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Estimation of Circular Saw Tooth Microgeometry

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Abstract. This study solves the problem of estimating the microgeometry of a circular saw tooth. For research, a circular saw with one false tooth, equipped with a VK6M hard alloy plate, was used as a cutting tool. The purpose of this study is to attempt to estimate the real wear curve of a wood-cutting tool edge. The cutting was performed on an experimental installation, which is a drive shaft with a saw attached to it, with the possibility of adjusting the cutting and feeding speeds. The tooth tip was photographed after some wear in a plane perpendicular to the short blade edge with 30-50^x magnification. The tooth contour was measured using a large BMI-2 toolmaker microscope. As a result of the study, a method for estimating the sharpness of the tool edge using tangent and subsequent calculations has been developed, which allows figuring out both the local curvature and the average curvature of the entire form of tooth. This method allows finding the sections of the form of tooth with minimal and maximum curvature, as well as figuring out the curvature of a particular section of the form of tooth and the area (wear) of this section. The proposed solution allows transitioning from qualitative features of wear to accurate quantitative estimates, expressed either in units of area or units of mass, which allows comparing the tool materials from which teeth are made in cases where microgeometry is approximately the same, while wear is different. The practical significance of this study lies in the possibility of estimating the state of the parameters of the cutting unit and allows predicting its changes during operation (the degree of wear, the frequency of re-sharpening, finding the ultimate tool service life)

Keywords: tool edge, wood cutting tool, wear, blunting

Introduction

Woodworking production is based on obtaining parts and products of the required shape, size, and roughness of the treated surface [1]. This can be achieved by using a cutting tool, the active part of which is the tooth (tool edge), which forms new cutting surfaces in the material.

One of the main operational requirements [1] for wood-cutting tools is to maintain its cutting capacity for a certain time. The microgeometry of the tool edge undergoes considerable changes during operation – the tooth is blunted due to wear of the tooth line material.

Blunting of cutting units is characterised by a change in their microgeometry, which occurs due to wear of the front and back of tooth during cutting. Tooth microgeometry is characterised by "wear curves" of the front and back of tooth. The nature of blunting, i.e., changes in the microgeometry of tooth, determine the cutting properties of the tool [2-4]. The degree of wear and the nature of changes in the microgeometry of the tool edge depends on several factors, the main of which are as follows:

– physical and technological properties of wood (type, humidity) [5-7];

– physical and mechanical properties of wood-cutting tool material;

– geometry of cutting units (cutting and sharpening angles);

– processing conditions and modes (cutting types, cutting speed, and feed rate) [8-10];

– conditions and modes of operation of the tool (accuracy and rigidity of the tool, duration of operation, geometric accuracy of the machine);

– quality of sharpening of cutting units.

An essential role in ensuring the required quality and accuracy of cutting is played by the tooth line with a

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certain microgeometry. When cutting wood, one needs to strive to ensure that the radius of rounding of the tooth line surface is minimal. Apart from transverse microgeometry, the saw tooth line is also characterised by longitudinal microgeometry.

The cutting unit has tooth lines, surfaces, and angles. The angular parameters must meet the cutting conditions and position the cutting part in space. Linear parameters must provide the necessary margin of safety and stability of the cutting unit.

Compliance of the tool with modern requirements is laid down during its design. The correct choice of tool design, material, dimensions, angular parameters, operating conditions, manufacturing technology, restoration, and repair directly affects its operational properties.

The scientific originality of this study lies in a new method for estimating the parameters of the form of tooth of the cutting unit, wherein the curvature is estimated by drawing tangents with a discrete step.

From the literature sources [11-15], it is known that many well-known Ukrainian and foreign scientists have estimated the parameters of microgeometry of saw teeth. The versatility of the parameters is significant, but not all of them are available for direct measurement [16-18]. Analysis of these studies has shown that most authors simplify the approach to real microgeometry of tooth, noting the rounding of the tool edge as a circle with a certain radius. The authors of the study proposed one of the methods for measuring the linear dimensions of saw teeth [19].

In most cases, the real tooth line of the tool is shown as a surface with a radius $\rho=const$ (with constant curvature) [1; 20; 21]. In fact, as a result of the authors' earlier studies of microgeometry of cutting units under various cutting conditions using a large BMI-2 toolmaker microscope, it was found that the curvature of the surface between the front and the back of tooth of the cutting unit is not a constant value of a certain radius, but a curve of variable value, which can only be conditionally estimated as a circular arc.

The purpose of this study is to establish a method for estimating the blunting curve of the edge of the cutting unit.

Materials and Methods

A circular saw was used as a cutting tool (Fig. 1) with one false tooth (Fig. 2), equipped with a VK6M hard alloy plate. Laminated particle board was used as the processed material. The scheme of cutting a particle board blank is presented in Figure 3. The cutting was performed on an experimental installation, the general view of which is presented in Figure 4.

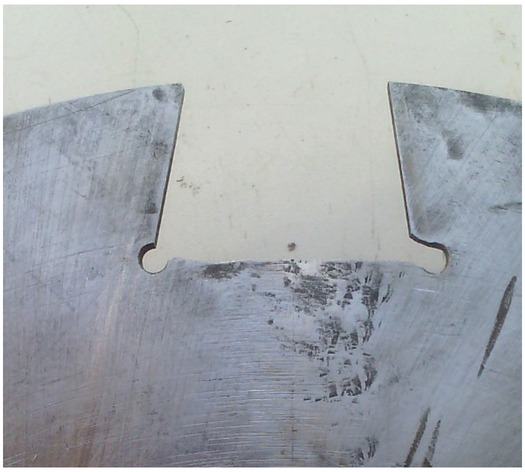

Figure 1. Saw disc fragment

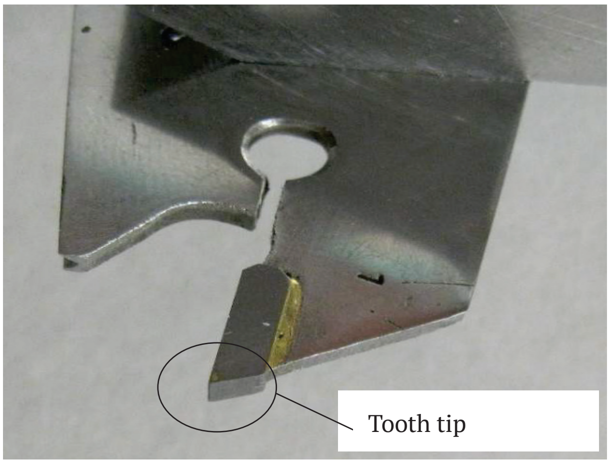

Figure 2. Inserted tooth of a circular saw

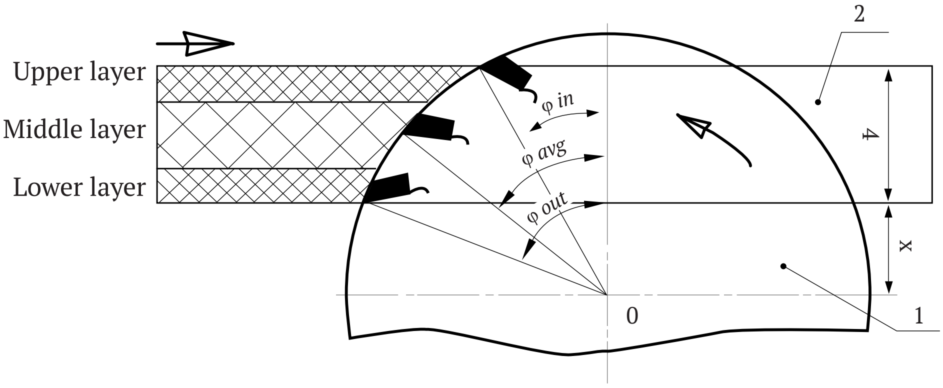

Figure 3. Particle board cutting scheme: 1 – saw; 2 – board

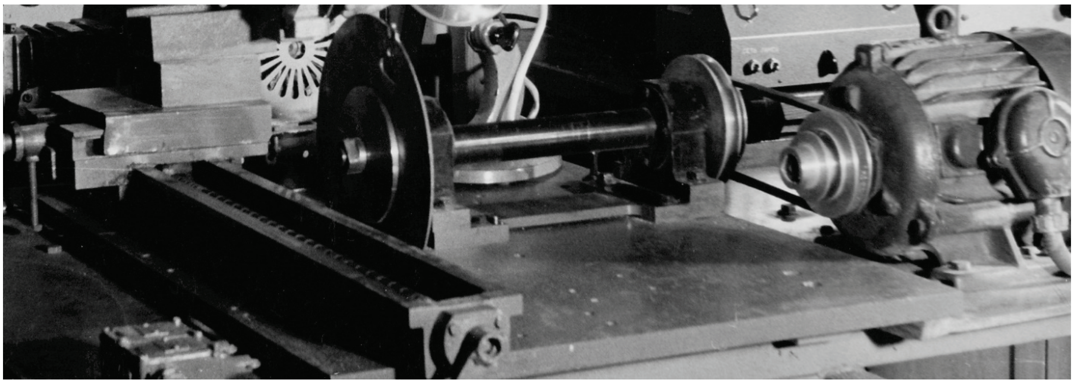

Figure 4. General view of the experimental setup

On a steel plate with a thickness of 25 mm, two bearing supports are mounted, in which the saw shaft rotates. On the one hand, the saw shaft is connected to an electric motor via a two-stage V-belt transmission. On the other hand, a saw blade is fixed between the flanges. The carriage with the fixed sample of the material under study is moved in rigid metal guides. The carriage is driven by an electric motor through a continuous variable transmission and a screw shaft. The particle board sample can move along three coordinate axes and is fixed in the desired position. The cutting disc has a wedge-shaped cutout into which a replacement tooth is inserted. The tooth is a metal plate of reverse wedge shape with a soldered hard alloy plate. The properties of the hard alloy and the geometry of the plate are dictated by the requirements of the experiment. The unit allows controlling and setting the cutting speed, feed rate, and working angle of incidence over a wide range of values. The high rigidity of the installation structure and the sturdy foundation on which it is installed eliminate any deformations and fulfil the conditions for reproducing experiments regardless of the time factor.

Experiments with a single-toothed saw avoid the influence of vibration from variable cutting forces, radial and tangential runout, out-of-roundness of the saw hole and the seat of the root flange, and non-flatness of the cutting disc.

The authors of this study conducted an experiment. Experiment conditions:

– saw tooth material: VK6M grade hard alloy;
– blade speed: 2960 min^{-1};
– cutting diameter: 396 mm;
– cutting path length in material: 4000 m;
– visualisation: large BMI-2 toolmaker microscope;
– angle of tooth point: 60°C.

The tooth under study, after operating to a given wear, was installed on the table of a large BMI-2 toolmaker microscope, the back of tooth was combined with the X-axis and photographed in this position with a magnification of $30\text{-}50^{x}$ (Fig. 5).

In the photo, the intersection point of the back and the front of tooth was aligned with the origin of coordinates, and tangent lines were drawn to the tooth contour in increments $\Delta\Phi = 15$. The intersection points of tangents with the abscissa axis were determined and the abscissa values at these points were measured (Fig. 6).

If the wear line is divided into several sections $\Delta\Phi$ within which a continuous arc is replaced with a tangent to it, then a polyline can be obtained that describes the original curve with a slight loss of accuracy (Fig. 6). Therewith, the estimation of straight-line parameters (angle, coordinates of the ends of segments) is greatly simplified. The proposed tangent method is simple and easy to implement in practice. Coordinates of construction points are calculated using analytical and descriptive geometry methods.

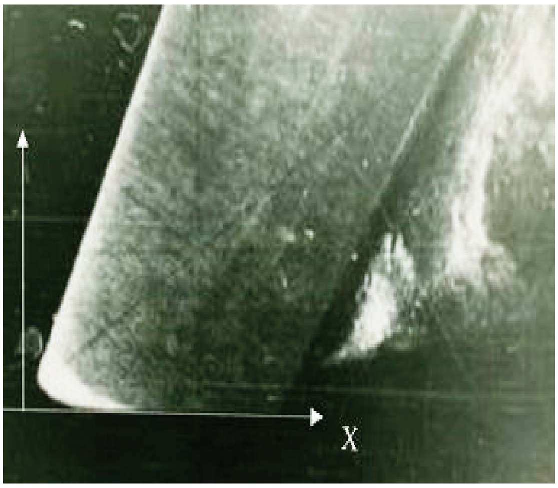

Figure 5. Micro-image of the tooth tip

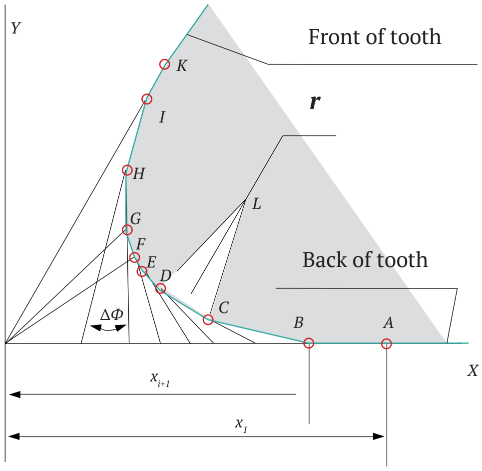

Figure 6. Form of tooth blunting curve

The profile of the cutting unit is obtained (e.g., using the optical method and image magnification), it is divided into separate segments using point marks. The smaller the distance between the points, the more the form arc tends to the straight line and the more accurately the real curvature of the tooth line can be described. The coordinates of the intersection point of adjacent tangents with angles Φ_i and Φ_{i-1} were calculated sequentially according to formulas:

$$X_i = \mathrm{X}_{\phi\mathrm{i}} - [(\mathrm{X}_{\phi-1} - \mathrm{X}_{\phi\mathrm{i}}) \times Sin(\Phi_\mathrm{i} - \Delta\Phi)/Sin\Delta\Phi] \times Cos\Phi_\mathrm{i}; \tag{1}$$

$$Y = \left[(\mathrm{X}_{\phi1} - \mathrm{X}_{\phi\mathrm{i}}) \times \frac{Sin(\Phi_\mathrm{i} - \Delta\Phi)}{Sin\Delta\Phi}\right] \times Sin\Phi_\mathrm{i}. \tag{2}$$

The distance d_i was found between two consecutive points of intersecting tangents (e.g., DC), as presented in Figure 6:

$$d_i = [(X_i - X_i - 1)^2 + (Y_i - Y_i - 1)^2]^{-2}. \tag{3}$$

For each interval $\Delta\Phi$ (e.g., DC) the radius of curvature r was calculated according to equation 4:

$$r = d/(2 \times Tg(\Delta\Phi/2). \tag{4}$$

Wear areas, or rather the area of the OABCDEFGHIKO shape, which is defined as the sum of the areas Si of the triangles ΔOGF (shown in the figure), ΔOFE, ΔOED and others are calculated using the formula:

$$S = \sum[0,5(-x_i + 1)(y_i - y_i + 1) + (y_i + 1)(x_i - x_i + 1)]. \tag{5}$$

Results and Discussion

An ideal tool edge is understood as a line of intersection (for a two-dimensional representation – a point) of the front and the back of tooth. It is impossible to obtain the face intersection as a line due to chipping of the tooth material near the face intersection. Therefore, the real tool edge is a curve of indeterminate direction located at some distance from the centre of coordinates. The real tool edge with a time in service constitutes a curved surface between the front and the back of tooth (for a two-dimensional representation – a curved line). Thus, from a geometric standpoint, blunting is the transformation of a point (conditionally) into a curve and the subsequent increase in the parameters of this curve.

The microphotograph of the tooth has markings, which adequately reflect the microgeometry of the worn-out tool edge. Figure 7 shows the contour of the form of tooth presented in Figure 6. Tangents illustrate the identity of the image in the photo presented in Figure 5 and the measuring diagram presented in Figure 8.

The given data of the measurement results refer to Figure 6 but without regard for the image scale. The measurement data is summarised in Table 1.

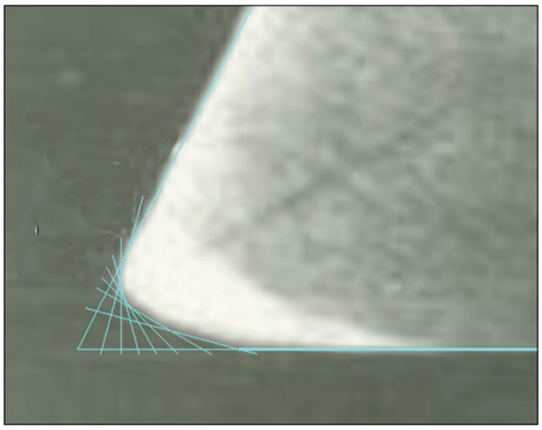

Figure 7. Tangents to the form of tooth

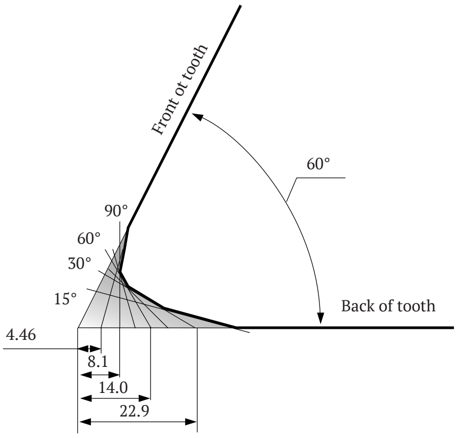

Figure 8. Measurement scheme

Table 1. Results of measurements and calculations of the blunting curve

Interval number	Angle of arrival	Coordinate, x	Distance, d	Curvature radius, r	Wear and tear area,S	
	degree	mm	mm	mm	mm^2	%
1	15	29.5	12.77	48.84	48.70	34
2	30	22.9	8.02	30.67	45.90	33
3	45	17.5	1.60	6.12	9.95	7
4	60	14.0	1.14	4.36	6.91	5
5	75	11.0	1.78	6.81	9.49	7
6	90	8.1	2.25	8.61	9.07	6

Table 1, Continued

Interval number	Angle of arrival	Coordinate, x	Distance, d	Curvature radius, r	Wear and tear area,S	
	degree	mm	mm	mm	mm²	%
7	105	4.5	5.20	19.89	11.20	8
	Mean		*4.68*	*17.90*	*20.17*	
	Max		*12.77*	*48.84*	*48.70*	
	Min		*1.14*	*4.36*	*6.91*	
	Sum				*141.22*	*100%*
Length of the form projection on the back of tooth, mm				*21.50*		
Length of the form projection on the front of tooth, mm				*9.25*		

The second column of Table 1 shows the values of the angles at which tangents to the form of tooth were drawn. Column X shows the coordinates of the intersection points of tangents with the X-axis. The bottom of Table 1 shows statistical indicators of average and extreme values.

Calculation results in Table 1 are illustrated by graphs in Figure 9. The distribution of tooth curvature along the contour, the area of the worn surface and the distance between the intersection points of tangents are given.

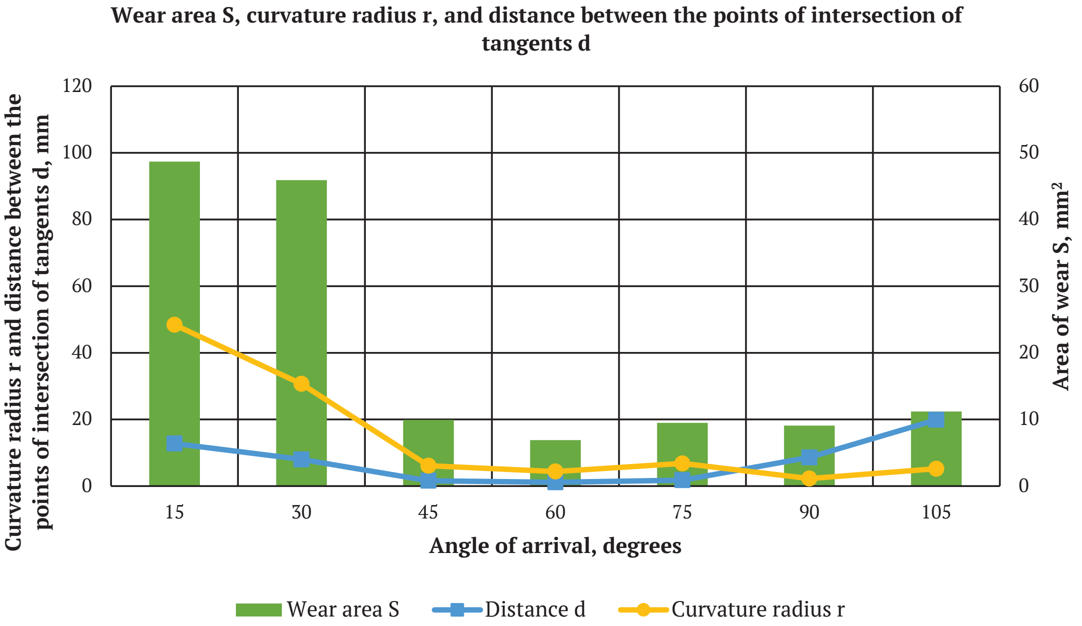

Figure 9. Distribution of saw tooth curvature

Clearly, the greatest curvature r_{min}=4.36 mm falls on the interval corresponding to the 60° angle of arrival. This is precisely the median interval No. 4. The curvature in the adjacent sections on the left and right is approximately the same (the radius of curvature is 1.5 times larger). The radius of curvature in Sections 6 and 7, i.e., adjacent to the front of tooth, slightly increases and reaches r_{min}=4.6. The radius of curvature in Sections No. 2 and No. 1, i.e., those adjacent to the back of tooth, increases significantly and reaches r_{min}=11.2. The radius of curvature adjacent to the back of tooth is 11.2 times the minimum radius and 2.5 times the radius of curvature in the area adjacent to the front of tooth.

The projection of the blunting form on the back of tooth (similar to the radius of curvature) is 2-3 times longer than on the front of tooth. This is inherent in saws that process laminated particle boards.

Table 1 shows the wear areas for each interval and the form as a whole. Clearly, as the radius of curvature (or distance d) increases, so does the wear area. The presence of interval wear values allows figuring out the intensity of wear of the tooth depending on the sawing conditions.

Knowing the distribution of the radius of curvature from the angle of inclination of the corresponding tangents, the reverse transformation can be performed, and the original form of tooth can be obtained. Figure 10 shows the form of tooth, which is constructed according to the data from Table 1.

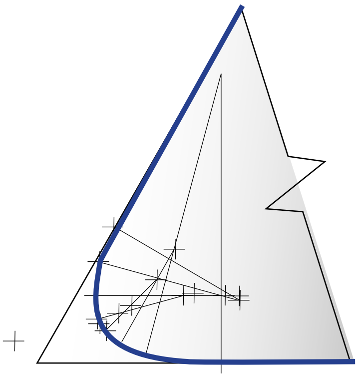

Figure 10. The form of tooth, constructed according to Table 1

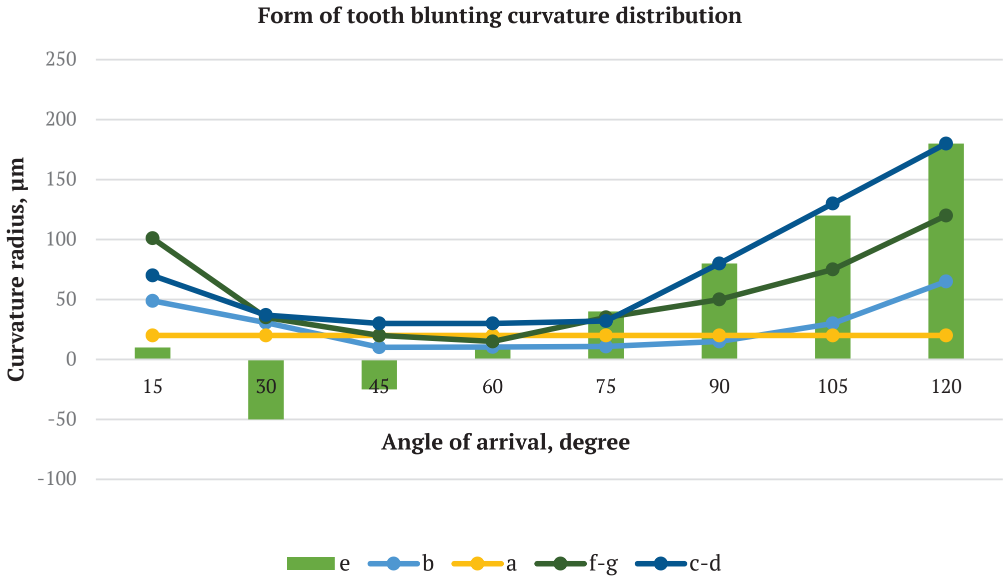

Figure 11. Form of tooth curvature

The form of tooth wear estimates for different cases of such wear are presented in Figure 11. The diagram suggests that the curvature of the form of tooth in the areas near the front and the back of tooth is always substantially less than the curvature in the central sections of the form.

For instance, if the curvature of the form of tooth is constant (circular arc), then it will be displayed on the graph as a straight line parallel to the abscissa axis (Fig. 11a). The sharper the tooth, the closer the line runs to the abscissa axis. The graph line of an absolutely sharp tooth completely coincides with the abscissa axis.

For the form of tooth in Figure 11e, which has worn out on the front of tooth in the form of a hole, the curvature in this area will have negative values, which is well observed in Figure 11e.

All graphs presented in Figure 11 suggest that the greatest sharpness of the form of tooth is always in the central parts of the form. Furthermore, they show exactly which part of the curvature reaches the highest value.

For instance, if the graph looks like a curve (Fig. 11f-g), which has one local minimum, then it is at this point that the tool edge is located. This is the point where the tangent to the form of tooth will be at an angle of approximately 50°. For the case presented in Figure 11a, the tool edge is the entire section of the form from 0°C to 120°C. If the graph looks like a curve (Fig. 11b), which has a weakly expressed extremum, then the tool edge is located in a region of approximately 40-60C°, and in the case of a curve (Fig. 11c-d) – within 30-75C°.

One of the possible methods for evaluating the form of tooth of a cutting unit is proposed, which is implemented as follows.

If in other studies [1; 4; 14] the tool edge wear curve had a circular shape, then in the authors' study the curve has a complex shape, which indicates a different nature of wear on both the front and the back of tooth.

Conclusions

Based on the conducted research, the following conclusions can be drawn:

1. Estimation of the tool edge sharpness by performing tangent and subsequent calculations is much more informative and objective than the method of selecting circles and allows finding both the local curvature and the indirect curvature of the entire form of tooth. In the future, using more modern toolmaker microscopes, the accuracy of further studies will considerably increase.

2. The proposed estimate allows finding sections of the form of tooth with minimal and maximum curvature.

3. During changes in sawing conditions (feed rate or

working angle of incidence), the estimation provides insight into the drift of the form of tooth sections with minimum and maximum sharpness or minimum and maximum wear. This means that by evaluating the parameters of the form of tooth after changing the sawing parameters, the process can be controlled, and the best (from a certain perspective) results can be achieved.

4. The tangent method allows not only to find the curvature of a particular section of the form of tooth (i.e., its microgeometry), but also to figure out the area (i.e., wear) of this section.

5. The tangent method allows moving away from the qualitative "more-less" characteristics of wear towards precise quantitative estimates expressed either in units of area or units of mass. This allows comparing the tool materials from which the teeth are made in cases where microgeometry is approximately the same, but the wear is different.

6. The tangent method is available for extensive application and does not require special equipment.

7. This method can be called numerical with confidence, since the result of applying the tangent method is a matrix of size 2×n (where n is the number of intervals or tangents). This is convenient for data transfer since there is no need to create graphic images.

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Анотація. В статті вирішується проблема оцінки мікрогеометрії зуба дискової пилки. Для досліджень в якості різального інструменту використовували дискову пилу з одним вставним зубом, що оснащений пластинкою твердого сплаву марки ВК6М. Метою дослідження є спроба оцінити криву реального зношення леза дереворізального інструменту. Процес різання здійснювали на експериментальній установці, що представляє собою приводний вал із закріпленою на ньому пилою з можливістю регулювання швидкостей різання та подачі. Вершину зуба пили фотографували після деякого зношення в площині, перпендикулярній короткій різальній крайці із збільшенням 30-50х. Вимірювання контуру зуба проводили за допомогою великого інструментального мікроскопу БМІ-2. В результаті досліджень розроблено метод оцінки гостроти леза за допомогою дотичних та наступних розрахунків, які дозволять визначити як локальну кривизну, так і середню кривизну всього профілю. Цей метод дозволяє виявити ділянки профілю з мінімальною та максимальною кривизною а також визначити кривизну конкретної ділянки профілю та площу (зношення) цієї ділянки. Запропоноване рішення надасть можливість здійснити перехід від якісних характеристик зношення до точних кількісних оцінок, які виражені або в одиницях площі або одиницях маси, що дозволить порівнювати інструментальні матеріали, із яких зроблені зуби, між собою у випадках, коли мікрогеометрія приблизно однакова, а зношення різне. Практична значущість роботи полягає в можливості оцінки стану параметрів різального елемента та дозволяє прогнозувати його зміни в процесі експлуатації (ступеня зношення, періодичності перезагострювання, визначення максимального ресурсу інструмента)

Ключові слова: лезо, дереворізальний інструмент, зношення, затуплення