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Mathematical Modelling and Correlation Between the Primary Waviness and Roughness Profiles During Hard Turning

Mite Tomov[a*], Bojan Prangoski[a], Pawel Karolczak[b]

[a]Faculty of Mechanical Engineering-Skopje, Ss Cyril end Methodius" University in Skopje, Karpos II, 1000 Skopje, North Macedonia.
[b]Department of Machine Tools and Mechanical Technologies, Wroclaw University of Science and Technology, 50-370 Wrocław, Poland

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Abstract

This paper presents a research primarily aimed at determining the correlations between the primary profile, waviness, and roughness profiles during hard turning, using mathematical modeling of the primary profile (Pa), the roughness profile (Ra) and the waviness profile (Wa). For this purpose, we employed the Design of experiments (DOE) principles expressing the roughness parameters models as a nonlinear function shape of the first order of the input variables: cutting speed (v), feed (f), depth of cut (a_p) and tool nose radius (r_ε). The models were done based on empirical data obtained by processing special rings made of stee lEN C55 (AISI 1055) with hardness of 53±1 HRC, using a CNC lathe. The obtained results are presented as mathematical models, but also as 3D diagrams which clearly show the change trends and their mutual relationships for the considered parameters.

Keywords: hard turning, surface roughness, primary profile, waviness profile, roughness profiles, mathematical modeling;

1. Introduction

C.L. He and all. in the research presented in [1] provide a detailed overview of the State-of-the-art of the influential factors and the applied methods used in surface roughness modeling in turning, regardless of whether the processed materials have normal or enhanced hardness. It is worth noting that when processing materials with enhanced hardness, i.e., hardness greater than 45 HRC, more and more attempts are made to replace grinding with turning [2-4]. Therefore, there is much research referring to hard turning surface roughness modelling and predicting. Agrawal A. and all., in [5] provide a table overview of the literature review of optimization studies on hard turning. Thus, [5-8] provide results of the impact of cutting parameters (cutting speed, feed and depth of cut) when optimizing and predicting the roughness of the surfaces, using the regression analysis technique, while the research [9-10] also analyze the impact of cutting speed, feed and depth of cut, but using the *Taguchi experimental design.* Research referring to, among other things, how tool geometry impacts the predicting of surface roughness during hard turning can also be found in [11,12]. The influence of the cutting tool materials on the roughness optimization is analyzed in [13-15], while the influence of the workpiece hardness on the roughness profile formation during hard turning is analyzed in [4,16-18]. Information on the impact of different cooling mediums is provided in the research in [19, 20].

A detailed analysis of the aforementioned research suggests that, regardless of the input parameters in the research (cutting parameters, tool geometry, cutting tool materials, workpiece hardness etc.), surface roughness optimization and prediction during hard turning is done for very few parameters, typically the Ra and Rz (Rt) parameters. This trend of replacing the term surface roughness with the Ra parameter continues even today when researching the processing of new materials [21,22] or when controlling complex machine parts [23].

Knowing that the roughness profile derives from the primary profile and total profile by applying appropriate filtering techniques [24], it is worth noting that the research [2-20] lacks information on waviness deviation and form deviation of the pieces, crucial values for the proper functioning of the parts.

This research aims at determining whether any correlation exists between the primary profile (P-profile), the waviness profile (W-profile), and the roughness profile (R-profile) during hard turning. This is very important because the primary profile, the waviness profile, and the roughness profile coexist and together they form the surface profile (the total profile) as a 2D representation of the surface topography. The justification of this research arises also from the fact that, according to DIN 4760, from a structural point of view, we can simultaneously define six types of deviations including waviness (2^{nd} order deviation) and roughness (3^{rd} to 5^{th} order deviation). We will analyze the correlation between the primary profile, the waviness profile, and the roughness profile using mathematical models for modelling the Pa, Wa, and Ra parameters.

* Corresponding author e-mail: mite.tomov@mf.edu.mk.

2. Method of mathematical modeling and correlation

We will analyze the correlation between the primary profile, the waviness profile, and the roughness profile using mathematical models for modelling the Pa, Wa, and Ra parameters. The term "correlation" used in this research should not be understood purely from a mathematical point of view (expressed by the correlation coefficient). We have used this term here to describe the relationship between the trends of the change of the considered parameters obtained from the nonlinear models.

Models for the Pa, Wa and Ra parameters, as a nonlinear function shape, equation (1), using a four-factorial plan experiments of the first order where the independent input variables comprise 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.

$$Pa, Wa, Ra = Constant \cdot v^a \cdot f^b \cdot a^c \cdot r_\varepsilon^d \quad (1)$$

The number of experiments is $2^4 = 16$, plus 4 experiments as a repetition in the middle points, total of 20 experiments. A detailed plan of the experiments is presented in Table 2.

In the experiments involving a repetition of the middle point (17-20) we intentionally deviated from the value of tool nose radius (r_ε). The calculation suggests that the geometric mean of the radius is approximately 0.7mm, while the research uses the value of 0.8mm. The reason is that there are no inserts with a radius of 0.7mm and the closest standard value available is 0.8mm.

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.

This research also includes the SE parameter in order to obtain information about the stability of the turning process. The SE parameter was calculated for the primary profile and modelled using mathematical models, similarly to the other considered parameters.

3. Experimental verification

3.1. Work piece material

This research uses work pieces made of steel EN C55 (AISI 1055). In order to achieve appropriate hardness of 53±1 HRC the work pieces were thermally enhanced. The pieces are made into rings in order to achieve uniform hardness throughout the entire cross-section. The size of the rings is ø100 x ø82 x 20mm and they are clamped on a special device using a flat key, Figure 1.

3.2. Machine and cutting tool

The work rings are processed using CNC lathe, shown on Figure 2, model OKUMA LB 15-II (C-1S) has variable spindle speed from 38 to 3800 rpm, feed rate from 0.001 to 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, Figure 2. Before processing starts in accordance with the experimental plan, the rings were processed in order to remove the circular run out from the clamping of the rings. A coolant (17% concentration of cutting oil in water) was applied during the machining of the rings. The pieces were processed using a holder designated ADPNN2525M15-A (Tungaloy), with κ_r= 62.5°, γ_o = 0°, λ_s= -10° and cutting T-CBN negative inserts designated 2QP-DNGA 150404-BXM20, 2QP-DNGA 150408-BXM20 and 2QP-DNGA 150412-BXM20 from the Tungaloy. Every working rings is processed using a new cutting edge of the insert, in order to eliminate the effect from the wear of the inserts.

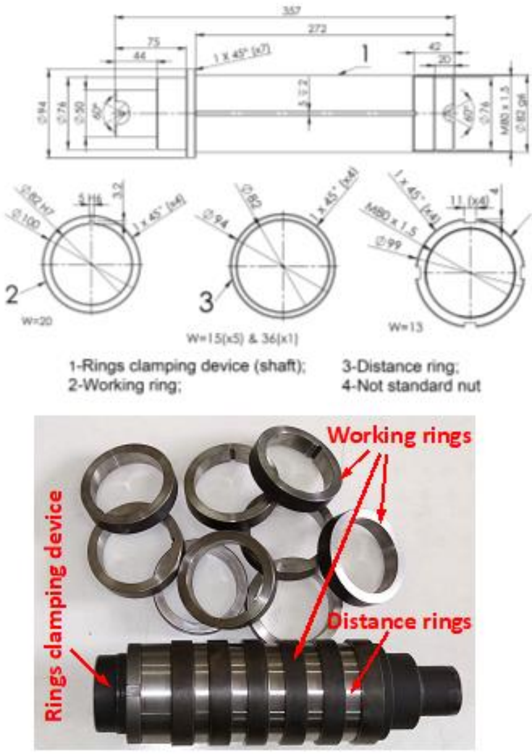

Figure 1. 2D drawing and realistic view of rings clamping device

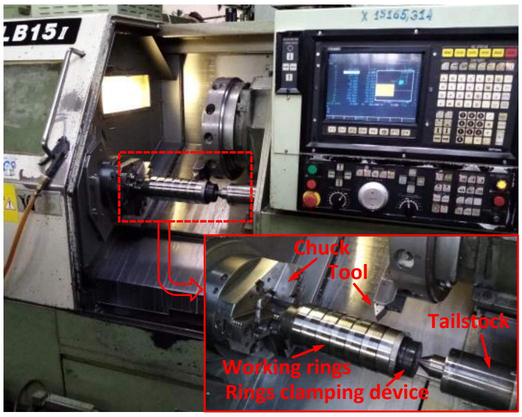

Figure 2. Ring clamping device setting of CNC lathe

3.3. Measurement equipment and conditions

The primary, roughness and waviness profiles of the processed rings were obtained using the procedure presented in Figure 3. The total profile measurements were done using the Surf test model No. SJ-410 (Mitutoyo make), Figure 4, in accordance with the measuring conditions presented in Table 1. The total profiles were measured at five equally spaced locations around the circumference of the work rings to obtain the statistically significant data for the test. A pick-up stylus used had a top angle of 60° and a top radius of 2 μm. A skidless pick-up was used. During the measurements, the instrument was mechanically leveled with respect to the measured surface. The measuring system was calibrated using a type C etalon with Ra=2.97 μm, and was verified using a type C etalon with Ra=6 μm. The used calibration etalons have a measuring uncertainty of 5%.

Table 1: Measurement conditions of primary, waviness and roughness profiles.

Profile/Parameters	Primary profile / Pa / SE	
Experiment No.	All	
Filter	Gaussian	
r_{tip} (μm)	2	
λs profile filter (μm)	2.5	
L evaluation length L = 1 x N (mm)	8	
Profile/Parameters	**Waviness profile / Wa**	
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	
λc profile filter (mm)	0.25	0.8
λf profile filter (mm)	2.5	
L evaluation length (mm)	5 x 2.5 = 12.5	
Profile/Parameters	**Roughness profile / Ra**	
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	
λs profile filter (μm)	2.5	
λc profile filter (mm) lr sampling length	0.25	0.8
ln evaluation length ln = N x lr (mm)	5 x 0.25 = 1.25	5 x 0.8 = 4

Table 2. Experimental plan and results.

No.	V (m/min)	f (mm/rev)	a_p (mm)	r_ε (mm)	*Pa* (μm)	*Wa* (μm)	*Ra* (μm)	*SE P-profile*
1	100	0.09	0.2	0.4	0.726	0.055	0.695	0.036
2	200	0.09	0.2	0.4	0.772	0.049	0.735	0.047
3	100	0.2	0.2	0.4	3.447	0.078	3.398	0.033
4	200	0.2	0.2	0.4	3.407	0.094	3.362	0.044
5	100	0.09	0.4	0.4	0.749	0.076	0.720	0.033
6	200	0.09	0.4	0.4	0.821	0.055	0.782	0.041
7	100	0.2	0.4	0.4	3.347	0.080	3.309	0.038
8	200	0.2	0.4	0.4	3.501	0.101	3.442	0.051
9	100	0.09	0.2	1.2	0.258	0.045	0.249	0.147
10	200	0.09	0.2	1.2	0.317	0.054	0.287	0.078
11	100	0.2	0.2	1.2	0.944	0.036	0.938	0.047
12	200	0.2	0.2	1.2	0.949	0.040	0.934	0.047
13	100	0.09	0.4	1.2	0.284	0.042	0.254	0.115
14	200	0.09	0.4	1.2	0.236	0.041	0.218	0.141
15	100	0.2	0.4	1.2	0.958	0.035	0.938	0.039
16	200	0.2	0.4	1.2	0.956	0.036	0.940	0.054
17	141.4	0.134	0.283	0.8	0.700	0.026	0.699	0.039
18	141.4	0.134	0.283	0.8	0.732	0.027	0.726	0.043
19	141.4	0.134	0.283	0.8	0.726	0.028	0.713	0.032
20	141.4	0.134	0.283	0.8	0.788	0.036	0.781	0.042

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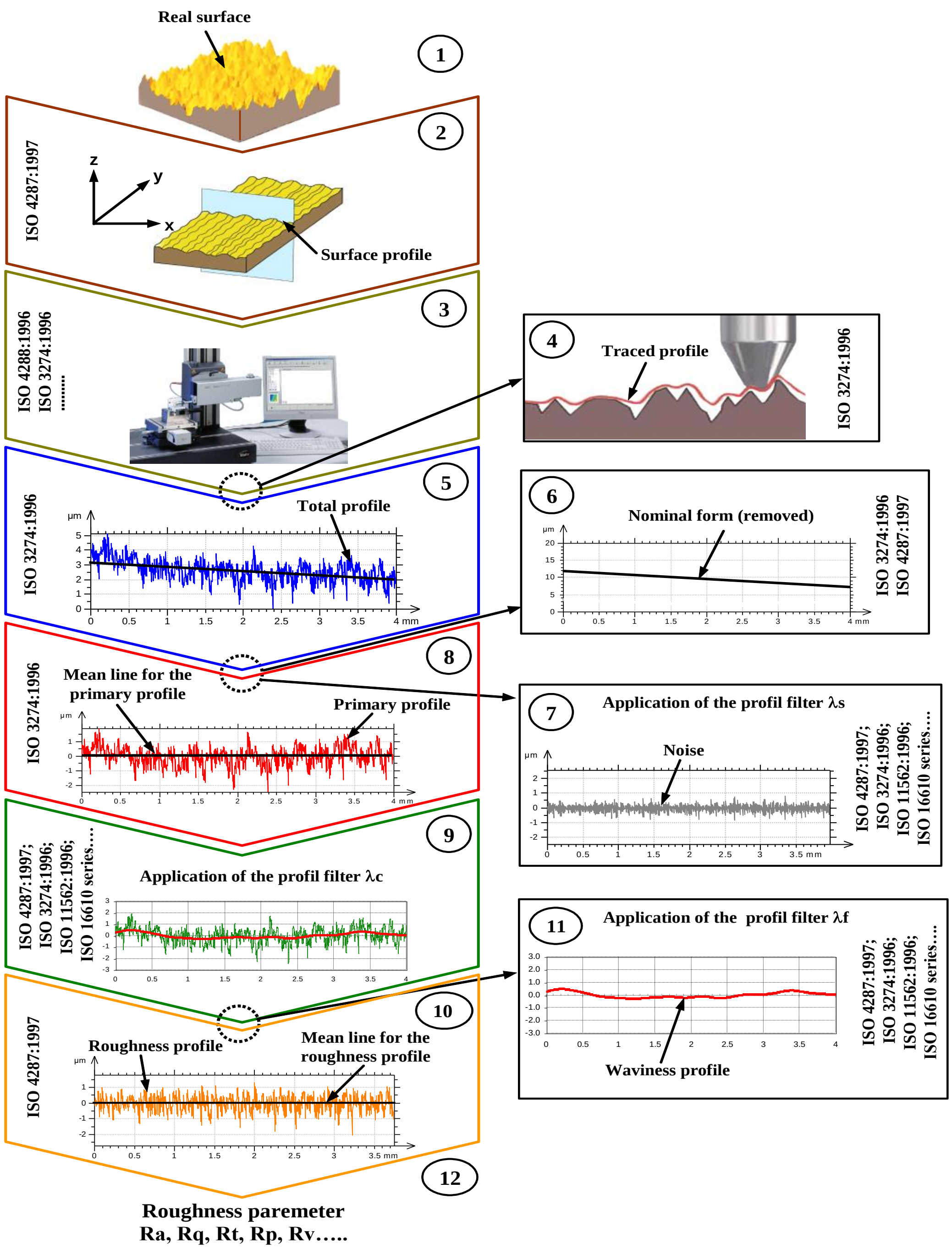

Figure 3. Procedure for obtaining the primary profile, the roughness profile, and the waviness profile [24]

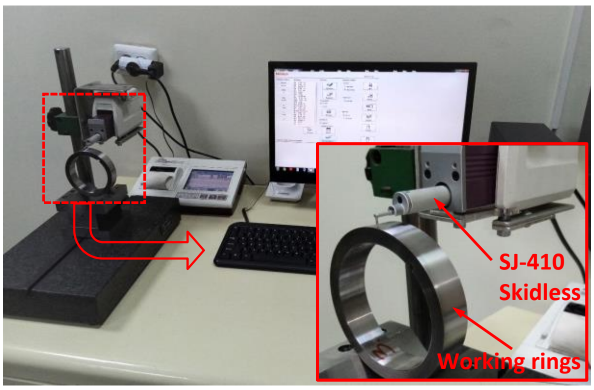

Figure 4. Surf test model No. SJ-410 (Mitutoyo make).

4. Results and discussion

The entire plan for the realization of the experiments, as well as the measured values for the parameters Pa, Wa, Ra and SE is presented in Table 2. The value of all parameters provided in Table 2 are mean values of five measurements.

The following mathematical models for the considered parameters were obtained based on the value from Table 2 and applying the methodology stipulated in point 2:

$$P_a = 15.259 \cdot v^{0.0379652} \cdot f^{1.722} \cdot a^{-0.0155956} \cdot r_\varepsilon^{-1.054} \quad (2)$$

$$W_a = 0.0406614 \cdot v^{0.0491459} \cdot f^{0.1290388} \cdot a^{0.0104809} \cdot r_\varepsilon^{-0.5093038} \quad (3)$$

$$R_a = 17.175 \cdot v^{0.0278376} \cdot f^{1.783} \cdot a^{-0.0278446} \cdot r_\varepsilon^{-1.071} \quad (4)$$

$$SE = 0.0095850 \cdot v^{0.1733292} \cdot f^{-0.5450216} \cdot a^{0.0656300} \cdot r_\varepsilon^{0.5575011} \quad (5)$$

The mathematical models expressed by the equations (2-5) represent first order models without mutual interaction and without factor significance evaluation. Their dispersion analysis together with an adequacy evaluation is provided in Table 3.

For the Wa parameter, the data in Table 3 suggest that the coefficient of determination is 0.64 which justifies its use in the first order model with mutual interaction. We decided to use a model without mutual interaction in order to enable the comparability with the models of the other considered parameters and because of the affirmative assessment of the adequacy.

The minus sign in the exponent in the term of the model indicates an inverse relationship between that term of the model and the modeled parameter.

In order to provide a graphic overview of the obtained mathematical models of the modeled parameters of the investigated hyperspace, the paper presents 3D graphs, Figures 5-8.

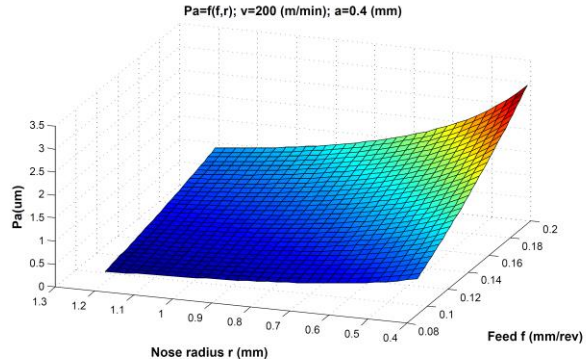

Figure 5. 3D graph for Pa, according to equation (2)

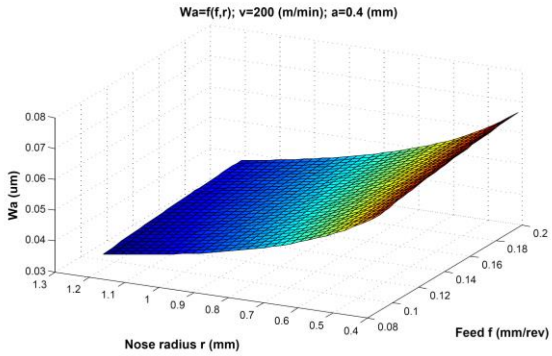

Figure 6. 3D graph for Wa, according to equation (3)

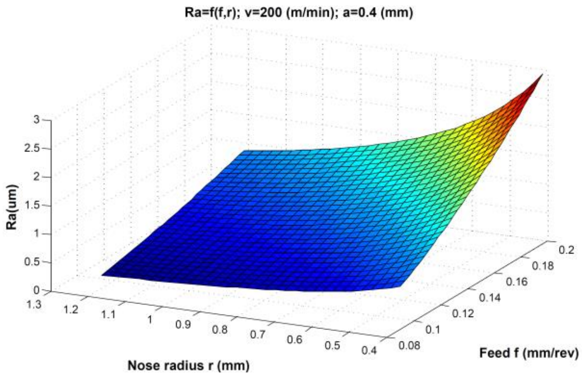

Figure 7. 3D graph for Ra, according to equation (4)

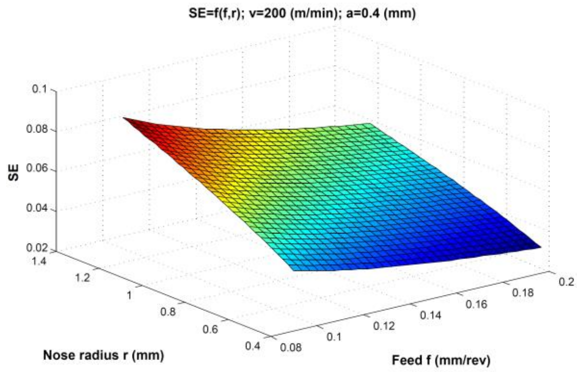

Figure 8. 3D graph for SE, according to equation (5)

If we compare the mathematical models for the *Pa* and the *Ra* parameters, equations (2) and (4), we will note a great similarity with respect to the input variables constants and exponents. There the feed (f) and the tool nose radius (r_ε) have a dominant influence. The increase of the cutting speed and the reduction of the depth of cut, although not significant, can contribute to the increase of the values of *Pa* and *Ra*. Figure 9 presents a 3D diagram showing the modelled surfaces for the *Pa* and *Ra* parameters. Figure 9 clearly demonstrates that *Pa* and *Ra* behave identically throughout the investigated hyperspace.

If we analyze the mathematical model for the Wa parameter, we will also conclude that the feed (f) and the tool nose radius (r_ε) have a dominant influence. However, their influence, especially the influence of f is significantly reduced, as shown by the value of their exponents. The comparison between the Ra mathematical model and the Wa mathematical model shows and increased influence of the cutting speed (v) and a sign change of the exponent for the depth of cut (a_p). Although, according to DIN 4760, the causes of 2nd order deviations (waviness) do not include the feed (f), the tool nose radius (r_ε), the cutting speed (v) and the depth of cut (a_p), when combined they can still cause some tool vibrations or elastic deformations on the work piece, which can directly impact the waviness.

It is interesting to compare the Wa mathematical model and the SE mathematical model, equations (3)and (5), Figure 10. The increase of the value of f can increase the value of Wa and reduce the value of SE, i.e., the increase of the r_ε value leads to a reduction of the Wa and an increase of the SE. This suggests that while waviness decreases, the stochastic character of the primary profile and the roughness profile, expressed by the SE parameter, increases. Still, we need to mention that the waviness profile derives from the mean line of the primary profile. The mean line of primary profile is obtained using profile filters. Any "imperfection" in obtaining the mean line does influence the shape of the waviness profile.

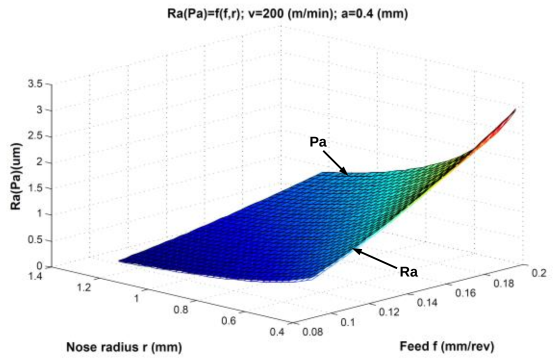

Figure 9. 3D graph for correlation between Pa and Ra

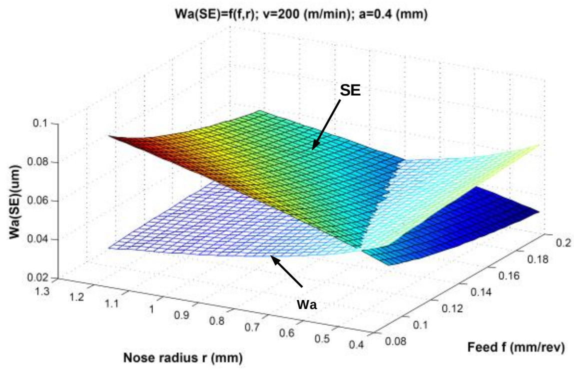

Figure 10. 3D graph for correlation between Wa and SE

Table 3. Dispersion analysis

		Degrees of freedom f	Sum of squares s	Dispersion s/f	Dispersion ratios fr	Table value ft	Model adequacy evaluation
	Residual sum	15	0.264080	0.017605			
	Experiment error	3	0.007536	0.002512			
Pa	Model adequacy	12	0.256544	0.021379	8.510	8.740	fr<ft adequate
	Multiple regression coefficient: R=0.9899						
	Residual sum	15	0.198609	0.013241			
	Experiment error	3	0.007023	0.002341			
Ra	Model adequacy	12	0.191586	0.015966	6.820	8.740	fr<ft adequate
	Multiple regression coefficient: R=0.9928						
	Residual sum	15	1.889	0.125933			
	Experiment error	3	0.065015	0.021672			
Wa	Model adequacy	12	1.824	0.151998	7.014	8.740	fr<ft adequate
	Multiple regression coefficient: R=0.6384						
	Residual sum	15	1.779	0.118613			
	Experiment error	3	0.053990	0.017997			
SE	Model adequacy	12	1.725	0.143767	7.988	8.740	fr<ft adequate
	Multiple regression coefficient: R=0.7526						

5. Conclusion

The research presented in this paper showed that there is a strict correlation between the primary profile (P-profile), the waviness profile (W-profile) and the roughness profile (R-profile) during hard turning. The SE parameter, particularly its small values, shows the stability of the hard turning process employed in this research. The great similarity between the Pa and the Ra parameters, especially the small value for the Wa parameter for all 20 experiments, perhaps provides the justification for emphasizing the roughness profile and the roughness parameters when modeling the geometric structure of the surface.

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