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Influence of workpiece inclination angle on the surface roughness in ball end milling of the titanium alloy Ti-6Al-4V

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ABSTRACT

Purpose: The aim of this work is to provide an in-depth understanding of the surface texture produced by various workpiece inclination angles using high speed finish ball end-milling of the titanium alloy Ti-6Al-4V.
Design/methodology/approach: This paper presents an approach to develop a mathematical model of surface roughness in end-milling by the experimental design methodology. Machining variables such as cutting speed, feed and radial depth of cut, which are easily controllable, are considered in building the model. The influence of the workpiece inclination angle on the surface roughness of the machined workpiece was also investigated.
Findings: According to the mathematical model, an increase in either the feed or the radial depth of cut increases the surface roughness, whilst an increase in cutting speed decreases it. The radial depth of cut ae is the most significant parameter in the model. Results analysis of the 2D/3D surface roughness parameters of the machined parts shows the improvement of the surface roughness quality when it is machined with a workpiece inclination angle of 25°.
Research limitations/implications: As perspectives of this work, we can study the influence of the different machining strategies on the surface integrity of this titanium alloy, including the study of the residual stress.
Practical implications: We propose to study the improvement of the surface quality of the orthopedic prostheses, which is an influencing parameter in their lifetime, by implementing the high speed cutting technique. The mathematical model of the surface roughness is a very important result of this work. In fact, it allows selecting the best cutting conditions to obtain a better workpiece surface quality.
Originality/value: In this work, three dimensional surface roughness parameters were studied: the 3D surface topographies were obtained using a 3D measurement station and the mathematical model of Sa. The arithmetic mean deviation of the surface was established in order to minimize the experimental works and to have an idea about the surface roughness evolution as a function of cutting parameters.
Keywords: Machining; Ball end milling; Workpiece inclination angle; Surface roughness; Titanium alloy

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1. Introduction

The end-milling process is one of the most widely-used material removal processes in industry. The cutting operations by end mills are employed for finish machining of sculptured surfaces such as medical prostheses, dies, moulds, turbine blades and aerospace parts. These products have very demanding specifications in surface quality, which in most cases represents a technical requirement for them.

Ball nose cutter is generally used for finish milling due to the fact that the cutter readily adapts well to machining free-form surfaces. However, finish milling on a plane surface generally results in short tool life since the effective cutting speed at its tip is zero and the effective chip space is very small [1-8]. A minimum cutter or workpiece inclination angle is therefore needed to avoid cutting at the tip of the cutter.

Extensive research work has been developed around the inclined milling operation. In particular, the topic of the surface roughness seems to have recently attracted the attention of many researchers. Baptista et al. (2000) [2] suggested that surface roughness was improved with the inclined milling in the feed direction. Tonshoff et al. (1989) [3] found that the optimal inclined angle was 15° in ball end-milling of block materials. Boujelbene et al. (2007) [4] found that downward/reverse milling with a tool inclination in the range of 10-25 degrees represents the optimum machining strategy in ball end-milling of a specific HB 300 pre-hardened mould steel Super Plast (SP 300).

Literature survey is scant on the study of the surface topography analysis relating to the workpiece inclination angles when high speed finish inclined milling is used. Previous works were either involved in conventional milling of easy-to-cut workpiece materials or machining with different cutter path orientations. Still, they were limited to the quantitative study of R_a value, except C.K Toh (2004) [5] who detailed the true surface topography of the machined surface with regard to the cutter condition. This paper studies the 3D surface roughness parameter, S_a, and provides a qualitative understanding of the analysis of the surface texture when high speed finish milling difficult-to-cut workpiece material is used which in this case is the titanium alloy Ti-6Al-4V. This paper develops an approach to develop a mathematical model of surface roughness in end-milling by experimental design methodology. Machining variables such as cutting speed, feed and axial depth of cut, which are easily controllable, are considered in building the model.

The single direction vertical upward tool orientation was purposefully chosen to highlight a better understanding of how to achieve an optimum machined surface when high speed finish milling free form medical prosthesis is used, via surface topography analysis.

2. Effects of inclination angle and feed upon effective cutting speed

Many researchers have studied the inclined milling process in the past few years. Schulz et al. [6] and Bouzakis et al. [7] showed that machining with an inclination between the workpiece and the hemispherical tool modifies the shapes and dimensions of the chips. In addition, Altan et al. [8] confirmed that this inclination angle improves the tool wear resistance of CBN in milling of moulds steel (45 HRC). Also, 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-axis of the nuance "Arcelor" SP 300 for plastic injection moulds pretreated to 300 HB. Recently, Iqbal et al [10] found that workpiece inclination angle proved to be the most influential parameter for surface roughness.

In this study, we attempt to determine the best inclination angle on the surface quality state according to the machining conditions, as well as the minimal values of workpiece inclination angle and the effective cutting speed $V_{c\text{-}eff}$ in every configuration.

In Figure 1, we are working in the case of inclined milling process, employing single direction vertical upward orientation. The effective diameter $D_{eff} \leq D$ of the end mill can be visualized as follows.

$$D_{eff} = 2 \times \max \begin{Bmatrix} R\sin(\theta - \arcsin(\frac{f_z}{2R})) \\ R\sin\theta \\ R\sin(\theta + \arccos(\frac{R-a_p}{R})) \end{Bmatrix} \tag{1}$$

The combinations of the maximum radius of tool R, axial depth of cut a_p, feed per tooth f_z and inclination angle θ, for which R_{eff} superior at 0, suggest that the centre of the tool is not involved in the cutting of the material [4-10].

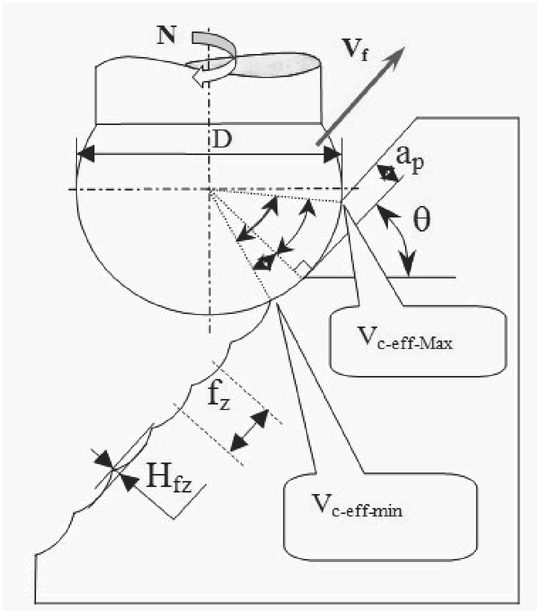

Fig. 1. The effective cutting speed $V_{c\text{-}eff}$ for inclined milling, Vertical up milling orientation

Eq. (1) suggests that the value of effective diameter of the tool depends on the axial depth of cut, feed rate and workpiece inclination angle. The maximum and the minimum cutting speeds $V_{c\text{-}eff\text{-}Max}$, $V_{c\text{-}eff\text{-}min}$ of the end mill can be represented as:

$$V_{c-eff-Max}=\frac{2\pi.N.R.\sin\left(\theta+\arccos\left(\frac{R-a_p}{R}\right)\right)}{1000} \qquad (2)$$

$$V_{c-eff-\min}=\frac{2\pi.N.R.\sin\left(\theta-\arcsin\left(\frac{f_z}{2R}\right)\right)}{1000} \qquad (3)$$

where $V_{c\text{-}eff\text{-}Max}$ denotes the maximum effective cutting speed, $V_{c\text{-}eff\text{-}min}$ represents the minimum effective cutting speed, R and D describe the nominal radius and the diameter of a ball-end cutter, θ denotes the surface inclination angle, a_p is the axial depth of cut, fz represents the feed per tooth a_e denotes radial depth of cut and N is the spindle speed.

3. Experimental work and conditions

The optimum selection of cutting conditions is very important in manufacturing processes as these ones determine surface quality and dimensional precision of the obtained parts. Thus, it is necessary to know, in advance, the properties relating to the surface quality and the dimensional precision by means of theoretical models which allow doing some predictions taking into account the cutting conditions such as the axial and radial depths of the cut, the feed per tooth (mm/tooth), the cutting speed, etc…

This study is mainly focussing on aspects related to surface quality and dimensional precision, which are the most important parameters form the point of view of selecting the optimum conditions of processes as well as of economical aspects. Functions making it possible to optimise parameters related to surface quality in HSM will be obtained by means of using design of experiments.

3.1. Experimental setup

A number of cutting experiments was carried out in order to obtain experimental data in wet cutting conditions on a Deckel Maho DMU 50 evolution five-axis CNC milling machine equipped with a maximum spindle speed of 18,000 rpm and Siemens control 840D [11] (see Figure 2). Cemented tungsten carbide uncoated inserts were used for the milling tests. These inserts are manufactured by Sandvik and their reference was R216F-16 40 E-L P20A and the tool holder reference was R216F-16A16S-063. The milling tool was changed after eight operations in order to assure that tool wear does not affect surface roughness.

3.2. Workpiece material

Titanium alloys have been widely used in the aerospace, biomedical, automotive and petroleum industries because of their good strength-to-weight ratio and superior corrosion resistance. However, it is very difficult to machine these alloys. Among all titanium alloys, Ti–6Al–4V is most widely-used. Thus, it has been chosen as the workpiece material in this study. Its nominal composition (wt%) and mechanical properties are shown in Tables 1 and 2, respectively [12,13].

a)

b)

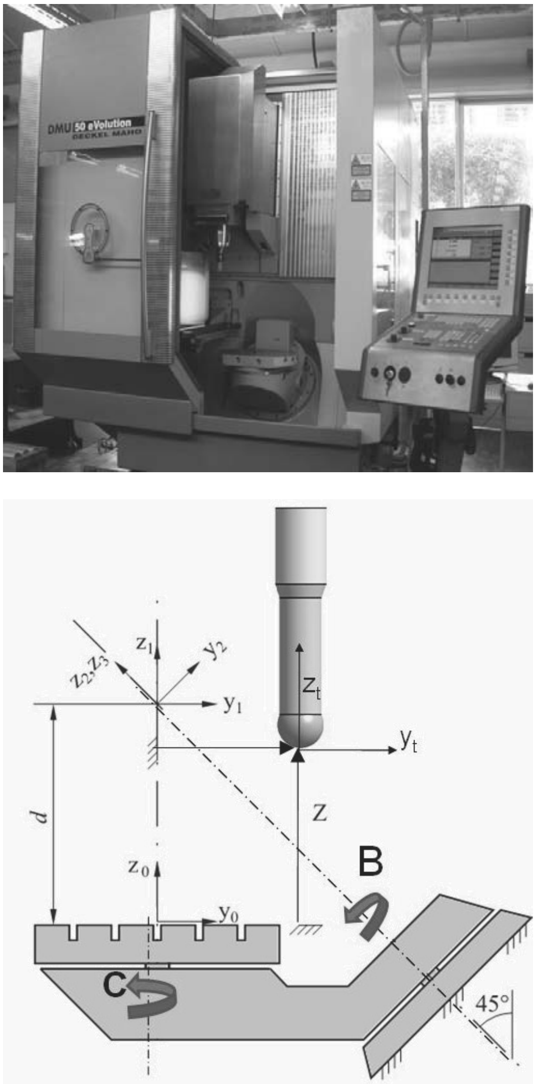

Fig. 2. Five-axis milling machine; (a) Machine picture, (b) Kinematics of 5 axis machine (3 axis X, Y, Z and 2 rotations B and C).

Table 1.
Chemical composition (%) of Ti–6Al–4V Alloy

Element	%
Ti	Balance
Al	6
V	4
Fe	0.3
C	0.08
N	0.05
H	0.01
O	0.2

Table 2.
Physical and chemical properties of Ti–6Al–4V Alloy

Melting point (°C)	1670
Thermal conductivity (W⁄m°K)	7,3
Hardness (HB)	350
Density (g⁄cm3)	4,43
Elongation (%)	14
Tensile strength (MPa)	1000
Modulus E (MPa)	115000

3.3. Surface roughness measurements

Surface roughness is defined as the inherent irregularities of the workpiece affected by machining processes. There are many parameters used in the literature and industry related to surface roughness. The most popular of the 3D parameters is the arithmetic deviation *Sa*, parameter characterizing the arithmetic mean heights of surface, and of the 2D parameters is the average roughness Ra. Mathematically, Ra is the arithmetic value of the departure of the profile from centreline along the sampling length [14]. The manufactured surfaces, in this study, were measured by a 3D measurement station STIL Micromeasure 2, which is optimized for roughness measurement and 3D micro-topography.

This station is equipped with an optical head which allows the sweeping of surface and a software program for the treatment of results. Two methods of analysis of surface qualities of the workpieces were adopted. An analysis of the 3D micro-geometrical surface quality obtained by sweeping on a square of 2 mm x 2 mm of the machined surface, with a step of 2 µm in $X_{Surface}$ and 2 µm in $Y_{Surface}$, in order to establish an associated surface and to highlight various topographies of surfaces.

To analyze these results, the implemented representation corresponds to the associated surface rectified and filtered in $X_{Surface}$ and $Y_{Surface}$ in order to represent only the topography of micro-geometry. The filters used are the Gaussian ones length of cut of 0,8 mm in $X_{Surface}$ and 0,8 in $Y_{Surface}$. Roughness measurements surfaces were repeated at least twice and an average of two Sa was recorded in Table 4. The second method of analysis used is the 2D determination of the parameters of roughness according to the average line; that is to say arithmetic *Ra* average deviation of the profile, *Rt* maximum height of the profile. The machined surfaces were cleaned by air-pressure before each roughness measurement.

3.4. Experimental conditions

Many points appeared important to consider. However, we limited ourselves to the exploration of the influence of the workpiece inclination angle on the surface roughness; all the experiments were carried out with the vertical up milling machining strategy (see Figure 3) and the cutting parameters of the Tables 3, 4, and 5.

4. Surface roughness model

A machinability model may be defined as a functional relationship between the input of independent cutting variables (cutting speed, feed per tooth, depth of cut) and the output known as response (surface roughness, tool life) of a machining process. In order to develop this model, it is necessary to design and carry out an experiment involving the work material and the cutting tool. The experimental work provides the response data as a function of the cutting speed V_c, feed per tooth and radial depth of cut. The experimental design methodology is a combination of experimental and regression analysis and statistical inference. This concept involves a dependent variable y called the response variable and several independent variables $x_1, x_2, \ldots, x_n$ [15-18].

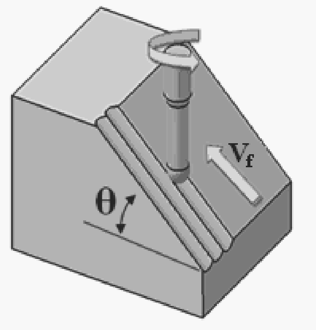

Fig. 3. Vertical up milling machining strategy

If all of these variables are assumed to be measurable, the response surface can be expressed as:

$$y = f(x_1, x_2 ..., x_n) \tag{4}$$

The goal is to optimize the response variable y. It is assumed that the independent variables are continuous and controllable by the experimenter with negligible error. The response or the dependent variable is assumed to be a random variable. For particular work-tool geometry, the surface roughness *Sa* in end-milling is assumed to be a function of cutting speed V_c, feed per tooth f_z and radial depth of cut a_e.

The multiplicative model [15 - 18] for the predicted surface roughness (response surface) in the end-milling in terms of the independent variables investigated can be expressed as:

$$S_a = C V_c{}^k f_z{}^l a_e{}^m \tag{5}$$

where S_a is the predicted surface roughness (µm) and *C, k, l* and *m* are the model parameters to be estimated from experimental data. Eq. (5) may be written as:

$$\ln S_a = \ln C + k \ln V_c + l \ln f_z + m \ln a_e \tag{6}$$

Two common forms of polynomials that can be adopted to represent the predicted surface roughness in end-milling are the first-order polynomial:

$$y = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \tag{7}$$

And the second-order polynomial

$$y = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \tag{8}$$

where y is the proposed predicted response (roughness) on the natural logarithmic scale, whilst x_0 = 1 and x_1,x_2,x_3, are logarithmic transformations of V_c, f_z and a_e respectively and b_i are parameters to be estimated by applying linear multiple-regression analysis.

The independent variables are coded as follow:

$$x_0 = \frac{Max + \min}{2} \tag{9}$$

$$\Delta x = \frac{Max - \min}{2} \tag{10}$$

$$X_i = \frac{x_i - x_0}{\Delta x} \tag{11}$$

$$X_1 = 2{,}8854 x_1 + 5{,}6439 \tag{12}$$

$$X_2 = 1{,}8205 x_2 - 8{,}1218 \tag{13}$$

$$X_3 = 2{,}3604 x_3 + 1{,}8419 \tag{14}$$

Although there are various types of design of experiments that can be considered, we are going to use factorial design in this study as it enables to experiment with all combinations of variables and levels.

The first order model of the surface roughness was developed by utilizing the least-squares method. Using 8 tests, the parameters in Eq. (5) were estimated, yielding the following surface roughness predicting equation:

$$S_a = 5{,}1.f_z^{\,0{,}095} V_c^{\,-0{,}083} a_e^{\,0{,}592} \tag{15}$$

Eq. (15) indicates that an increase in either the feed or the radial depth of cut increases the surface roughness, whilst an increase in cutting speed decreases it. This equation is valid for the ball-end milling of the titanium alloy Ti-6Al-4V using carbide uncoated tools with the following cutting parameters ranges:

$0{,}1 \le f_z \le 0{,}2\ mm/tooth$,

$50 \le V_c \le 150\ m/min$,

$0{,}3 \le a_e \le 0{,}7\ mm$.

Figure 4 shows the effects of the three parameters tested upon the surface roughness parameter Sa. From the slopes of plots it is obvious that the effect of only the radial depth of cut a_e is significant (see Figure 4 c). In fact, it can be seen that increasing the values of radial depth of cut leads to worsening of the machined surface because of the fact that higher a_e values cause the formation of cusps of increased height values. These cusps result in increasing the surface roughness values; especially for the roughness measured along the pick feed direction.

5. Influence of the inclination angle in the surface topography

According to many researchers, C.K. Toh [5], A. Antoniadis [19] and M. Cosma [20], the surface roughness obtained with vertical up milling is better than the one obtained with vertical down milling. In Fact, down milling operations along inclined surfaces should be avoided as much as possible. When down milling, the chip thickness is large at a low cutting speed. So, there will be a risk of centre frittering, especially when the cutter hits the bottom area. It is somehow better for the cutting process to do up milling along inclined surfaces as the chip thickness has its maximum at a more favourable cutting speed [15-25].

The influence of the workpiece inclination angle on the surface roughness is demonstrated in Figure.5. In this figure the 3D analysis of micro-geometrical surface quality is illustrated.

a)

b)

c)

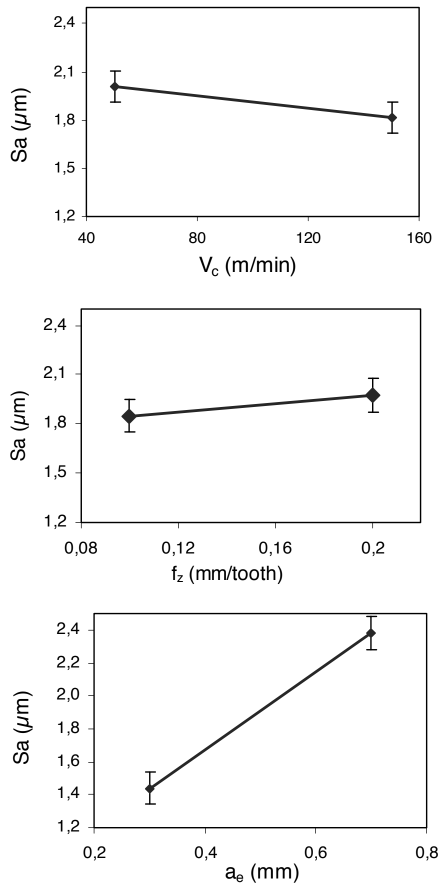

Fig. 4. Effects of tested parameters upon surface roughness Sa; (a) $Sa = f\,(Vc)$, (b) $Sa = f\,(f_z)$, (c) $Sa = f\,(a_e)$

The analysis of the results of the surface micro-geometrical topography and the parameters characteristic of the profile of the machined parts, with or without slope of workpiece, shows the improvement of the quality of surface roughness when it is machined with a slope of 25°:

- Good micro-geometrical topography of surface,
- Better values of the parameters of arithmetic average deviation of roughness (Ra = 0.3 to 0.7 µm), of undulation (Wa = 0.6 to 0.7 µm) and of profile (Pa = 0.4 to 1 µm),
- Low values of the 3D parameters of surface texture (see Figure.6) (arithmetic mean deviation of the surface Sa = 1.06 µm, root mean square deviation of the surface Sq = 1.26 µm) and low anisotropy.

Table 3.
Levels of independent variables and coding identification

		General model			Linear model		
Level	Coding	f_z (mm/tooth)	V_c (m/min)	a_e (mm)	$x_1 = \ln f_z$	$x_2 = \ln V_c$	$x_3 = \ln a_e$
Min	-1	0.1	50	0.3	-2.3026	3.9120	-1.2040
Max	1	0.2	150	0.7	-1.6094	5.0106	-0.3567

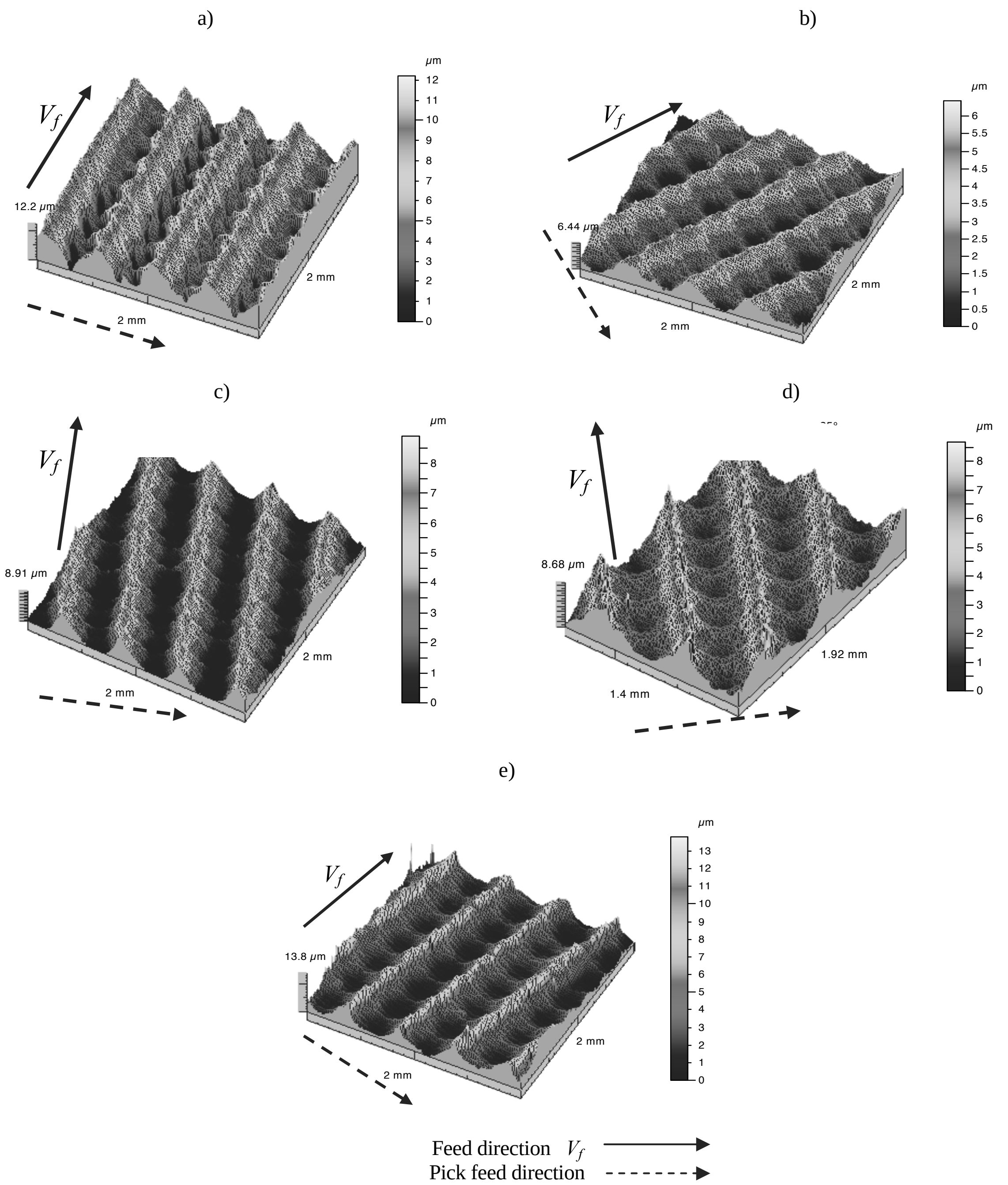

Fig. 5. 3D surface topographies for various workpiece inclination angles; (Axial depth of cut a_p=0,4 mm; Feed per tooth fz=0.15 mm/tooth, Radial depth of cut: a_e = 0.5 mm , Vertical up milling); (a) $\theta = 0°$, (b) $\theta = 25°$, (c) $\theta = 45°$, (d) $\theta = 60°$, (e) $\theta = 88°$

Table 4.
Experimental conditions and results

Trial number	Cutting parameters			Coding			Surface roughness
	f_z (mm/tooth)	$V_{c\text{-}eff}$ (m/min)	a_e (mm)	X_1	X_2	X_3	Sa (µm)
1	0.1	50	0.3	-1	-1	-1	1.42
2	0.2	50	0.3	1	-1	-1	1.53
3	0.1	150	0.3	-1	1	-1	1.37
4	0.2	150	0.3	1	1	-1	1.44
5	0.1	50	0.7	-1	-1	1	2.46
6	0.2	50	0.7	1	-1	1	2.62
7	0.1	150	0.7	-1	1	1	2.14
8	0.2	150	0.7	1	1	1	2.31

Table 5.
Experimental conditions to study the influence of the workpiece inclination angle

D = 16 mm ; f_z = 0.15 mm/tooth ; a_p = 0.4 mm ; a_e = 0.5 mm;
N = 3000 rev/min ; V_f = 900 mm/min ; Dry cutting ;
Vertical up milling/ One-way

Trial	1	2	3	4	5
Angle (°)	0	25	45	60	88

On the other hand, for the parts machined with a normal or quasi-normal tool on the surface to machine, the result of the analysis of the surface quality reveals a bad micro-geometrical quality:

- Poor Topography, crushing cut,
- Too much vibration,
- Strong anisotropy checked by the parameters related to average line: of roughness (Ra = 0.8 with 1.66 µm), of undulation (Wa = 0.7 to 0.9 µm) and of profile (Pa = 1 to 2.2 µm).

6. Conclusions

In this paper, the effect of inclination angle in the ball-end milling was presented. From the results, it appeared that the effect of inclination angle in the resulting surface quality is very important.

Moreover, we showed the importance of 5-axis machining. This technology allows the slope between the cutting tool and the surface to be machined. This considerably improves the obtained surface roughness. Indeed, the problem of 3-axis machining results from the existence of very low cutting speeds when the axis of the ball-end mill is normal on the workpiece surface. This mode of machining generates a bad quality of surface roughness, leading to surfaces of poor topography and of strong anisotropy which can be observed by comparing the values of the transversal and longitudinal parameters of the surface roughness.

Inclined milling with hemispherical-end tool generates a variation of the effective cutting speed which depends on additional parameters of the cut such as the inclination angle and the tool path, and other operational parameters: radial depth of the cut a_e, feed per tooth f_z as well as the feed direction. It is suitable to claim that the machining directions and strategies also influence the micro-geometry, the machined surface integrity and tool life, which should be studied to optimize the surface quality of the medical prostheses.

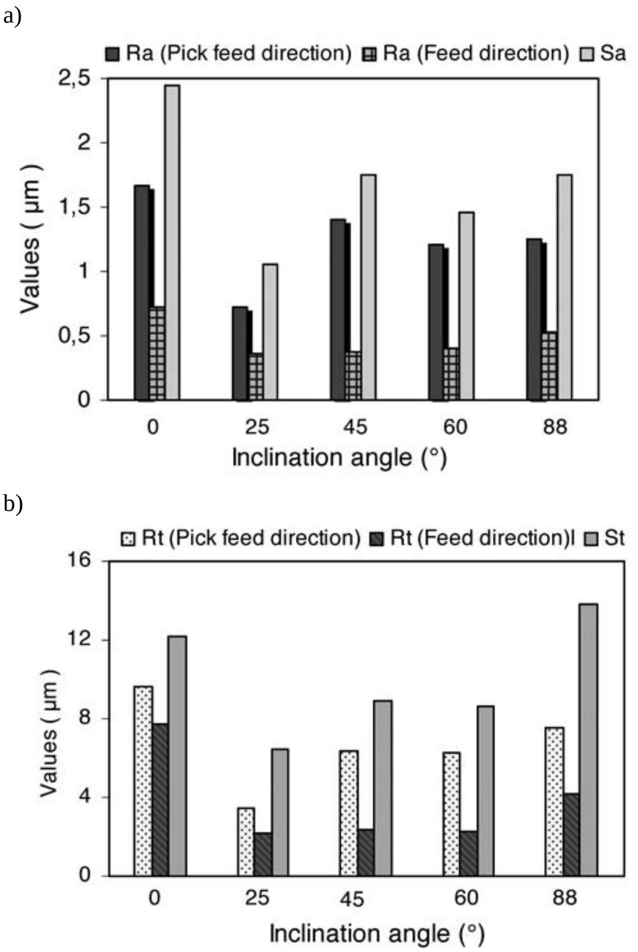

Fig. 6. Parameters of roughness according to the Feed and Pick feed directions; (a) Values Ra and Sa, (b) Values Rt and St

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