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THEORETICAL SURFACE ROUGHNESS OF SURFACES MACHINED BY SINGLE POINT CUTTING TOOLS

У статті представлений один з можливих методів теоретичного визначення шорсткості поверхні за допомогою математичного моделювання. Визначення параметрів шорсткості було зроблено для відомої геометрії інструмента. Також визначені зв'язки між теоретичною й вимірюваною величиною шорсткості обробленої поверхні даної геометрії інструмента.

В статье представлен один из возможных методов теоретического определения шероховатости поверхности с помощью математического моделирования. Определение параметров шероховатости было сделано для известной геометрии инструмента. Также определены связи между теоретической и измеряемой величиной шероховатости обработанной поверхности данной геометрии инструмента.

In the article one possible method of theoretical surface roughness determination with help of a general mathematical model is introduced. The determination of surface roughness parameters (R_a, R_z, R_{max}) was done for a given tool geometry. We also created relations between theoretical and measured values of the roughness of surfaces machined with this tool geometry.

1. Introduction

Accuracy of parts and quality of machined surfaces should be ensured in the finishing operation. In this paper we deal with the geometry of surface, which is one of the important characteristics of surface quality and determinative of tribological properties of working surfaces. Production engineers can only plan manufacturing procedures used in finishing operations correctly, if the roughness index values of surface for the chosen procedure and their changing gears to technological data and tool geometry (factors which determining the roughness) used in the given procedure are known.

One possible method of the determination of the prospective roughness on machined surfaces is the use of roughness values determined on grounds of theoretical roughness.

Various modeling procedures and techniques presented in Table 1 shows, how comprehensive researches goes on to determine the surface roughness, surface quality and surface integrity [2].

Examinations and results will be introduced was done by a solution which implements more targets. The essence of this solution is that it is determine the theoretical indexes and set up connections with real indexes.

The calculation method used by us [1] was endeavored for:

the model should be general, to the effect that it should be capable to determine all roughness values which can be derived by theoretical way;

cutting tools with various geometries can be compared in the basis of roughness values (hereby these can be redeemed or substituted)

the cutting-ability of the material can be ranked by comparison of theoretical and real values the roughness values can be automatically planned for tools with arbitrary profiles

Table 1 – Major research groups dealing with surface roughness and part accuracy determination [2]

Currently Active Major Research Groups		Models for Machining performance	
		Surface roughness, surface integrity	Part Accuracy
Modelling tools and techniques	Analytical	Altintas, Armarego, Bouzakis, Colding, Grabec, Klocke, Koren, Oxley, Rehsteiner	Ostafiev, Patri
	Numerical	Altan, Altintas, Bouzakis, Koren, Leopold, Reutsch, Ueda	
	Experimental	Bouzakis, Colding, Grabec, Klocke, Koren, Le Maitre, Leopold, Nakayama, Narutaki, van Luttervelt, Warnecke	Ostafiev, Patri, van Luttervelt
	AI-based	Fang, Leopold, Li, Rehsteiner, Warnecke	van Luttervelt
Summary of Present status		- Very limited predictive modeling attempts. - Purely geometric relationships - Complex relationship noted between surface roughness and operational parameters, work materials and chip breaker types.	- Closely related with and dependent on other macining performance measures. - Traditional correlation with machine tool vibrations.
Future directions		- Developing predictive models - Establishing tool-chip interactions with the cutting conditions and corresponding material flow behavior.	- Urgent need for modeling attempts on part accuracy. - Analytical modeling of a machining system for process and structural stiffness.

2. General mathematical model for the cutting edge

A cutting tool with general profile in the tool base plane (geometrical model) is designed, whereof the edge geometry of any realistically possible tool can be deducted. For the mathematical description the cutter should be placed into an x-y coordinate system, which plane is match to the base plane, and the pitch point is in the zero point. The cutter is described by emplacement angles and lengths of cutting edges (Figure 1) [1].

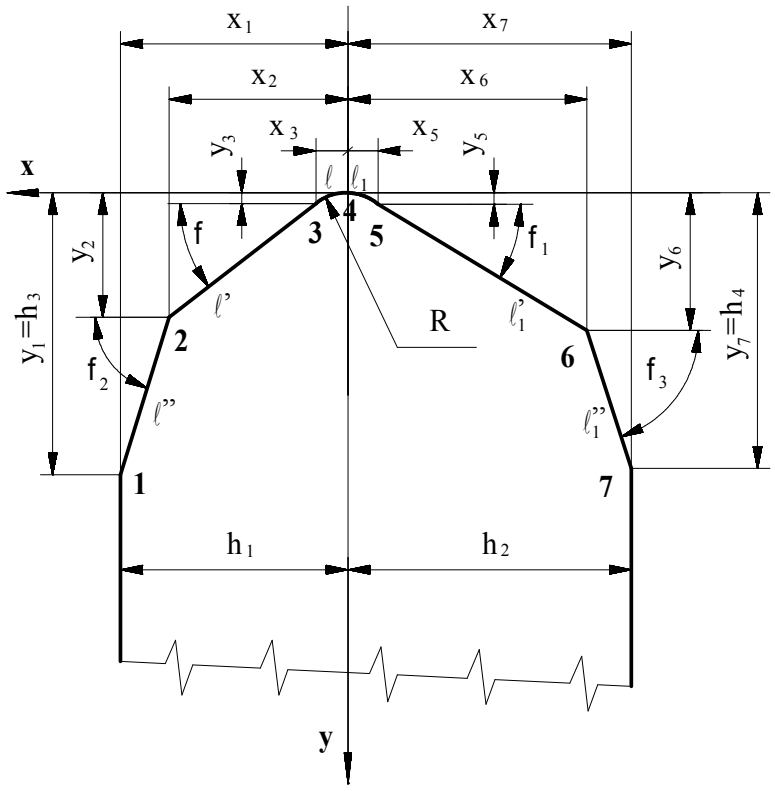


Figure 1 – Typical points of the general profile

The essence of the mathematical model developed by Kundrák J. thus the following:

1. Design a fictional complex cutting tool (which has all of the possible edge sections) in the tool base plane (xy-coordinate plane).
2. Edge sections of the complex tool were given by y=f(x) functions, while their intersection points with xy-coordinates.
3. The edge geometry for every specific tool is deducted from this general mathematical model by the practical substitution of function parameters.

The general cutter profile can be described in the following form

$$L = f\left(\ell, \ell', \ell'', \ell_1, \ell_1', \ell_1''\right) \tag{1}$$

The edge sections can be divided into two groups: main and auxiliary edges.

Description of main edges:

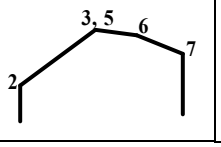
$$\begin{aligned} \ell &= R - \sqrt{R^2 - x^2} && where: && x_4 \le x < x_3 \\ \ell' &= tg\kappa_{r1} \cdot x + b && where: && x_3 \le x < x_2 \\ \ell'' &= tg\kappa_{r2} \cdot x + b_2 && where: && x_2 \le x < x_1 \end{aligned} \quad (2)$$

Description of auxiliary edges:

$$\begin{aligned} \ell_1 &= R - \sqrt{R^2 - x^2} && where: && x_5 \le x < x_4 \\ \ell_1' &= tg\kappa_{r1}' \left| x \right| + b_1 && where: && x_6 \le x < x_5 \\ \ell_1'' &= tg\kappa_{r2}' \left| x \right| + b_3 && where: && x_7 \le x < x_6 \end{aligned} \quad (3)$$

The specific configurations can be deducted from the cutter with general profile, a cutter with facet is shown in Table 2.

Table 2 – Cutting tool profile variant derived from the general profile

Configuration (edge forms)	Edge section (length) values	Parameters of the edge	Description of the edge
	$\ell = 0;$ $\ell'' = 0;\ \ \ell_1 = 0;$	R=0 $\varphi<90°;$ $\varphi_1<90°;$; $\varphi_2=90°;$ $\varphi_3<90°;$	$L = f(\ell', \ell_1', \ell_1'')$

3. Determination of theoretical value of surface roughness

The micro-geometrical profile and the roughness of the machined surface can be described by three kinds of index numbers: real, theoretical and measured values.

We consider as approximate information to the real (actual) surface in practice the section-scan probing methods in the profile section, such as measurements done by touch (diamond pin) or without touch (focused laser beam).

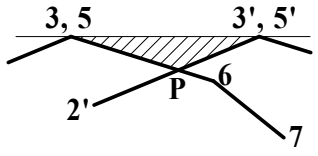
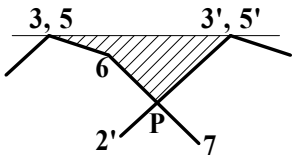
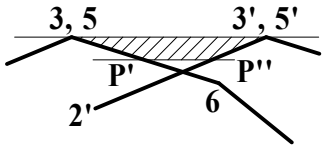
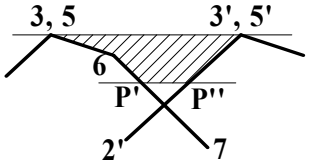
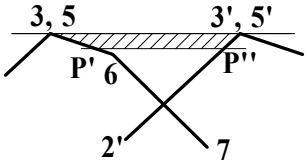
More researchers have already dealt with the determination of theoretical surface roughness values. They have determined the calculated roughness parameters by analytical formulas. It is necessary to deduct the formulas gained by this way separately for each cutter type, therefore it is a common characteristic for the worked out methods, that they are primarily limited to cutters with round pitch and to the determination of maximum irregularities [3].

Advantage of the previously introduced model is that it permitted the determination of theoretical values of roughness parameters (R_a, R_{max}, R_z, t_p) for any tool with determined edge which can be formed in the reality.

Theoretical $R_{max}=R_z$, R_a, t_p (t_p which belongs to arbitrary cropping height) values can be calculated on the basis of tool geometry interpreted in tool base plane and of the feed rate.

Theoretically evolving roughness profiles for the faceted tool can be seen in Table 3.

Table 3 – Possible roughness variations in the base plane for the given tool configuration

Possible theoretical roughness variations	
	
	 

Hereinafter a software will be introduced, which can help to determine most important roughness parameters (R_{max}, R_z, R_a, t_p) based on Kundrák's general mathematical model.

4. Software for calculation of theoretical roughness indexes

Using variable edge parameters and technological data, the completed software is able to define the theoretical indexes of surface roughness for an edge-configuration chosen by the user. For data input and display of the final results it provides graphic user's surface, the starting page of which can be seen in Figure 2.

From the general edge profile, having nine derivative configurations it is capable to define the values of R_{max}, R_z, R_a, t_p theoretical indexes. Figure 3 shows the result of run belonging to a tool configuration introduced before. Apart from this, the program is capable to find mathematical relations between theoretical values and technological and tool-geometrical data and also between the calculated theoretical and measured values. Also it is capable to draw the curve of the function describing the relationship between the data in the case of proper parameters.

5. Definition of roughness of cut surfaces

Hereinafter the relation between the theoretical and realistic roughness will be shown through the results of cutting experiments made by two different tools.

The most accurate information about the real surface roughness can be obtained by measurements. Theoretical roughness of the surface is a more inaccurate approximation of the reality, which is determined mathematically

with different negligence. According to observations theoretical and measured values of roughness vary in similar tends, hence it is possible to search for relations between the theoretical roughness calculated in advance and its measured values in the range of investigated technological data. Measured data vary in a determined trend as functions of theoretical values; therefore a mathematical relation can be established between them with the help of regression analysis.

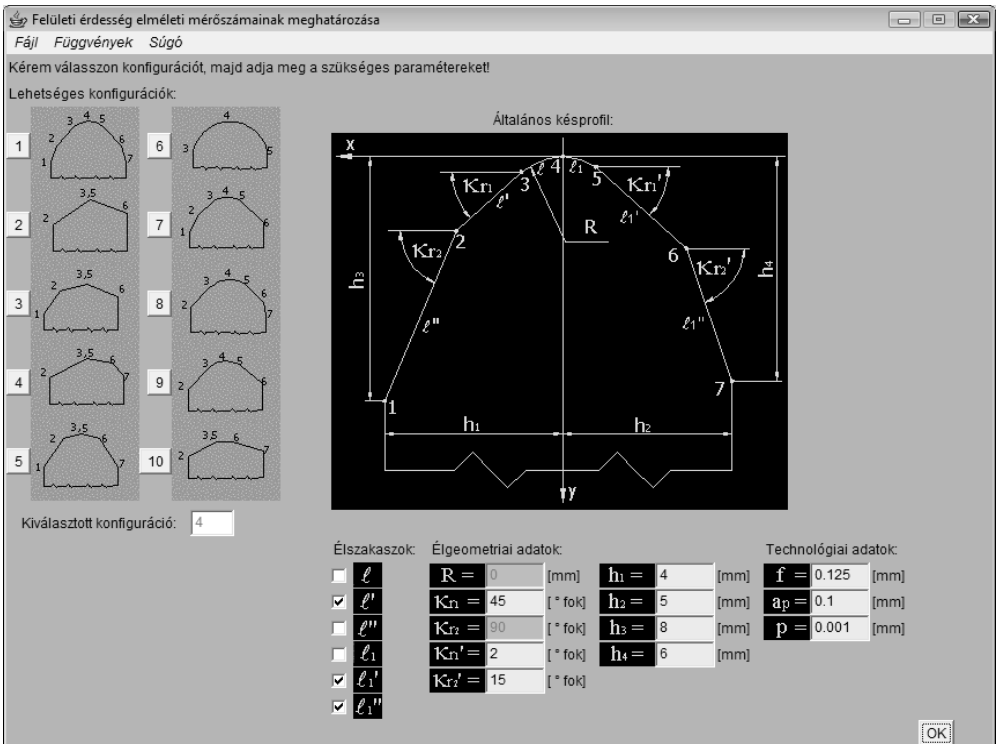


Figure 2 – The starting screen of the program made for calculating the theoretical roughness

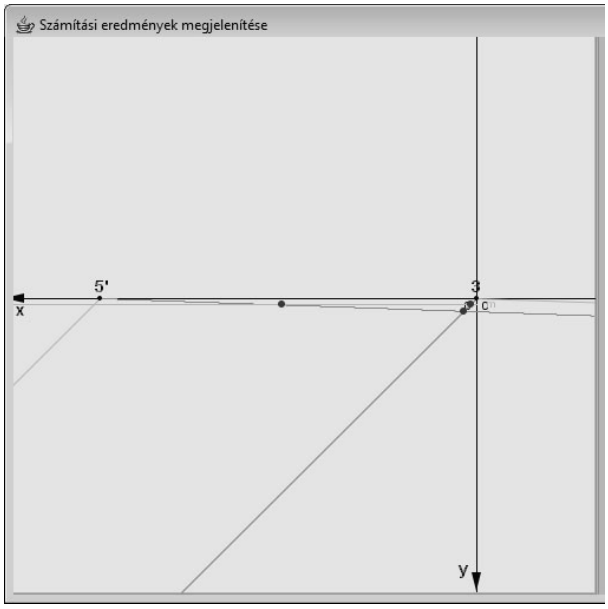


Figure 3 – The graphic display of the theoretical roughness calculated by the program

The defined relationships make the design ability of the cut surface's roughness possible.

However, it is worth to examine the relations between theoretical and real roughness values for various reasons:

the closer the real value is to the theoretical one, the easier it is to cut the part (material)

assists to decide that which geometry with different constructions but resulting the same theoretical roughness results closer theoretical values to real ones.

5.1 Experimental environment

Our experiments were made by the following conditions:

Experimental conditions:

- Workpiece:
  - material: 100Cr6
  - hardness: HRC 62 ± 2
- Tools:
  - material grade: CBN Composite 01 (K01) and Composite 10 (K10)
  - geometry: : γ_o=-5°; α_o=α_o'=15°; λ=0°; κ_{r1}=45°; κ_{r1}'=2°; κ_{r2}'=15°; b_ε=0,3 mm
- Machine tool: universal lathe, ИЖ250, E400-1000
- Technological data:
  - v=60 m/min;
  - a=0,1 mm;
  - f=0,025 – 0,125 mm/rev
- Measuring instruments: S8P type Perthometer
  - measure head type: Focodyn laser measure head
  - measure lenght: 1,75 mm
  - base length: 0,8 mm
  - diameter of the focused laser beam: 1μm

5.2 Experimental results

- Theoretical values

The theoretical values of roughness indexes were defined by the software and the method outlined at the beginning of this article (Table 4).

Table 4 – Theoretical roughness values

Feed rate, mm/rev	Theoretical roughness characteristics, μm		
	R_{aT}	R_{zT}	R_{maxT}
0.025	0.21	0.84	0.84
0.05	0.42	1.68	1.68
0.075	0.63	2.53	2.53
0.1	0.84	3.37	3.37
0.125	1.05	4.21	4.21

- The measured roughness values of the cut surface

Under the above mentioned conditions and cutting data the experiments were made with both of the tools with different feeds. On the machined surfaces the values of R_{max}, R_z, R_a roughness indexes were measured. The average of the measuring results is summarized in Table 5.

Table 5 – Average of measuring results for the two tools

Feed rate, mm/rev	Roughness characteristics, μm					
	Composite 10			Composite 01		
	R_a	R_z	R_{max}	R_a	R_z	R_{max}
0.025	0.52	3.00	4.50	1.00	5.00	6.80
0.05	0.85	4.50	6.00	1.20	5.60	7.40
0.075	1.12	5.50	6.90	1.30	6.00	7.80
0.1	1.35	6.50	7.80	1.35	6.50	8.00
0.125	1.50	7.50	8.80	1.40	6.80	8.20

- Evaluation of experimental results

When evaluating the results, we would like to draw your attention to the following:

- The values of R_{zT} and R_{maxT} are the same, it comes from the method of calculation;
- theoretical value – as cutting was done by tools with identical edge geometry – is the same for each tool;
- the character of the theoretical and real roughness changes is the same.

Figure 4 shows the comparison diagrams for the three examined roughness characteristics.

The approximation can be made by $R_{(a,z,max)R}=R_{(a,z,max)T}+C_{(a,z,max)}$, relation, which can provide a relatively food approach. But the approximation below is more accurate:

$$R_{(a,z,\max)R} = C_{1(a,z,\max)} \cdot R_{(a,z,\max)T}^{\;C_{2(a,z,\max)}} \tag{4}$$

Therefore by the latter is provided the mathematical relation with which, and with the help of the theoretical values, the real roughness can be designed. The definition of C_1, C_2 constants was done with the help of regression analysis. The approximation accuracies of equations were given by the value of the coefficient of determination (R^2).

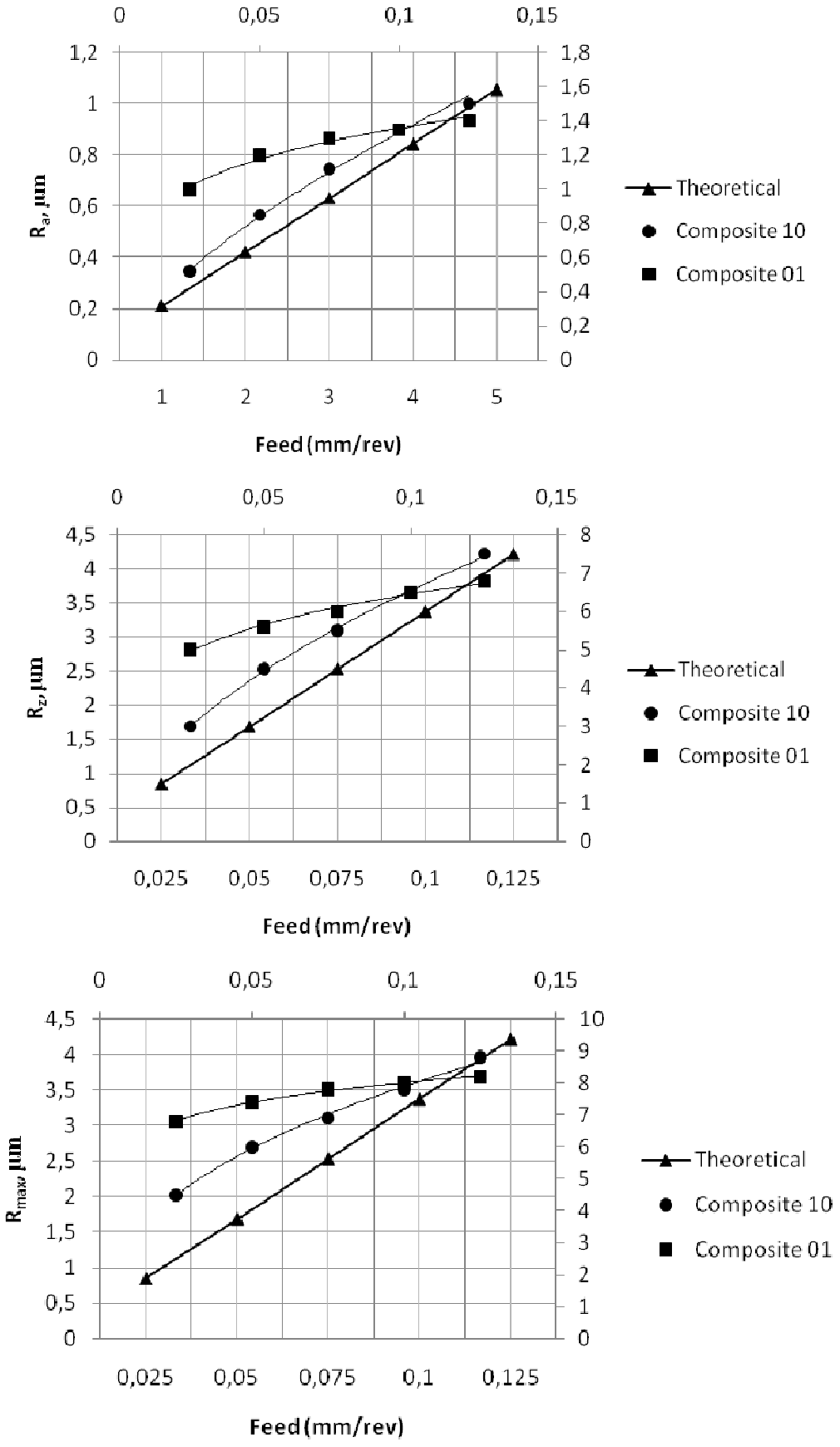


Figure 4 – Comparison of theoretical roughness values and measured roughness values

For Composite 10 tool:

$$R_{aR} = 1,493 \cdot R_{aT}^{0,667}; \qquad R^2 = 0,997$$

$$R_{zR} = 3,311 \cdot R_{zT}^{0,562}; \qquad R^2 = 0,999 \tag{5}$$

$$R_{\max R} = 4,808 \cdot R_{\max T}^{0,407}; \qquad R2 = 0,997$$

For Composite 01 tool:

$$R_{aR} = 1,406 \cdot R_{aT}^{0,209}; \quad R^2 = 0,982$$

$$R_{zR} = 5,117 \cdot R_{zT}^{0,191}; \qquad R^2 = 0,989 \tag{6}$$

$$R_{\max R} = 6,950 \cdot R_{\max T}^{0,117}; \quad R2 = 0,997$$

Conclusion

In the examined cases, with the help of the elaborated mathematical model and/or calculation method, the real roughness can be determined with good approach. Our plan for the future is to further develop this process for description of the theoretical values of 3D roughness values and also for determination of the expected roughness values.

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