



Experimental analysis of end mill axis inclination and its influence on 3D areal surface texture parameters

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Abstract. The surface quality of machined parts depends highly on the surface texture that reflects the marks of the tool during the cutting process. The traditional theoretical approach indicates that these marks are related to the cutting parameters (e.g. cutting speed, feed, depths of cut), the machining type, the part material, the tool, etc. The influence of these factors has been widely studied by researchers and they have been considered in milling process models proposed to predict the final surface texture.

Nevertheless, if an accurate prediction is desired, these milling models must include different geometrical errors influencing the cutting edges path on the part. In this paper, we present the results of a study showing the influence of real mill-axis inclination on 3D surface texture. Therefore, experiments with simple, end mill tool operation, with constant cutting parameters and four different cutting directions (the directions that we labelled as North, South, East, and West) in accordance with the machine coordinate system were performed. Using optical 3D areal surface texture measurement techniques with the Bruker Contour device, we obtained areal surface texture parameters for analysis. Descriptive statistical analysis and one-way ANOVA analysis were performed to detect the factor significances and their influence on 3D areal surface texture parameters. The results from ANOVA and graphical analysis clearly identified tool-axis inclination in the South and East directions. If a relationship between tool-axis inclination and surface texture parameters can be demonstrated, this calculation can be included in the model of 3D surface texture formation. Improving the mathematical model with all possible errors occurring in high speed machining operations helps to obtain more precise surface height parameter S_z results for simple end mill operation. The model is suitable for complicated machining operations with ball end mill tools.

Key words: 3D areal surface texture parameters, tool inclination angle error, end mill, high speed machining.

1. INTRODUCTION

Surface quality, including 3D surface texture, is the most important indicator with respect to machined surfaces [1]. To ensure high quality of the injection

mould surface, avoiding external finishing operations, it is important to take the principle machining technological factors into account. We are interested in the model development to select the appropriate cutting conditions that guarantee the mould quality with a minimal machining cost. In this field, many researches are available, dealing with the mathematical modelling

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of the cutting process, however, most of them result in differences between measured and modelled surface roughness parameters. To diminish this error, it is important to detect the most important parameters of the cutting process, which affect the surface formation process. These factors are related not only to cutting conditions, but also to factors (tool sharpening error, concavity angle on the bottom face) which cannot be modified directly. Furthermore, these factors intervene during the finishing processes rather than in the rough machining. To develop a cutting tool geometrical movement model, such factors as tool deformation errors, performed by increased cutting forces during the machining process, tool alignment position, and tool sharpening error, are important [1,2]. A combination of tool manufacturing errors and coupling inaccuracies could generate tool radial run-out errors, i.e. discrepancies between the theoretical axis and the tool's real axis [1–5]. In Section 2 we give an overview of several research works on surface roughness prediction that have considered other factors, such as tool run-out, and other surfaces such as laterally machined surface. In Section 3 and Section 4 the methodology of experimental analysis is described and a geometrical model is provided accordingly.

2. STATE OF ART

The authors of several other research projects have sought to develop predictive models for the influence of tool axial and radial run-out values on surface roughness parameters. Baek et al. [2] distributed a simple approximation to predict surface roughness based on the geometrical dislocation of the tool cutting edges. Franco [6] also used a descriptive model to include tool error in his surface roughness prediction model. Both of these studies, along with others [5,7], include these run-out errors in surface roughness predictive models. Tool run-out errors usually consist of two elements: axial run-out that affects the depth of the cut in the axial direction of the workpiece and radial run-out, which influences the surface roughness mainly owing to the feed per tooth and radius of cutting edges [2]. Both the radial and axial tool run-outs on the Z -axis affect the surface texture formation. The relative displacement of the cutting tool tip in the Z direction affects the machined surface roughness [2,8].

At milling operations, where surface geometry has been generated with the bottom face of the end mill, the path of the end mill tool follows a curvilinear trajectory. This trajectory is caused by tool deflection errors, cutting forces, tool-axis inclination, and machine head/spindle

inaccuracy, as well as by alignment errors. Therefore, it is also necessary to include the effect of cutting forces and vibrations in the geometrical simulation, as Dang et al. [9] and Arizmendi et al. [10] suggested. In such situations, the cutter path influences the geometry of the surface cut by the machined bottom [8]. All these run-out errors affect the machined areal surface texture. Most of them are used to predict 2D surface roughness parameters [1–3,6,11], but it is more important to describe 3D surface texture, as it reflects the overall surface quality and errors. The above publications mostly consider run-out errors resulting from tool edge displacements or vibrational effect, as well as tool geometry. However, the errors between predicted and measured values hint at other important cutting process parameters, such as tool-axis inclination due to machine inaccuracy. If surface heights (irregularities) depend on the machining direction, there may exist a constant tool-axis inclination error due to the interaction of machine inaccuracies, mounting inaccuracy, and tool sharpening error. The goal of the present research is to determine mathematically the influence of the tool-axis inclination angle error, relative to the plane of the tool path, on the areal surface height parameter S_z . This article analyses and explains the influence of the tool-axis inclination angle on the change of size for the surface texture descriptive parameter (S_z), in the vertical (Z) direction, depending on the direction of the machining.

3. METHODOLOGY

In this section the influence of the actual mill axis direction on surface texture is considered. Theoretically, the end mill axis (Z direction) is perpendicular to the machined part (XY plane), but the real flat-end mill direction will be different as a consequence of not only tool deflection originated from cutting forces but also of the tilting axis of the machine head.

To check whether an error variable exists, it is necessary to perform experimental analysis. As the ball-end milling process involves complex tool and envelope geometry caused by the cutting edge [5], it is easier to use an end mill tool to describe the tool-axis inclination error. This is the easiest way to check the behaviour of the machining system and prove the influence of the tool alignment between the spindle axis and the tool's theoretical axis on the formation of surface roughness. The experimental operations were performed with two flute-end mill tools, to represent each cutting edge movement over the material's surface. The same approximation can be integrated subsequently for a model with a ball-end mill tool.

To make a model more like a real experimental situation, we applied the same cutting conditions as used in previous research [12] on high-speed ball-end milling to the flat-end milling experiments. This article describes the influence of the cutting tool-axis inclination error on the parameters of 3D surface texture. The cutting conditions used are widely employed in die and mould manufacturing.

The experiment was designed to collect data on machine accuracy and to prove its influence on machined surface texture. In the experiment, samples with four different cutting directions were developed. These samples provide a tool-axis inclination test against the workpiece. In theory [4,7] the milling tool has some inclination error affecting the tool's rotational movement against the workpiece; analysis of this sample should prove that this is the case.

The cutting was performed using rectangular tool movement to ensure straight tool movement in any direction. A KONDIA B500 CNC milling machine was used. The schematics of one of the samples processed is illustrated in Fig. 1.

The tool was only used in the indicated area (light grey slot). A MITSUBISHI end mill tool, MS2MSD1000 with the cutting diameter of 10 mm (Fig. 2) was selected for the machining process. This is a tungsten carbide (WC) cutting tool with a MITSUBISHI UWC – TiAlN (MIRACLE) coating. The whole tool diameter engagement was used in the cutting process. Both, DOWN (climb) and UP (conventional) milling modes appeared in each cut due to full tool engagement. It is possible to observe the movement of the tool tip point more clearly all over the contact area.

Figure 2 represents the tool end surface concavity angle $\alpha = 2^\circ$ and therefore, the tool tip point complimentary angle $\alpha'' = 88^\circ$.

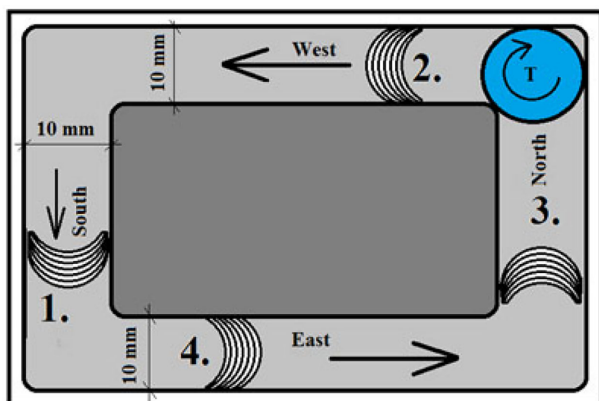


Fig. 1. Sample machining and sampling scheme. The numbers indicate the measurement order.

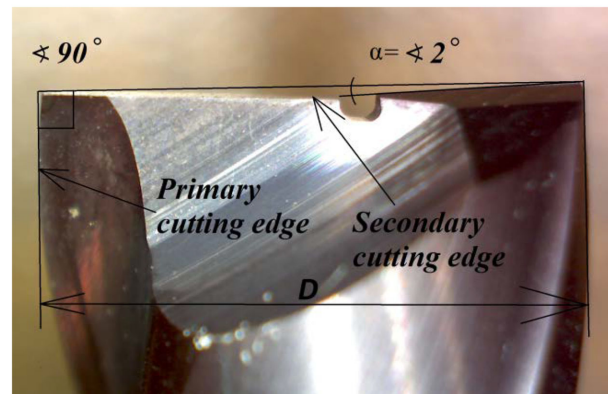


Fig. 2. MS2MSD1000 tool angles.

The cutting conditions were the same as in our previous research [12]:

- (a) tool diameter: $D = 10$ mm;
- (b) feed per tooth, f_z : 0.1 mm/tooth;
- (c) spindle speed, n : 4775 rpm, equivalent to 150 m/min cutting speed V_c ;
- (d) axial cutting depth: 0.3 mm.

The 3D surface measurements were performed in the Department of Mechanical and Industrial Engineering, Tallinn University of Technology. The measurements were made with a Bruker Contour GT3 optical measuring device following the instructions presented below:

- (1) prepare the device for 3D surface topography measurements, take the environmental conditions into account, and calibrate the measurement device;
- (2) place the measurement sample on the machine table and adjust the level of it;
- (3) adjust the settings of the measurement device for the type of material and reflection of the surface;
- (4) adjust the cutting direction according to the machine, to ensure the same measurement alignment for all samples;
- (5) take a control measurement, apply the filters, and check the obtained surface parameters;
- (6) if the control measurement is successful, make the main measurements; if not, adjust the machine.

All the results recorded following the measurement protocol were saved in a data file with the numbering of sample, measurements, and location specification. After the measurements, the data was processed with self-developed surface texture analysis software, based on the Python programming language. An example of areal texture after the cutting process is represented in Figs 3 and 4.

Fig. 3. Sample 3D texture measurements for the South cutting direction; V_f is feed speed (mm/min).

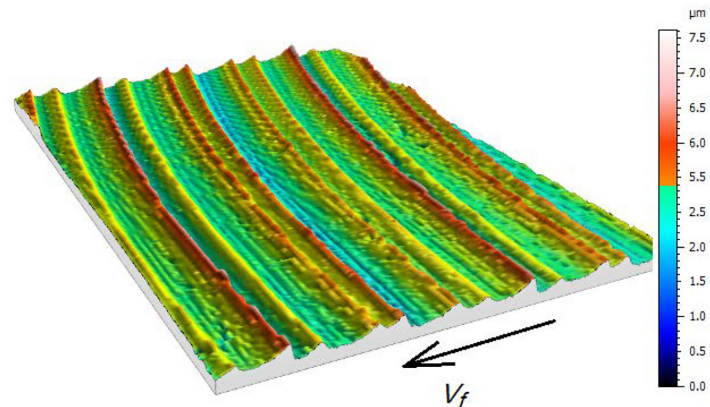
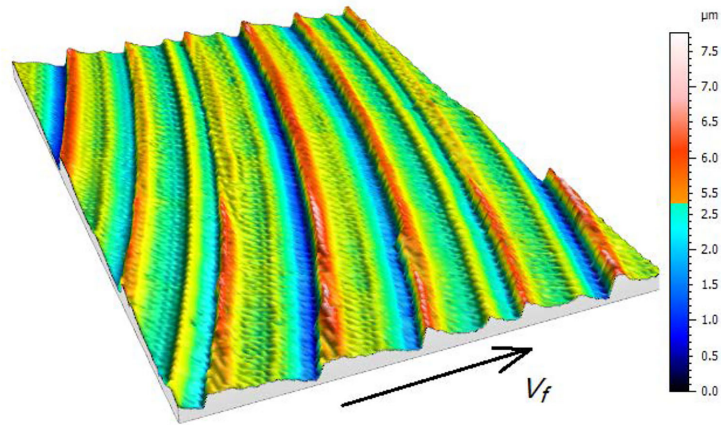


Fig. 4. Sample 3D texture measurements for the North cutting direction; V_f is feed speed (mm/min).



4. RESULTS

The first step involved a visual analysis of the obtained measurement images, showing the measured surface texture. Afterwards, we performed a descriptive analysis of the measurement data. Descriptive analysis provides a description of the basic features of the data in a study. It offers a simple summary of the sample and the measurements.

Visual sample analysis (Figs 3 and 4) indicates that the surface pattern is dependent on the tool feed direction. The flattest surface peak slope decreases in the cutting feed direction. This slope results from the cutter's clearance side of the cutting edge. The distances between the highest peaks coincide with the cutting feed per tooth, $f_z = 0.1$ mm. Between these highest points there are smaller peaks, resulting from the tool rotation direction. In future research, the appearance of those points will be analysed.

Before starting ANOVA analysis, it is necessary to determine the independent and dependent process parameter variables. As tool deflection has a geometrical

behaviour, the surface roughness is affected in absolute values. If there were no significant changes in the values of the average height parameters of 3D surface texture, i.e. S_a (average height of the surface in μm) and S_q (root mean square roughness), there would be an absolute surface height value which could be dependent on geometrical tool deformations and tool orientation errors. Furthermore, the measured S_a and S_z values indicate smoother value changes due to feed direction change. The S_z parameter is the maximum height of the surface (according to ISO 25178-2:2012) and it is the most indicative parameter to describe a theoretically machined surface. At this stage, a null hypothesis (H_0) was defined and the analysis was conducted to confirm or reject it. The null hypothesis H_0 means that the tool movement direction has no effect on the surface texture parameter S_z .

Descriptive analysis contributes to the obtained measurement values. Table 1 shows that the statistical skewness for the average surface height parameter S_a is close to standard deviation. There are no unreliable measurement values and the distribution corresponds to

Table 1. Factors and measurements

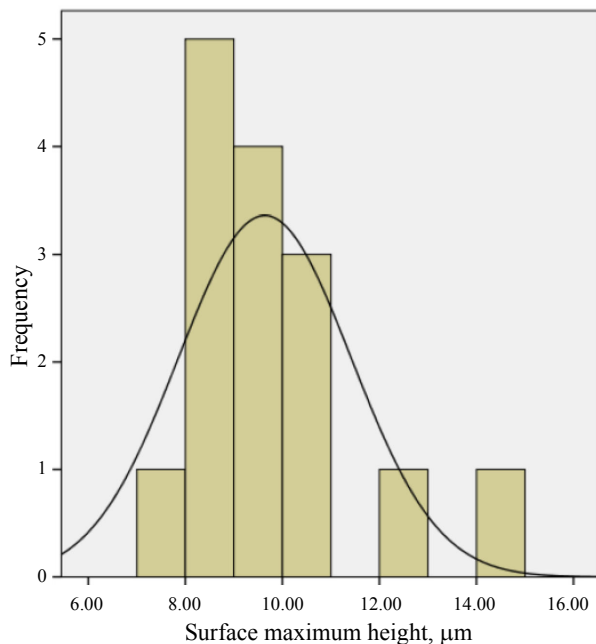
Sample	Direction	S_a , μm	S_z , μm
111	South	1.017 33	10.604 45
112	South	1.160 82	9.191 31
121	West	1.148 25	8.292 17
122	West	0.890 45	8.460 29
131	North	1.125 16	8.083 3
132	North	1.162 29	7.898 54
141	East	1.000 01	9.337 74
142	East	1.097 79	10.041 44

Sample – sample number; Direction – machining direction from top view; S_a , S_z – surface texture parameters.

normal distribution. Therefore, the kurtosis coefficient indicates that data repetition frequency is concentrated more around the mean value, compared to normal distribution. Table 1 represents a part of the experimental factors and areal texture parameters of the measured surface.

On the other hand, the analysis of the parameter S_z showed high skewness and even higher kurtosis parameters, which drew our attention due to high data variation. To check the reliability of the measured data, a frequency histogram of all measured S_z values is presented in Fig. 5.

Table 2 displays the descriptive statistics of such variables as mean values, standard deviation, minimum and maximum parameter values, skewness and kurtosis

**Fig. 5.** Frequency distribution histogram of the surface maximum height parameter S_z .**Table 2.** Statistics of measurement data; S_a and S_z are surface texture parameters

	S_a , μm	S_z , μm
Mean	1.075 262 50	8.988 655 0
Std. deviation	0.097 389 548	0.974 998 79
Variance	0.009	0.951
Skewness	-1.056	0.599
Kurtosis	0.267	-0.932
Minimum	0.890 450	7.898 54
Maximum	1.162 290	10.604 45

of data distribution. The descriptive analysis defined the standard deviation of the parameter S_z as 0.974 998 79. All variables belong to 3σ standard deviation, representing data reliability.

The next step was to analyse the significance of the feed direction for the surface texture parameter S_z . By applying ANOVA one factor analysis (the other factors are constant), the significance coefficient of 0.007 was found (Table 3). This represents the possibility that the H_0 hypothesis is true as 0.007%. A similar outcome was obtained for the parameter S_{tr} – texture aspect ratio (not represented in Table 2). The significance factor here is $p = 0.01$.

Analysing the data for the average surface height parameter S_a and surface texture kurtosis S_{ku} , we may consider that the significance parameters are $p = 0.7$ and $p = 0.167$ (not shown in Table 2). As they are greater than 0.05, we may assume they are not significant in this case.

The plot of the mean data values (Fig. 6) illustrates the effect of the tool movement direction on the surface parameter S_z value. The effect of the tool-axis inclination angle on the formation of that parameter can be directly related with the tool movement direction, considering

Table 3. Test of between-subject factors

Source	Type III Sum of squares	df	Mean square	F	Sig.
Corrected Model	7.072 ^a	3	2.357	20.201	0.007
Intercept	660.829	1	660.829	5663.027	0.000
DIR	7.072	3	2.357	20.201	0.007
Error	0.467	4	0.117		
Total	668.368	8			
Corrected Total	7.539	7			

^a R Squared = 0.938 (Adjusted R Squared = 0.892), df – degrees of freedom, F – ANOVA F value, sig. – significance coefficient, DIR – tool direction factor, Intercept – correction factor, Corrected – correction with error, Total – total sum of squares before the correction factor.

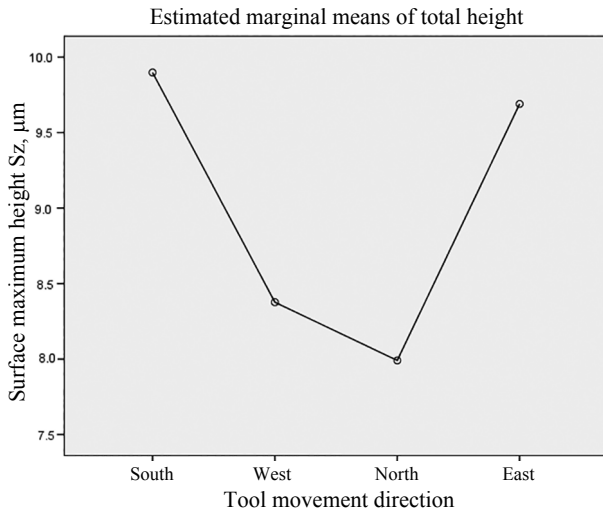


Fig. 6. The dependence of the total surface height maximum value on the machining or tool movement direction.

that the total tool axis inclination is influenced by both the machine Z-axis direction that is constant and tool deflection that is always opposite to feed direction. The highest tool-axis inclination error occurred in the South–North direction. In Fig. 6 we can see that the difference between values in the South–North direction is greater than in the East–West direction. If we estimate the same analysis for the parameter S_a , we obtain no significant differences in the values dependent on the tool direction when the movement is located on the same axis. However, significant differences were found when comparing S_z values in both directions: South–North and East–West.

The average value in the South–North direction is $8.9444 \mu\text{m}$, in the East–West direction $9.03291 \mu\text{m}$.

The graph in Fig. 6 reveals the differences in surface parameters obtained in the same cutting conditions. The parameter S_z reflects the total tool-axis inclination angle φ_T (Fig. 7). This angle includes various influences related to the tool deflection angle φ_{def} and the tool constant inclination angle φ_{inc} (Eqs (4.1) and (4.2)). Considering this, we can calculate the inclination angle component in both directions, South–North and East–West:

$$\varphi_T = \varphi_{\text{inc}} + \varphi_{\text{def}}, \quad (4.1)$$

$$\varphi_T = \varphi_{\text{inc}} - \varphi_{\text{def}}. \quad (4.2)$$

The total tool-axis inclination angle (represented in Fig. 7) was calculated using Eq. (4.3). To extract the φ_T value from this equation, we used a solution for the quadratic polynomial equation in particular form (Eq. (4.4)). Equation (4.4) comes from geometrical relations shown in Fig. 8.

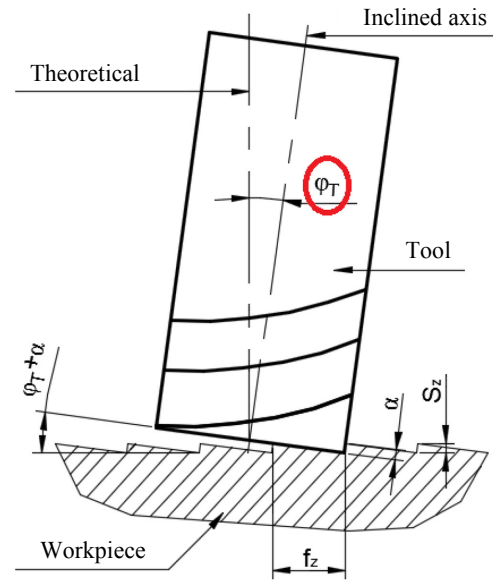


Fig. 7. Tool theoretical axis and the inclination angle φ_T .

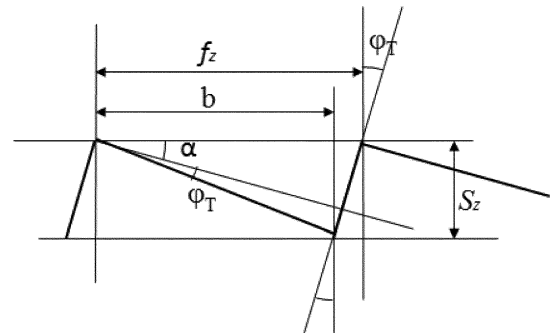


Fig. 8. Geometrical relation of the location of the tool tip-point and surface texture parameter S_z .

$$S_z = \frac{f \times \text{tg}(\varphi_T + \alpha)}{1 + \text{tg}(\varphi_T + \alpha) \times \text{tg}(\varphi_T)}, \quad (4.3)$$

$$(\text{tg}(\varphi_T))^2 - \frac{f}{S_z} \times \text{tg}(\varphi_T) + \left(1 - \frac{f}{S_z} \times \text{tg}(\alpha)\right) = 0, \quad (4.4)$$

where S_z – total height value of surface texture (μm), α – concavity angle (rad) (see Fig. 2), φ_T – total tool-axis inclination angle (rad), f – feed per tooth.

The solution for Eq. (4.4) was obtained by the determination of the roots in the generalized form of the quadratic polynomial equation:

$$ax^2 + bx + c = 0, \quad (4.5)$$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}, \quad (4.6)$$

where a , b , and c are coefficients according to the specified quadratic equation (4.4):

$$a = 1, \quad b = -\frac{f}{S_z}, \quad c = \left(1 - \frac{f}{S_z} \times \text{tg}(a^n)\right).$$

These coefficients were calculated taking into account the geometry of the tool position against the workpiece, explained in Fig. 8.

It is important to remember that tool deflection consolidates the inclination on one side of the tool, but reduces it on the other side.

Having obtained the mathematical relation between the tool-axis total inclination angle and surface texture parameter S_z (Eq. (4.3)), we can calculate exact tool-axis inclination angle values. Regression analysis showed the theoretical correlation function between the measured surface texture parameter S_z and total tool inclination angle φ_T (Fig. 9). The vertical axis represents the calculated tool-axis inclination angle, while the horizontal axis represents the measured surface texture parameter S_z . This regression represents the S_z value at a specific total tool-axis inclination value.

With this manner, Eq. (4.7) can be used to calculate the parameter S_z , by taking the total measured tool-axis inclination angle and tool concavity angle into account:

$$S_z = 0.0058(\varphi_T) - 0.0425. \quad (4.7)$$

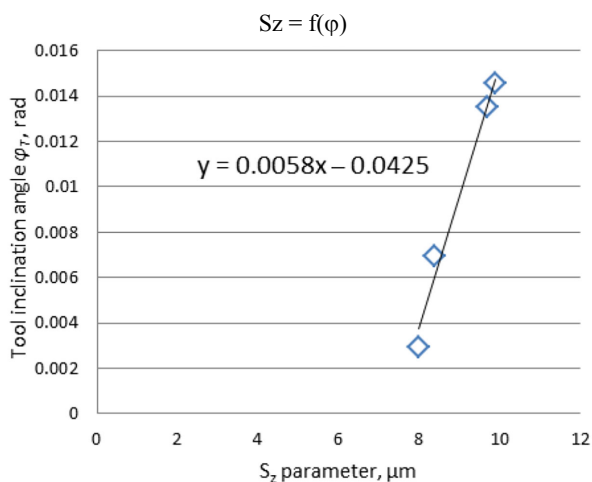


Fig. 9. Theoretical influence of the parameter S_z on the value of the tool inclination angle φ_T .

5. CONCLUSIONS

From the analysis of the technological parameters and tool movement direction performed in this study we can draw the following conclusions.

ANOVA analysis indicates the significance of the tool-axis inclination hypothesis. As such we reject the H_0 hypothesis and accept the H_1 hypothesis that the tool movement direction has a significant influence on the surface maximum height parameter S_z . Therefore, this inclination represents/collects the machine alignment errors and their influence on the surface texture parameters. Of course, the parameters that are most influenced are those directly related to the tool's geometrical properties (e.g. tool's concavity angle).

The calculations made showed high tool inclination values in both directions. The highest tool-axis inclination was observed in the South and East directions. Logically, with high inclination values in an opposite direction, the marks should disappear from the front cutting edge of the tool movement in the North and West directions. But, while this inclination angle is smaller than the tool's bottom cutting edge relief angle, the marks can still be observed. The surface height has been decreased, accordingly. It is significant that in the orientation with a low inclination influence, the marks appear on the remachined surface from the back edge.

None of the processed samples revealed marks left from the back or non-working cutting edge. This confirms the statement of an additional effect working in the cutting process. This effect could be tool deflection caused by the increased forces of high speed machining. This tool deflection either minimizes or increases the tool inclination effect.

The next step of this research is to analyse and identify the relationship between tool deflection (caused by forces working against the tool cutting edge) and surface topography. Afterwards, the entire geometrical simulation will be based on the model developed and its results.

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Ekspérimentaalne analüüs otsfreesi kaldenurga hälbe osas ja selle mõju 3D pinna tekstuuri parameetritele

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Otsfreesi kaldenurga hälbe mõju on analüüsitud eesmärgiga lisada antud parameeter töödeldud pinna kolme-mõõtmelise tekstuuri moodustamise matemaatilisse mudelisse. Pakutud töödeldud pinna tekstuuri matemaatiline mudel sobib otsfreesimise teel saadud pinna S_z ehk pinna maksimaalse kõrguse parameetri suuruse määratlemiseks või ennustamiseks.

Uuringu käigus tehtud ANOVA ja graafilise analüüsi tulemusena on tõestatud, et otsfreesi liikumissuunal ning kaldenurgal on töödeldud pinna pinnakareduse parameetrite formeerimisele oluline mõju. Freesi liikumist on vaadeldud põhja, ida, lõuna ja lääne suunas. Kõige suurem freesi kaldenurk on lõuna ja ida suunas freesimisel. Sellega seonduvalt on töödeldud pinna maksimaalse kõrguse parameetri S_z suurus ka suurem antud suundades freesides. Samas on maksimaalse kõrguse parameeter S_z väiksema suurusega siis, kui otsfreesi kaldenurga suurus on väiksem kui tööriista lõikeserva abitanurk.

Järgmistes uuringutes tuleb analüüsida otsfreesi läbipainde suurust, tingituna vertikaalsest jõu komponendist, ja selle mõju töödeldud pinna tekstuuri parameetritele.