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INFLUENCE OF TOOL AXIS INCLINATION ANGLE ON THE SURFACE ROUGHNESS IN BALL END MILLING OF OLC45 (C45) MATERIAL

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Abstract: *Ball end milling has a relatively high share in the cutting process. Due to the widespread use of this process it is essential to know the parameters that can influence the process to achieve the optimum and adequate quality of machined surface. Besides the cutting regime parameters for milling operations with ball nose end mills the angle of inclination of the cutting tool axis has a great importance. The present paper includes a summary of international investigation and optimization of surface quality depending on the parameters involved in the process and in particular the inclination of tool axis.*

Key words: *milling, roughness, ball end mill, angle, inclination.*

1. INTRODUCTION[1]

The analysis on possibilities of obtaining a high quality surface after the milling operation with ball end mills can lead to the removal of a significant part or even all of the subsequent finishing operations. Obtaining a high quality of surfaces machined with ball end mills can be possible only considering the influence of a number of factors such as: the stability of machine tools, the correct choosing of cutting tools and cutting parametters, material machined and the angle of the tool against the surface normal. All these factors should be chosen to have a minimal negative influence in the process. The influence of these factors on the machined surface quality is of great interest for both researchers and those involved in the production activity with ball end mills. Various mathematical models are proposed in terms of surface quality prediction.

Theoretical models proposed take into account in addition to cutting speed and advance the following parameters: cutting depth [2, 6, and 8], cutting depth and radial depth [4], hardness of the material and tool radius [5]. The ues of ball end mills in many areas has contributed greatly to increasing the research in this area, which led to the elaboration of different structural models of ball end mills and different technical solutions and guidance, so that the factory practice results to be obtained in superior economic conditions.

A large number of researchers have focused theyr attention on the influence of inclination angle of the cutting tool axis relative to the surface normal.

This paper is analyzing the possibilities of machining on NC machines using ball end mills by providing a tool axis inclination with respect to surface normal machined and its influence on surface quality.

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2. THE ANALYSIS OF TOOL AXIS INCLINATION

Processing opportunities on NC machine tools with five degrees of freedom enable processing of different areas by providing a second inclination angle or cutting tool in relation to the normal to the surface, to achieve better cutting conditions and therefore a high quality machined surface.

Analysis of milling process by inclination of tool axis by a single angle of inclination is useful in relation to 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. Especially for a small number of items processed where NC program implementation should be done in shortest possible time and with superior quality machined surface, this method is effective and hence, require some guidance in order to increase performance and even for different cases are processed performs of different qualities in terms of material.

Thus, depending on the choice of the inclination angle corresponding to a certain axis, angles can be applied to tool around the axis *X* or *Y*, *Z* respectively, corresponding to the structural characteristics of machine tools. Inclination angles proposed for analysis in this paper around the X axis by angle A (Fig. 1a) and the *Y* axis by angle B (Fig. 1b).

3. EFFECTS OF INCLINATION ANGLE UPON EFFECTIVE CUTTING SPEED

The geometric parameters used set for milling of different surfaces the analysis of changes in effective cutting speed values is important, depending on the speed and angle practiced by the tool axis relative to the surface normal.

In this paper the geometrical parameters values used are presented in Table 1.

The feed of tool does not affect the cutting speed, which is why it was not necessary to consider establish the value of this parameter. Effective speed milling $V_{c\text{-}eff}$ is given by relation (1) [3]:

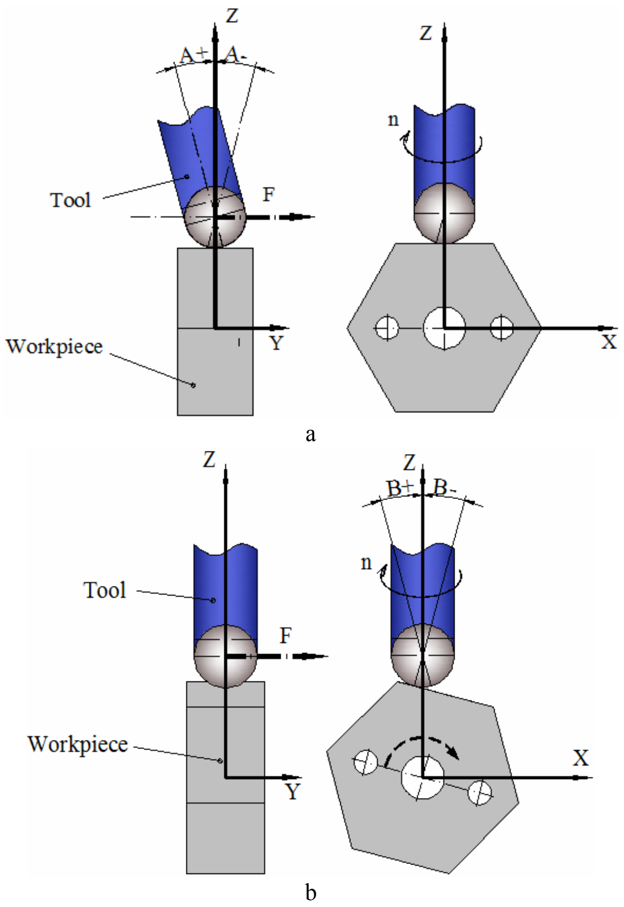

Fig. 1. Inclination of tool axis: *a* – by axis A; *b* – by axis B.

Table 1

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

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

with the following condition:

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

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].

Based on this relation (1), the effective cutting speed values can be determined depending on the angle of inclination of the tool axis relative to the machined surface normal. These values were determined and grouped in Table 2. for a lower speed n = 10 000 rot/min and for a speed n = 15 000 rot/min, taking into account the inclination of the tool axis while the depth of cut and step on the crossing remain constant.

Analyzing these results were achieved chart effective cutting speed variation depending on the angle of inclination of the tool for two ranges of speed, and the evolution curve shown in Fig. 2.

Table 2

Effective cutting speed values

Nr.	Tool axis inclination θ_n [degree]	Spindle speed n [rot/min]	Effective cutting speed V_{c-ef} [m/min]
1	15	10 000	234.6
2		15 000	352
3	30	10 000	341.8
4		15 000	512.7
5	45	10 000	425.3
6		15 000	638
7	60	10 000	480.3
8		15 000	750.52
9	75	10 000	502.3
10		15 000	753.5
11	90	10 000	502.64
12		15 000	753.6

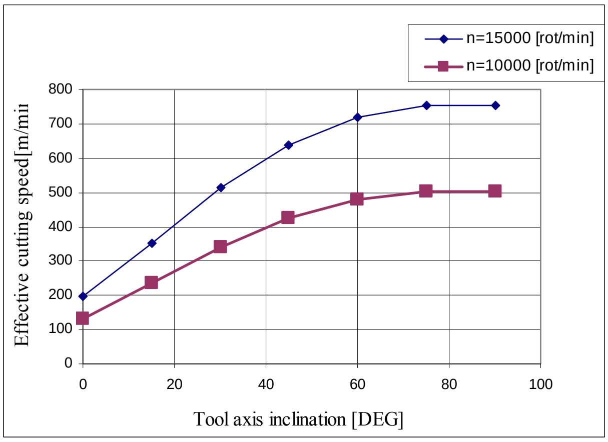

Fig. 2. Effective cutting speed variation depending on the angle of inclination of the tool.

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 occurs. The paper [1] shows that machining by using a cutting tool angle between the axis and machined surface can contribute to a higher quality of machined surface.

Much of the research carried out, is limited to analysis on surface quality for a lower inclination angle between 0 and 20 degress [10], or between 0 and 30 degress [7]. For values that require tilting the tool axis relative to machined surface it is noted that in practice the angle of 45 degrees for inclination of tool axis the quality of surface is low [3]. In order to compact all these informations and to establish a variation of the quality surface it is necessary to extend the studies of influence of the tool axis inclination upon surface quality. We attempt to determine the best inclination angle on the surface quality state according to the machining conditions for diferent quality of the material.

4.1. Experimental setup

It was necessary to carry out a number of cutting experiments to obtain experimental data. This experiments were made by using a OKUMA MU400VA five-axis CNC milling machine equipped with a maximum spindle speed of 15 000 rpm (Fig. 3.). The tools and the holder are manufactured by Mitsubishi Carbide and their reference was SRG16C-VP15TF for inserts and SRM2160SNM for the tool holder. The inserts were changed after processing two pieces. The experiments were made at S.C. RAMIRA S.A.

4.2. Workpiece material

The workpiece has the shape indicated in Fig. 4, with six machining surface that was machined at different inclination angle. The material used was OLC-45 (C45) with the following caracteristics: 0.42÷0.50% C, 0.50÷0.80% Mn, 0.17÷0.37% Si, maximum 0.040% P, etc. The workpiece was processed by termic treatment obtaining the hardness: 34 HRC and 54 HRC.

4.3. Surface roughness measurements

Surface roughness is defined as the inherent irregularities of the workpiece affected by machining process.

Fig. 3. Five-axis milling machine.

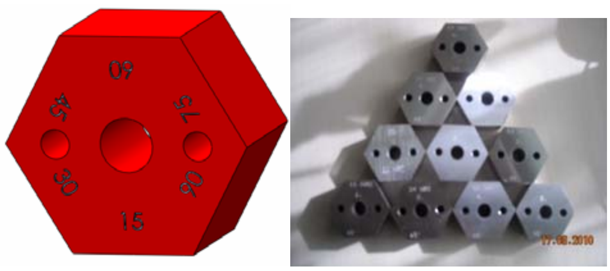

Fig. 4. Workpiece configuration.

Fig. 5. Roughness tester TR200 with adaptor device.

Table 3

Experimental conditions

Number of piece	Spindle speed [rot/min]	Inclination angle [deg]
1	10 000	A0B15 A0B30 A0B45 A0B60 A0B75 A0B90
2	15 000	
3	10 000	A0B-15 A0B-30 A0B-45
4	15 000	A0B-60 A0B-75 A0B-90
5	10 000	A15B0 A30B0 A45B0 A60B0 A75B0 A90B0
6	15 000	
7	10 000	A-15B0 A-30B0 A-45B0
8	15 000	A-60B0 A-75B0 A-90B0

There are many parameters used in the literature and industry related to surface roughness. The most popular of the 2D parameters is the average roughness *Ra* [3]. Mathematicaly, *Ra* is the arithmetic value of the departure of the profile from centerline along the sampling length [9]. To measure surface roughness with high accuracy the measurements was made both the advance direction and perpendicular to it. To ensure conditions of perpendicularity and parallelism between roughness tester feeler TR200 and feed direction was necessary construction of the device shown in Fig. 5.

4.4. Experimental conditions

Because a great number of factors can influence the surface roughness, in the experiments we focused our attention on the influence of inclination angle of the tool upon surface quality. All experiments were conducted using in feed milling direction and parameters indicated in Table 1, 2 and 3.

5. EXPERIMENTAL RESULTS AND DISCUSSION

Experimental data on surface quality of the measurements obtained were analyzed in feed direction and perpendicular to feed direction. So, these results were centralized in Tables 4 and 5 for each angle that was analized.

Choice of inclination angle of tool axis relative to the surface normal is important because siginificant differences can arise in terms of quality. Both, absolute value of the angle of inclination and direction of this angle are very important. Variation of surface quality when machined OLC 45 with hardness 34 HRC is presented in

Table 4

Experimental results for material with 34 HRC

Nr.	Direction to measure	Tool angle inclination					
		15	30	45	60	75	90
1	Parallel	0.142	0.181	0.185	0.203	0.172	0.184
	Perpendicular	0.285	0.329	1.420	0.451	0.599	0.570
2	Parallel	0.201	0.145	0.215	0.194	0.190	0.254
	Perpendicular	0.288	0.357	1.797	0.414	0.537	0.489
3	Parallel	0.175	0.229	0.243	0.279	0.283	0.286
	Perpendicular	0.800	0.725	1.473	1.151	1.115	0.778
4	Parallel	0.182	0.213	0.214	0.205	0.306	0.211
	Perpendicular	0.423	0.269	1.394	0.253	0.408	0.560
5	Parallel	0.273	0.327	1.476	0.525	0.429	0.548
	Perpendicular	0.215	0.325	0.686	0.270	0.253	0.272
6	Parallel	0.237	0.438	0.827	0.312	0.559	0.479
	Perpendicular	0.201	0.334	0.838	0.490	0.503	0.296
7	Parallel	0.444	0.508	1.632	0.391	0.597	0.443
	Perpendicular	0.378	0.266	0.686	0.345	0.508	0.485
8	Parallel	0.356	0.244	0.836	1.075	0.739	0.986
	Perpendicular	0.330	0.242	0.501	0.955	0.629	0.362

Table 5

Experimental results for material with hardness 54 HRC

Nr.	Direction to measure	Tool angle inclination					
		15	30	45	60	75	90
1	Parallel	0.142	0.155	0.213	0.110	0.152	0.180
	Perpendicular	0.372	0.322	1.763	0.538	0.987	0.925
2	Parallel	0.186	0.212	0.183	0.173	0.316	0.296
	Perpendicular	0.320	0.335	1.795	0.455	0.897	0.432
3	Parallel	0.272	0.269	0.184	0.231	0.169	0.155
	Perpendicular	0.829	0.708	1.402	1.183	1.133	0.734
4	Parallel	0.250	0.119	0.175	0.184	0.237	0.266
	Perpendicular	0.406	0.279	1.202	0.386	0.850	0.578
5	Parallel	0.211	0.334	1.557	0.338	0.462	0.495
	Perpendicular	0.203	0.258	0.712	0.202	0.230	0.350
6	Parallel	0.132	0.559	0.975	0.339	0.539	0.379
	Perpendicular	0.206	0.254	0.754	0.255	0.647	0.425
7	Parallel	0.349	0.548	1.747	0.370	0.640	0.438
	Perpendicular	0.188	0.304	0.765	0.334	0.479	0.468
8	Parallel	0.328	0.238	0.718	0.646	0.819	0.668
	Perpendicular	0.234	0.199	0.874	0.707	0.572	0.483

Figs. 6–13 and Figs. 14–21 for material with 54HRC hardness. In this paper, the results were analized for different spindle speed for each angle of inclination and different materials.

If tilt the tool axis in direction of B axis without tilting in the A axis direction, registers a relatively slow variation of surface quality at various values of inclination angle, regardless of the speed and quality of machined material. If measurements made parallel to the feed direction this is obvious (Figs. 6–9. and Figs. 14–17), but in case of measurements made on the perpendicular direction to the feed direction (Figs. 10–12 and Figs. 18–21) is recorded a decrease in surface quality corresponding angle 45 degrees. If is necessary to practice this angle of inclination, quality of surface can be improved by increasing cutting speed revolutions.

Generaly is to note that the tool axis tilt in direction of axis B leads to a better quality surface that can be

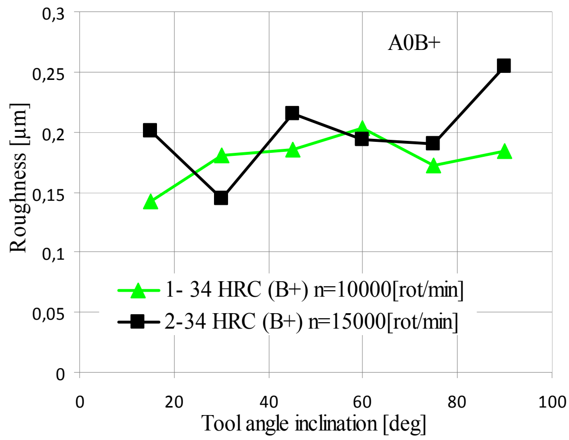

Fig. 6. Roughness measured in feed direction.

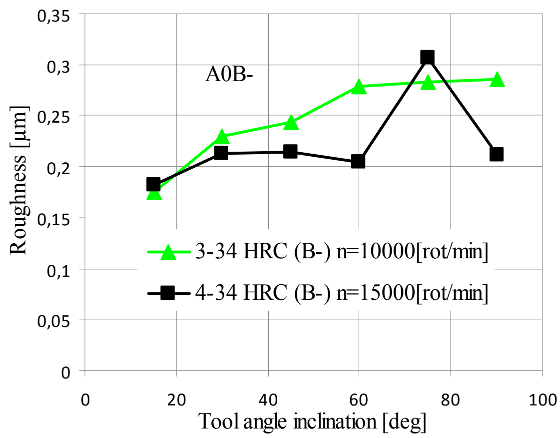

Fig. 7. Roughness measured in feed direction.

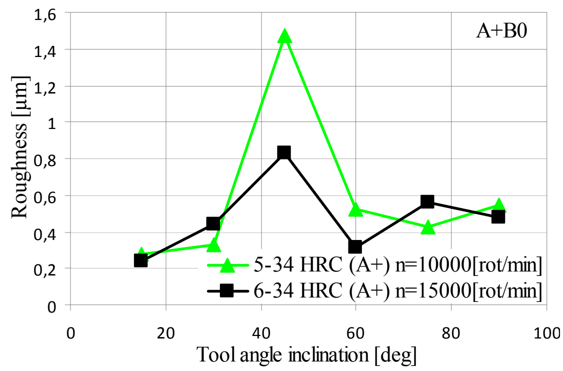

Fig. 8. Roughness measured in feed direction.

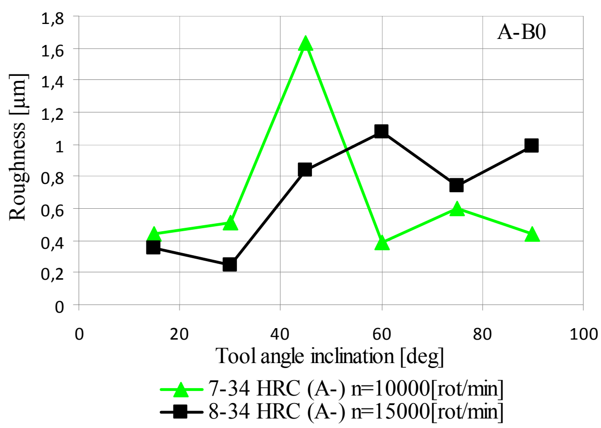

Fig. 9. Roughness measured in feed direction.

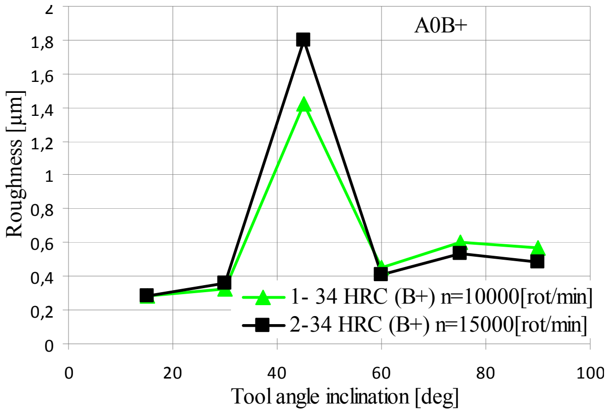

Fig. 10. Roughness measured perpendicular to feed direction.

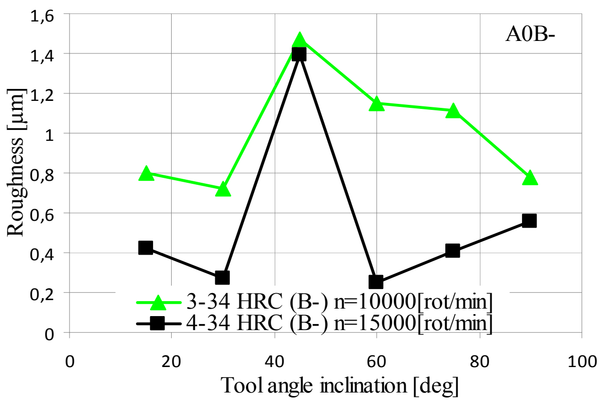

Fig. 11. Roughness measured perpendicular to feed direction.

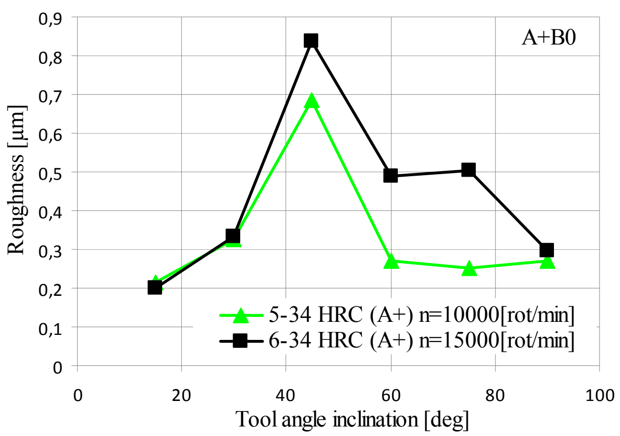

Fig. 12. Roughness measured perpendicular to feed direction.

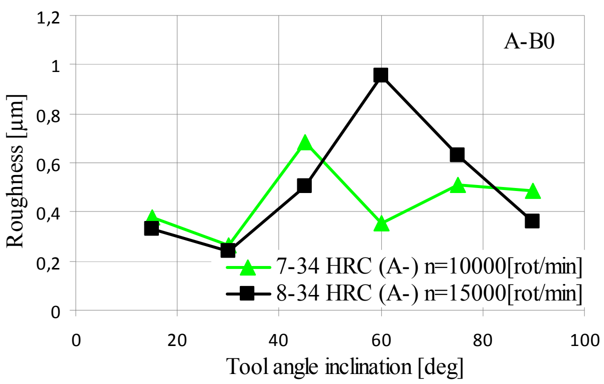

Fig. 13. Roughness measured perpendicular to feed direction.

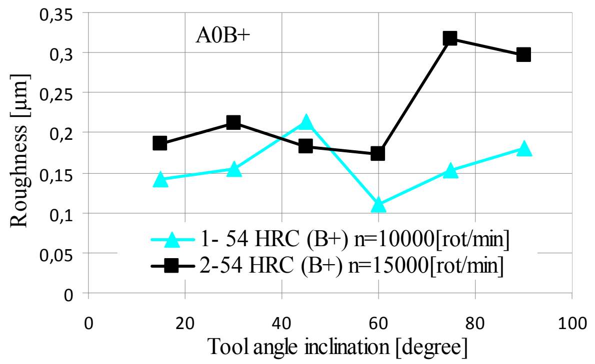

Fig. 14. Roughness measured in feed direction.

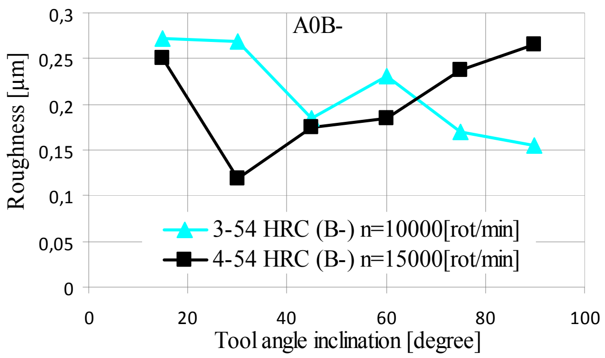

Fig. 15. Roughness measured in feed direction.

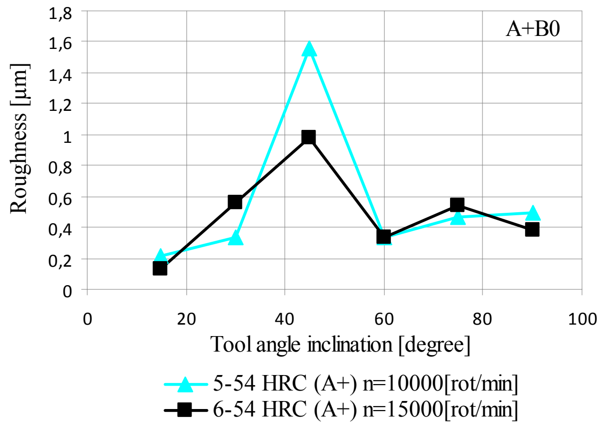

Fig. 16. Roughness measured in feed direction.

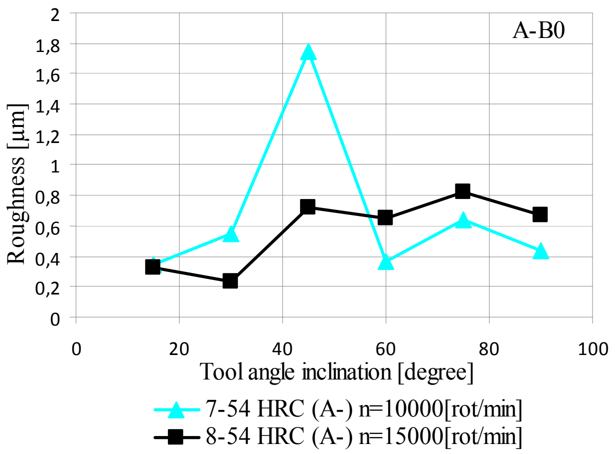

Fig. 17. Roughness measured in feed direction.

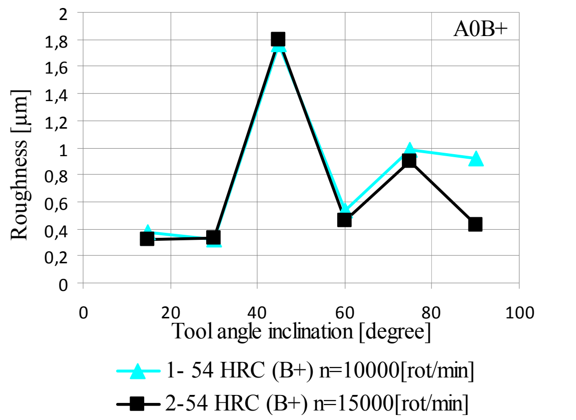

Fig. 18. Roughness measured perpendicular to feed direction.

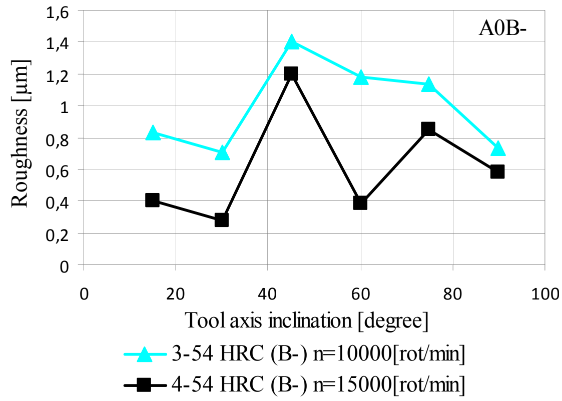

Fig. 19. Roughness measured perpendicular to feed direction.

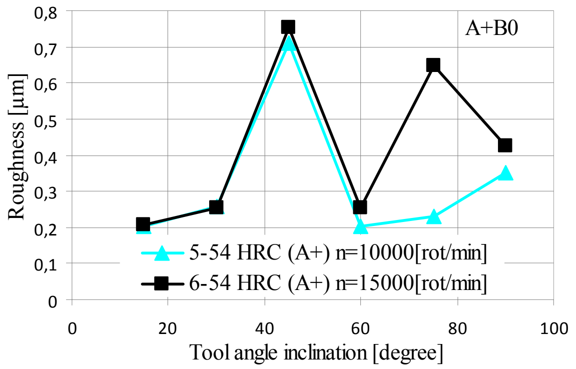

Fig. 20. Roughness measured perpendicular to feed direction.

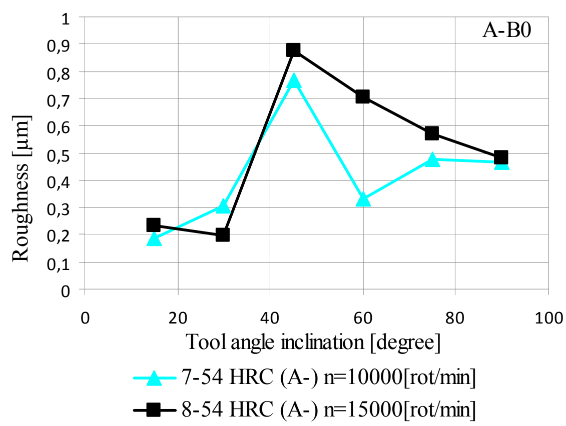

Fig. 21. Roughness measured perpendicular to feed direction.

compared with the roughness obtained from the tilt axis in the axis A direction. It may also be noted as to the tool axis inclination of 60 degrees in the area values is indicated using a speed lower cutting speeds respectively. over this value allows a higher quality surface with increasing speedle speed. For different hardness. for same values of inclination angle the roughness evolution may be compared if the measurements direction was the same.

6. CONCLUSIONS

Using the inclination angle value of 45 degrees should be avoided. Tilt on axis B direction must be used against axis A direction. Over 60 degrees value of inclination angle is indicated to increased the spindle speed to improve the surface quality. Roughness evolution for different materials follows a similar curve.

The results may be very practice for establish the best angle of tool axis inclination in milling with ball end mills.

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