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ACTUAL CONTACT AREA ON THE WORN CLEARANCE FACE OF THE CUTTER WITH THE ROUND KYBORITE INSERT

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Abstract. *For a tool equipped with a circular cutting insert, a dependence is proposed for calculating the nominal area of the contact area on the back surface. It is proved that the actual area of the contact area of the tool differs significantly from the nominal one due to the presence of a system of micro-irregularities, which makes a difference in the assessment of machining process parameters. Using the example of a tool equipped with a circular cutting insert made of polycrystalline cubic boron nitride ciborite, an approach to determining the actual contact area of the back surface with the workpiece during finishing turning of hardened steel is considered. The possibility of taking into account the influence of the system of irregularities in the contact area, determined by the parameters of its topography, on the size of the actual area is shown, and the ratio of the actual and nominal areas of the contact areas of the tool is determined, and it is found that, depending on the degree of development of the microrelief, the ratio of the actual and nominal areas of the contact surface of the cutter differs by at least 20%. It is shown that the actual contact area is also related to the total length of the main and auxiliary cutting edges, determined by the maximum values of the main and auxiliary angles in the cutter plan, and the size of the wear chamfer on the back surface of the cutter.*

Keywords: *cutting tool; clearance face; Kyborite PCBN; contact area; irregularities; actual contact area.*

1. INTRODUCTION

There are many scientific publications devoted to the determination of contact stresses on the working areas of cutting tools.For example, [1,2] provides a general methodology for determining contact stresses on tool working areas, and [3] adjusts this approach to the case of using tools made of superhard materials when machining hardened steels.At the same time, when determining the stresses in these works, the distribution of cutting forces relative to the nominal contact area is considered both on the rake and clearance surfaces of the tool. It is quite clear that such a simplification is justified for approximate calculations, but can introduce significant errors in the case of the presence of a developed system of waves and icronormalities on the contact areas of elements of any friction pair, which results in a significant discrepancy between the value of the actual contact surface area and the nominal one [4, 5]. The formation of such a system of irregularities on the working surfaces, and, accordingly, the determination of the actual area of the contact area, should be considered as a result of wear of the cutting tool [6, 7].

This paper proposes an approach to determining the actual contact area of a tool, considered on the example of the clearance face of a cutter equipped with a round cutting insert made of a polycrystalline superhard composite (PCBN) Kyborite [8], when machining hardened steel.

2. METHODS

The study was carried out when turning hardened steel ШХ-15 with a cutter with a round insert RNMN 070300 made of Kyborite PCBN. Cutting modes: cutting speed - 120 m/min, feed - 0.08 mm/rev.

The images were obtained using a BRUKER ContourGT 3D Optical Microscope. The length of the profile was determined by the KU-A curvimeter using longitudinal and transverse profilograms with the same scale along the X, Y axes.

3. RESULTS

For a better understanding of the processes of contact between cutting tools and the workpiece, we use a predictive model, according to which, at the moment the clearance face of the cutter touches the workpiece, the processed material deforms on the cutting surface. Gradually, the deformation of the material being processed changes from elastic to plastic. Being in a deformed state, the material undergoes plastic shear and turns into chips, and both plastic and elastic deformation occurs on the clearance surface of the cutter during contact, accompanied by elastic recovery of the processed workpiece material after it leaves contact with the cutter.

It should be noted that the actual contact area of a sharp cutter in the plastic contact areas depends on the set of irregularities formed during tool manufacturing and is larger than their nominal area. The areas of elastic contact are smaller than their nominal area.

To find the nominal contact area of a tool equipped with a round cutting insert with the workpiece surface, the contact diagram shown in Fig. 1. For a simplified view of the contact surface, the part of the contact surface formed by the cutting edge with a radius of curvature is not shown.

Assuming that the radius of curvature of the cutting edge and the back angle of the cutter are the same along the entire working length of the cutting edge, we assume that the contact surface will be limited to the *ABDC* shape, which is a truncated cone with a generic OO_1 and an angle α. However, such a solution introduces some errors, since the radius of curvature and the contact length of the elastically restored part of the deformed material are comparable values. So, let's imagine the area of this surface as a rectangle, which is a scan of the surface of a truncated cone with a part of a circle with a radius *r* equal to the radius of the top of the cutting tool and a rectangular scan of a part of a toroidal surface with a large outer radius *r* equal to the radius of the top of the cutting tool and an end radius *ρ* equal to the radius of curvature of the cutting edge.

In fact, such a shape is similar to a trapezoid, but in real conditions, due to the small values of the clearance angle, this distinction can be neglected by aligning the bases of the trapezoid and considering them equal to the total length of the cutting edges.

Then the contact area is defined as:

$$A_3 = h_y\left(b + b_1\right). \tag{1}$$

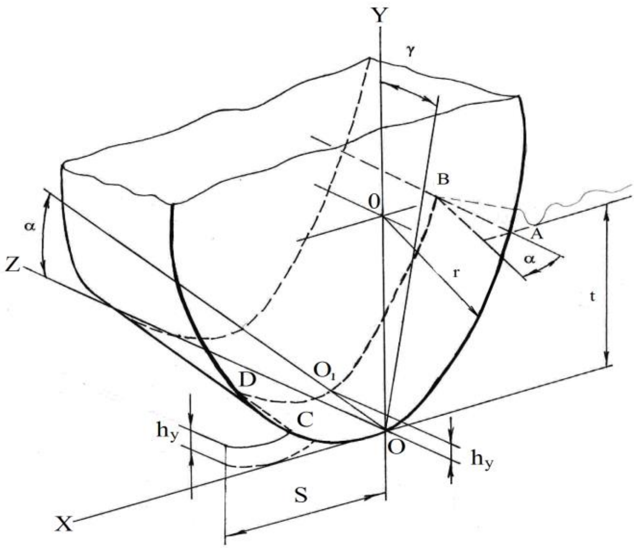


Figure 1 – Diagram for determining the contact area of the clearance face of a cutter with a radius at the tip with the machined surface

To calculate the nominal contact area of a cutting tool with a radius at the tip with the machined surface, the diagram shown in Fig. 2. According to it, we have:

$$\Psi_1 = arccos\left(1 - \frac{r}{cos\,\gamma}\right), \tag{2}$$

$$\Psi_2 = arcsin\left(\frac{S + h_y}{2r}\right) \tag{3}$$

then:

$$\cup \mathrm{OA} = b = r\,arccos\left(1 - \frac{t}{r\,cos\,\gamma}\right), \tag{4}$$

$$\cup \mathrm{OC} = b_1 = r\,arcsin\left(\frac{S + h_y}{2r}\right). \tag{5}$$

By summing up the individual segments of the *AC* arc, we get its length:

$$\cup \mathrm{AC} = (b + b_1) = r\left[arccos\left(1 - \frac{t}{r\,cos\,\gamma}\right) + arcsin\left(\frac{S + h_y}{2r}\right)\right] \tag{6}$$

.

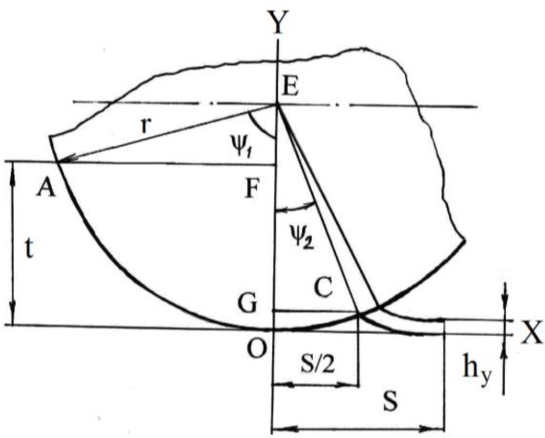


Figure 2 – Diagram for calculating the nominal contact area of a cutting tool with a radius at the tip with the surface to be machined

After substituting into equation (6) the values of the length of contact between the back surface and the machined surface from equation (5), the value of the elastic recovery height from equation (2) and the total length of the cutting edges from equation (1), we obtain the equation for calculating the nominal contact area of a sharp cutter with a radius at the apex:

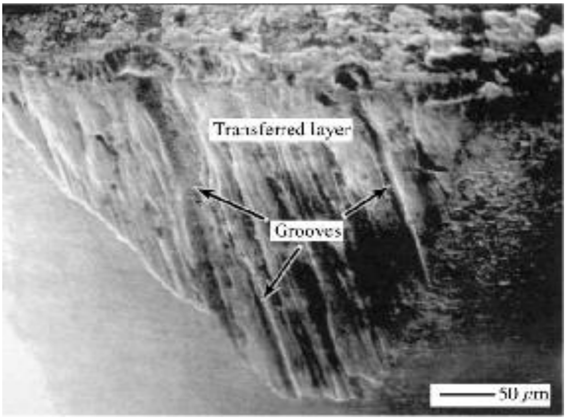
$$A_3 = \rho\left[arccos\left(0{,}5+\frac{\tau}{\sigma_T}\right)+0{,}4\left(\frac{\sigma_T-\tau}{\sigma_T\, sin\alpha}\right)\right]\cdot, \qquad (7)$$

$$\cdot r\left\{arccos\left(1-\frac{t}{r\, cos\gamma}\right)+arcsin\frac{1}{2r}\left[S+0{,}4\rho\left(1-\frac{\tau}{\sigma_T}\right)\right]\right\}.$$

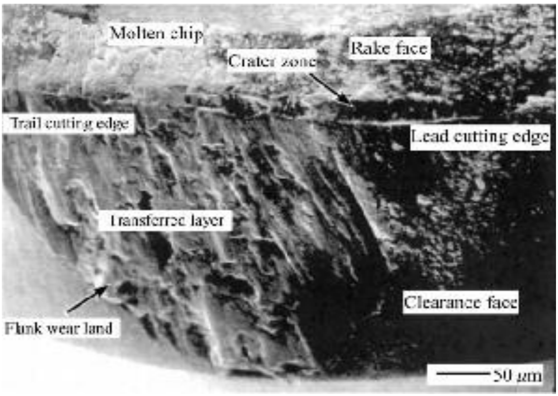
During the prewear period of the tool, when the sharp edge of the cutter plunges into the workpiece, an active interaction with the workpiece occurs, accompanied by micro-crushing of particles from the tool composite, wear of the tool along the rake and clearance surfaces, which leads to an increase in the radius of curvature of the cutting edge, an increase in the contact surface and a more even distribution of thermobaric loads on the working part of the cutter, which creates the prerequisites for the transition to the period of steady-state wear.

A typical example of a worn back surface of a tool is shown in Fig. 3 [9]. It should be noted that the contact surfaces have characteristic furrows, grooves, and protrusions located in the direction of the common cutting feed – speed vector [9–11].

Fig. 4 shows optical-electronic images of the worn area on the clearance surface of a tool equipped with a round cutting insert made of Kyborite PCBN after turning ShKh-15 steel. Although the geometrical parameters of the cutting parts of the BZN6000 cutters shown in Fig. 3 and the RNMN 070300 Kiborite PCBN insert shown in Fig. 4 differ significantly, the topography of the worn surface has a similar appearance with rounding of the cutting grooves characteristic of PCBN and breakouts of crystallite blocks from the superhard tool material. Such images and the resulting profilograms by coordinates allow us to quantify the depth of depressions and the height of protrusions relative to the nominal position of the cutting edges [7].



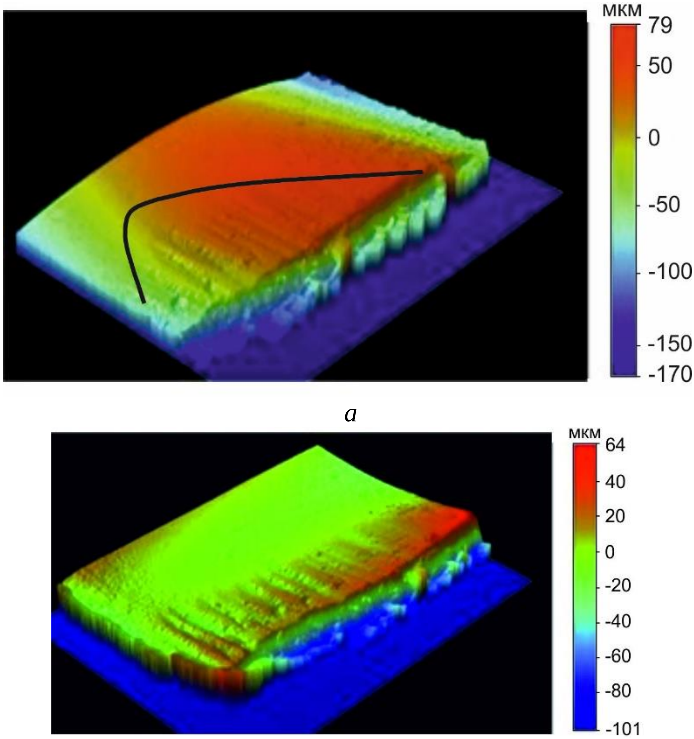
a



b

Figure 3 – Contact surfaces of a tool made of BZN6000 PCBN when turning hardened steel

Digital processing of the obtained images makes it possible to determine the line of protrusions and depressions on the worn surface of the tool. The 3*D* image and quantitative values of the heights of the protrusions and the depths of the depressions shown in Fig. 3, *b*, clearly demonstrate the contour of the worn area on the clearance surface of the insert and show that the actual contact area of the cutter with the workpiece is much larger than the nominal one.



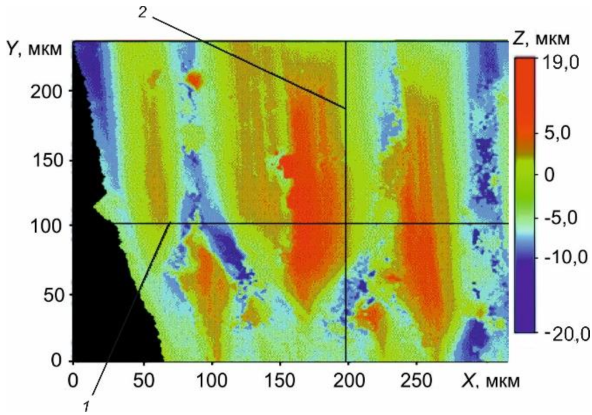
a

b

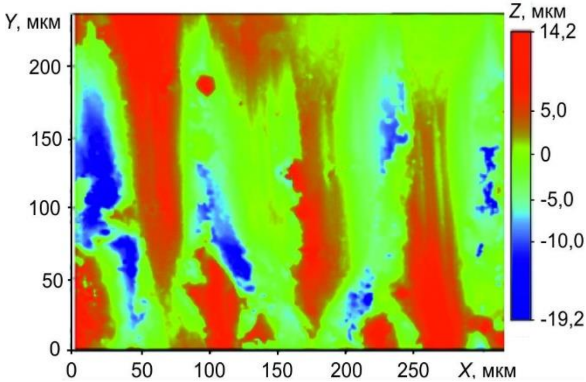
Figure 4 – 3*D* image of the wear area on the cutter surface (*a*) and 3*D* image of the wear area on the clearance face (*b*) of a PCNB cutter after machining ШХ15 steel, pointed to the straightened cutting edge

This circumstance should be taken into account when determining contact loads on the clearance face of the tool and calculating the components of the cutting force. Consider the profilograms obtained at different areas of contact between the worn clearance surface of the tool and the machined surface of part (Fig. 5).

The *X*-axis scanning direction is along the tool's straightened cutting edge, and the *Y*-axis scanning direction is along the cutting speed vector, i.e., the width of the wear chamfer. The profilograms show both the height of the depressions and the depth of the profile depressions on the worn surface and the frequency of their formation, which correlates well with the transverse feed rate of the workpiece during machining.


2
Y, мкм
Z, мкм
19,0
5,0
0
-5,0
-10,0
-20,0
200
150
100
50
0
0
50
100
150
200
250
X, мкм
1

a


Y, мкм
Z, мкм
14,2
5,0
0
-5,0
-10,0
-19,2
200
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100
50
0
0
50
100
150
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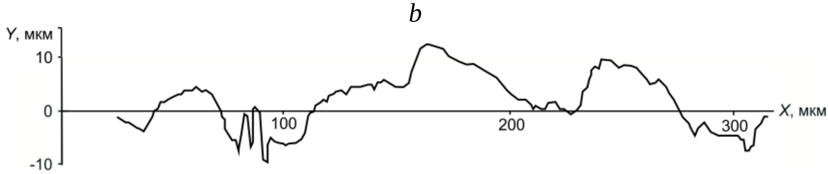
250
X, мкм

b


Y, мкм
10
0
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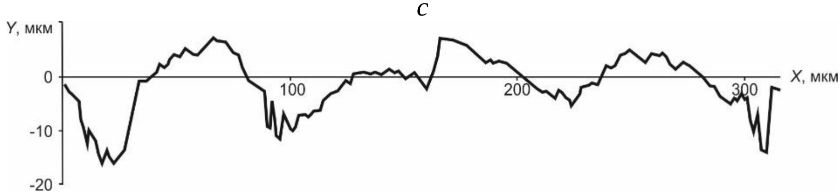
X, мкм

c


Y, мкм
0
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X, мкм

d

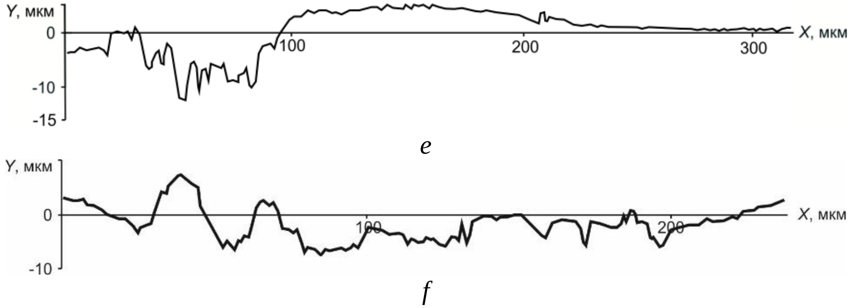

Figure 5 – Topogram of the contact surface (*a*, *b*), profilograms of irregularities in the directions of *X (c, d*), *Y* (*e*, *f*) by coordinates: *Y* = 105.3 μm (direction *1*) (*c*), *Y* = 102.4 μm (*d*), *X* = 199.0 μm (direction *2*) (*e*), *X* = 87.9 μm (*f*) (*a, c, e* – area *1*; *b, d, f* – area *2*)

The profilograms also show the maximum values of microroughness *Z* and the angles of inclination of the profile irregularities. Fig. 5 shows the tribograms and profiles (according to directions *1*, *2*) of the worn surface.

Analysis of the obtained data on the profile of the worn surface allows us to establish the ratio of the profile length to its projections in different parts of the worn surface.

Depending on the coordinate, the measured data characterize the profile of the worn surface both in the areas of plastic and elastic contact with the treated surface. The obtained data on the actual and nominal lengths and their ratio are summarized in Table 1.

Analyzing the difference in the actual bump profile along the wear zone along the cutting edge, we observe a longer bump length near the area where the main cutting edge cuts into the allowance material. The actual length of the profile in this direction is on average 1.37 times longer than the nominal length.

The difference between the lengths of the actual and nominal (100 μm) profiles in the direction from the front surface to the wear boundary in the same area is on average 1.62 times. The average deviations from the nominal length of the profile from the cutting edge to the wear boundary are 1.29 times. That is, a more developed wear surface is observed in the direction along the cutting edge.

Having obtained such data on the values of the profile lengths in each direction of the defined sections and on the segments by coordinates, we can find the integral values of the actual contact areas on each segment of the measured profile of the wear surface irregularities by solving the defined integral of the form:

$$A_{\Phi LxLy} = \int_{Lx_0}^{Lx_i} \int_{Ly_0}^{Ly_i} dLxdLy \,. \qquad (8)$$

Table 1 – Absolute and relative values of the profile length on individual sections of the wear surface

№	Coordinate *Y*	Site, µm	L_X, µm	*X*, µm	L_X/X
1	105,3	28–100	95	72	1,32
2		100–200	125	100	1,25
3		200–315	130	115	1,13
$\Sigma_{1\text{-}3}$		**28–315**	**350**	**287**	**1,22**
4	102,4	0–100	143	100	1,43
5		100–200	110	100	1,10
6		200–315	150	115	1,30
$\Sigma_{4\text{-}6}$		**0–315**	**403**	**315**	**1,28**
	Coordinate *X*	Site, µm	L_Y, µm	*Y*, µm	L_Y/Y
7	199,0	0–50	97	50	1,94
8		50–100	65	50	1,30
9		100–150	55	50	1,10
10		150–200	55	50	1,10
11		200–237	40	37	1,08
$\Sigma_{7\text{-}11}$		**0–237**	**312**	**237**	**1,32**
12	87,9	0–50	65	50	1,30
13		50–100	65	50	1,30
14		100–150	65	50	1,30
15		150–200	66	50	1,32
16		200–237	40	37	1,08
$\Sigma_{12\text{-}16}$		**0–237**	**301**	**237**	**1,27**

Similarly, the nominal rear surface on the same coordinate segments can be calculated by solving the integral:

$$A_{3xy} = \int_{x_0}^{x_i} \int_{y_0}^{y_i} dxdy \,. \qquad (9)$$

The obtained numerical values of the actual and nominal areas of the worn clearance face of the cutting tool calculated by formulas (8) and (9), respectively, and their relative values are summarized in Table 2.

Analyzing the data obtained, it should be noted that on the worn part of the tool with a round Kyborite PCBN cutting insert, the largest difference in the actual contact area with the machined surface compared to the nominal one is observed in the zone of greatest wear, which is closest to the front surface, at a distance of ~ 100 μm.

Averaging the data obtained over the total length of the worn profile from the front surface to the boundary of the wear zone, the actual contact area exceeds the nominal one by 1.6 times.

To find the actual contact area along the entire contour of the wear zone, which can be represented as a curved triangle, let's try to solve the defined integral, in which the length of the profile in the direction of the cutting edge is indicated as the average value of the actual length Lx = 376.5 μm over the entire area from 0 to 315 μm, and Ly = 306.5 μm over the area from 0 to 237 μm.

Table 2 – Absolute and relative values of actual and nominal areas in individual sections of the wear surface profile

№	Coordinates	Site, μm		$A_Ф$, μm^2	$A_Н$, μm^2	$A_Ф/A_Н$
		X	*Y*			
1	*X* = 198,966 *Y* = 105,278	28–100	0–100	9215	3600	2,56
2		100–200	100–200	8125	5000	1,63
3		200–315	200–237	7150	5750	1,24
4		28–315	0–237	109200	68019	1,61
5	*X* = 87,873 *Y* = 102,380	0–100	0–100	9295	5000	1,86
6		100–200	100–200	7150	5000	1,43
7		200–315	200–237	9750	5750	1,70
8		0–315	0–237	121303	74655	1,62

In general, the integral equation is as follows:

$$A_{ФLxLy} = \int_{Lx_0}^{Lx_i} \int_{Ly_0}^{Ly_i} 0{,}5 dLxdLy \cdot \qquad (10)$$

According to the calculation, the actual area of the contact area is $A_{ФLxLy}$ = 0.058 mm^2, the nominal area is $A_{НLxLy}$ = 0.037 mm^2.

4. CONCLUSIONS

As a result of the measurements and calculations, it was found that the presence of grooves on the worn rear surface of a tool equipped with a round Kyborite PCBN cutting insert when turning hardened steel ShKh–15 leads to an increase in the actual area of the contact area with the workpiece by 1.57 times compared to its nominal area.

However, it is necessary to take into account the fact that the projection of the worn part of the cutter will not always have a shape close to a triangle, and to carry out calculations in accordance with the actual wear contours.

Comparing the obtained ratios and taking them into account the increase in the length of the actual contours in the *Y* direction equal to 1.6, it can be argued that the data obtained in [7] on the ratio of the actual and nominal areas of the cutter wear surface have values that are at least 20% lower.

The obtained quantitative results reflect exclusively the ratio of contact surfaces as a result of the interaction of the tool material PCBN Kyborite with the machined hardened steel ShKh–15, but the described methodology for estimating the actual area of the worn area can be applied to other superhard polycrystals with a similar wear pattern. At the same time, for a more reasonable conclusion about the contact area, in addition to the surface profilogram of the plastic part of the contact, it is necessary to consider several profilograms of the surface of the elastic part, due to the fact that the height of micronorhomogeneities along this area decreases to its level on the unworn surface.

Given the use of a round insert, depending on the complexity of the workpiece profile, the actual wear area is determined not only by the total length of the main and auxiliary cutting edges, determined by the maximum values of the main and auxiliary angles in the cutter plan, but also by the size of the wear chamfer on the clearance face of the cutter and the degree of development of the microrelief of the contact area on the worn surface of the cutter.

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ФАКТИЧНА ПЛОЩА КОНТАКТНОЇ ДІЛЯНКИ НА ЗНОШЕНІЙ ЗАДНІЙ ПОВЕРХНІ РІЗЦЯ З КРУГЛОЮ РІЗАЛЬНОЮ ПЛАСТИНОЮ КИБОРИТУ

Анотація. *Для інструменту, оснащеного круглої різальної пластиною, запропонована залежність для розрахунку номінальної площі контактної ділянки по задній поверхні. Доведено, що фактична площа контактної ділянки інструменту суттєво відрізняється від номінальної за рахунок наявності системи мікронерівностей, що вносить помилку під час оцінки показників процесу обробки. На прикладі інструменту, оснащеного круглою різальною пластиною із полікристалічного кубічного нітриду бору (ПКНБ) киборіт, розглянуто підхід до визначення фактичної площі контакту задньої поверхні інструменту з оброблюваною деталлю із загартованої сталі під час чистового точіння. Показана можливість врахування впливу системи нерівностей на контактній ділянці інструменту, визначеної за параметрами її топографії, на розмір фактичної площини та визначено співвідношення фактичної та номінальної площ контактних ділянок інструменту. Встановлено, що в залежності від ступеню розвиненості мікрорельєфу співвідношення фактичної і номінальної площ контактної поверхні різця відрізняються, щонайменше, на 60%. Отримані кількісні результати відображають виключно співвідношення контактних поверхонь в результаті взаємодії інструменту, оснащеного ПКНБ киборіт, з оброблюваною деталлю із загартованої сталі ШХ-15, але описана методика визначення фактичної площі зношеної ділянки може бути застосована і для інструментів з іншими композитами з аналогічною картиною зношування. В той же час, для більш обґрунтованого висновку про площу контактних ділянок інструменту, крім профілограми поверхні пластичної частини контакту, необхідно розглядати декілька профілограм поверхні пружної частини ділянки контакту, у зв'язку з тим, що висота мікронерівностей на цій ділянці зменшується до її рівня на незношеній поверхні. Наведено, що фактична площа контактної ділянки пов’язана також із загальною сумарною довжиною головних і допоміжних різальних кромок, визначених максимальними значеннями головного та допоміжного кутів у плані інструменту, а також величиною фаски його зносу по задній поверхні.*

Ключові слова: *різальний інструмент; задня поверхня; киборит ПКНБ; контактна ділянка; нерівності; фактична площа контакту.*