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Variation cutting speed on the five axis milling

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ABSTRACT

Purpose: The aim of this research is to make a study of the effective cutting speed variation in milling with a ball end tool is studied. Then an experimental study of the effect of finishing strategies on surface texture, roughness is described. The material of a specific HB 300 pre-hardened mould steel Super Plast (SP 300).
Design/methodology/approach: The methodology has consisted to dertemine cutting speed of each mode of tilt tool in five axes machining, and of proving a series of configurations and parameters combinations: cutting speed Vc, feed rate Vf, and tilt tool in multi-axis milling.
Findings: This paper has investigated the effect of the tool orientation on the variation effective cutting speed, on the surface texture, while multi-axis milling. Experimental results have shown that disadvantages of three axes machining results from the existence of very low cutting speeds, even null when the tool axis is normal to the machined surface. This mode of machining generates a bad surface quality. Surfaces have a poor topography and important anisotropy. A suitable slope of the cutting tool by the means of the fifth machine tool axis, improves considerably work piece machined surface quality; Good micro-geometrical surface topography and lower surface roughness.
Research limitations/implications: A possible future work would be the development of a general the phenomenal of the residual stress of the cutting on the five axis machining. The behavior is of the residual stress studies are planed in the future.
Practical implications: The relationship found between the effective cutting speed and surface texture work piece has an important practical implication since it allows selecting the best cutting condition combination from the points of view both the security and the economy for the established requirements in each case. Results are of great importance in for aerospace and automotive industry.
Originality/value: The paper is original since the bibliographical review has allowed testing that, although works about these themes exist, none approaches the problem like it has been made in work.
Keywords: Machining; Effective cutting speed; Multi-axis milling; Tool orientation; Surface texture; Dies and moulds

1. Introduction

Complex shaped parts such as dies, moulds, prostheses, turbine blades and aerospace parts can efficiently be machined by five-axis milling.

Computer aided design (CAD) software systems give us the potential to model very complex shapes. The growing complexity of products has been pushing the development of new manufacturing technologies. Complex or organic geometries introduce different and more complex manufacturing problems [1] when lower surface roughness and minimum machining costs are objectives to be pursued.

At the same time, in order to reduce costs, high speed machining (HSM), which utilises high cutting speeds and consequently significant federates, has become popular. Therefore, machine tools have evolved in this direction. They now integrate linear motorization for the translation axes that can reach federates of about 20-40 m/min and torque motors for the rotation axes [2-3]. Generally, 5-axis machines have a structure based on a 3-axis Cartesian structure with the addition of two rotary axes.

In milling surfaces of dies and moulds the machining and polishing operations represent sometimes approximately two thirds of the total manufacturing costs [4-5]. A suitable machining strategy can lower significantly manual labor as well as time and cost. Frequently, polishing operations are necessary due to the inappropriateness of machining strategies.

Dies and mould are usually machined using 5-axis ball end milling. Due to the increasing demand for higher accuracy, lower machining time, and higher surface integrity, several researchers [6-20] have investigated the effect of cutter orientation on surface roughness and tool life. Based on a comparative study of milling at different inclination angles, they concluded that downward/reverse milling with a tool inclination in the range of 10-20 degrees represents the optimum machining strategy [7].

Several studies of 5-axis milling have been performed by various authors. Rao et al. [19] showed both the avoidance of gouging and the selection of an effective cutter profile for an optimal choice of the feed direction for 5-axis milling. Baptista and Antune Simoes [20] suggested that surface roughness was improved with the inclined milling in the feed direction. Tonshoff and Hernandez-Camacho [21] found that the optimal inclined angle was 15° in ball end-milling of block materials.

To reduce the polishing cost of dies and moulds, appropriate machining strategy and appropriate cutting conditions should be selected to improve the dimensional accuracy, the surface texture and roughness while fine milling. Machining strategy includes the tool path pattern and the tool orientation. The cutting conditions include the cutting edge geometry, the feed rates, and the cutting speeds.

This work aimed at studying and analyzing different finishing strategies with different cutting conditions to assess their influence on surface roughness, and tool life. In this paper, firstly, the effective cutting speed variation in milling with a ball end tool is studied. Then an experimental study of the effect of finishing strategies on surface texture, roughness and tool wear is described.

The experimental study is applied to multi-axis ball-nose end milling of a specific HB 300 pre-hardened mould steel Super Plast (SP 300), widely used for plastic injection mould making.

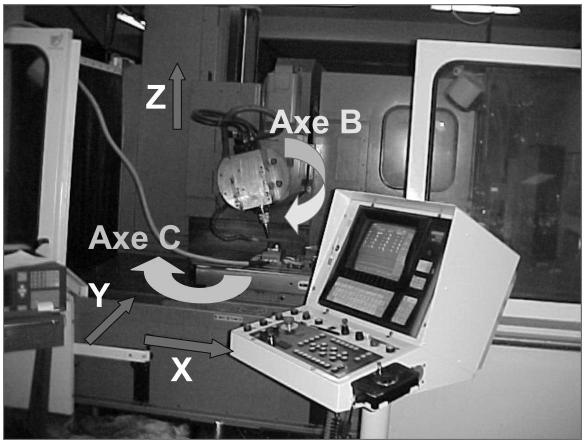


Fig. 1. Five axis milling machine

2. Muti-axis milling and cutting speed variation

2.1. Multi-axis milling

Multi-axis machining is a technology which underwent important innovation; it allows the realization of complex shape pieces for aeronautical and automotive industries, and for dies and moulds.

Milling surfaces dies and moulds often requires the utilization of two supplementary rotary axes, (fourth and fifth axes) of the machine-tool, to improve the precision of machining, with respect to geometry of the workpiece and surface quality, to increase tool life and avoid collision between cutter and the part (see Figure 1).

The study aim is to improve of process in the case of a plane surface milled with ball-end tool.

The required objective is to control the produced surface quality. The objective is to optimize the trajectory and the inclination of the cutting tool in five axes milling, (in one-way and zigzag) in relation to the quality of micro-geometrical surface texture of milled surface.

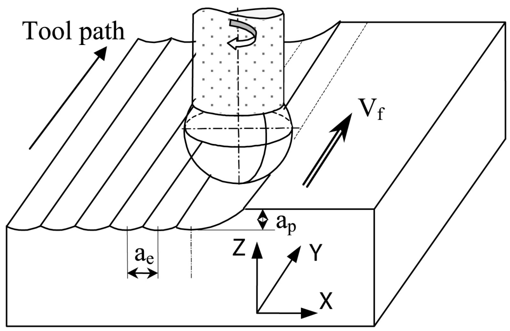
Figure 1 show the five-axis machine tool. The machine have a 3 axis Cartesian structure (X, Y, Z) with the addition of tow rotators axis of the table (C) and the second rotation axe of the spindle (B).

2.2. End milling without inclination

The majority of the workshops of machining use 3-axis machine tools for milling operations. Under these conditions, the axis of the cutting tool is fixed and generally normal on the machined surface (see Figure 2).

The tool path in milling is the trajectory of the cutter centre, witch is also known as the Cutter location (CL) path, and is given by the NC part program. The cutter contact (CC) path is the tangential trajectory between the ball-end cutter and the part surface, and is shifted from the tool path by a distance equal to the cutter radius R. When the cutter moves in parallel trajectories, scallops are created on the finished surface. The distance between the parallel trajectories is the CC path interval or radial engagement a_e, which depends on the local curvature of the surface, the size of the cutter, and the allowable scallop height H remaining on the surface after the operations machining.

a)



b)

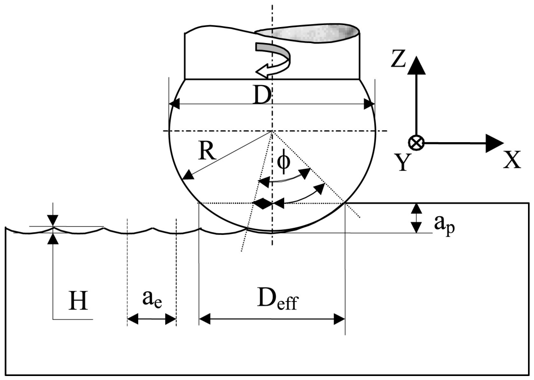


Fig. 2. Normal tool axes to the machined surface; (a) 3 dimensions (b) 2 dimensions

The calculation of the radial engagement a_e or cutter contact CC path interval for milling flat planes machined by a ball end cutter is relatively simple. When the milling operation is completed, scallops remain on the finished surface a shown in Figure 2 (a-b). For a given allowable scallop height H, the radial engagement a_e can be obtained by following relation (1).

$$a_e = 2\sqrt{R^2 - (R - H)^2} \tag{1}$$

where a_e denotes the radial engagement or cutter contact CC path interval, R denotes the radius of a ball-end cutter, and H denotes the allowable scallop height.

The scallop height, H is the residual thickness on the part after finish machining which is generally eliminated by polishing. It depends only, when the cutting conditions are appropriate (weak feed per tooth f_z), on the nominal diameter D or nominal radius R of the ball-end mill and of the step of radial engagement a_e. It is clear that, for same radial engagement, the scallop height increases when the diameter of the cutter decreases (see Figure 3).

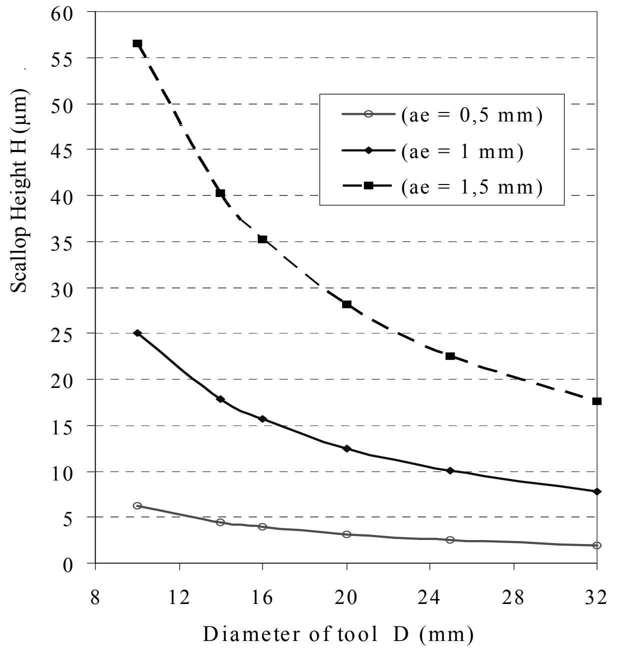


Fig. 3. Evolution of the scallop height H in function of the tool diameter D and of the radial engagement a_e

$$H = R\left(1 - \sqrt{1 - \left(\frac{a_e}{2R}\right)^2}\right) \tag{2}$$

where H denotes the scallop height, R denotes the nominal radius of a ball-end cutter, and a_e denotes the radial engagement.

The figure 3 shows the evolution of the scallop height H according to the tool nominal diameter D and the radial engagement depth a_e.

Generally, in the case of the complex shapes machining, the effective cutting speed $V_{c\text{-}eff}$ varies, following the inclination of the ball-end cutter in relation to the manufactured elementary surface. However, in 3 axis milling, tool axis is normal to the machined surface (see Figure 2 a-b), the cutting speed $V_{c\text{-}eff}$ is given by the relation (3):

$$V_{c\text{-}eff} = \frac{\pi . n . \left(2\sqrt{D . a_p - a_p^{\,2}}\right)}{1000} \tag{3}$$

where $V_{c\text{-}eff}$ denotes effective cutting speed, D denotes the nominal diameter of a ball-end cutter, a_p denotes the axial engagement or axial depth of cut and n denotes spindle speed.

2.3. Machining with slopes of the tool

Schulz et al. [7], Bouzakis et al. [11] showed that machining with a slope of the hemispherical tool modifies the shapes and dimensions of the chips. In addition, Altan et al. [10] confirmed that the slope of the tool improves the tool wear resistance of CBN in milling of moulds steel (45 HRC). Recently, Tounsi et al. [9] showed that the slope of the carbide tool coated with (TiCN), influences the cutting forces and the surface quality in milling 5-axes of the nuance "Arcelor" SP 300 for plastic injection moulds pretreated to 300 HB.

In this survey, one is going to determine the best combination of the inclination angle and the sense of feed rate V_f of the tool on the surface quality state according to the machining conditions, as well as the minimal values of the inclination angle of the ball-end cutter and the effective cutting speeds correspondents in every configuration.

In order to avoid working with a slight effective cutting speed $V_{c\text{-}eff}$ or neighbouring of 0 m/min (normal tool axis to the machined surface), the tool axis must be inclined to an angle θ superior to a minimal value that depends on the machining configuration.

- Tool inclination θ_n according to the negative rotation sense - B, the feed rate direction V_f according to the Y axis and the radial engagement a_e according to the sense + X (see Figure 4); condition to satisfy:

$$\theta_n \rangle \arccos\left(\frac{R - a_p}{R}\right) \tag{4}$$

where θ_n denotes tool inclination angle, R denotes the nominal radius of a ball-end cutter and a_p denotes the axial engagement or axial depth of cut.

Figure 4 shows the tilted tool position θ_n according to the negative rotation sense - B to the machined surface.

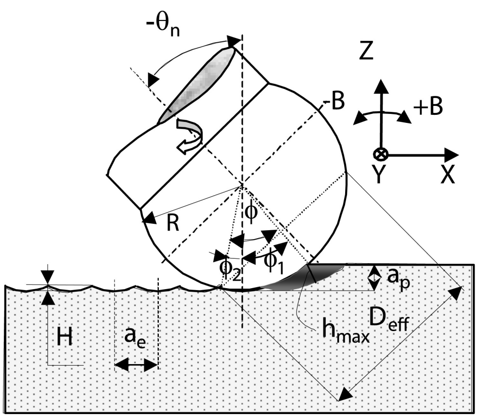


Fig. 4. Tilted tool position θ_n according to the negative rotation sense - B to the machined surface

Tool inclination θ_n according to the positive rotation sense + B, the feed rate direction V_f according to the Y axis and the radial engagement a_e according to the sense + X (see Figure 5); condition to satisfy:

$$\theta_n \rangle \arcsin\left(\frac{a_e}{2R}\right) \tag{5}$$

Figure 5 shows the tilted tool position θ_n according to the positive rotation sense + B to the machined surface.

When the tool is inclined there for example with an angle of slant (in relation to the normal vector of the machined surface (according to the negative sense -B or the positive sense + B) around the Y axis of the machine tool (see Figure 4 and Figure 5), the effective cutting speed $V_{c\text{-}eff}$ of the ball-end cutter varies according to the position of the tool:

Case 1:

Tool inclination θ_n according to the negative rotation sense - B, the feed rate direction V_f according to the Y axis and the radial engagement a_e according to the positive sense + X (see Figure 4):
The effective cutting speed $V_{c\text{-}eff}$ is given by equation (6):

$$V_{c\text{-}eff} = \frac{\pi.n.D \sin\left[\theta_n + \arcsin\left(\frac{a_e}{2.R}\right)\right]}{1000} \tag{6}$$

with the condition :

$$\arccos\left(\frac{R - a_p}{R}\right) \langle \theta_n \leq 90 \tag{7}$$

where $V_{c\text{-}eff}$ denotes effective cutting speed, R and D denotes the nominal radius and diameter of a ball-end cutter, θ_n denotes tool inclination angle, a_p denotes the axial engagement or axial depth of cut, a_e denotes the radial engagement and n denotes spindle speed.

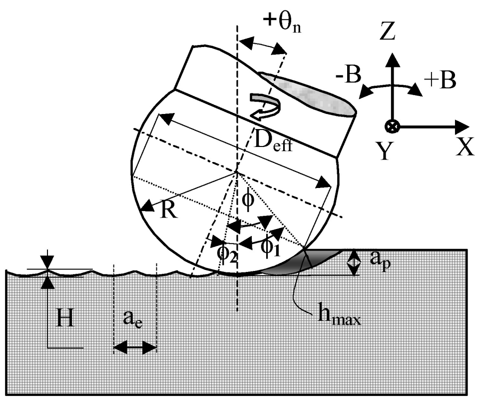


Fig. 5. Tilted tool position θ_n according to the positive rotation sense + B to the machined surface

Case 2:

Tool inclination θ_n according to the positive rotation sense +B, the feed rate direction V_f according to the Y axis and the radial engagement a_e according to the positive sense + X (see Fig. 5):

The effective cutting speed $V_{c\text{-}eff}$ is given by equation (8):

$$V_{c\text{-}eff} = \frac{\pi.n.D \sin\left[\theta_n + \arccos\left(\frac{R - a_p}{R}\right)\right]}{1000} \tag{8}$$

with the condition :

$$\arcsin\left(\frac{a_e}{2.R}\right)\langle\theta_n \le 90 - \arccos\left(\frac{R-a_p}{R}\right) \qquad (9)$$

Case 3:

Tool inclination θ_n according to the negative rotation sense - B, the feed rate direction V_f according to the Y axis and the radial engagement a_e according to the negative sense - X: The effective cutting speed $V_{c\text{-}eff}$ is given by the equation (8).

Case 4:

Tool inclination θ_n according to the positive rotation sense + B, the feed rate direction V_f according to the Y axis and the radial engagement a_e according to the negative sense - X: The effective cutting speed $V_{c\text{-}eff}$ is given by the equation (6).

3. Experimentation and analyses

3.1. Experimental procedure

The cutting experiments were carried out on a 5-axis vertical milling machine 'Gambin 120 CR' equipped with the numerical control unit 'Num 1060 -Telemecanique'. They were performed under dry cutting conditions (see Figure 1).

The material of the work-piece is a hardened steel type SP300 recently developed for Super Plast SP 300 widely used for plastic injection moulds. The hardness of this material is 300 HB. Its chemical composition is presented in Table 1.

Table 1.
Chemical composition of the SP300 steel

Chemical composition	C	Mn	Cr	Mo	S	Specific additives
Weight (%)	0.25	1.3	1.3	0.4	0.02	Ca, V, B

The ball-end tool from, "Widia" is composed of two teeth and is a carbide base (94% WC + 6% Co) coated with TiCN (Table 2).

The study aimed to compare machined surfaces based on six different finishing strategies. The radial depth of cut or radial engagement a_e, axial depth of cut a_P, feed per tooth f_z and the feed-rate V_f, are kept unchangeable. The table 3 gives constant machining parameters.

Table 2.
Tool geometries

Carbide coating	TiCN
Diameter D	16 mm
Teeth number	2
Rake angle	0 °
Flank angle	15 °

The increasing attention to the environmental and health impacts of industry activities by governmental regulation and by the growing awareness in society is forcing manufacturers to reduce or eliminate the use of lubricants [22]. The advantages of try milling are:

Non-pollution of atmosphere or of water which reduces the danger to health, in particular, skin and respiratory damage,
No residue of lubricant on machined components which reduces or eliminates cleaning costs and associated energy consumption,
No residue of lubricant on evacuated chips which reduces disposal costs and the associated energy consumption.

Table 3.
Cutting parameters

Radial cutting depth a_e (mm)	0,5
Axial depth of cut a_p (mm)	0,4
Feed per tooth f_z (mm)	0,1
Feed-rate V_f (mm/min)	377

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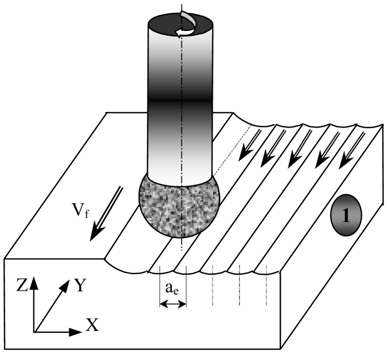
Non-pollution of atmosphere or of water which reduces the danger to health, in particular, skin and respiratory damage,
No residue of lubricant on machined components which reduces or eliminates cleaning costs and associated energy consumption,
No residue of lubricant on evacuated chips which reduces disposal costs and the associated energy consumption.

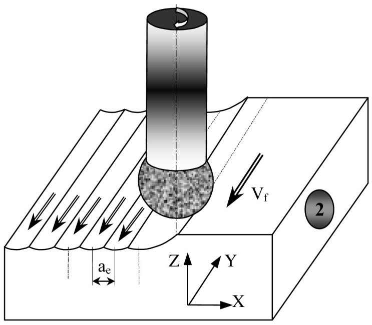
However, the machining operation was used not of lubricants. The spindle speed, directions and the angles of inclination of the tool used for each finishing configuration strategy are presented at Table 4 and Figure 6.

Table 4.
Machining configuration (from (1) to (6))

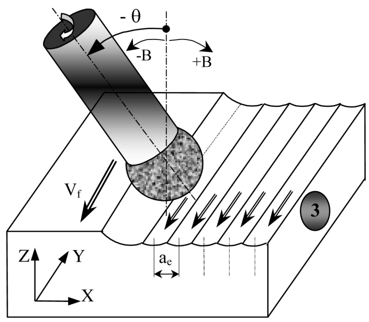
Configuration	Tool angle θ (°)	Spindle speed n (rpm)	Feel slope of the tool
(1)	0	3695	Without inclination, a_e towards –X, V_f direction is according to –Y
(2)	0	3695	Without inclination, a_e towards +X, V_f direction is according to –Y
(3)	-17	1886	Inclination according to –B, a_e towards –X, V_f direction is according to –Y
(4)	-17	1886	Inclination according to –B, a_e towards +X, V_f direction is according to –Y
(5)	0	3695	Without inclination, a_e towards +X, V_f direction is in zigzag
(6)	-17	1886	Inclination according to –B, a_e towards –X, V_f direction is in zigzag



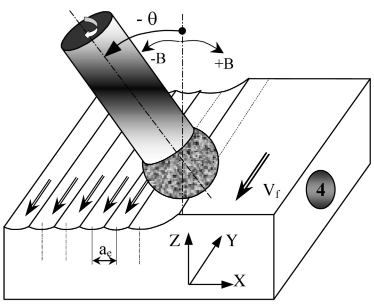
Configuration (1)



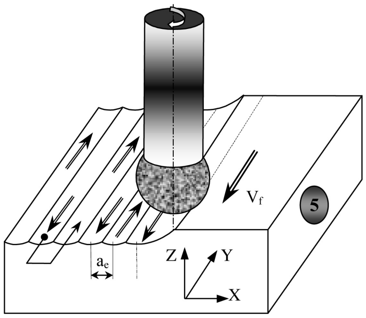
Configuration (2)



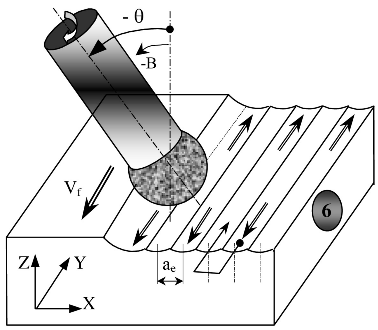
Configuration (3)



Configuration (4)

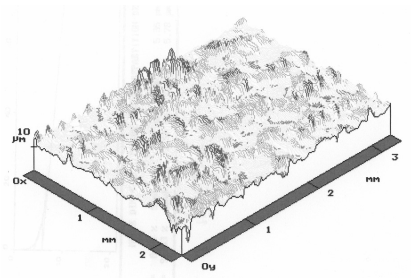


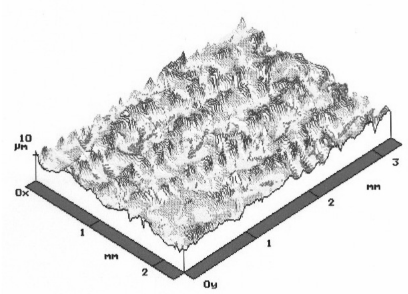
Configuration (5)

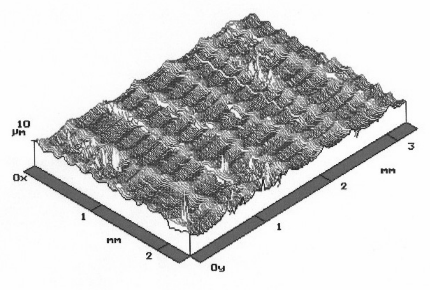


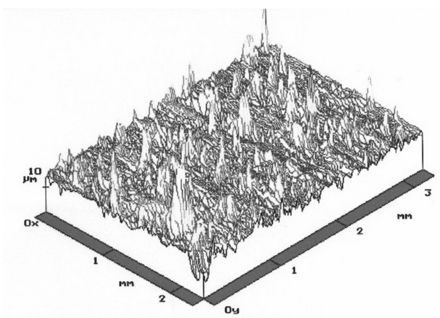
Configuration (6)

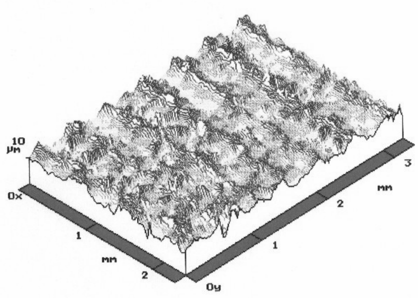
Fig. 6. Six machining configurations


Configuration (1)


Configuration (2).


Configuration (3).


Configuration (4)


Configuration (5)

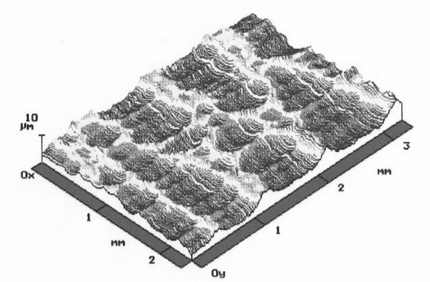

Configuration (6)

Fig. 7. Micro geometric topography of machined surfaces for six configurations

3.2. Experimental results and discussion

At present, in most industrial applications, 2D surface roughness parameters such as Ra and Rt are commonly used. However, it is a recognised fact that surfaces inter act in three dimensions and in two dimensions.
Consequently, specifying 2D surface parameters can be quite restrictive and misleading.
Additionally 3D surface roughness parameters can assess real properties of roughness which clearly relate to the manufacturing route and the surface functionality.

3D surface topography measurements were carried out using 3D Surfascan with a 90° diamond conical stylus of 2 µm tip radius. The sampling area for each specimen was set to 3 mm x 4 mm of the machined surface, and the *y*-axis measurement interval was set to 12 µm. The number of data points collected for 4 mm length (*x*-axis) line was 1024.
To characterise surface topography, statistic parameters are used: Sa and Sq, respectively, The arithmetical average mean deviation of the surface and root average square value of the surface departures within the sampling area.

The presentation of topographies of surfaces of the six milling configurations (1) to (6), (see Figure 7) is obtained of the 3D Surfascan (Somicronic) profilometer via an associated surface and filtered in *x*-axis and *y*-axis, in order to represent only the surface micro-geometry.

The analysis of the results of the micro-geometrical topography of surface (see Figure 7), and the parameters characteristic 2D/3D (of the profile of the machined work-piece, show the improvement of the machined surface texture quality-piece when it is machined with inclination of tool axis of -17° following Y and milling in one-way (Figure 7. configuration (3)). Surface texture obtained from the third finishing strategies present the following characteristics:

- Good micro-geometrical surface topography,
- Regular depth and distance between two consecutive paths on all the machined surface,
- Better values of the arithmetic average deviation of roughness (Ra = 0.6 µm to 0.7 µm), of waviness (Wa = 0.6 µm to 0.7 µm) and of profile (Pa = 0.9 µm to 1 µm),
- Low values of the three dimensional parameters of surface roughness (see Figure 8) (arithmetic mean deviation of the surface Sa = 0.7 µm, root mean square deviation of the surface Sq = 1 µm) and low anisotropy.

On the other hand, if the tool axis is normal on the machined surface, and machined in one-way or in zigzag, (Figure 7 configurations (1), (2), (5)), the result of the analysis of the surface quality presents a bad micro-geometrical quality:

- Mediocre topography, crushing cut,
- Important anisotropy checked by the parameters of roughness (Ra = 1.05 µm to 1.2 µm), of waviness (Wa = 0.7 µm to 0.9 µm) and of profile (Pa = 1.5 µm to 1.7 µm).
- High values of the three dimensional parameters of surface texture (see Figure 8) (arithmetic mean deviation of the surface Sa = 1.3 µm, root mean square deviation of the surface Sq = 1.6 µm).

The significant difference between the results in the longitudinal and transverse direction shows well the deterioration of the surface quality obtained in three axis machining: when work is completed with a normal tool axis on the machined surface (machining with very low cutting speeds, even null in the centre of the cutter (configuration (1), (2) and (5)).

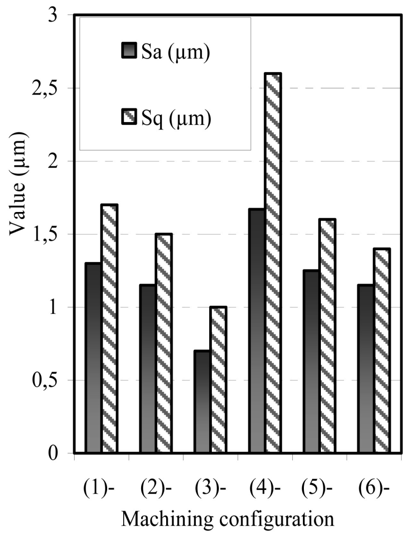


Fig. 8. Parameter 3D surface roughness Sa and Sq of six machining configurations

On the other hand, the fact of using the fifth machine spindle with a suitable inclination of the tool axis improves considerably the surface quality and the cutting process.

These analyses reveal also the influence of the tool trajectory on the surface topography. All the values of the two-dimensional and three-dimensional parameters of surface quality of the machined piece in zigzag are very high compared to the part machined in one-way ticket with the same inclination of the tool axis (respectively configuration (6) and configuration (3) see Figure 6 and Figure 7). In fact, the micro-geometrical topography of the surface (Figure 7 configuration (6)) of machined in zigzag presents an important variation of depth and distance between two successive paths because the irregular cutter deflection and the variation horizontal component of the cutting force. Moreover, the evolutions recorded between two peaks are random, which involves much more difficulties during manual polishing.

The examination of the results of the topography and the parameters of surface quality of the machined piece according to the configuration (4), with a tool inclination of -17° following -Y, (see Figure 6 configuration (4) , Figure 7 and Figure 4) present a bad micro-geometrical surface, including several peaks and hollow of very large values on all the machined surface.
Surface obtained is strongly rough, with an important anisotropy. The maximum height of roughness Rt reaches a very large value (Rt = 27 µm) for configuration (4) as compared to of the Rt = 10 µm for configuration (3).

In addition, a strong level of noise during the work of the cutter was recorded during the machining operation. All these negative results are the consequence of the kinetics of the cut; indeed, the active part of the edge of cut near to the tool axis has a feeble cutting speed factory the great section of chip (h_{max} maximum thickness of the chip) (see Figure 4). We can conclude that milling according to the configuration (4) is unfavorable not only for the surface quality of the produced work-piece but also for the tool life.

4. Conclusions

This paper has investigated the effect of the tool orientation on the variation effective cutting speed, on the surface texture, while multi-axis milling of dies and moulds for plastic injection.

Experimental results described in previous paragraphs have shown that disadvantages of three axes machining results from the existence of very low cutting speeds, even null when the tool axis is normal to the machined surface. This mode of machining generates a bad surface quality. Surfaces have a poor topography and important anisotropy: the values of the transversal and longitudinal surface quality parameters are very different.

A suitable slope of the cutting tool by the means of the fifth machine tool axis, improves considerably work piece machined surface quality:

- Good micro-geometrical surface topography.
- Lower surface roughness.
- Lower polishing time.

Acknowledgments

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