

Modelling of multiple surface roughness parameters during hard turning: A comparative study between the kinematical-geometrical copying approach and the design of experiments method (DOE)

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ABSTRACT

This paper proposes and applies two different methodologies for modelling the roughness parameters in hard turning. The first method is based on the kinematical-geometrical copying of the cutting tool geometry onto the machined surface including a feedback loop through the parameter of statistic equality of sampling lengths in surface roughness measurements (SE). The other method employs the Design of Experiments (DOE) principles expressing the roughness parameters as first order nonlinear function of the input variables: cutting speed v , feed f , depth of cut a_p , and tool nose radius r_e . The research includes the R_a and R_z roughness parameters which are commonly modelled throughout the research works, and additionally develops models for the R_p , R_v and $R_{mr(c)}$ roughness parameters which are more challenging to model compared to R_a and R_z as they depend more on the shape of the roughness profile and position of its mean line. Both methodologies for all roughness parameters were verified using a CNC lathe and special rings made of steel EN C55 with hardness of 53 ± 1 HRC. Considering that the roughness profile is just a part of the total geometric deviations of the processed surfaces, and it is obtained from the total profile using software filtration, the research also considers the W_a parameter (waviness profile), as well as the deviations from the circularity (out-of-roundness) of the processed rings as indicators for the stability of the machining process.

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1. Introduction

The significance of surface roughness in the functioning of the mechanical parts is well known, irrespective of the method and the mechanical processing technique applied to obtain them. C.L. He *et al.* in the research presented in [1] provide a detailed overview of the state-of-the-art of the influential factors and the methods applied in surface roughness modelling in turning, regardless of whether the processed materials have normal or enhanced hardness. In addition, Trung and Tinh [2] propose a novel approach for determining the minimum surface roughness based on four multi-criteria decision-making methods including MAIRCA, EAMR, MARCOS and TOPSIS, however only the R_a parameter is considered. Kramar and Cica [3] employ a Response Surface Methodology (RSM) to obtain the models for the R_a and R_t roughness parameters. Interestingly, they optimize the input parameters of the model for obtaining the lowest roughness

using a cuckoo search (CS) algorithm. The research studies [4-7] present a concurrent use of multiple methods (response surface methodology, artificial intelligence obtained through artificial neural networks, fuzzy logic, genetic algorithms, simulated annealing (SA) algorithm, goal-attainment method, regression response optimization) for modelling the surface roughness attained with milling and turning machining processes, as well as a comparison of the results. Mgwatu [8] develops and computes two machining optimization models to provide inclusive decisions of machining parameters, tool wear and surface quality while maximizing material rate and minimizing production costs. Kang *et al.* [9], using simulation study, investigate the influence of controlled vibration amplitudes and frequencies on the process of shaping the roughness profile and the subsequent values of the R_a and R_t parameters.

On the other hand, it is worth noting that, when processing materials with enhanced hardness, i.e., hardness greater than 45 HRC, increasing efforts are made to replace grinding with turning [10-12]. Therefore, there is considerable research referring to hard turning surface roughness modelling and predicting. Agrawal *et al.* [13] provide a literature review of optimization studies on hard turning. Thus, in [13-17] are described results of the impact of cutting parameters when optimizing and predicting the roughness of the surfaces. The impact of the tool geometry on the surface roughness estimation during hard turning, among other matters, is investigated in [18-20]. The influence of the cutting tool materials and workpiece hardness on the roughness profile formation during hard turning is analyzed in [12, 21-25], while information on the impact of different cooling mediums is provided in the research works in [26, 27].

A detailed analysis suggests that, regardless of the input parameters considered in the research (cutting parameters, tool geometry, cutting tool materials, workpiece hardness etc.), surface roughness optimization and prediction during hard turning is performed for limited number of roughness parameters, typically the R_a and R_z (R_t) parameters. Mite *et al.* in [28, 29] conclude that even though considered surfaces can have nearly identical values of the R_a and R_z (R_t) parameters, their roughness profile forms can be different, leading to a dissimilar behavior during the exploitation process.

This means that, when optimizing and predicting surface roughness as a result of hard turning, multiple roughness parameters need to be considered in order to define the roughness profile shape uniquely and accurately. Thus, unlike the previously referenced studies, this research, in addition to the R_a and R_z parameters, also considers the R_p , R_v and $R_{mr(c)}$ parameters for the same measured roughness profile. The distinctiveness of these parameters is that their values are quite sensitive to the roughness profile shape and the position of the mean line of the profile and therefore, it is more cumbersome to model and predict their values.

Another possible shortcoming of the previously referenced research refers to the fact that the roughness profile is considered as an independent variable, disregarding the fact that it derives from the total profile using software filtration, a procedure described in [30]. Research [31] confirms a tight correlation between the primary, waviness, and roughness profile in a stable hard turning process.

In the presented study, two different methods will be conducted and presented for modelling and predicting multiple roughness profile parameters, i.e., the R_a , R_z , R_p , R_v and $R_{mr(c)}$ parameters. The first method will employ Kinematical-Geometrical copying (K-G) of the cutting tool geometry onto the machined surface, whereas the second method will consider Design of Experiments (DOE) methodologies, more specifically a nonlinear first-order function. Furthermore, the waviness information of the profile (the W_a parameter) as well as the out-of-roundness of the investigated pieces will be applied as methods to control and verify that the roughness profiles are obtained from a stable hard turning process. The modelling based on kinematical-geometrical copying of the cutting tool geometry onto the machined surface includes a feedback loop dependent on the condition of the processing.

2. Materials, methods, and experimental work

2.1 Kinematical-geometrical (K-G) copying method

Mite *et al.* [32] propose mathematical models for predicting the values of the roughness parameters R_a , R_z , R_p , R_v , $R_{mr(c)}$ as a function of the stability and the conditions of the turning process used to form the surface roughness. The mathematical models indicated in [32] are verified by turning of normal hardness materials (33 ± 1 HRC). This research will use those models to predict the values of the roughness parameters during hard turning. The mathematical models are a function of the angles λ_s , γ_o , κ_r , the radius r_ε and the feed f . The angles λ_s , γ_o determine whether a circular part or an ellipse will be reflected onto the processed surface, where a circular part is defined when both angles are equal to zero. The angle κ_r additionally determines the position of the ellipse relative to the processed surface. The angles λ_s , γ_o directly impact the process of chip formation.

The maximum height of the roughness profile (R_z) will be calculated as follows [32]:

$$R_z = R_{z_{k-g}} \cdot e^{3SE} \quad (1)$$

where:

$$R_{z_{k-g}} = r_\varepsilon \sqrt{t} - \sqrt{r_\varepsilon^2 t - \frac{f^2}{4 \cos^2 \omega} t^2} \quad (2)$$

$$\varphi = \kappa_r - \arctg\left(\frac{\tg \lambda_s}{\tg \gamma_o}\right) \quad (3)$$

$$\omega = \arctg\left(\frac{\tg \gamma_o}{\cos(\arctg(\frac{\tg \lambda_s}{\tg \gamma_o}))}\right) \quad (4)$$

$$t = 1 - \cos^2 \varphi \cdot \sin^2 \omega \quad (5)$$

r_ε – nose radius of the inserts, κ_r – entering angle, f – feed rate, λ_s – inclination angle, γ_o – rake angle. The calculation of the parameter of statistic equality of sampling lengths in surface roughness measurement (SE) requires the measuring of the primary surface profile and a determination of the z-coordinates of the primary profile points. Then, SE is calculated as follows [30]:

$$SE = \frac{K_{sm}}{K_s} \quad (6)$$

where:

$$K_{sm} = \frac{s_{max}^2 - s_{min}^2}{s_{max}^2} \quad (7)$$

s_{max} – the maximum standard deviation calculated for primary profile points (z-coordinates) within the sampling lengths, s_{min} – the minimum standard deviation calculated for primary profile points (z-coordinates) within the sampling lengths, and:

$$K_s = \frac{\bar{s}^2}{s_p^2} \quad (8)$$

$\bar{s}$ – the standard deviation calculated as the mean value of the individual standard deviations calculated for primary profile points (z-coordinates) within the sampling length, s_p – the standard deviation calculated for all points of primary profile (z-coordinates) within the evaluation lengths.

The maximum profile peak height of the roughness profile (R_p) will be determined as follows [32]:

$$R_p = R_{p_{k-g}} \cdot e^{2SE} \quad (9)$$

where:

$$R_{p_{k-g}} = \left| \frac{r_\varepsilon^2 \cos \omega}{2f} \left(\arctg \frac{Y_2}{X_2 \cos \omega} - \arctg \frac{Y_1}{X_1 \cos \omega} \right) \right| - \left| \frac{X_1 Y_2 - X_2 Y_1}{2f} \right| \quad (10)$$

$$X_1 = \sin \varphi \sqrt{\frac{r_\varepsilon^2}{t} - \frac{f^2}{4 \cos^2 \omega}} + \frac{f \cos \varphi}{2} \quad (11)$$

$$X_2 = \sin \varphi \sqrt{\frac{r_\varepsilon^2}{t} - \frac{f^2}{4 \cos^2 \omega}} - \frac{f \cos \varphi}{2} \quad (12)$$

$$Y_1 = \frac{H - Rz_{k-g}}{\cos \varphi} - \operatorname{tg} \varphi \cdot X_1 \quad (13)$$

$$Y_2 = \frac{H - Rz_{k-g}}{\cos \varphi} - \operatorname{tg} \varphi \cdot X_2 \quad (14)$$

$$H = r_\varepsilon \sqrt{1 - \cos^2 \varphi \sin^2 \omega} \quad (15)$$

The maximum profile valley depth R_v , according to [32], will be determined as follows:

$$Rv = Rv_{k-g} \cdot e^{3SE} \quad (16)$$

where:

$$Rv_{k-g} = Rz_{k-g} - Rp_{k-g} \quad (17)$$

Arithmetical mean height of the roughness profile Ra will be determined as follows [32]:

$$Ra = Ra_{k-g} \cdot e^{SE} \quad (18)$$

where:

$$Ra_{k-g} = \left| \frac{r_\varepsilon^2 \cos \omega}{f} \left(\left(\operatorname{arctg} \frac{Y_4}{X_4 \cos \omega} \right) - \left(\operatorname{arctg} \frac{Y_3}{X_3 \cos \omega} \right) \right) \right| - \left| \frac{X_3 Y_4 - X_4 Y_3}{f} \right| \quad (19)$$

$$X_3 = \frac{(H - Rz_{k-g} + Rp_{k-g}) \sin \varphi + \cos \varphi \cdot \cos \omega \sqrt{r_\varepsilon^2 t - (H - Rz_{k-g} + Rp_{k-g})^2}}{t} \quad (20)$$

$$X_4 = \frac{(H - Rz_{k-g} + Rp_{k-g}) \sin \varphi - \cos \varphi \cdot \cos \omega \sqrt{r_\varepsilon^2 t - (H - Rz_{k-g} + Rp_{k-g})^2}}{t} \quad (21)$$

$$Y_3 = \frac{H - Rz_{k-g} + Rp_{k-g}}{\cos \varphi} - \operatorname{tg} \varphi \cdot X_3 \quad (22)$$

$$Y_4 = \frac{H - Rz_{k-g} + Rp_{k-g}}{\cos \varphi} - \operatorname{tg} \varphi \cdot X_4 \quad (23)$$

Load length ratio of the roughness profile $R_{mr(c)}$ will be determined as follows [32]:

$$Rmr(c) = \frac{Rmr(c)_{k-g}}{e^{SE}} \quad (24)$$

where:

$$Rmr(c)_{k-g} = \left(1 - \frac{2 \cos \omega \sqrt{r_\varepsilon^2 t - \left(\sqrt{r_\varepsilon^2 t - \frac{f^2}{4 \cos^2 \omega} t^2 + c} \right)^2}}{f \cdot t} \right) \cdot 100 \% \quad (25)$$

The limitations of the mathematical models developed on the basis of kinematical-geometrical copying, stipulated in [32], also apply to this research.

2.2 Design of experiments

This section presents the mathematical models for the R_a , R_z , R_p , R_v , $R_{mr(c)}$, SE and W_a parameters, as nonlinear functions denoted with the Eq. 26. For acquiring the required data for empirical modelling, four-factorial plan experiment of first order was conducted, where the independent input variables comprised cutting speed v , feed f , tool nose radius r_ε and depth of cut a_p , with repetition in the middle point of the investigated hyperspace. Table 1 provides the values of the defined independent variables. The number of experiments is $2^4 = 16$, with additional four experiments for the repetitions in the middle points. Table 2 provides the detailed plan of experiments. The verification of the adequacy of the obtained mathematical models employs the Fisher test with a significance level of $\alpha = 0.05$. The accuracy of the mathematical models is defined at 95 % confidence interval.

$$Parameter = Constant \cdot v^a \cdot f^b \cdot a^c \cdot r_\varepsilon^d \quad (26)$$

2.3. Defining of the investigated hyperspace (input independent variables)

The mathematical models based on kinematical-geometrical copying are a function of the angles $\lambda_s, \gamma_o, \kappa_r$, the radius r_ϵ and the feed f . The angles $\lambda_s, \gamma_o, \kappa_r$ characterize the cutting tool and they will not change during the experiments, whereas the radius r_ϵ and the feed f will change. To provide comparability and consistency of the results with the other model, the values of r_ϵ and f will be kept identical as in the DOE. As aforementioned, the independent variables in the first-order nonlinear mathematical model comprise of the cutting speed v , feed f , depth of cut a_p , and tool nose radius (r_ϵ), and their values are summarized in Table 1. Considering the cutting tool (insert) that the producer recommends (described in sub-chapter 2.5) for continuous cutting the following parameter ranges should be employed: cutting speed v from 80-250 m/min, depth of cut a_p from 0.05-0.5 mm and feed (f from 0.03-0.2 mm).

Starting from the conclusion stated in the introduction of this paper, that increasing efforts are made to replace grinding with turning, the authors of this paper were attentive to the selection of the values for f and a_p .

In typical industrial applications, the lower limit of the R_a parameter during classical grinding is 0.2 μm . Considering the well-known theoretical equation for determining $Ra = f^2/32r_\epsilon$ during turning, an insert radius $r_\epsilon = 1.2$ mm and $Ra = 0.2$ μm yields that the feed is $f = 0.087$ mm/rev. Therefore, this research adopts a lower limit for f of 0.09 mm/rev, while the upper limit reflects the recommendations of the cutting tool producer. When selecting the minimum value for the depth of cut (a_p), the authors assured that the ratio f/a_p is always less than or equal to one. This is crucial since under such circumstances the general "shape" of the chip cross section does not change significantly, which impacts the chip formation process and the geometric structure of the surface. Therefore, the paper adopts a lower limit for a_p of 0.2 mm, and twice as big upper limit.

Table 1 Input parameters and their levels

No.	Parameters	Level 1	Central point	Level 2
1	Cutting speed (v), m/min	100	141.4	200
2	Feed (f), mm/rev	0.09	0.134	0.2
3	Depth of cut (a_p), mm	0.2	0.283	0.4
4	Tool nose radius (r_ϵ), mm	0.4	0.8	1.2

2.4 Work piece material

This research uses work pieces made of steel EN C55 (AISI 1055). To achieve appropriate hardness of 53 ± 1 HRC, the work pieces were thermally enhanced. The pieces are made into rings to achieve uniform hardness throughout the entire cross-section. The size of the rings is $\varnothing 100 \times \varnothing 82 \times 20$ mm and they are clamped on a special device using a flat key (Fig. 1).

2.5 Machine and cutting tool

The work rings are processed using CNC lathe, shown on Fig. 1, model OKUMA LB 15-II (C-1S). The lathe provides variable spindle speed from 38-3800 rpm, feed rate from 0.001-1000 mm/rev and 15 kW spindle drive motor. From one side the work pieces are clamped in the chuck, while on the other side, they lean on the tailstock (Fig. 1). Before performing the machining experiments, the rings were processed to remove the circular run out from the clamping of the rings. During the machining of the workpieces in accordance with the defined DOE, a coolant (17 % concentration of cutting oil in water) was applied. The pieces were processed using a holder designated ADPNN2525M15-A (Tungaloy), with $\kappa_r = 62.5^\circ$, $\gamma_o = 0^\circ$, $\lambda_s = -10^\circ$ and cutting T-CBN negative inserts designated 2QP-DNGA 150404-BXM20, 2QP-DNGA 150408-BXM20 and 2QP-DNGA 150412-BXM20 (Tungaloy). The angles γ_o and λ_s are defined perpendicularly to the axis of rotation. Every working ring is processed using a new cutting edge of the insert, to eliminate the effect from the wear of the inserts. In models based on the kinematical-geometrical copying principle, the angle γ_o equals -0.0001° , to avoid the mathematical constraints stipulated in [32].



Fig. 1 Experimental equipment

2.6 Measurement equipment and execution of experiment

The out-of-roundness of the work rings is measured using a Roundtest RA-400 (Mitutoyo), Fig. 2. To avoid potential impact of the elastic deformation of the working rings caused by clamping, the authors measured the circularity while the rings remained clamped on the device, as shown on Fig. 2. The primary, roughness and waviness profiles of the processed rings were measured using a Surf test model No. SJ-410 (Mitutoyo), Fig. 3. The considered parameters were measured at five equally spaced locations around the circumference of the work rings to obtain the statistically significant data for the test. The profiles and parameters were measured and calculated in accordance with the ISO standard recommendations, i.e. in accordance with the procedure for obtaining the primary profile, the roughness profile, and the waviness profile presented in [30]. Table 2 provides the measurement conditions when obtaining the primary, roughness, and waviness profiles. The $R_{mr(c)}$ parameter was calculated at a level of 30 % of R_z ($30R_z$) from the highest peak of the roughness profile, i.e. $c = 30\%$ of $R_z \mu\text{m}$, for all considered roughness profile. A pick-up stylus with top angle of 60° and top radius of $2 \mu\text{m}$ was utilized, as well as a skidless pick-up. During the measurements, the instrument was mechanically levelled with respect to the measured surface. The measuring system was calibrated using a type C etalon with $R_a = 2.97 \mu\text{m}$, and was verified using a type C etalon with $R_a = 6 \mu\text{m}$. The used calibration etalons have a measuring uncertainty of 5 %. The parameter SE was calculated for a primary profile in accordance with the conditions listed in Table 2.

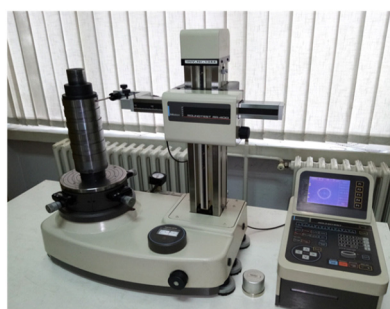


Fig. 2 Roundtest RA-400 (Mitutoyo)

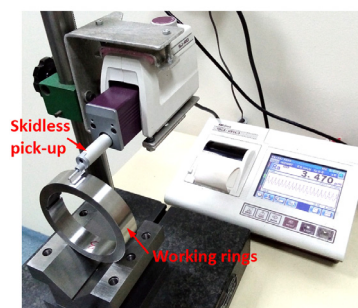


Fig. 3 Surf test model No. SJ-410 (Mitutoyo)

3. Results and discussion

Table 3 shows the entire plan for the realization of the experiments, as well as the measured values for: the roughness parameters R_a , R_z , R_p , R_v and $R_{mr(c)}$, the parameter SE determined for the primary profile, the parameter W_a determined for the waviness profile and the out-of-roundness values. The value of all parameters provided in Table 3, except for the out-of-

roundness, are derived as mean values of five measurements. The values for the out-of-roundness in Table 3 are mean values of three measurements. Furthermore, this research includes the parameter W_a that reflects the waviness profile. Constitutionally, according to DIN 4760 and [32], the roughness profile forms as third, fourth and fifth order deviations, while the waviness profile forms as a result of second order deviations. Out of all the second order deviations, off-center clamping can greatly influence waviness. To obtain a comprehensive picture of the conditions for forming the roughness profiles, the parameter W_a and the out-of-roundness of the working rings are also considered and measured. Table 3 shows the values of the out-of-roundness. The out-of-roundness of the work rings is not subject to mathematical modelling. However, a non-linear function of the first order model is established for the W_a parameter.

Table 2 Measurement conditions of roundness, primary, roughness and waviness profiles

Profile/Parameters		Primary profile / P_a / SE	
Experiment No.		All	
Filter		Gaussian	
r_{tip} (μm)		2	
λ_s profile filter (μm)		2.5	
L evaluation length (mm)		8	
$L = 1 \times N$ (mm)			
Profile/Parameters		Waviness profile / W_a	
Experiment No.	1,2,5,6,9,10,13,14	3,4,7,8,11,12,15,16,17,18,19,20	
Filter		Gaussian	
r_{tip} (μm)		2	
λ_c profile filter (mm)	0.25		0.8
λ_f profile filter (mm)		2.5	
L evaluation length (mm)		$5 \times 2.5 = 12.5$	
Profile/Parameters		Roughness profile / R_a	
Experiment No.	1,2,5,6,9,10,13,14	3,4,7,8,11,12,15,16,17,18,19,20	
Filter		Gaussian	
r_{tip} (μm)		2	
λ_s profile filter (μm)		2.5	
λ_c profile filter (mm)	0.25		0.8
l_r sampling length (mm)			
l_n evaluation length (mm)	$5 \times 0.25 = 1.25$	$5 \times 0.8 = 4$	
$l_n = N \times l_r$ (mm)			

Table 3 Experimental plan and results

No.	v (m/min)	f (mm/rev)	a_p (mm)	r_ϵ (mm)	SE <i>P-profile</i>	R_z (μm)	R_p (μm)	R_v (μm)	R_a (μm)	R_{mr} ($30R_z$) (%)	W_a (μm)	Out-of-roundness (μm)
1	100	0.09	0.2	0.4	0.036	3.098	1.992	1.106	0.695	14.1	0.055	0.658
2	200	0.09	0.2	0.4	0.047	3.313	2.074	1.239	0.735	15.5	0.049	0.633
3	100	0.2	0.2	0.4	0.033	14.148	9.262	4.886	3.398	14.4	0.078	0.700
4	200	0.2	0.2	0.4	0.044	14.084	9.310	4.774	3.362	13.7	0.094	0.732
5	100	0.09	0.4	0.4	0.033	3.010	1.891	1.120	0.720	14.9	0.076	0.689
6	200	0.09	0.4	0.4	0.041	3.209	2.047	1.162	0.782	14.2	0.055	0.705
7	100	0.2	0.4	0.4	0.038	13.789	9.017	4.771	3.309	14.3	0.080	0.933
8	200	0.2	0.4	0.4	0.051	14.334	9.475	4.932	3.442	13.0	0.101	0.893
9	100	0.09	0.2	1.2	0.147	1.329	0.795	0.534	0.249	10.7	0.045	0.533
10	200	0.09	0.2	1.2	0.078	1.345	0.742	0.603	0.287	18.6	0.054	0.603
11	100	0.2	0.2	1.2	0.047	4.039	2.541	1.498	0.938	15.2	0.036	0.842
12	200	0.2	0.2	1.2	0.047	4.089	2.715	1.375	0.934	14.2	0.040	0.795
13	100	0.09	0.4	1.2	0.115	1.413	0.742	0.671	0.254	15.2	0.042	0.551
14	200	0.09	0.4	1.2	0.141	1.052	0.639	0.413	0.218	12.0	0.041	0.400
15	100	0.2	0.4	1.2	0.039	4.138	2.636	1.498	0.938	13.3	0.035	0.681
16	200	0.2	0.4	1.2	0.054	4.297	2.796	1.501	0.940	12.8	0.036	0.652
17	141.4	0.134	0.283	0.8	0.039	2.962	1.848	1.114	0.699	16.0	0.026	0.433
18	141.4	0.134	0.283	0.8	0.043	3.236	2.005	1.230	0.726	13.4	0.027	0.568
19	141.4	0.134	0.283	0.8	0.032	3.325	2.058	1.309	0.713	14.1	0.028	0.675
20	141.4	0.134	0.283	0.8	0.042	3.362	2.216	1.146	0.781	12.9	0.036	0.500

The reason pertains to the fact that the SE parameter determined for the primary profile, as well as the primary profile itself, contain the waviness. From a measurement point of view, the boundary between the waviness profile and the roughness profile is defined by the applied λ_c profile filter. Any deficiencies or inappropriate choices for the applied λ_c profile reflect on the

shape of the roughness profile. In addition, from a constitutional point of view, the selection of the combination of values for cutting speed (v), feed (f), depth of cut (a_p) and tool nose radius (r_ϵ) can also influence the vibrations on the tool and the machine. The following mathematical models for the considered parameters were obtained based on the values from Table 3 and applying the methodology stipulated in sub-chapter 2.2:

$$R_z = 77.533 \cdot v^{-0.0121541} \cdot f^{1.673} \cdot a^{-0.0322310} \cdot r_\epsilon^{-0.9691411} \quad (27)$$

$$R_p = 50.514 \cdot v^{0.0145691} \cdot f^{1.775} \cdot a^{-0.0406075} \cdot r_\epsilon^{-1.026} \quad (28)$$

$$R_v = 26.753 \cdot v^{-0.0516292} \cdot f^{1.515} \cdot a^{-0.0190284} \cdot r_\epsilon^{-0.8838959} \quad (29)$$

$$R_a = 17.175 \cdot v^{0.0278376} \cdot f^{1.783} \cdot a^{-0.0278446} \cdot r_\epsilon^{-1.071} \quad (30)$$

$$R_{mr(30Rz)} = 10.732 \cdot v^{0.0202365} \cdot f^{-0.0328251} \cdot a^{-0.0730024} \cdot r_\epsilon^{-0.0278032} \quad (31)$$

$$SE = 0.0095850 \cdot v^{0.1733292} \cdot f^{-0.5450216} \cdot a^{0.0656300} \cdot r_\epsilon^{0.5575011} \quad (32)$$

$$W_a = 0.0406614 \cdot v^{0.0491459} \cdot f^{0.1290388} \cdot a^{0.0104809} \cdot r_\epsilon^{-0.5093038} \quad (33)$$

The mathematical models expressed by the Eq. 27-33 represent first order models without mutual interaction and without factor significance evaluation. Table 5 provides their dispersion analysis together with an adequacy evaluation. The negative sign in the exponent in the term of the model indicates an inverse relationship between that term and the modelled parameter. The SE parameter model, Eq. 32, obtained in accordance with the DOE was used to obtain the values necessary to calculate the roughness parameters according to the kinematical-geometrical copying model, Eq. 1,9,16,18,24. The percentage differences between the mean values of the measurements and the theoretically calculated values of the parameters modelled according to K-G and DOE, are systematized in Table 4. The negative sign before the values in Table 4 indicates that the theoretical value is lower than the measured value. The paper presents 3D graphs, Figs. 4 to 20, in order to provide a graphic overview of the obtained mathematical models of the modelled parameters, but also to show the differences between the models obtained using different techniques of the investigated hyperspace. For every roughness parameter, the paper presents three graphs selected in a state with the biggest percentage difference, from Table 4, between the kinematical-geometrical copying model (K-G) and the DOE.

Table 4 Percentage difference between measured average values and calculated values according to the two techniques

No.	R _z (%)		R _p (%)		R _v (%)		R _a (%)		R _{mr} (30Rz) (%)		SE (%)
	K-G	DOE	K-G	DOE	K-G	DOE	K-G	DOE	K-G	DOE	DOE
1	-7.9	7.3	-8.5	3.1	-15.7	13.1	-2.8	6.7	9.8	4.3	16.6
2	-13.5	0.0	-11.8	0.1	-27.5	-0.9	-8.7	3.1	0.3	-3.8	3.2
3	-3.1	-11.4	-3.7	-9.2	-7.5	-14.5	-1.7	-10.0	8.2	-0.5	-17.6
4	-1.5	-11.8	-3.5	-8.7	-3.9	-15.9	-0.6	-6.7	12.1	5.4	-39.9
5	-3.8	7.9	-2.6	5.4	-16.5	10.8	-6.6	1.4	4.1	-6.8	26.2
6	-8.8	0.9	-9.8	-1.4	-18.7	4.2	-15.8	-5.1	8.5	0.0	18.6
7	-0.1	-11.0	-0.7	-9.3	-4.6	-13.3	0.8	-9.2	8.5	-5.3	-30.5
8	-2.9	-16.3	-5.0	-13.7	-6.9	-21.4	-3.1	-11.4	16.7	5.9	-57.6
9	-24.9	-15.4	-21.2	-19.3	-50.6	-10.8	-7.7	-8.7	29.4	25.3	-85.9
10	-22.6	-17.7	-10.9	-10.3	-65.1	-29.7	-23.7	-22.5	-24.5	-28.6	11.8
11	16.5	7.8	17.1	7.5	7.0	7.3	17.0	1.6	1.8	-9.5	8.6
12	17.1	5.9	12.6	2.2	16.3	11.8	17.3	3.8	7.9	-0.6	18.3
13	-31.4	-25.5	-12.4	-14.7	-87.1	-41.0	-9.9	-12.9	-0.9	-11.9	-39.7
14	5.2	5.8	5.2	2.3	-11.6	10.0	5.6	4.8	19.1	12.4	-51.4
15	15.1	3.4	14.4	1.3	7.7	6.1	16.8	-0.4	13.9	-0.8	26.9
16	13.6	-1.1	10.5	-3.6	9.4	2.4	16.6	1.3	16.7	4.5	10.9
17	10.1	9.4	11.2	8.9	-1.4	9.5	7.6	3.0	-3.5	-14.3	28.6
18	1.8	1.1	3.6	1.1	-12.0	0.0	4.0	-0.8	13.1	4.0	22.1
19	-0.9	-1.7	1.1	-1.5	-19.2	-6.4	5.7	1.0	8.9	-0.6	41.1
20	-2.0	-2.8	-6.5	-9.3	-4.4	6.8	-3.3	-8.4	16.4	7.7	23.6

Table 5 Dispersion analysis

		Degrees of freedom f	Sum of squares s	Dispersion s/f	Dispersion ratios fr	Table value ft	Model Adequacy evaluation
R_z	Residual sum	15	0.293426	0.019562			
	Experiment error	3	0.009897	0.003299			
	Model adequacy	12	0.283529	0.023627	7.162	8.740	fr < ft adequate
Multiple regression coefficient: R = 0.9877							
R_p	Residual sum	15	0.218346	0.014556			
	Experiment error	3	0.016825	0.005608			
	Model adequacy	12	0.201521	0.016793	2.994	8.740	fr < ft adequate
Multiple regression coefficient: R = 0.9918							
R_v	Residual sum	15	0.475066	0.031671			
	Experiment error	3	0.015825	0.005275			
	Model adequacy	12	0.459240	0.038270	7.255	8.740	fr < ft adequate
Multiple regression coefficient: R = 0.9762							
R_a	Residual sum	15	0.198609	0.013241			
	Experiment error	3	0.007023	0.002341			
	Model adequacy	12	0.191586	0.015966	6.820	8.740	fr < ft adequate
Multiple regression coefficient: R = 0.9928							
$R_{mr(30R_z)}$	Residual sum	15	0.231928	0.015462			
	Experiment error	3	0.025964	0.008655			
	Model adequacy	12	0.205964	0.017164	1.983	8.740	fr < ft adequate
Multiple regression coefficient: R = 0.2649							
SE	Residual sum	15	1.779	0.118613			
	Experiment error	3	0.053990	0.017997			
	Model adequacy	12	1.725	0.143767	7.988	8.740	fr < ft adequate
Multiple regression coefficient: R = 0.7526							
W_a	Residual sum	15	1.889	0.125933			
	Experiment error	3	0.065015	0.021672			
	Model adequacy	12	1.824	0.151998	7.014	8.740	fr < ft adequate
Multiple regression coefficient: R = 0.6384							

In the mathematical models for calculating the R_z , R_p , R_v and R_a parameters, Eq. 27-30, obtained using the DOE methodology, the feed (f) and the tool nose radius (r_ϵ) have a dominant influence. The feed is proportionally correlated, while the tool nose radius is inversely proportional to the values of the parameters. Still, the feed has a bigger impact than the radius. The cutting speed (v) and depth of cut (a_p) have insignificant impacts. Interestingly, in all models, Eq. 27-30, the impact of the depth of cut is inversely proportional. Although insignificant, this means that an increase of the depth of cut will stabilize the process of transforming the removed material into a chip. Due to the fact that, for the $R_{mr(c)}$ parameter, the paper adopts “c” as a function of the R_z parameter, none of the input variables (v , f , a_p , r_ϵ) in the model have a dominant impact.

The SE parameter model, Eq. 32, and Fig. 5, show that the depth of cut has the least impact on the stochastic character of the primary profile, while the feed and the tool nose radius have comparably strong impacts, but with different signs. On one hand, considered on a micro-plan, the radius increase disturbs the deterministic nature of the irregularities along the primary profile, resulting in an increased value of the SE parameter. However, on a mezzo-plan, the increase of the radius “irons out” the unevenness which leads to a waviness profile with a smaller W_a , reflected in Eq.33, and Fig. 20. Although to a lesser extent and direction relative to the radius, the feed also influences the value of the W_a parameter. This influence cannot be attributed only to the changes related to the increase of the feed (for example: increased cutting forces), but also to the imperfection of the shape of the middle line generated by the λ_c profile filter. Table 4 shows that the calculated and measured values of the parameters R_p and R_v differ the most, expressed in percent. These parameters directly depend on the position of the roughness profile mean line.

Another conclusion is that the experiments with lower f/r_ϵ ratios feature bigger deviations. The patterns described above also apply to the percentage differences between the values calculated according to the models based on the kinematical-geometrical copying and the measured values, Table 4. If we compare the percentage difference of both models, we can conclude that the DOE mathematical models yield values slightly closer to the measured values. This is because for the SE parameter, responsible for compensating the theoretical values in accordance with the real processing, there are large percentage differences between the values determined in accordance with the SE model, Eq. 32, and the actual measured values, Table 3.

This, in turn, can be attributed to the “sensitive nature” of the SE parameter. The graphic comparisons presented in Fig. 5-19, clearly indicate small differences between the values of the modelled roughness parameters obtained in accordance with the two considered mathematical modelling methodologies. More importantly, the change trends along one or the other axis should be followed continuously. The biggest difference in this respect, exists for the parameters $R_{mr(c)}$, where the DOE model, throughout the hyperspace, yields smaller values relative to the kinematical-geometrical copying model, Fig. 16, 18 and 19, without any intersecting lines or overlapping. The measured small values for the out-of-roundness of the working rings, in itself indicates that the entire process of obtaining the roughness profile was implemented under a strictly controlled and stable turning process.

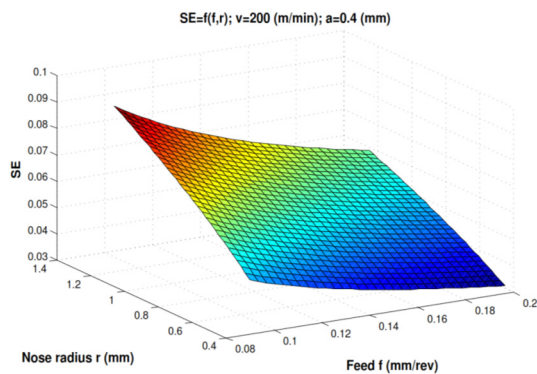


Fig. 4 3D graph for SE ($v = 200 \text{ m/min}$, $a_p = 0.4 \text{ mm}$)

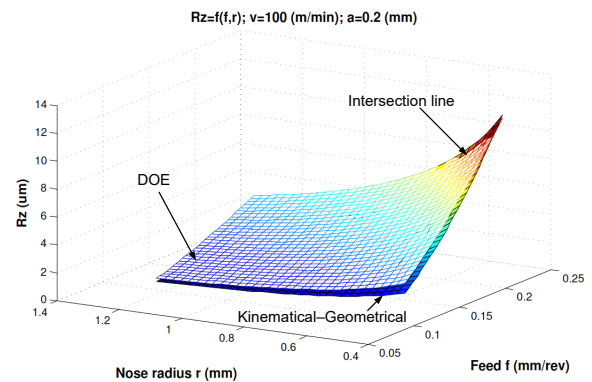


Fig. 5 3D graphs for R_z ($v = 100 \text{ m/min}$, $a_p = 0.2 \text{ mm}$)

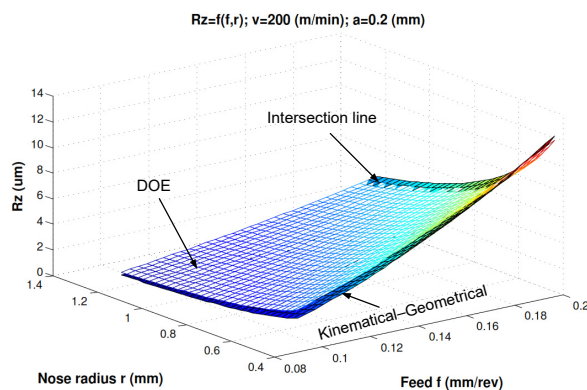


Fig. 6 3D graphs for R_z ($v = 200 \text{ m/min}$, $a_p = 0.2 \text{ mm}$)

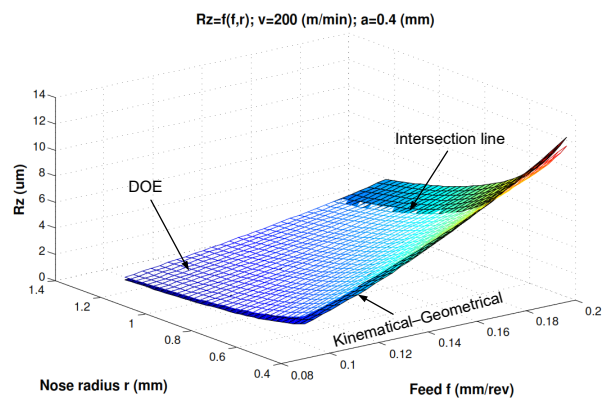


Fig. 7 3D graphs for R_z ($v = 200 \text{ m/min}$, $a_p = 0.4 \text{ mm}$)

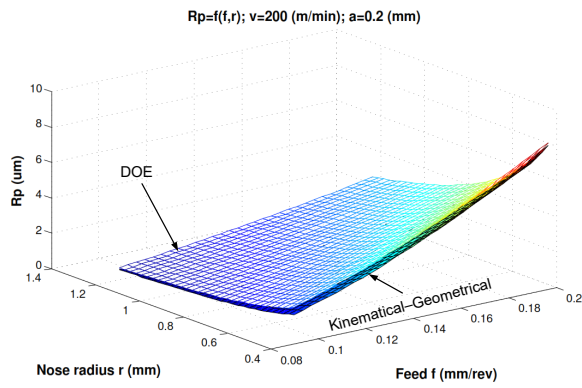


Fig. 8 3D graphs for R_p ($v = 200 \text{ m/min}$, $a_p = 0.2 \text{ mm}$)

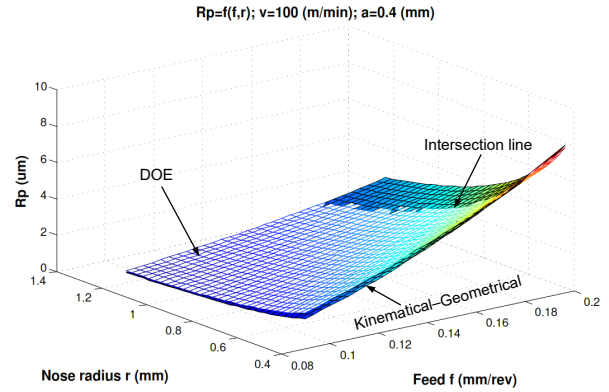


Fig. 9 3D graphs for R_p ($v = 100 \text{ m/min}$, $a_p = 0.4 \text{ mm}$)

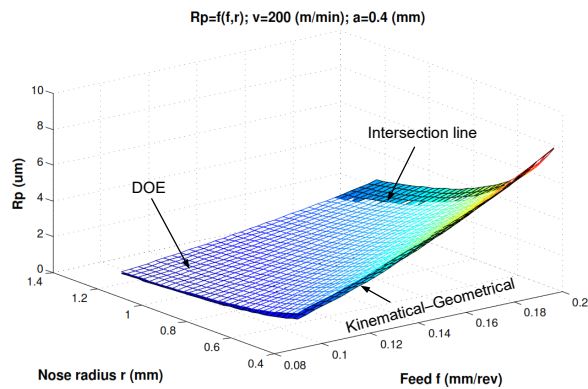


Fig. 10 3D graphs for R_p ($v = 200 \text{ m/min}$, $a_p = 0.4 \text{ mm}$)

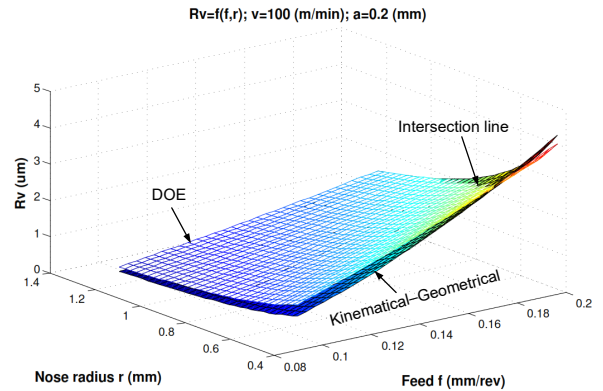


Fig. 11 3D graphs for R_v ($v = 100 \text{ m/min}$, $a_p = 0.2 \text{ mm}$)

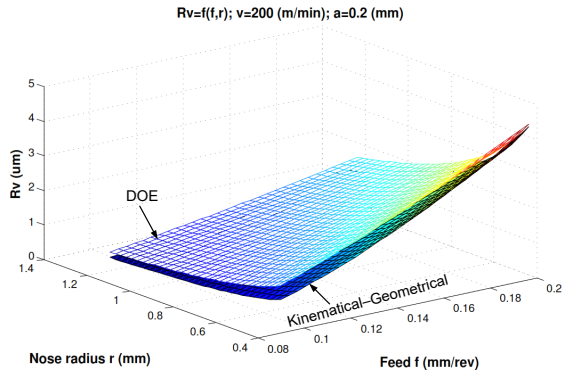


Fig. 12 3D graphs for R_v ($v = 200 \text{ m/min}$, $a_p = 0.2 \text{ mm}$)

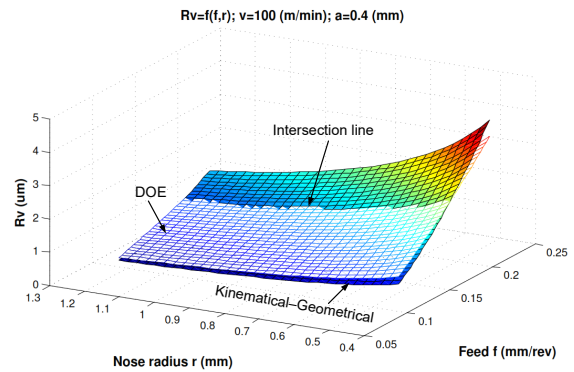


Fig. 13 3D graphs for R_v ($v = 100 \text{ m/min}$, $a_p = 0.4 \text{ mm}$)

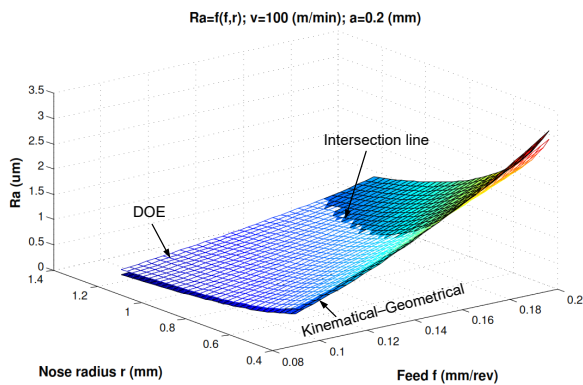


Fig. 14 3D graphs for R_a ($v = 100 \text{ m/min}$, $a_p = 0.2 \text{ mm}$)

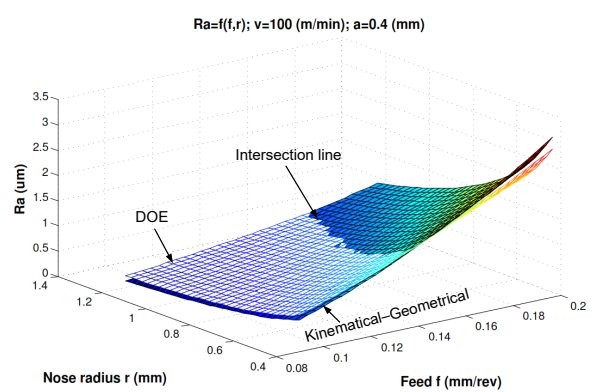


Fig. 15 3D graphs for R_a ($v = 100 \text{ m/min}$, $a_p = 0.4 \text{ mm}$)

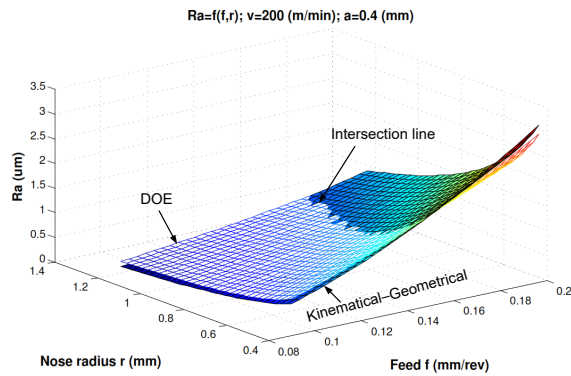


Fig. 16 3D graphs for R_a ($v = 200$ m/min, $a_p = 0.4$ mm)

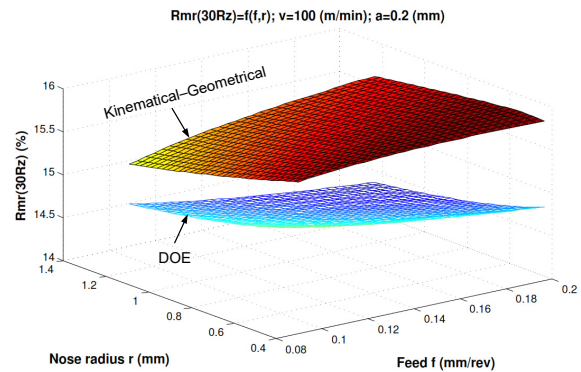


Fig. 17 3D graphs for $R_{mr}(30R_z)$ ($v = 100$ m/min, $a_p = 0.2$ mm)

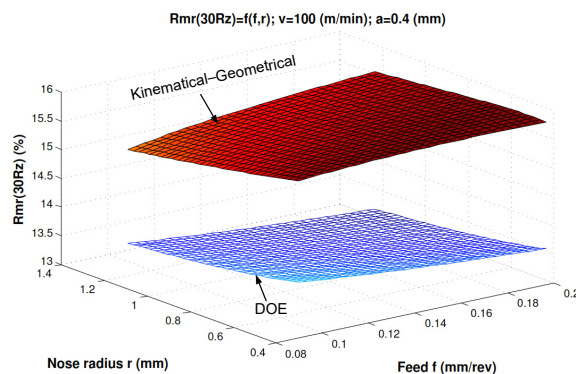


Fig. 18 3D graphs for $R_{mr}(30R_z)$ ($v = 100$ m/min, $a_p = 0.4$ mm)

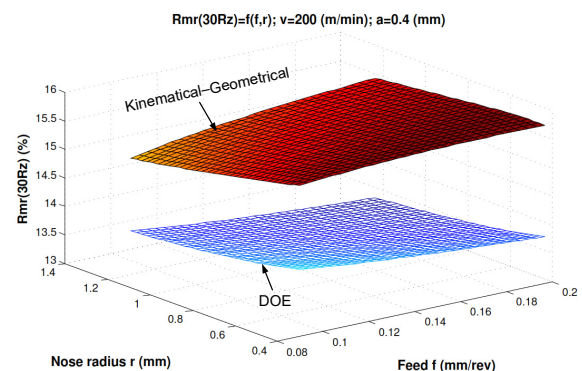


Fig. 19 3D graphs for $R_{mr}(30R_z)$ ($v = 200$ m/min, $a_p = 0.4$ mm)

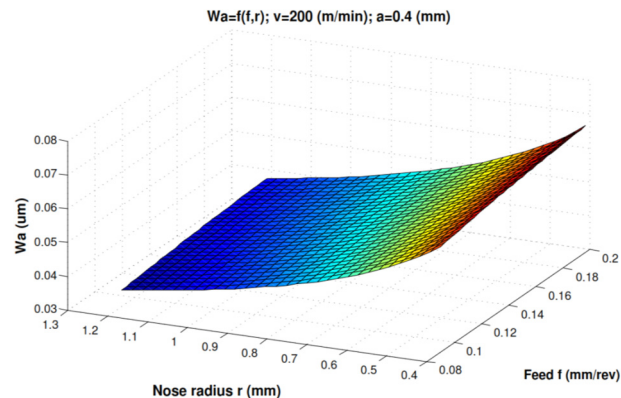


Fig. 20 3D graphs for W_a ($v = 200$ m/min, $a_p = 0.4$ mm)

4. Conclusion

The simultaneous modelling of multiple roughness parameters using two different approaches, the kinematical-geometrical copying method and the DOE method, as well as the comparison between the two, clearly showed their strengths and weaknesses.

The mathematical models expressed as a nonlinear first order function can accurately model the roughness parameters during hard turning. This showed that all obtained mathematical models are adequate although they estimate multiple roughness parameters for the same processed surface (the same roughness profile). The difference between the measured values of the roughness parameters compared to the values theoretically calculated with the DOE models is acceptable. However, it should be noted that from the practical point of view, the empirically derived roughness parameter models depict the process accurately solely in the conditions in which they had been obtained. Any changes of machines, clamping methods, working pieces,

different geometry tools etc., means a new model of the roughness parameters needs to be derived referring to those precise machining conditions. The mathematical models of the roughness parameters obtained using the method of kinematical-geometrical copying (K-G) of the cutting tool onto the processed surface, including the SE parameter, were shown that likewise successfully model the roughness parameters during hard turning. Their graphical presentations showed a great similarity with the graphical presentations of the DOE models. The SE parameter from these models make the link between the theoretically calculated values and the actual condition of the cutting process. In other words, the SE parameter also considers, to an extent, the 'difficult' modelling factors. From a general practical point of view, the models based on the kinematical-geometrical copying of the cutting tool including the SE parameter have a broader applicability. It is sufficient to model the SE parameter and then to calculate multiple roughness parameters. The measurements of the deviations from out-of-roundness of the working rings, as well as the modelling of the waviness parameter Wa showed the stability of the turning process used to obtain the roughness profiles.

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