SURFACE ROUGHNESS VARIATION IN BALL END MILLING OF C45 MATERIAL. PART I: INCLINATION OF TOOL AXIS IN FEED POSITIVE DIRECTION

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Abstract: *This paper primarily presents important experimental results, about surface roughness variation in ball end milling, for the case of tool axis inclination in feed positive direction. Secondary, using experimental results an mathematical model was proposed in order to estimate the surface roughness for different values of tool axis inclination. Because the surface roughness is a good indicator for process performance, it is important to identify the optimum conditions in order to obtain good results with low cost. In this paper the influence of inlination angle and speendle speed value upon surface roughness was investigate. The final purpose of this study is to develop an prediction function of surface roughness in ball end milling for the case of inclination in feed positive direction.*

Keywords: *inclination, milling, roughness, angle, direction.*

1. Introduction

The cutting tool life and the quality of manufactured surface constitute the more important factors in each manufacturing process [1]. Milling, using ball-end tools is extensively used for the finishing processes for freeform surfaces [2].

In ball end milling it is possible to obtained a high quality of surface machined only considering the influence of a great number of factors such as: inclination angle of tool axis against surface normal, cutting parameters, material quality of workpiece, cutting tools properties and stability of machine tools. All these factors should be chosen to have a minimal negative influence in the process. This is why a great number of researchers are involved to study the influence of these factors on the machined surface quality.

Variation of surface roughness and tool life upon effects of four parameters, namely, hardened steels's microstructure, workpiece inclination angle, cutting speed and radial depth was study in paper [9].

Another paper [8], present an model for surface roughness with following variables: feed, cutting speed and depth of cut.

If in paper [16] the researchers conclude that feed rate was the most significant machining parameter used to predict surface roughness, in paper [9] the most important parameter is considered the angle of tool axis inclination.

Because the cutting speed at the center of a ball-end cutter is equal to zero, this unfavorable cutting condition leads to poor workpiece surface qualities and tool wear. By introducing an inclination of the tool-axis in raport with surface normal, the zero cutting speed condition can be avoided [4].

Some theoretical models for prediction of surface roughness are proposed by a great number of researchers. In papers [3], [12] and [14], is proposed an model with influence of cutting speed and cutting depth. Influence of cutting speed, cutting depth and radial depth is analyzed in paper [6]. Another proposal model was presented in study [8] where the cutting speed , hardness of material and tool radius was considered the most important parameters.

After the literature rewiev, it is possible to conclude that the surface roughness is particularly sensitive to the spindle speed and inclination angle of tool axis.

2. The Analysis of Tool Axis Inclination

In order to identify the best conditions for ball-end milling proces in terms of inclination angle it is necesary to identify both the value of inclination angle and direction of inclination.

Depending on the choice of the inclination angle corresponding to a certain axis, rotation can be applied to tool axis around the axis X,Y respectively Z, corresponding to the structural characteristics of machine tools.

Analysis of milling process by inclination of tool axis by a single angle of inclination is useful in relation to lead and tilt after two angles because it is easier to track implementation of the program and the possibilies to avoid collision are smaller and easier to avoid [11].

Identification of optimal value for inclination angle was the subject of an important number of researches. The difference between their results and solutions conclude that the problem was not solutioned yet. In this way, in paper [16] found that with inclination of the workpiece at 15 degrees value are obtained the best results. The optimum value for inclination angle indicated in paper [13] is located between 15 degrees and 20 degrees.

The studies [15] and [7] suggested that a tool inclination in the range of 10 degrees to 20 degrees represents the optimum machining strategy for high-speed milling in the die and mould making industry.

The posibilities of tool axis inclination in feed direction are presented in Fig. 1. In this paper was investigated the situation of inclination in feed positive direction with geometric elements shown in Fig. 2.

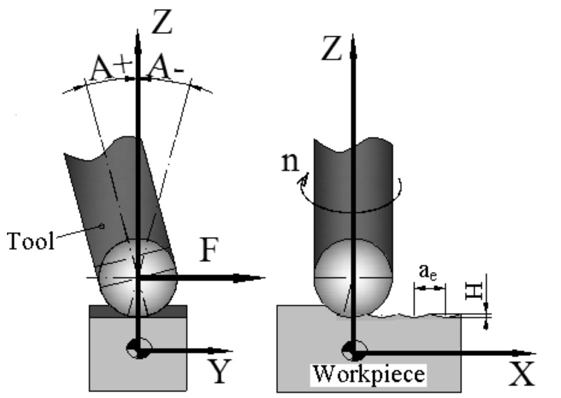

Figure 1: *Inclination of tool axis in feed direction*

3. Investigation of Effective Cutting Speed Variation

Variation of cutting speed is considered in most study an important parameters which may influence the surface roughness. In this way it is important to know the variation of effective cutting speed and the variables that leading to this situation. Geometrical, effective cutting speed depend by inclination angle value, spindle speed and tool diameter. In present study the tool diameter is considered constant with value indicated in Table 1. Both, inclination angle and spindle speed are variables of process in our experiments.

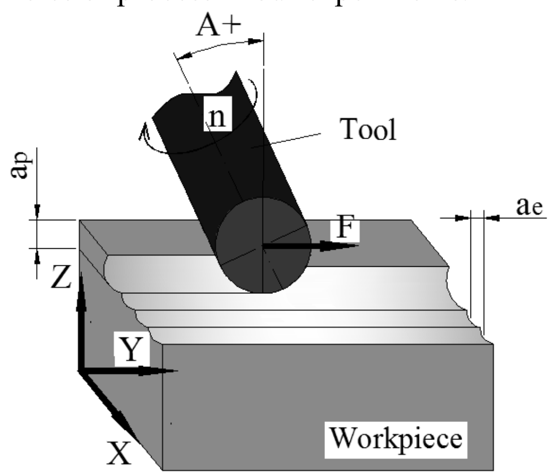

Figure 2: *Inclination of tool axis in feed positive direction*

Effective cutting speed $V_{c\text{-}eff}$ is given by relation (1) [5]:

$$V_{c-ef} = \frac{\pi \cdot n \cdot D \sin\left[\theta_n + \arccos\left(\frac{R - a_p}{R}\right)\right]}{1000} \quad (1)$$

with the following condition:

$$\arcsin\left(\frac{a_e}{2R}\right)\langle\theta_n \leq 90 - \arccos\left(\frac{R - a_p}{R}\right), \quad (2)$$

where:

-D – nominal diameter of tool [mm];

-a_p – cutting depth [mm];

-*n* – spindle speed [rot/min];

-θ_n – inclination of tool axis [grade];

-R – tool radius [mm].

Using the relation (1) we establish the values for effective cutting speed coresponding to our experiments. For each values of inclination angle and spindle speed that was used in present experimental study, was calculated the values for effective cutting speed and indicated in Table 1. For each value of inclinationa angle we used four different value of spindle speed, this fact led to obtaining four different values of effective cutting speed.

Table 1: Effective cutting speed values

Nr.	Tool axis inclination A [degree]	Spindle speed n [rot/min]	Effective cutting speed V_{c-ef} [m/min]
1	15	7500	175,9
2		10000	234,6
3		12500	293,2
4		15000	352
5	30	7500	256,2
6		10000	341,8
7		12500	427,04
8		15000	512,7
9	45	7500	318,8
10		10000	425,3
11		12500	531,4
12		15000	638
13	60	7500	360,1
14		10000	480,3
15		12500	600,13
16		15000	750,52
17	75	7500	376,5
18		10000	502,3
19		12500	627,6
20		15000	753,5
21	90	7500	376,8
22		10000	502,64
23		12500	628
24		15000	753,6

Based on the results presented in Table 1 it is possible to establish the dependence of effective cutting speed upon influence of inclination angle and spindle speed. Using the software TableCurve3D and interpolation method the variation of effective cutting speed may be plotted like a surface represented in Figure 3. Also, it is easy to establish values of effective cutting for another value of inclination angle and spindle speed which are different from those used in present paper.

For values of inclination angle less than 45 degrees, growth rate of effective cutting speed is high from one interval to another. For values of inclination angle higher than 45 degrees, growth rate of effective cutting speed is small from one interval to another. Increasing the value of spindle speed leads to a linear increase of effective cutting speed.

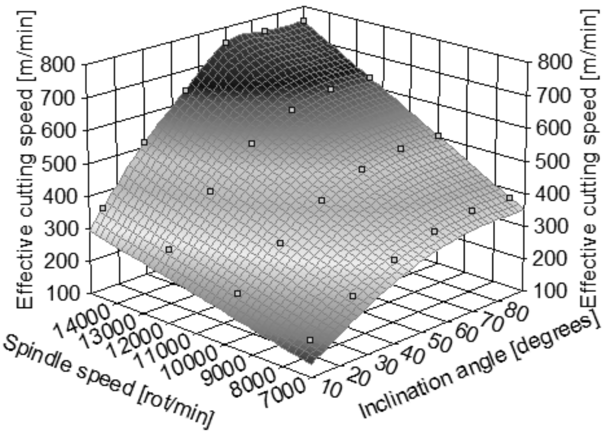

Figure 3: *Effective cutting speed variation depending by inclination angle and speendle-speed*

4. Experimental Work and Conditions

In the process of cutting with ball end mills, especially on complex surfaces, the cutting conditions vary depending on the point-area of contact between the cutting tool edge and workpiece [11]. Machining by using a cutting tool angle between the axis and machined surface can contribute to a higher quality of machined surface [1].

Considering that for values of inclination angle upper 30 degrees, much of the research carried out, are limited to analysis on surface quality for a lower inclination angle between 0 degrees and 20 degrees [17], or between 0 degrees and 30 degrees [13]. In paper [5] the researchers conclude that tilting the tool axis relative to machined surface with 45 degrees led to a low quality of surface. In order to verify and extend all these informations, to determine a variation of surface roughness it is necessary to make some experimental study. We attempt to establish the influence of inclination angle and spindle speed on the surface roughness, for inclination of tool axis in feed positive direction.

4.1 Experimental Setup

To begin analysis of surface roughness for different values of inclination angle and spindle speed, was necessary to make a number of experiments in conditions of tool axis inclination in feed positive direction. The experiments was made at S.C. RAMIRA S.A. by using an OKUMA MU400VA five-axis CNC milling machine presented in Fig. 4. The tools and the holder are manufactured by Mitsubishi Carbide and their reference was SRG16C-VP15TF for inserts and SRM2160SNM for the tool holder.

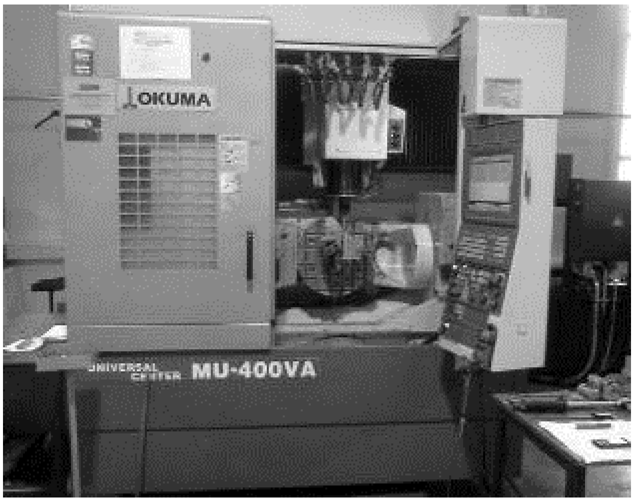

Figure 4: *MU400VA five-axis milling machine*

4.2 Workpiece Configuration

The workpiece geometry is indicated in Fig. 5. It is easy to see that the workpiece have six surface that was machined with ball end mill at different inclination angle. The material used was C45 with the following features: 0,42…0,50% C, 0,50…0,80% Mn, 0,17…0,37% Si, maximum 0,040% P etc.

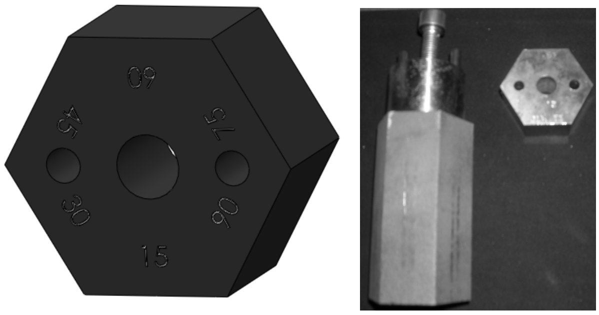

Figure 5: *Workpiece configuration*

4.3 Surface Roughness Measurements

In paper [5], the surface roughness is defined as the inherent irregularities of the workpiece affected by machining process. Between a great number of parameters used in literature, in paper [5] the author say that the most popular of the 2D parameters is the average roughness Ra. Mathematicaly, Ra is the arithmetic value of the departure of the profile from centerline along the sampling length [10]. To measure surface roughness with high accuracy the measurements was made in feed direction and perpendicular to feed direction. To ensure conditions of perpendicularity and parallelism between roughness tester feeler TR200 and feed direction was necessary the construction of the device shown in Fig. 6.

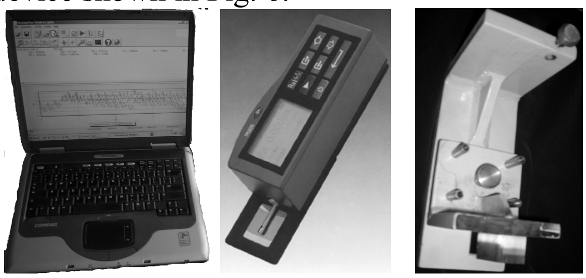

Figure 6: *Roughness tester TR200 with adaptor device*

4.4 Experimental Conditions

Based on the conclusions identified in paper [11], which shows that milling in feed direction leads to the best surface roughness, all the experiments was made using milling in feed direction. Direction of tool axis inclination that was study in our experiments was inclination in feed positive direction.

In this paper the geometrical parameters values used are presented in Table 2.

Table 2:Geometric parameters used

Nr	Geometric elements	Units of measurement	Values
1	Diameter of ball end mill	mm	16
2	Cutting depth	mm	0,2
3	Axial depth	mm	0,2
4	Feed per tooth	mm	0,1

The values of inclination angle in feed positive direction, that were used in our experiments are indicated in Table 3.

5. Experimental Results and Mathematical Modeling

The results of experiment about variation of surface roughness when inclination of tool axis is made in feed positive direction were centralized in Table 4. In terms to have a good knowledge of surface quality, the measurements of roughness was made in feed direction and perpendicular to feed direction.

Table 3: Experimental conditions

Nr	Direction of inclination	Milling direction	Inclination angle [degree]
1	Feed positive direction	Conventional milling	A15B0 A30B0 A45B0 A60B0 A75B0 A90B0

According with results presented in Table 4, we can say that choise of inclination angle of tool axis relative to the surface normal and spindle speed value is important, because siginificant differences can arise in terms of quality.

Table 4: Experimental results

Inclination angle A positiv [degrees]	Spindle speed [rot/min]	Roughness [µm]	
		Feed direction	Pick feed direction
15	7500	0,494	0,526
	10000	0,282	0,536
	12500	0,280	0,304
	15000	0,329	0,434
30	7500	0,425	0,511
	10000	0,367	0,506
	12500	0,325	0,544
	15000	0,260	0,483
45	7500	0,958	1,888
	10000	1,441	1,542
	12500	0,505	0,688
	15000	0,929	1,018
60	7500	0,396	0,424
	10000	0,445	0,607
	12500	0,230	0,383
	15000	0,387	0,380
75	7500	0,417	0,460
	10000	0,531	0,712
	12500	0,332	0,621
	15000	0,519	0,585
90	7500	0,614	0,799
	10000	0,852	0,575
	12500	0,454	0,679
	15000	0,971	0,502

Variation of surface roughness in ball end milling of C45 in condition of different inclination angle values in feed positive direction and at different value of spindle speed is presented in Fig. 6 for measurements made in feed direction.

For the situation when measurements was made perpendicular to feed direction variation of surface roughness is presented in Fig. 8.

In order to drawing the surface that represent the variation of surface roughness for measurements made in feed direction and perpendicular to feed direction was used the software TableCurve3D.

If in Fig.7 and Fig.9 are represented the variation of surface roughness by using experimental data, situation that is useful when in practice we used the same values. For different values of spindle speed and inclination angle in feed positive direction was necesary an interpolation method to estimate the surface roughness value for another values of this parameters. In this way, using the software TableCurve3D we identified by selection from a great number of function, an model of function that was the most closest to experimental results.This function was „Cosine Series Bivariate Order 3".

The function used for estimating the surface roughness variation for measurements made in feed direction, with specific parameters, is represented in Fig.8. For measurements made perpendicular to feed direction the function for estimating surface roughness variation, with specific parameters, is indicated in Fig.10.

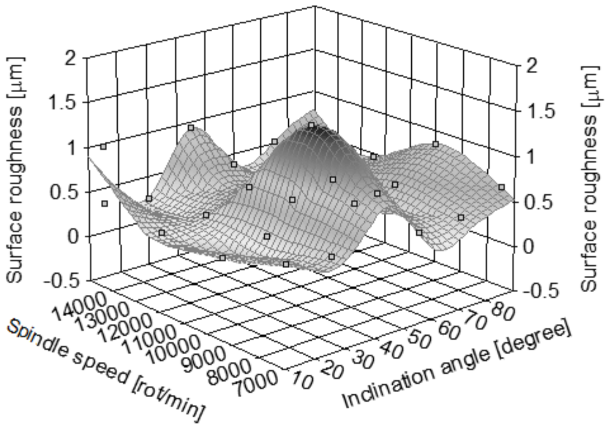

Figure 7: *Surface roughness variation by experimental results for mesurements in feed direction*

The comparison between results of measurements and mathematical results obtained by using estimating function shows that variation of surface roughness may be estimated with an error of less than ten percent.

Using the proposed function the surface roughness may be estimate for all values of caught in between 0 degrees to 90 degrees for inclination angle in feed positive direction, and 7000 [rot/min] to 15000 [rot/min] for spindle speed.

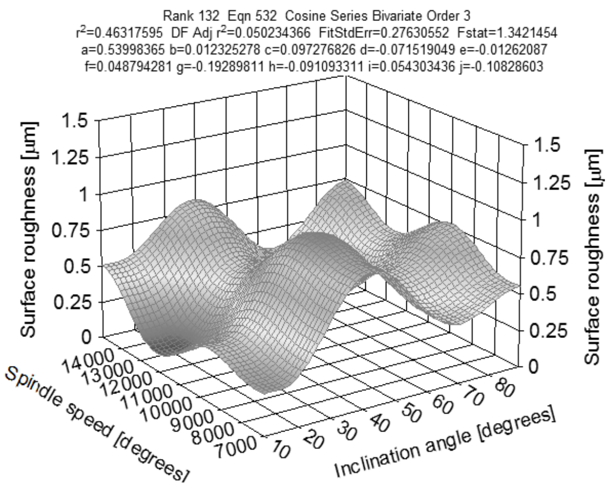

Figure 8: *Surface roughness variation by prediction function for measurements in feed direction*

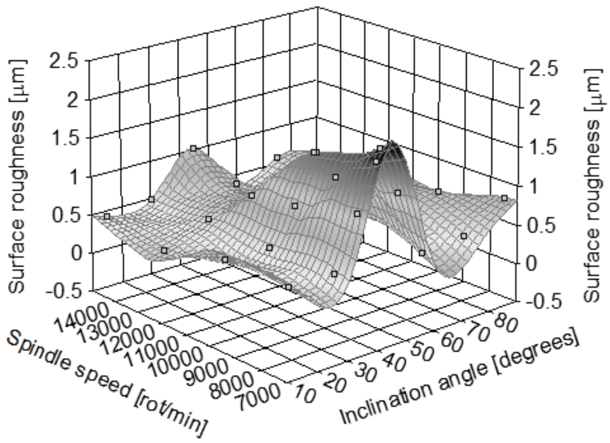

Figure 9: *Surface roughness variation by experimental results for mesurements in pick feed direction*

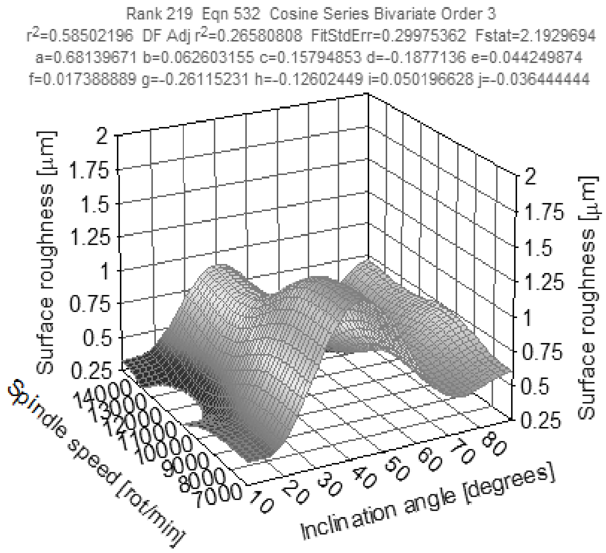

Figure 10: *Surface roughness variation by prediction function for measurements in pick feed direction*

6. Conclusions

The results may be very practice for establish the best angle of tool axis inclination in milling with ball end mills, when direction of inclination is in feed positive direction.

The best results for surface roughness are obtained for values of inclination angle in feed positive direction in interval 15 degrees and 30 degrees. Good results are obtained also in interval coresponding to 60 degrees and 75 degrees

Using the inclination angle value of 45 degrees should be avoided because the surface roughness is the worst.

In the interval 30 degrees to 45 degrees the surface roughness values have a significant increase, but in interval 45 degrees to 60 degrees have a significant decrease.

In terms of spindle speed the best results of surface roughness was obtained in the interval 12000 rot/min to 13000 rot/min. The worst values of surface quality was obtained near the 10000 rot/min.

The experimental data obtained and estimating function proposed lead to the correct choise of inclination angle value and spindle speed value when ball end milling with inclination of tool axis in feed positive direction.

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