Calculation of the complex of virtual surface roughness parameters obtained in the simulation geometric grinding model

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Abstract. At the final operations of manufacturing parts, grinding processes are applied that ensure the achievement of high accuracy of the product and low roughness of its surfaces. A promising area for studying the parameters of surface roughness obtained by grinding is a virtual relief surface simulation. A brief review of geometric models of various researchers is given. In the previously developed simulation geometric model, a virtual relief surface is formed after grinding. The urgent task is to determine the roughness parameters from the existing profile, although all the initial data for this are available. The development of an algorithm and a software module, as well as a set of solutions for calculating the roughness parameters of a virtual relief surface obtained in a simulation geometric model, is considered. In the algorithms, the middle line is constructed, the arithmetic mean deviation of the profile $R_a$ is calculated, all maxima and minima of the profilogram chart are determined, five maxima and five minima are selected, the parameter $R_z$ is calculated, the parameter $R_{max}$ is calculated, the profile reference length $t_p$ is determined for twelve levels of line $p$, the intersection points of the profile and the middle line are determined and the parameter of the average pitch of roughness $S_m$ is calculated, all the protrusions on the profilogram are determined and the average pitch of local protrusions $S$ is calculated. Implementation of the presented algorithm, including all the above actions, in the object-oriented programming language C# in the Visual Studio C# software product enabled us to obtain software that can calculate all basic roughness parameters, such as $R_a$, $R_z$, $R_{max}$, $t_p$, $S_m$ and $S$ according to the virtual surface from the geometric model.

1. Introduction
At the final operations of manufacturing parts, grinding processes are applied that ensure the achievement of high accuracy of the product and low roughness of its surfaces are applied. That is why the direction of studying the influence of various input process parameters on the surface roughness is one of the most important scientific problems in the grinding field. The study of surface roughness obtained by grinding is carried out in three main directions: building of empirical dependencies, building of analytical dependencies of profile formation in a certain section, and building of simulation models of a relief surface.

One of the most promising methods for studying the parameters of surface roughness obtained by grinding is simulation of a relief surface. In this direction there is a number of domestic and foreign works by the following authors: A.M. Kozlov and V.V. Efremov [1], X. Zhou and F. Xi [2], E.
Salisbury, K. Vinod Domala, K. Moon, M. Miller and J. Sutherland [3], J. Jianga, P. Gea, W. Bia, L. Zhanga, D. Wanga, Y. Zhanga [4]. One of the similar models developed by A.A. Dyakonov and L.V. Shipulin is a geometric simulation model [5], which is part of a complex simulation model of grinding processes [6]. In this model, a virtual relief surface is formed after grinding, but the problem of determining roughness parameters from the existing profile has not been solved, although all the initial data for this are available.

In most countries of the world, six parameters are accepted as criteria for assessing roughness, of which three characterize the height of roughness (vertical parameters), and three characterize the pitch sizes of roughness (horizontal parameters). Vertical parameters include $Ra$, $Rz$, $R_{max}$, and horizontal include $tp$, $S$, $Sm$. Considering the virtual surface obtained in the simulation geometric model [5], we note that it is presented in the form of a two-dimensional matrix $H_{ij}$, each element of which is the coordinate of the position of the regular grid nodes on the workpiece surface from an ideal horizontal plane. To determine the roughness parameters, we consider a certain cross section transverse to the cutting speed direction, mathematically represented by a column vector. Thus, there is an array of coordinates for nodes position of the grid $h_i$, for which it is necessary to develop an algorithm to determine roughness parameters $Ra$, $Rz$, $R_{max}$, $tp$, $S$, and $Sm$.

2. Calculation of roughness parameter $Ra$

The middle line is the line that divides the measured surface profile in such a way that, within the base length, the sum of the squares of the distances of the profile points $h_i$ to this line is minimal:

$$\sum_{i=1}^{n} (h_i - m)^2 \rightarrow \min,$$

where $n$ is the number of points in the array, $m$ is the middle line position.

To implement this condition with the help of information technology is possible as follows. Let us define the boundaries of the interval within which the middle line can be found. Next, we will draw 100 consecutive horizontal lines in the obtained interval, and for each we will calculate the sum of the squares of distances using the formula (1), then from the array of sums with the help of software we will choose the smallest, which will become the accepted middle line of the profile. Figure 1 shows the result of the SW-based determination of the middle line.

![Figure 1. Result of SW-based determination of the middle line](image)

Moving from the array of depths $h_i$ to the array of deviations $y_i$, according to formula (2), we will calculate the arithmetic mean deviation of the profile according to formula (3):

$$y_i = h_i - m,$$

$$Ra = \frac{1}{n} \sum_{i=1}^{n} |y_i|.$$

As a result of calculating the arithmetic mean deviation of the profile according to the formula, value $Ra = 0.148 \, \mu m$ is obtained with the help of software.
3. Calculation of roughness parameter $R_z$

The calculation of parameter $R_z$ is performed according to the formula (4):

$$R_z = \frac{1}{5}\left(\frac{1}{3}\sum_{j=1}^{5} h_j \bigg| \sum_{j=1}^{5} h_j \bigg)\right).$$

For this, it is necessary to determine five largest projections and depressions. To accomplish this task, we will define all the peaks and mark them on the profilogram, and then select five largest projections and depressions out of them. We will introduce an additional array containing data on the increments of the profile heights:

$$\delta_i = \begin{cases} +1 & \text{npu } h_{i+1} > h_i; \\ -1 & \text{npu } h_{i+1} < h_i. \end{cases}$$

Next, we will proceed to the determination of peaks. To do this, we create another empty array where the presence of peaks is recorded. Thus, if the increment was positive and became negative, then it is the projection peak. And in the opposite case - it is the depression peak. Therefore, iterating over the entire array of increments made it possible to find all the peaks of the projections and depressions using software. Fig. 2 shows the result of the search.

![Profilogram with marked peaks of projections and depressions](image)

Then, five maximum projections and depressions were selected from the array of peaks, whose values are used to calculate parameter $R_z$ (in our case, a software calculation gave the following result $R_z = 0.387 \mu m$).

4. Calculation of roughness parameter $R_{max}$

The greatest height of profile $R_{max}$ roughness is defined as the distance between the points of the highest peak and the deepest depression according to the formula:

$$R_{max} = y_j^{\text{max}} + y_j^{\text{min}},$$

Due to the program calculation of the highest height of the profile irregularities for the profilogram in Fig. 1, a value of $R_{max} = 9.966 \mu m$ was obtained.

5. Calculation of roughness parameter $t_p$

The relative reference profile length $t_p$ is determined by the formula:

$$t_p = \frac{1}{n} \sum_{i=1}^{n} h_i,$$

Next, it is necessary to lay down a segment at a distance $p$ from the line of profile projections, taken as a percentage of $R_{max}$ and through its end draw a line parallel to the middle line $m$. Then we need to determine the number of such segments $n$ and their value $h_i$. For the software implementation of the task, the following calculation algorithm is proposed. First of all, it is necessary to determine the distance $p$ by the following formula:
Next, we will organize an enumeration cycle by $y_i$, and check each iteration of the cycle - at what level is $y_i$. If $y_i$ is higher than $p$, then this value is added to the total reference length; if it is lower, then we do not take it into account. Fig. 3 illustrates a two-dimensional data array in which the width of one bar is taken equal to $1 \, \mu m$. The bars that are above $p$ are marked in green, and those below are marked in red. Thus, it is possible to determine the number of green bars, and as a result, calculate the total reference length.

![Figure 3. Two-dimensional data array](image)

As a result of software calculation, the following values of the relative reference length are obtained: $t_p = 0.2 \%$ with $p = 5 \%$; $t_p = 0.6 \%$ with $p = 10 \%$; $t_p = 1.2 \%$ with $p = 15 \%$; $t_p = 2.4 \%$ with $p = 20 \%$; $t_p = 5.6 \%$ with $p = 25 \%$; $t_p = 10.5 \%$ with $p = 30 \%$; $t_p = 25.4 \%$ with $p = 40 \%$; $t_p = 39.9 \%$ with $p = 50 \%$; $t_p = 59.0 \%$ with $p = 60 \%$; $t_p = 75.0 \%$ with $p = 70 \%$; $t_p = 83.6 \%$ with $p = 80 \%$; $t_p = 87.2 \%$ with $p = 90 \%$. Profilograms with a section at the level $p$ for twelve of its values are constructed in software. Figure 4 shows the result of a software calculation and construction of a relative reference length for cases where line $p = 70\%$.

![Figure 4. Profilograms where marked $p = 70\%$](image)

**6. Calculation of roughness parameter $Sm$**

The average pitch of roughness $Sm$ is determined by the formula:

$$S_m = \frac{b_0}{N - 1} \left( \frac{X_{X_{-1}} - X_1}{N - 1} \right).$$

For its calculation, it is necessary within the base length to determine the number of intersections of the profile with the middle line. After that, it is necessary to measure the length of the segment of the middle line $b_0$, which is limited by the first and the second last intersection point of the profile with the middle line (Fig. 5).
Figure 5. Diagram for determining segment \( l_0 \) at the middle line level

To implement the task with the help of software is possible as follows. We will enumerate all the points of the curve of profile line \( y_i \). When \( y_i \) is greater than \( y_{i-1} \), then the current point is above the middle line, and the previous one is lower. That is, the following condition is satisfied:

\[
\begin{cases}
y_i > y_{i-1} \\
y_i > m \\
y_i < m
\end{cases}
\]  \( \text{(10)} \)

Fulfillment of these conditions means that this point is the intersection of the increasing surface profile and the middle line. Thus, you can find all the points when the surface profile intersects with the middle line, as well as their number \( N \).

Implementation of the above algorithm in software made it possible to build the image shown in Fig. 6, as well as to calculate value \( Sm = 0.012 \) μm.

Figure 6. Profillogram for calculating parameter \( Sm \)

7. Calculation of roughness parameter \( S \)

Using previously found profile maximum points shown in Fig. 2, we will determine their number \( M \) and calculate the distance from the first to the last projection, as \( l_{01} = X_M - X_1 \), where \( X_M \) is the coordinate of the last protrusion; \( X_1 \) is the coordinate of the first projection. In conclusion, \( S \) is calculated by the following formula:

\[
S = l_{01} \frac{M}{M - 1} = \frac{X_M - X_1}{M - 1}.
\]  \( \text{(11)} \)

Implementation of the above algorithm made it possible to mark all peaks on the profilogram and obtain an illustration of this in Fig. 7 using software. The program also enables you to get an average pitch of local projections \( S = 0.004 \) μm.
8. Conclusion
In the course of work, the software calculation algorithms of altitude and pitch roughness parameters were developed. These algorithms made it possible to implement a program for calculating roughness parameters from a given array of point coordinates in C# programming language.

Acknowledgments
This research was funded by Ministry of Science and Higher Education of the Russian Federation (grant No. FENU-2020-0020).

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