Model of the Surface Roughness Prediction in Turning

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Abstract: *Surface roughness is one of the parameters thanks to which machining can maintain itself as a competitive method of component production in various areas of industry. By predicting the roughness of the machined surface by simulation, it is possible to improve the surface quality and speed up the process of determining suitable cutting parameters for the production of parts by machining. This article deals with developing a surface roughness prediction model and comparing it to another model for verification of its function.*

Keywords: *model, surface roughness, turning process, machining*

1 INTRODUCTION

Today the productivity is the main key for the manufacturing industries to compete in the world and the global market. Increasing productivity, materials availability, and high precession technologies are the main objective of the industries. To stay relevant the machining industry has to increase the production quality and reduce its cost. The parameters which affect this demand are tool geometry, coating technology of cutting tools, cutting parameters, manufacturing, and price of the quality [8].

The machining technologies as turning [12] are the typical technologies for cutting materials. Turning as one of the machining processes is used for the production of various parts in different sectors such as the automotive, aerospace, or mechanical engineering industries [2]. The main aim is to produce those parts from a workpiece with a specified shape and characteristics such as surface roughness, residual stress, and others [13] There are a couple of studies that show there are some advantages in using turning with geometrically defined cutting edges for the production of new parts. These advantages are better surface integrity, flexibility, cost efficiency, and production that is friendly to the environment. Even though these advantages exist, the industry only slowly accepting this technology because of several remaining problems such as geometrical inaccuracies and high cutting forces caused by tool wear and lower surface finish quality [3].

The irregularity of machined surface is affected by various factors such as a tool, feed, cutting speed, tool geometry, and environmental conditions of the machining process. This irregularity consists of peaks and valleys that can be measured and used to define surface conditions and performance. Numerous researches tried to connect the dependence of the machining process parameter and surface conditions but only focus on the average roughness parameter *Ra*. This parameter is useful for the general purpose of determining the surface quality but does not provide much information when there are sharp spikes and deep valleys on a surface [9].

A considerable number of tests are needed to find an adequate relation between the surface roughness and the cutting parameters such as cutting speed, depth of cut, tool tip radius, etc. Serious attention has been dedicated to the research of surface roughness through the years. Important design features were formulated such as parts subject to fatigue loads, precision fits, esthetic requirements, and others. It was found that surface finish in turning is influenced by various cutting parameters like cutting speed, feed rate, depth of cut, material characteristics, tool geometry, stiffness between machine tool, cutting tool and workpiece, built-up edge, etc. [7].

Surface topography and its measurement and analysis are important factors in every industry. More attention is paid to the 3D characterization of the surface roughness due to availability of the measurement methods that are optical and nondestructive. Several ISO standards are established to properly describe the significance of two-dimensional profile and three-dimensional areal roughness parameters. Different features refer to different roughness parameters such as amplitude, spatial distribution, or pattern of surface. Traditionally the average maximum height *Rz* or maximum height *Rt* are used to review surface features [1].

The physical causes of the roughness of the machined surface include copying the shape and roughness of the cutting edge itself into the workpiece, the existence of vibration (oscillation) of the tool and workpiece [10], the existence of built-up on the edge. So far, precise analytical equations have been used to determine roughness, e.g. for milling, the author calculated the parameters *Rz* and *Ra* [5] or experimental equations obtained under different technological conditions e.g. [12]. The third way to determine the roughness of a machined surface is modeling and simulation approaches [6].

Surface roughness is frequently used as a quality factor for machined mechanical parts. Therefore, the development of various roughness prediction tools began, which can be divided into three groups. The first group includes the experimental methods for the prediction of surface roughness based on the design of experiments. The second group of methods is also based on the design of experiments but is extended to another mathematical method such as regression or neural networks. The last group of surface roughness prediction methods depends on the kinematical-geometrical copying of the cutting tool onto the machined surface. The advantage of these methods is that they don't contain any limitations related to equipment or space. On the other hand, they lack accuracy in specific conditions because they take into consideration only some cutting parameters such as feed f, tool radius r_β, and angles Kr, Kr', λ and γ but they don't include parameters like a cutting speed v_c or depth of cut a_p, which are necessary for the implementation of the transformation process of the removed material into

a chip [4,11]. Methodologies and practices such as machining theory, the Taguchi method, and artificial intelligence are being employed for the prediction of surface roughness parameters [7].
This research will focus on creating a computer model of the cutting edge and its use in the simulation of roughness due to a physical cause – copying the shape of the cutting edge into the workpiece for the turning technology. It will be then compared to another model to verify its accuracy and to find limitations of the model.

2 MODEL OF THE CUTTING TOOL AND SURFACE ROUGHNESS

For the creation of the model of surface roughness prediction, first, it is to create the model of the cutting tool geometry. The model of a cutting tool, in this case of the insert, can be in 2D space divided into 2 straight lines and a semi-circle. These basic objects were created by generating points, each of which was assigned *X* and *Y* coordinates. To generate those points separate equations were used for every object. The shape of the equations for every object was:

Straight-line A:

$$x_{iA} = [r_n \cdot \sin(\kappa_r) \cdot (-1)] - i \cdot \Delta x \quad (1)$$

$$y_{iA} = x_i \cdot \tan(\kappa_r) + \frac{r_n}{\cos(\kappa_r)} - r_n \quad (2)$$

Straight-line B:

$$x_{iB} = r_n \cdot \sin(\kappa_{r'}) + i \cdot \Delta x \quad (3)$$

$$y_{iB} = y_i \cdot \tan(\kappa_{r'}) + \frac{r_n}{\cos(\kappa_{r'})} - r_n \quad (4)$$

Semi Circle:

$$x_{jC} = [r_n \cdot \sin(\kappa_r) \cdot (-1)] + j \cdot \Delta x \quad (5)$$

$$x_{iC} = [r_n \cdot \sin(\kappa_r) \cdot (-1)] + k \cdot \Delta x \quad (6)$$

where, X_i is the ith coordinate of the ith point on the *X*-axis, Y_i is the ith coordinate of the ith point on the *Y*-axis, Δx is the distance between two points that are next to each other and it was equal to 10^{-6} mm, r_ε is the cutting tool tip radius, κ_r is the tool main cutting edge angle and $\kappa_{r'}$ is the tool secondary cutting edge angel. To generate enough points and to create a smooth shape of the cutting tool *i* goes from *0* to *N*, in this case, $N = 10^6$. To ensure there will be enough points in a semi-circle to intersect with points of the straight-line B, first, equation 5 was created. The *j* here is defined as $2 \cdot i$ to ensure that at least one point here is the same as the point in straight-line B. After that, the intersection and its position were found and the k in equation 6 goes from 0 to the position of the intersection to ensure a connection between semi-circle and straight-line B. After equations for each object were defined and the points were generated they were stored in two matrices of $N \times 1$ size, from which one contained coordinates on the *X*-axis, called *X1* and the second one contained coordinates on the *Y*-axis, called *Y1*. After that, the matrices were plotted. The whole geometry and the plot were created using software MATLAB. As a first step, it was created the first geometry, as seen in Fig. 1.

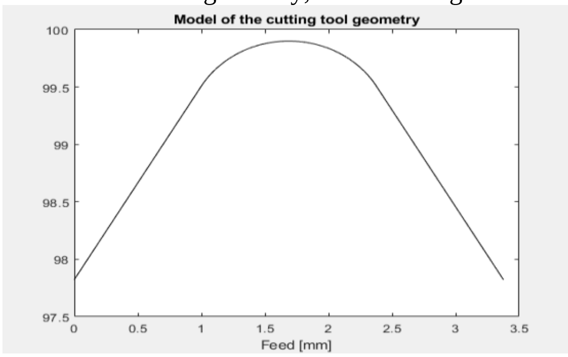

Fig. 1. Model of the cutting tool geometry

The second geometry was needed to simulate the toolpath of the cutting tool for the creation of a roughness model. It was made by adding the value of the feed to the points stored in matrice *X1*, creating a new matrice of coordinates *X2*. Coordinates on *Y*-axis were unchanged, but for better manipulation, matrice *Y2* was also created containing the same values as *Y1*. After this was done the intersection between these two geometries was found using linear interpolation of these 4 matrices, in Fig. 2.

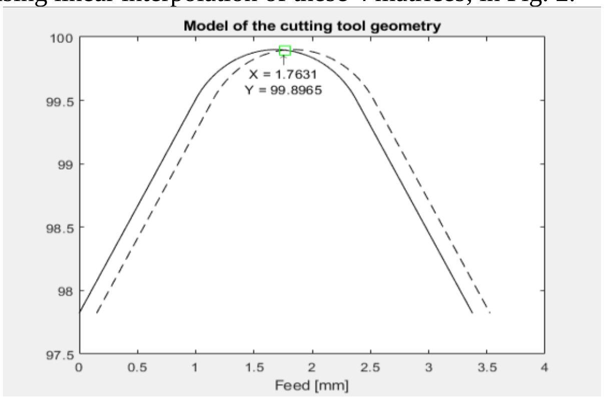

Fig. 2. The intersection between 2 toolpaths

When cutting tool geometry was created and the intersection between two tool paths was found it was possible to create a roughness model. It is possible to divide roughness in turning into two classes. The first is roughness in the cutting direction. The second one, which is often used for the measurement of surface roughness in this technology because it is more significant. Factors that have an impact on this type of roughness are theoretical roughness, which is determined by the cutting tool geometry and the feed, tool wear, adhesion, vibration, and others. It is hard to recognize which factor affects the real surface roughness more. Because of that, these parameters are classified into three groups as theoretical roughness, roughness due to instability of the machining system, and roughness due to instability in the cutting process. This paper deals with the first and last group of roughness [13]. Theoretical roughness was created by finding coordinates from the matrice *X1* which lie on a line passing through the intersection and coordinates from matrice *Y1* that go from the *Y*-axis coordinate of the intersection point to the maximum of the *Y1* matrice. After the first toolpath was created the process was the same as in creating the model

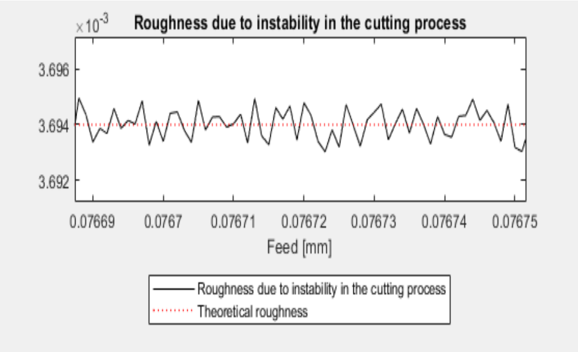

Fig. 4. Difference between theoretical surface roughness and surface roughness caused due to instability in the cutting process

of cutting tool geometry, adding a value of feed to the *X*-axis coordinates to creating the next tool footprint, Fig. 3.

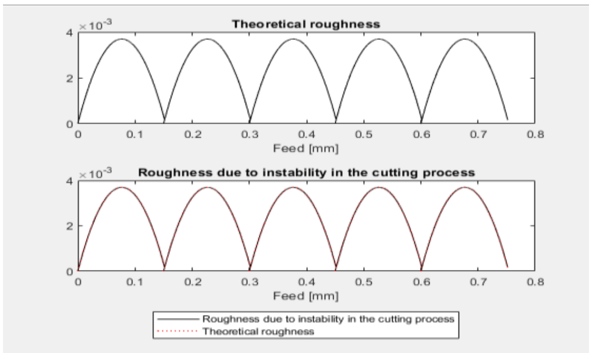

Fig. 3. Model of the theoretical roughness and the roughness caused due to instability in the cutting process

Roughness due to instability in the cutting process was made by adding a random number from the interval of -10^{-6} to 10^{-6} to the coordinates on the Y-axis to ensure the creation of the effect of the adhesion, built-up edge, or burr on a workpiece, which is on Fig. 3. After that, they were plotted. At first, they look almost identical, but after zoom in on the second plot, that is in Fig. 4, it is observable that there is a difference between a theoretical roughness and the roughness created due to instability in the cutting process.

After models were created the values of surface roughness parameters *Rz, Rq, Rv, Rp* were calculated. Parameter *Rz* was calculated as the highest point of the model. Maximum profile peak height *Rp* was found out by first calculating the mean line of the profile then subtracting the minimum of the profile from it. Maximum profile valley depth *Rv* was then calculated by subtracting the parameter *Rp* from the maximum height of the profile *Rz*. Calculation of these two parameters was made like this because the model is upside down, so valleys are on the top and the peaks are on the bottom of the profile. Last parameter *Rq*, which is the root mean square average of the profile heights was calculated by first calculating the square of all values on the *Y*-axis, then finding out the mean of those numbers, and then finding the square root of that result.

3 EXPERIMENTAL VERIFICATION

To verificate the developed model of surface roughness prediction, it was compared to a mathematical model made by Tomov et. al [11]. This mathematical model for predicting roughness parameters is based on the kinematical-geometrical copying of the cutting tool onto the machined surface [11]. It was recreated in excel for this article to be able to compare every combination of feed and tool nose radius for the prediction of roughness parameters. As input parameters, their model uses feed f, the tool nose radius r_ε, and angles $\kappa_r, \gamma_o, \lambda_s$.

In comparison, the model developed in this article uses feed f, and the radius r_ε but only uses angles κ_r, κ_r'. The values used for input parameters are in Table 1.

Table 1: Cutting parameters used for the model

Parameters	**Values**		
Feed f [mm]	0.1	0.173	0.3
Tool nose radius r_ε [mm]	0.4	0.8	1.6
κ_r [°]	45	45	45

After calculation was done values were registered into the table and plotted on graphs and compared to each other. Values of roughness parameters are in Table 2. Surface roughness parameters that have a *k-g* index have values of the model made by Tomov and parameters without the index have values of our developed model, presented in this article.

Table 2: Predicted roughness parameters of both models

f/r_ε combination	**Rz [μm]**	**Rz_{k-g} [μm]**	**Rp [μm]**	**Rp_{k-g} [μm]**	**Rv [μm]**	**Rv_{k-g} [μm]**	**Rq [μm]**	**Rq_{k-g} [μm]**	**SE**
0,1/0,4	3,299	3,153	2,227	2,104	1,072	1,049	0,808	0,808	0,073
0,1/0,8	1,679	1,563	1,138	1,041	0,541	0,522	0,412	0,400	0,058
0,1/1,6	161,975	0,785	80,988	0,524	80,987	0,262	37,172	0,202	
0,173/0,4	9,748	9,353	6,561	6,209	3,187	3,144	2,386	2,430	0,198
0,173/0,8	4,887	4,714	3,292	3,144	1,595	1,569	1,196	1,209	0,087
0,173/1,6	280,219	2,338	140,109	1,557	140,110	0,781	53,928	0,600	
0,3/0,4	29,705	29,347	20,038	19,713	9,667	9,633	7,286	7,471	0,179
0,3/0,8	14,533	14,063	9,763	9,344	4,770	4,719	3,553	3,640	0,235
0,3/1,6	485,931	7,082	242,964	4,723	242,967	2,359	93,517	1,816	

Comparison of the predicted roughness parameters by articles model and the model developed by Tomov (k-g index)

In Figures 5 to 8, it is shown how those two models deviate from each other.

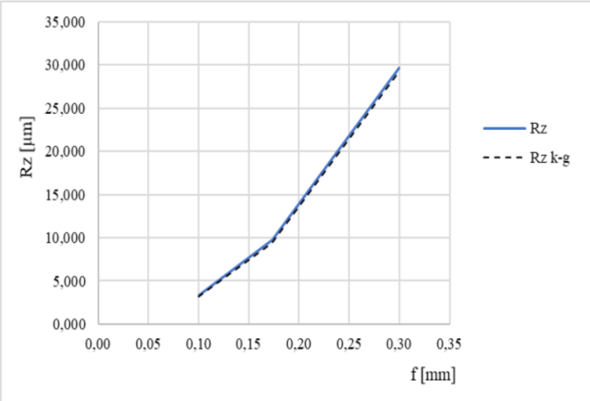

Fig. 5. Development of the surface roughness parameter Rz depending on feed for the tool tip radius r_ε = 0.4mm

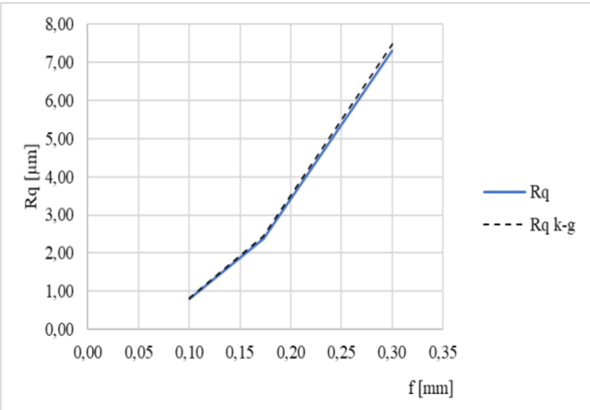

Fig. 6. Development of the surface roughness parameter Rq depending on the feed for the tool tip radius r_ε = 0.4 mm

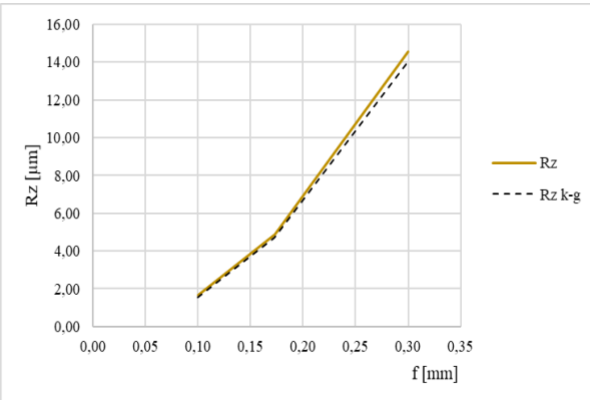

Fig. 7. Development of the surface roughness parameter Rz depending on the feed for the tool tip radius r_ε = 0.8 mm

As can be seen, the predicted values of the roughness parameters of the two models are not very different. The main reason why the values differ is the way each model calculates these parameters.

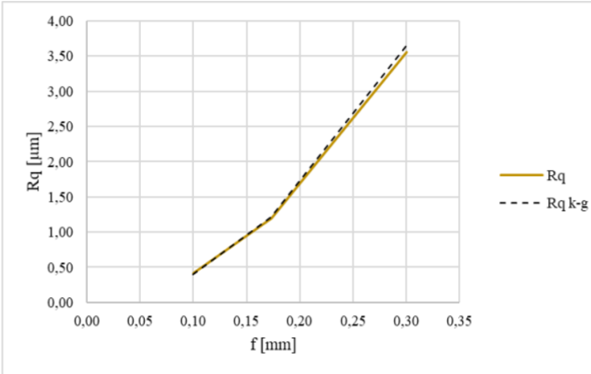

Fig. 8. Development of the surface roughness parameter Rq depending on the feed for the tool tip radius r_ε = 0.8 mm

The difference may also be due to the different software used for developing each model.

4 RESULTS

Values are organized in table 2 for the roughness parameters calculated first by the developed model for surface roughness prediction and then by the one created by Tomov et. al. [11]. Measured parameters were the maximum height of the profile Rz, maximum profile peak height Rp, maximum profile valley depth Rv and root mean square average Rq.

As seen in table 2 and also in figures 5 to 8 values calculated by each model of surface roughness prediction do not deviate from each other that much. The deviation is caused mainly by a different way of calculating parameters.

The limitation of the developed model is seen when the feed is very different from the tool nose radius. This is due to the ratio between these parameters is too big and the programed model is unable to properly plot the model of cutting edge and then unable to properly calculated surface roughness parameters.

The model developed in this article is not using angels such as γ_o or λ_s, calculating the roughness parameters differently, which results in the removal of some limitations such as γ_o cannot be 0 or that γ_o cannot be equal to λ_s with opposite sign, when tool cutting edge angle κ_r has certain values.

Both models for the prediction of surface roughness share a similar limitation. The cutting tool nose radius can't be equal to zero because the models aren't then able to calculate roughness parameters.

5 CONCLUSIONS

The model developed in this article can predict roughness parameters when certain conditions are met as seen when compared to another model that was verified with experiments for turning operation on a lathe. It can also create a 2D visualization of the cutting tool geometry, toolpaths, and also the difference between theoretical roughness and roughness caused due to instability in the cutting process. Conditions that must be met are that tool tip radius r_n cannot be much larger than feed f, and also tool tip radius r_n cannot be equal to zero, because then the model of the cutting tool cannot be properly created and surface roughness parameters aren't calculated or are calculated incorrectly.

More development should be done to remove the model limitations mentioned above. It would also be practical to extend the model by surface roughness caused due to instability of the machining process and combine it with the instability in the cutting process to get a more complex picture of the surface roughness. Moreover, the model works only for the prediction of surface roughness parameters for turning operations. It would be appropriate to extend the model to drilling or milling operations.

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