward one.*

Keywords: *roughness; stock removal; up and down milling; high speed cutting; molds and dies.*

1. Introduction

Machining technology using High Speed Cutting (HSC) has been quite attractive in the milling operations for moulds and dies. Recent work by Finzer (1998) and Eberlein (1999) demonstrated the potential of this technology in such segment. When machining of moulds and dies with complex 3D forms the operations are usually initiated in 2 ½ axes, beginning with a prismatic block of material. In this operation, a stock material is scheduled to be removed by the following finishing operation. Although this stock is considered by the system CAM as being homogeneous over all the final profile, an excess of material is left after roughing because it cannot be removed due geometric limitations on the contact between the tool and the final surface, according to Geist (1999).

This excess of material can also vary as a function of three factors: cutting depth (a_p); curvature degree, or inclination of the surface, and geometry of the tool, Souza (2001). Although most of the current CAM systems use sophisticated algorithms to identify these areas, with the purpose of minimizing the problem, this is a fact that always happens in a production sequence of moulds and dies. Large variations in the excess of material, such as a stairway form, can produce dimensional and form variations.

This fact can be significant when using HSC since the output of such process is expected to be better than a conventional one (Gomes, 2001). These variations start when the cutting edge finds a higher depth of cut, which causes cutting force to become higher, bending the end mill, during finishing operation. The rigidity of a tool can be compared to a cantilever beam submitted to a force at its end. The bending of the tool is directly proportional to its length and inversely to its diameter SANDVIK (1999). On the other hand, when a tool starts cutting it can excites the natural vibration of the structure that answers the excitement producing a waving surface and, if the system cannot absorb the energy, it will become unstable and the vibrations can grow exponentially until the tool breaks, or produce a poor surface quality (Altintas, 2000). An AISI P20 steel workpiece was used to study the effects of stock material variations, due to the stairways left by roughing cut, on the finishing operation. A workpiece containing three surfaces at different angles was used to test two diameter ball nose end mills with two in-balance lengths in finish cutting conditions.

1.1. Experimental work

Figure 1 shows the 3 surfaces with different angles of inclination. These surfaces are defined as: surface "A" at 75°; surface "B" at 45° and surface "C" at 7° all with reference to the horizontal plan.

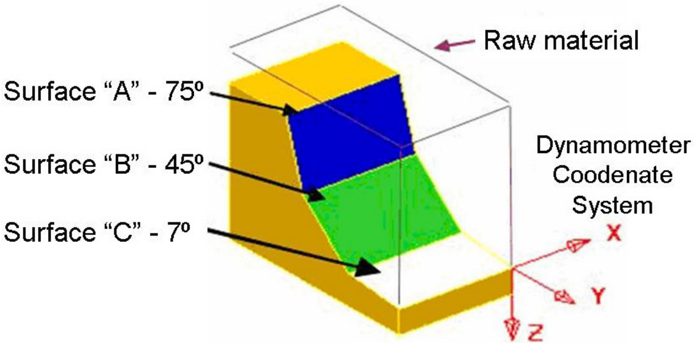


Figure 1. Geometry of the workpiece

The workpiece material was 80 mm x 50 mm x 70 mm made of AISI P20 steel with 30 HRc. Initially, it was rough cut from a cubic block producing the shape shown Fig. 1. The choice of this material was due to its wide variety of applications in the mould and die industry. Details of the tools used for roughing and finishing are in Tab. 1.

Table 1. Details of the tools used for roughing and finishing.

Diameter [mm]	Operation	Helix angle (°)	Total length [mm]	Cutting length [mm]	Flutes number	Coating
6	finishing	30	57	10	2	(TiAl)N
12	finishing	30	83	22	2	(TiAl)N
12	roughing	30	73	16	4	(TiAl)N

Figure 2 shows the aspect of the tools.

Figure 2. General aspect of the tools used in the tests

The tests were carried out in a machining center with top speed of 24.000 rpm and 15 kW of power in the main spindle. The machining parameters used are illustrated in the Tab. 2.

Table 2. Roughing and finishing machining parameters.

Machining	Tool code	a_e [mm]	a_p [mm]	Rot. [rpm]	f_z [mm]	Vc [m/min]	Estrategy
Roughing	End mill Ø 12 mm, 4 flutes	3,0	0,5	2700	0,10	100	offset
Finishing	Ball Nose Ø 12 mm, 2 flutes	0,2	0,2	10000	0,08	376	downward
Finishing	Ball Nose Ø 6 mm, 2 flutes,	0,2	0,2	10000	0,08	188	downward

The bending force was measured by a KISTLER dynamometer, model 9272, using a PCMCIA card 16XE card with a LabView application program. The surface quality was assessed by Ra values measured using a Mytutoyo model SJ201. Roughness was measured perpendicularly at the feed direction and the surface texture was assessed by the images from a digital camera at an optical microscope.

2. Results and discussion

2.1. Stock removal resulting of the rough operation

The workpiece was initially rough-cut with the 12 mm end mill cutter. Therefore, the resulting surface contained steps, in stairway form, which must be removed by the finishing operation. Fig. 3 shows the aspect of the three different surfaces at the workpiece.

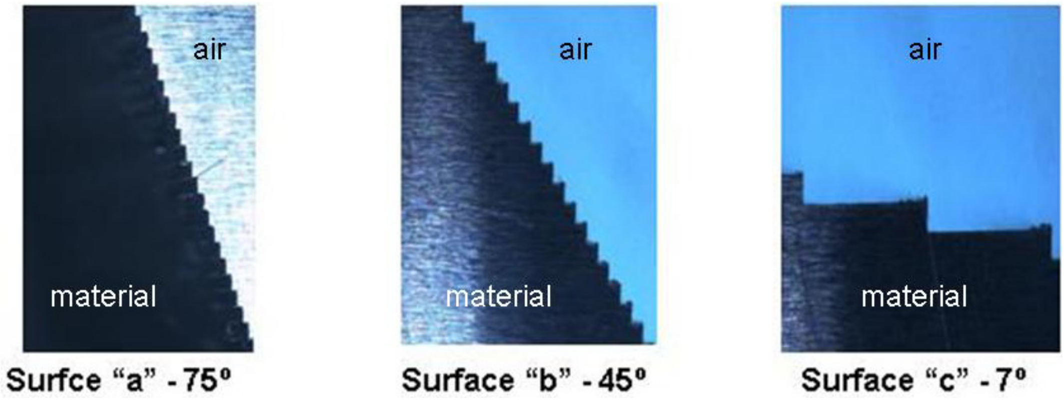
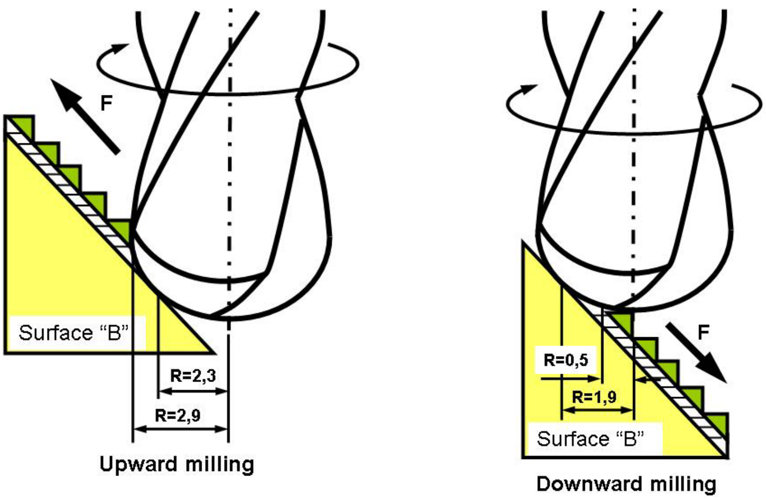


Figure 3. Resulting surfaces at different angles

The theoretical value of stock removal, input to the CAM software for calculation of the programs, was of 0,2 mm. The tool/workpiece contact is defined as a function of surface inclination, tool geometry (circle), stock removal and of the milling path. Fig. 4 shows, as an example, the tool/workpiece contact using a 6 mm ball nose in the surface “B”. It can also be seen the differences between the theoretical and the real stock removal. Therefore, during the finishing operation there is a significant variation of the depth of cut and, consequently a variation on the cutting forces that could cause bending. Usually, to avoid this variation, operations of semi-finishing are executed, with more rigid end mill, larger diameters and smaller balance lengths, wherever possible.



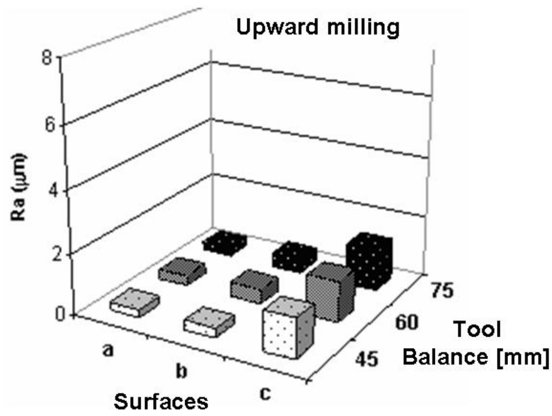
(a) Upward milling (b) Downward milling

Figure 4. Contact of the tool in function of the milling direction

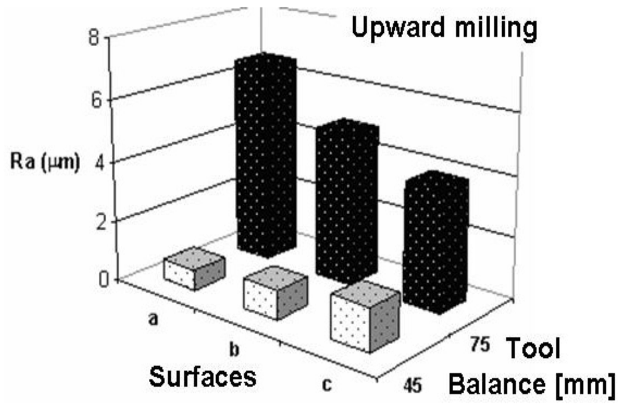
Based on Figure 4, it can also be noted a significant variation on the effective cutting diameter. For example, in the upward milling the radius of contact changes between 2,9 and 2,3 mm (tool of 6 diameter mm) and in the downward direction the change are between 1,9 mm and 0,5 mm. These variations are considered for the stock removal of 0,2 mm on the finishing profile

2.2. analysis of the surface quality

The Figure 5 shows, for the 12 mm tool the roughness Ra according to different in-balance length, end mill diameter and surfaces of the workpiece.



(a) 12 mm diameter



(b) 6 mm diameter

Figure 5. Roughness Ra according to different in-balance length, end mill diameter and workpiece surfaces

Variations on the surface angle have a minor influence on surface roughness. The tool central area, where the cutting speed is zero, is the most critical region when ball nose are used, because the material is formed, instead of cut, with higher intensity, especially in plans close to 90 degrees of its rotation axis. Additionally, chip removal in the center of the tool is more critical too, due to the small space in the rake surface SANDVIK (1999). Therefore, smaller roughness values are obtained with HSC and positive rake angles, both can be observed at surface "A". With the increase of the in-balance length a small increase of Ra was verified for the 12 mm diameter tool. That can be accounted for the tendency of dynamical instability of the spindle. A simple run was performed with 6 mm diameter tool in downward milling, Fig. 6.

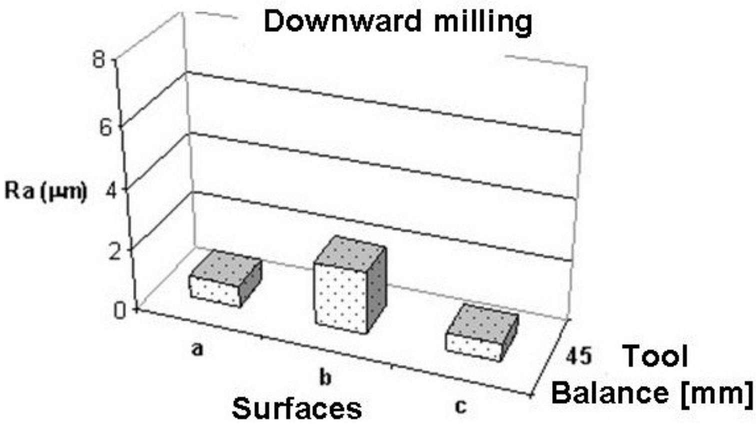


Figure 6. Roughness Ra for the tool of diameter 6 mm (downward direction)

When the tests were carried out with the downward milling roughness Ra was almost the same. Upward milling should be preferred for high angles, where the steps are not very high and the effect of cutting with the tool central can be avoided. That effect can be much stronger in plans closer to horizontal producing peaks, which increase the roughness, according Saraiva (2000). The Fig. 7 shows the aspect of the wear tool of 6 mm with balance length of 75 mm.

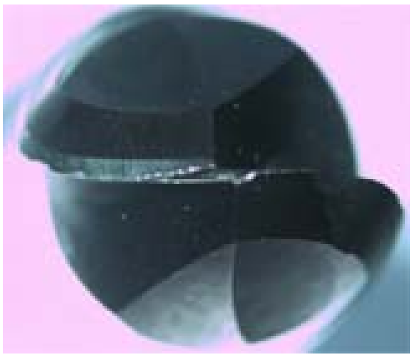


Figure 7. Tool wear generated by instability in the process.

On surfaces very close to horizontal, better roughness was obtained with downward milling, compared to upward milling, as shown in Fig. 8. That happened because in downward cutting the tool begins at the minor variation of the depth of cut, climbing smoothly the step. Contrastingly, when cutting upwards the edge faces the highest depth of cut first, bending itself much more and abruptly, leaving material to be removed at that point.

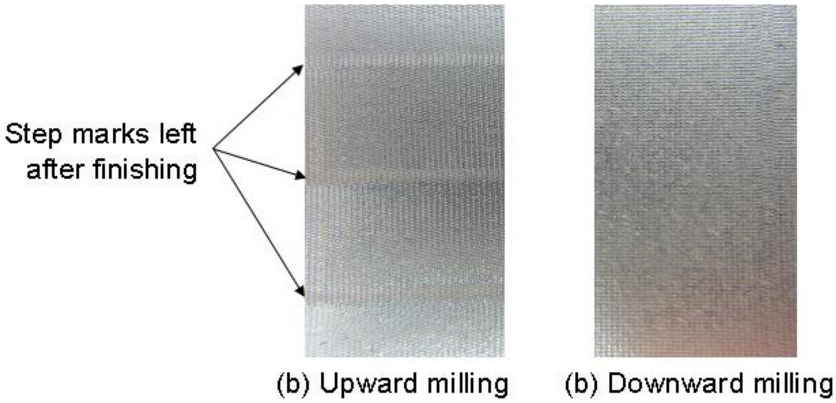


Figure 8. Surface finishing obtained at Surface “C” with 6 mm diameter tool, 45 mm in-balance.

2.3. Experimental measurement of the static rigidity of the tool

In order to estimate the static rigidity of the tools they were pressed statically against the milled surface, in increments of 0,01 mm at a time. Fig. 9 shows a schematic of the experimental method used.

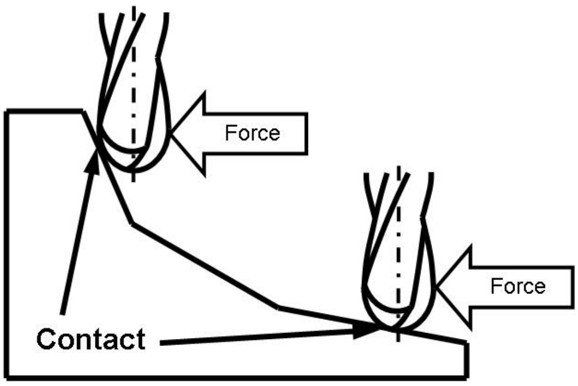


Figure 9. Outline of the experimental method used for estimate of the static rigidity of the end mill.

Minor deformations certainly occurred at the contact region, since the workpiece was not very hard (35 HRc) and sliding may have occurred on surface “C”, as well. However, the method is a first and prompt indication of stiffness for the whole spindle system. For example, for the 6 mm tool at surface “A” the in-balance length differences can be 2,5 and 4 times from surface “B” to “C”, respectively, according to theoretical calculations. Fig. 10 shows the experimental results of the stiffness for the 6 mm tool.

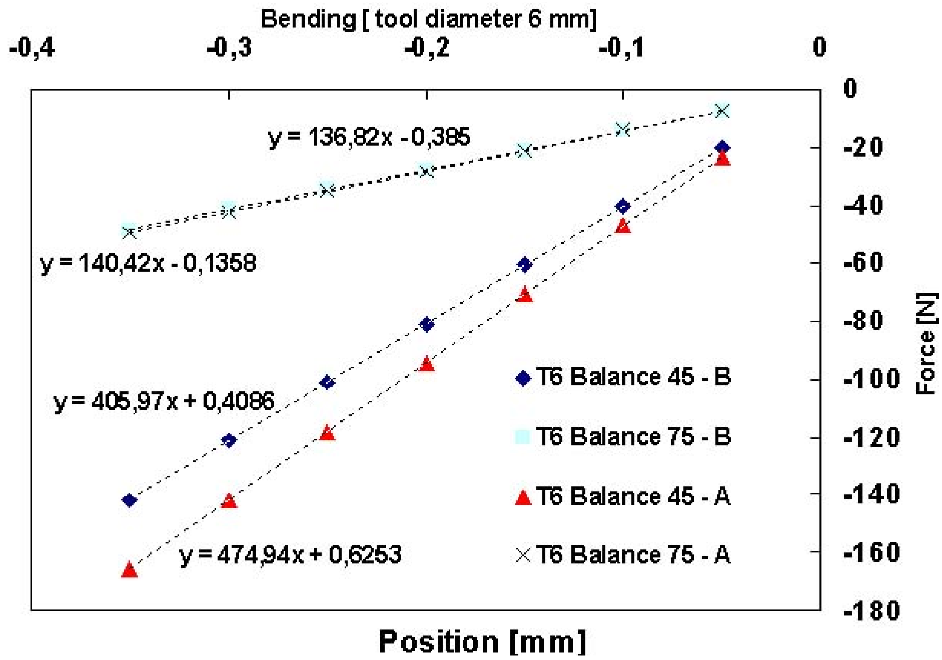


Figure 10. Result of the rigidity tests for the tool of 6 mm

As expected, the stiffness of the tool is larger with balance of 45 mm than to 75 mm, for a factor of approximately 3 times. We can consider theoretically that the tool is a fixed beam under the action of a radial force, due to the cutting process. Being so, a decrease in the length in-balance from 75 to 45 mm, should increase the rigidity in the proportion of the cube of the reason among the lengths. In tests carried out the theoretical value is of 4,63 being higher then to the found in the stiffness tests. The reason is the fact of the measurement included the stiffness of the whole system: spindle/grip system/workpiece and tool, which certainly is smaller and that behaves as a combination of "*ideal*" springs in series.

The values of stiffness found during the tests, therefore, smaller than those calculated theoretically, about 87,5% for the balance length of 75 mm and 63,2% for the balance length of 45 mm. The small stiffness of the system when working with the tool of 6 mm with 75 mm of balance length, in combination with the interrupted cut, typical of the milling process, and by cutting force variable, due to the variations in the thickness of the chips, were probably responsible for the high roughness Ra obtained in this case. The smallest stiffness provides larger bending conditions in response to the actions of the cutting force. As the forces are variable in the time, the whole system tends to vibrate in amplitude that, most of times, can be of the same order of chip thickness. The milling process is interrupted cutting with a frequency of performance of the edges, close to those natural of the mechanical system in action.

Figures 11, 12 and 13 show the form error of the profiles of the three surfaces. For each surface, 100 points were measured along its length. Figure 10 shows the profile of the surface “A” where the maximum value of form error was less than 1 μm to the 6 mm tool and less than 0,5 μm for the 12 mm tool. Figure11 shows the values of form error for the surface "B" as being less than 0,5 μm for all tools. Although there appears to be a difference between those errors on both surfaces, they might be the same and differences are at the same order of measurement errors.

In Figure 12 the maximum error for the surface "C" was 1,5 μm when cutting with 6 mm and 75 mm in-balance. At that surface it can also be noted 3 major peaks, which resulted from the 3 steps left by the roughing operation. With the tool used, combined with the upward milling, the increase in cutting forces, due to the excess of material, was enough to bend the tool. The bending caused peaks of about 1,5 μm, which may be a significant amount of material in some applications. In all the other cutting conditions used the excess of material could be removed without leaving errors higher than 0,5μm.

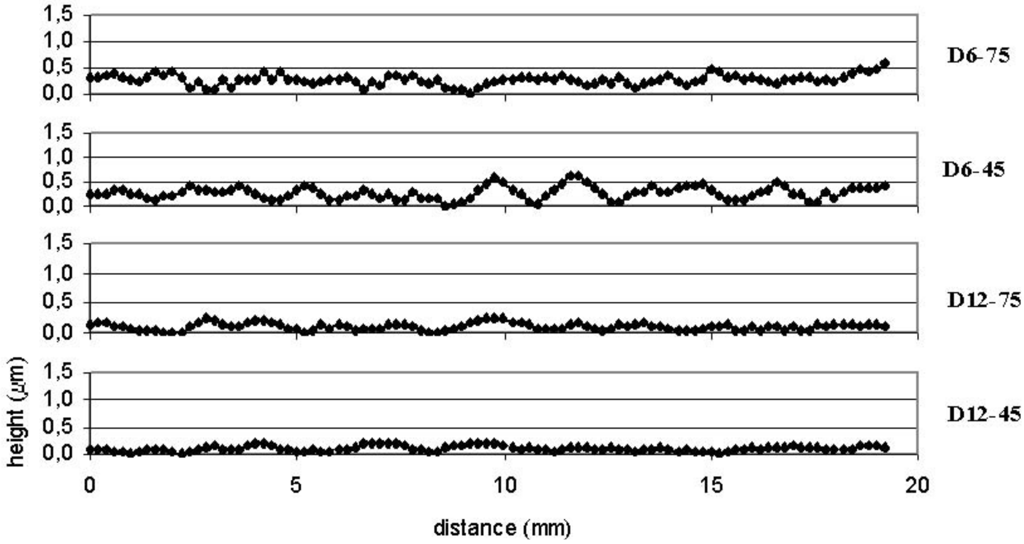


Figure 11. Form error in the Surface "A"

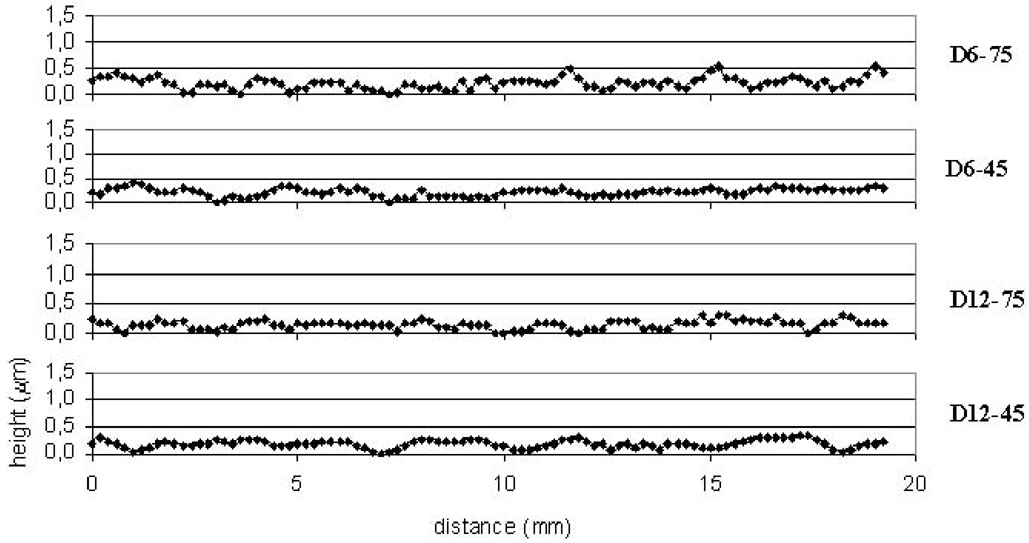


Figure 12. Form error in the Surface "B"

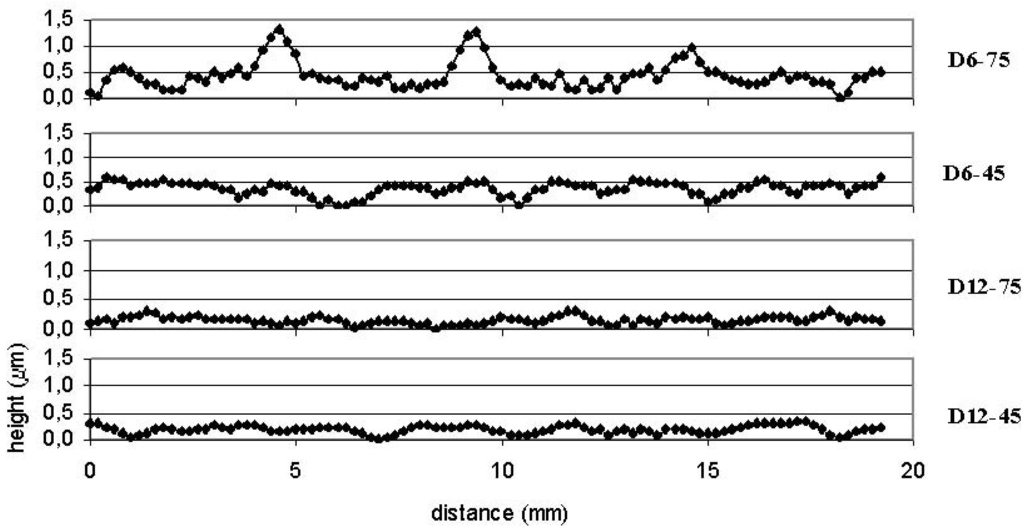


Figure 13. Form error in the Surface "C"

3. Conclusions

The present paper experimentally investigated few effects of stock removal left by roughing operations on the final end milled surfaces, which led to the following first conclusions:

1. Roughing operations on complex 3D surfaces with end milling tools using Z off set strategy leaves an excess of material, additionally to the theoretical layer, whose volume varies as a function of surface inclination. The smaller the inclination, starting from the horizontal plan, the larger is the amount of material.
2. When end milling those surfaces in finishing operations the contact point, between the workpiece and the ball nose tool depends on the inclination. That causes a significant variation in the effective cutting speed, with important consequences for the surface finishing.
3. In the same way the cutting direction, upward and downward milling, significantly alters the kinematics of cutting, modifying the contact angle and the effective cutting speed. In the downward milling, depending on the inclination of the surface, contact point can be dangerously close to the center. Such situation may be very harmful to chip formation due to the low effective cutting speed.
4. Surface roughness could be a low as around 1,0 μm Ra, but it all depends on end mill diameter and in-balance length. Higher values as much as around 6,0 μm Ra were obtained when using 6,0 mm diameter end mill combined with 75 mm in-balance length. Low values were also obtained when cutting with 6,0 mm diameter tool with 45 mm in-balance, both in upward and downward milling strategy.
5. The proposed way of measuring end mill stiffness demonstrated to yield results lower than the theoretical calculations, based on a cantilever, but it takes into account the whole system stiffness. If a very rigid workpiece can be used, the method may be more appropriated. The method, however, has shown that there can be a significant difference in stiffness when milling complex 3D surfaces in which the contact point varies on ball nose end mill. It is particularly significant when using 6 mm diameter end mill.
6. The low stiffness on 6 mm diameter end mill, combined with large steps on stock material to be removed by the finishing operation were the main responsibles for dimensional variation on surface "C", leaving the same step patterns. Peaks were as high as 1,5 μm, which may be significant in some applications.

4. Acknowledgements

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