Analysis of existing approaches for describing the parameters of single sections during grinding

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Abstract. The paper presents an analysis of various approaches to the formation of an abrasive grain trace in the process of finishing abrasive processing. It is noted that the trace of abrasive grain has a significant impact on the working conditions of the tool and the output parameters of the process. It is established that in the process of interaction of abrasive grains and the processed material, sections can be formed both in the form of a comma and in the form of a segment, which cannot be obtained in real conditions of the processing. It is shown that such an approach to all types and modes of grinding can lead to significant errors in the calculations and, as a result, an incorrect assessment of the influence of processing modes on the technological parameters of the grinding process. The study shows the need to obtain analytical dependencies for calculating the size of individual sections when changing the distances between the contacting grains of the abrasive tool in a wide range.

1. Introduction
Ensuring the quality indicators of parts in the process of their mechanical processing is one of the important factors that affect the entire production process of competitive mechanical engineering products. In this process, an important role is played by the methods of finishing the critical surfaces of parts, which largely determine their quality indicators. The most common finishing methods in mechanical engineering are the methods of abrasive processing. Such physical phenomena during cutting with abrasive tools as heat generation, wear and destruction of abrasive grains and abrasive tools, micro-cutting are well studied. At the same time, we should note that the analysis of the contact process of the workpiece and the tool is most commonly made by the authors based on their assumption about the shape of a single cut, since the work of abrasive grains is largely determined by the size and shape of the cut (primarily its thickness). Accordingly, when analyzing the interaction of the tool with the workpiece and making assumptions about the shape of individual sections, it is necessary to take into account existing approaches when describing the kinematics of grinding and the parameters of individual sections.

2. Materials and methods
During the grinding process, the abrasive grains located on the working surface of the circle are moved relative to the part along the trajectories determined by the specified working movements. The trajectories of abrasive grains determine the shape of the surface to be processed, as well as the shape
and geometric characteristics of the metal particles to be removed – single sections, which affects the working conditions of the tool and the output parameters of the process [1-8, etc.]. The due attention to the issue of the trajectory of the relative working movements of abrasive grain was first paid by E.N. Maslov. Instead of the simplified cutting trajectory of a circle used in the works of his predecessors, E.N. Maslov proposed the equations that determine the cutting trajectory with abrasive grain and can be considered the starting points for the theoretical study of the grinding process. According to [4, 6, 9, etc.], the trajectory of cutting-scratching with abrasive grain during flat grinding will be a trochoid, however, as the analysis [10, 11] shows, as a result of the accepted simplifications, a system of equations describing a helical trochoid, and not a helical hypocyclic curve, is obtained. In [8], it is shown that in the case of flat grinding, the trajectory of the abrasive grain is an elongated cycloid.

The following parameters depend on the shape of the cut removed by a single abrasive grain and its dimensions (length and thickness) [7-13, etc.]:
- the actual length of contact of the abrasive grain with the part;
- the time of this contact;
- the depth of penetration of abrasive grains into the material;
- the force required to cut the metal with the abrasive grain and the energy expended to remove the metal;
- cutting work, and, consequently, the temperature arising in the contact zone of the abrasive grain with the processed material;
- phase transformations and related change in the physical properties of a near-surface layer of the ground material caused by stresses and heating of the material in the contact zone of the abrasive grain with the grinding part.

The opinions of researchers about the most likely cut shape for grinding are diverse and contradictory. So, assuming that in the process of grinding the tops of neighboring cutting grains fall into one section, a number of domestic and foreign researchers [2, 6, 14-16, etc.] believe that the cut has the shape of a comma. Based on the fact that the probability of exact hitting the vertices of two neighboring grains in the same section is equal or close to zero, as well as on experimental data, the group of researchers [18-23] believes that the section has the shape of a segment.

The authors [6, 15, 16, etc.] prefer the comma-shaped form, but note that when grinding, sections of various configurations are removed and in some specific conditions there may be a segment-like shape, in others - a comma-shaped one. According to [6, 8, 12, 15, etc.], the cut shape depends on the speed of the wheel and the details of the depth of cut, and in the presence of a longitudinal feed, on the location of the grains in different parts of the wheel [24, 25]. A slightly different point of view on the issue of cut shapes from those presented earlier was expressed in [26, 27]. It is argued that both the comma-shaped and the segment-shaped cut are the result of the idealization of the grinding process, and they cannot be obtained in real conditions.

Most authors [1, 4, 6, 7, 11, 15, 27, etc.] in their classification of the cut forms formed with a continuous increase in the speed of the workpiece relative to the speed of the grinding wheel proceed from the ratio of the cut thickness to the length and divide them into five classes (Figure 1).

After analyzing the opinions of researchers about the shape of the cut during grinding, we can draw the following conclusions:

1. When grinding, sections of a wide variety of configurations are removed, which for specific conditions can be characterized by the most probable shape of the section.
2. Depending on the modes of grinding, one of the cut forms changes into another.
3. Schematizing the grinding process, some scientists give preference to the comma-shaped cut shape, others – to the segment-shaped one, extending one of the cut forms to all processing modes.

The cut shape of a single grain is characterized not only by the geometric outline, but also by the dimensions such as the cut thickness and the length of the contact curve. The length of the curve of contact of the abrasive grain with the part is the length of the section of the trajectory of the relative
working movements of the abrasive grain passing through the material of the part. If we take the circle as the trajectory of the grain relative to the part, we will have the length of the contact arc.

The influence of these parameters of the cut on the grinding process is decisive, however, the cut thickness has a predominant effect on the process. The thickness of the layer removed by one grinding grain determines: dullness of grains (wheel resistance), cutting force developed by one grain, roughness of the ground surface, instantaneous temperature in the zone of grain operation.

Consider the existing dependencies for calculating the parameters of the comma-shaped slice.

**Figure 1.** The types of cuts formed when the speed of the workpiece is continuously increased relative to the speed of the grinding wheel.

Taking a circle cutting path and a comma-shaped cut, the condition that the grains are located on the working surface of the circle at equal distances from the axis of the circle and are evenly distributed over its surface, and the distance between adjacent grains lying in the same plane perpendicular to the axis is much less than the length of the curve of contact of the wheel and the part, the authors [2, 6-8, 12, 13, 28-31, etc.] have derived formulas for determining the maximum thickness of the metal cut, removed by a separate abrasive grain, depending on various grinding parameters. When determining the dimensions of the comma-shaped cut, these dependencies for surface grinding can be reduced to the form:

1. contact arc length \( l = \sqrt{Dt_f} \);
2. contact arc length with regard to roughness (see figure 2,a)

\[
l = \sqrt{D(t_f - y)},
\]

(1)

where \( D \) – grinding wheel diameter, mm; \( t_f \) – actual microcutting depth, \( \mu m \); \( t_f - y \) – width of the cutting surface at the considered level.

- actual microcutting depth (according to the recommendations [12, 32, 34] and using the diagram shown in figure 2, b)

\[
t_f = 0.739Q_2 + \sqrt{0.546Q_2^2 + \frac{13.66V_0\Delta r}{k_c(V_k \pm V_0)n_g\sqrt{D\rho_g}}},
\]

(2)

where \( Q_2 \)– total material removal, mm; \( k_c \) – the chip formation coefficient; \( V_k \) – speed of movement of the part, m/min; \( V_0 \) – circumferential speed of the grinding wheel, m/s; \( n_g \) – is the number of grains per unit volume of the working layer of the tool; \( \rho_g \)– radius of rounding of the grain top, \( \mu m \); \( \Delta r \)– is the value of radial metal removal, \( \mu m \).
Then the dependencies for determining the length of the contact arc and the thickness of the cut in flat grinding will take the form:

\[
l = \sqrt{D \left[ 0.739Q_\Delta + \sqrt{0.546Q_\Delta^2 + \frac{13.66V_r \Delta r}{k_c(V_k \pm V_g) U_s \sqrt{D \rho_g}}} \right] - y}
\] (3)

\[
a_{\text{max}} = \frac{2V_a \sqrt{t_f}}{60V_k} \sqrt{\frac{1}{D}}
\] (4)

In such formulas obtained from geometric constructions, the translational movement of the center of the circle during its rotation through an angle corresponding to the distance between the contacting grains is not taken into account. With this simplification, the cut thickness is not measured along the normal to the cutting surface, which leads to an error.

**Figure 2.** The scheme of contact of the wheel with the ground surface during flat grinding.

E.N. Maslov used the equations of the trajectory of the relative working movement obtained by him to propose formulas for determining the length of the contact curve of the wheel with the \( L_c \) part and the maximum cut thickness \( a_{\text{max}} \) for surface grinding with the periphery of the wheel. The latter was obtained by dividing the maximum total cut thickness by the number of grains within the contact arc:

\[
L_c = \left[ 1 \pm \frac{V_a}{60V_k} \right] \sqrt{D t_f}.
\] (5)

\[
a_{\text{max}} = \frac{V_a \sqrt{t_f}}{60V_k} l_g \sqrt{\frac{1}{D \cdot B}}
\] (6)

where \( l_g \) – actual distance between successively contacting grains, \( \mu m \); \( S \) – longitudinal feed, mm/rev; \( B \) – circle width, mm.

However, when determining the length of the contact curve in the considered equations, we assume that the cut begins from the axis of the grinding wheel. This leads to the fact that they do not reflect the dependence of the contact length on the actual distance between the contacting grains lying in the same plane perpendicular to the axis of the circle.

The authors [7, 23, 26], analyzing the formulas for calculating the thickness of the comma-shaped cut, found that the chip thickness calculated for real cases of grinding according to the formulas [2, 6-8] and other authors who adopted the comma-shaped chip formation scheme has a very small value, different from the chip thickness that can be collected during grinding. They note that the existing formulas do not allow you to accurately determine the thickness of the chips, but only give some
general idea of the effect of the feed rates, speeds and diameters of the circle and the part on the thickness of the chips, and, consequently, on the entire grinding process.

In the works [8, 9, 23, 26], the obtained refined equations of trajectories are used to propose the dependences for calculating the length of the contact curve for flat grinding. But the analysis of the calculation results for these dependences shows that they are valid only for the case when the contacting grains are within the arc of contact of the circle with the part, and the obtained refinements, in comparison with the formulas [4], are very insignificant and can be neglected.

At the same time, when substituting in them the value of the distance between the abrasive grains that exceeds the length of the contact arc, the error can reach 100\% or more. Therefore, if the distance between the grains is greater than the length of the contact arc, then the thickness of the cut can be calculated using the formula [8, 21, 22, 26, etc.].

\[
Z = t - \frac{Rr + r^2}{R} \left[1 - \cos \left( \arcsin \frac{\sqrt{(2R + 2r - t)(2R - r)(2r - t)}}{2r(R + r - t)} \right) - \frac{180}{\pi Rn} \ln n \right] \tag{7}
\]

where \(Z\) – the thickness of the cut with one abrasive grain, mm; \(R, r\) – the radii of the grinding wheel and the part, \(\mu m\); \(t\) – the grinding depth, \(\mu m\); \(l_g\) – the distance between the abrasive grains, \(\mu m\); \(n, n_k\) – the number of revolutions of the part and the circle, rpm.

When deriving formula (7), a circle is used as a simplified trajectory, but the portable movement of the center of the circle during its rotation by an angle corresponding to the distance between the contacting grains is taken into account, so that the thickness of the cut is determined by the normal to the cutting surface. Therefore, formula (7) can be used for any distances between the contacting grains, within which, under these grinding modes, there is a comma-shaped cut shape. The amount of error in the calculation of this formula due to the simplification of the trajectory is not set.

In the case of a segment-shaped slice, the length of the contact curve is determined by doubling the length of the contact curve (arc), determined by the dependencies for the comma-shaped slice shape [7, 17, 22, 23, 31 etc.]. The thickness of the cut with a segmental shape is assumed to be equal to the depth of grinding. However, the question of the grinding depth (the actual cutting depth during grinding) in the literature is disclosed inconsistently.

So, the works [4, 7, 9, etc.] note that the existing opinion that the actual cutting depth \(t\) is less than the transverse feed \(t\) is erroneous. On the contrary, the actual cutting depth is always greater than the cross feed and under normal grinding conditions exceeds it by 15 ... 30 times. It is proposed to calculate the actual cutting depth using the formula \(t = n \times t\), where the value of \(n\) varies within 1 ... 12, depending on the shape of the slices, the grain size of the circle, the degree of different heights, their wear and other processing conditions. The works [5, 8, 12, 21] take into account the elastic pressing of the technological system and state that the grinding depth will be different. And it lies within the limits of \(t = t - c \pm x\), where \(c\) is the amount of pressing directed towards a decrease in the cutting depth, \(mm\); \(t\) is the transverse feed, \(mm\); \(x\) is some part of the protrusion (+) or depression (−), \(mm\), which remained not removed during the previous grain pass. In cases where \(x = c\), the cutting depth is equal to the transverse feed. When \(x\) has a minus sign, i.e. the grain falls into the trough, \(t\) is less than \(t\), and vice versa. The value of \(x\) can be greater than \(t\). Thus, the thickness of many chips removed during grinding exceeds \(t\) by 2 times or more, but not by 15 ... 30 times.

The thickness and width of the cut determine the cross-sectional area, which is used when calculating the cutting force on the grain and the volume of a single cut [5, 12, 22, 23, etc.]. The cross-section of the cut is a copy of the cutting part of the grain of an arbitrary shape and in the studies is replaced by an equivalent geometric figure in accordance with the accepted simplified shape of the grain and its cutting part. The theoretical shape of the cut is considered to consist of two sections: segmental and trapezoidal, in accordance with the presence of the abrasive grain of the radius of rounding of the vertex and the rectilinear generatrix.

The width and thickness of the layer functionally depend on each other – the greater the thickness of the removed layer corresponds to its greater width. This dependence is expressed by the equation
4. Conclusion

Based on the analysis, the current state of the kinematics of grinding with the periphery of the wheel and the determination of the parameters of single cuts can be characterized as follows:

1. When grinding, two types of cut are generally distinguished: comma-shaped and segmented. Without denying the possibility of any of these forms appearing under certain modes and conditions, the researchers, schematizing the grinding process, extend one of the cut forms taken as the basis of the theory, to all types and modes of grinding. Under certain conditions such an approach can lead to significant errors in the calculation, mismatch between the calculated and experimental technological indicators of the grinding process and an incorrect assessment of the influence of processing modes on technological indicators.

2. There are no criteria to determine the probable shape of the cut for specific modes of grinding.

3. The existing dependencies for calculating the thickness of the comma-shaped cut are of a particular nature and cannot be used for research when changing in a wide range of grinding modes and parameters describing the relief of the circle, without preliminary analysis of their error. The aforementioned shortcomings in the field of studying the kinematics of grinding pose, as one of the local ones, the task of obtaining dependencies for calculating with sufficient accuracy the sizes of single sections when changing in a wide range of distances between the contacting grains.

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