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# SUBSTANTIATION OF PARAMETERS FOR THREE-CUTTER BORING HEAD WITH ALLOWANCE AND FEED DISTRIBUTION AND ASYMMETRIC CUTTER POSITION

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***Summary.*** *Popular constructions as well as recommendations and dependencies concerning boring tools parameters substantiation are analyzed. Comprehensive approach and new methods of technological and design parameters determination for three-cutter boring heads operating with simultaneous allowance and feed distribution are proposed. Two design versions of three-cutter heads providing simultaneous allowance and feed distribution during the cutting process are presented. Dependencies for the determination of feeds for revolution, for single finishing tool and cutting depth on roughing and finishing tools depending on their geometrical parameters for both versions as well as formulae for determination of angular positions of roughing and the second finishing tools relatively to the first one are derived. Optimization of the major and minor cutting edge angles according to the criteria of maximum machining efficiency and given surface roughness is carried out.*

***Key words:*** *technological and design parameters, boring head, roughing and finishing tools, feed, cutting depth, surface roughness height of micro-irregularities.*

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**Statement of the problem.** Boring is one of the most important treatment operations in modern mechanical engineering, which requires besides high efficiency, affecting the products cost, high accuracy on which depends the reliability of operating of some mechanisms, units and machines in whole. The highest efficiency is obtained when the boring heads are used, which provide simultaneous allowance and feed distribution during cutting [1, 2], and accuracy is provided when boring tools operating with the feed distribution are used [1, 2].

That is why the development of scientific grounded approach to the design of boring tool, which would provide good enough accuracy, being highly efficient and with needed roughness of the treated surface, is the pressing problem.

**Analysis of the latest investigations and publications.** The problem of substantiation of parameters for boring tools was analyzed in many scientific publications. In many papers [3–8] the methods for design and construction of boring tools for special treatment conditions were proposed. For example, in paper [3] the method of calculation and the design of improved boring head as well as interpreting of its design parameters were proposed for providing the needed treatment accuracy. In paper [4] the method of structurization of the boring heads design for treatment of the ring grooves was presented, and in paper [5] the method of improving the quality of holes in casing products was analyzed, which deals with the balancing of cutting forces and torques, which makes possible to raise the accuracy of treated holes. In some papers [4, 6–13] recommendations for the both the technological and structural parameters of the boring tools are presented. For example, while using the boring head presented in the paper [6] the recommended cutting depth is $t=0,3…0,7$ *mm*, and when the head described in paper [7] is used, the recommended values of cutting depth at the first cutter are $t_1=0,1…0,5$ *mm*, at the second $t_2=0,03…0,07$ *mm*. The head described in [8] provides the cutting depth, which is equal to that the relation of the general allowance to the cutters number.

In [6] the recommended $\varphi = 60^0$ for the rough treatment and for the finishing are $\varphi = 45^0$, $\varphi' = 10^0$, $r = 0.4$ mm. In paper [9] the boring head with different values of the primary clearance angles in the plane is presented, here $\varphi_1 - \varphi_2 = arctg(t/s)$. In paper [8] the cutters are recommended to be replaced relatively the other towards the axis in 2 mm, and in [8] it is shown, that the axis replacement of cutters is found according to the formula $\chi = \psi \cdot s/360$, where $\psi$ – is the angle displacement of one cutter relatively the other in the plane, which is perpendicular to the head axis. In paper [11–13] original designs of the boring heads are analyzed, but substantiation of their design or technological parameters are not available.

In papers [14–16] the recommendations for determination of technological or structural parameters of four-cutter boring heads without taking into account the radius at the cutter top are presented, in paper [17] the radii of the cutter tops being taken into account on the basis of roughness models are presented in [18]. In paper [19] the approach to the cutters positions in the three-cutter boring head, operating with simultaneous allowance and feed distribution, is analyzed but not in details, and it needs further substantiation.

The presented paper will partially eliminate the gaps in this area having proposed the complex approach and new method for determination technological and design parameters of the three-cutter boring heads operating with simultaneous allowance and feed distribution, application of which will make possible to design the tools of this type providing high efficiency and quality of the treated surface.

**The Objective:** to carry out substantiation of technological and design parameters of three-cutter boring heads providing simultaneous allowance and feed distribution while cutting.

**Statement of the task:** 1. To develop the method for substantiation of technological design parameters of three-cutter boring heads providing simultaneous allowance and feed distribution while cutting. 2. To propose dependencies for finding the main technological and design parameters. 3. To optimize the finishing cutters, the maximum efficiency being provided.

**Results of investigation.** Investigations of the technological-design parameters are carried out for the boring head, which is treating simultaneously with the allowance and feed distribution, providing the needed roughness of the treated surface basing on the mathematic models presented in [18]. The essence of method for finding technological and design parameters for the three-cutter boring heads (TBH) with one roughing and two finishing cutters is that of determination of the angle positions of finishing cutters and their tops, the top of the second finishing cutter (SFC), is matching with the maximum micro-roughness, created by the first finishing cutter (FFC). The position of the roughing cutter is specified by the condition of providing the balance of all acting radial components of cutting forces. The value of the primary $\varphi$ and secondary $\varphi'$ angles at the plane on the finishing cutters are assumed to be equal $\varphi_1 = \varphi_2 = \varphi$ and $\varphi'_1 = \varphi'_2 = \varphi'$. Non-uniform position of the finishing cutters in its turn will result in non-equal height of micro-roughnesses. To eliminate this disadvantage two methods for specifying two versions of the TBH design performance were proposed: the first – correction of $\varphi$ on SFC – $\varphi_{2K}$, the second – correction of $\varphi'$ on SFC – $\varphi_{2K}$. To solve these tasks let us use the general scheme for roughness formation by the proposed TBH presented in Figure 1.

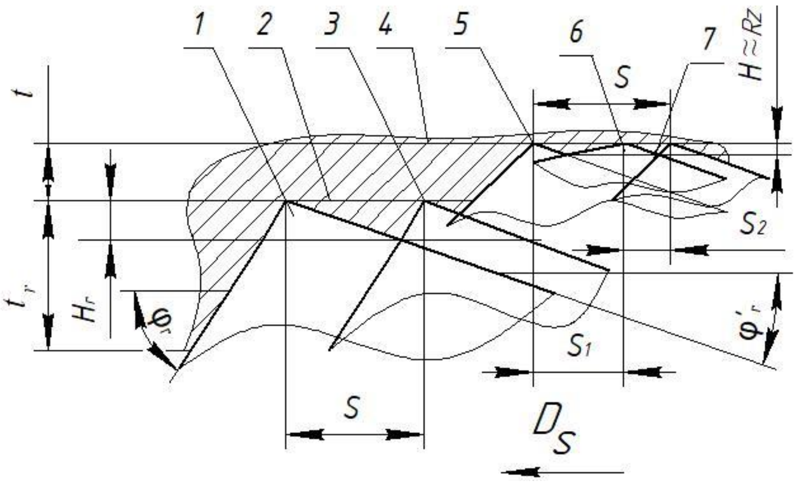


**Figure 1.** General scheme for forming the roughness of the TCH treated surface providing simultaneous allowance and feed distribution: 3 and 1 – are the roughing cutter position in the moment of the blank revolution beginning and in the moment of its completion correspondingly; 2 and 4 – is the trajectory of the top motion of roughing and finishing cutters correspondingly; 5 and 7 – is the FRC position at the moment of the revolution beginning and at the moment of completion; 6 – is the SRC position after the revolution completion

Let us analyze the scheme of position of the finishing cutters and forming the rough surface according to the first version (1) of the TBH design performance (Figure 2).

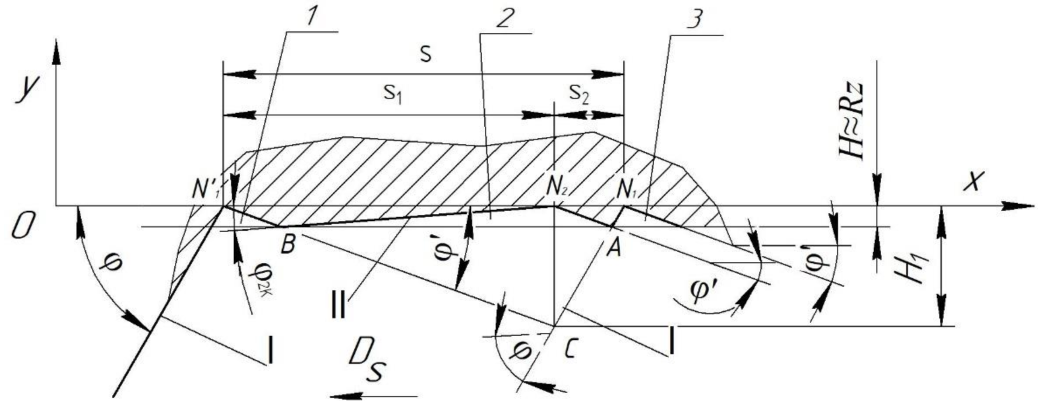


**Figure 2.** Scheme of the finishing cutters position according to the first version and roughness forming of the treated surface: 3 and 1 – is the position of the first finishing cutter in the moment of the revolution beginning and in the moment of its completion correspondingly; 2 – is the position of the second cutter replaced relatively the 1-st in the angle $\theta_1$

To determine such technological parameters as the feed value on the finishing cutters let us introduce the coordinate system in *Ox* (Figure 2). The axis *Ox* is directed to the right (in the reverse direction of the feed) and the tops of all finishing cutters are located on it, and *Oy* is directed upwards. Let us choose arbitrary point on the axis *Ox* – $N_1$ and locate the FRC -3 in it at the moment of revolution. Then let us plot the beams to the axis *Ox* at the angles $\varphi$ and $\varphi'$. They will show the position of the primary and secondary cutting edges (PCE and SCE) of the FRC in the moment of the revolution beginning. Having provided the value $H \approx Rz$ and having used [18], the feed value on SRC will be:

$$s_2 = H \cdot (ctg\varphi + ctg\varphi'). \qquad (1)$$

The obtained feed on the axis *Ox* will be presented by the segment $N_1N_2$. The point $N_2$ corresponds to the SRC top-2 at the moment of the revolution completion. The location of the secondary cutting edge SRC will be obtained having plotted the straight line from the point $N_2$ to the axis *Ox* at the angle φ'.

Having plotted the straight line $N_2$ perpendicular to axis *Ox* to the crossing with the SRC PCG at the moment of the revolution beginning, we will obtain the point C and section $N_2C$. Having plotted the line from the point C to the crossing with the axis *Ox* at the angle $\varphi'$, we will obtain the PFC position at the moment of the revolution completion -1, and, correspondingly the feed value on the revolution (s, mm/rev), which is equal to the segment length $N_1'N_1 = N_1N_2 + N_2N_1'$ (Figure 2). Having taken into account, that $N_1N_2 = s_2$ and $N_2N_1' = N_2C \cdot ctg\varphi'$ (from $\Delta N'_1N_2C$), and $N_2$C corresponds to the value $H_1$, that is, $N_2C = H_1 = s_2 \cdot tg\varphi$ (from $\Delta N'_1N_2C$), and having substituted the feed value $s_2$ from (1), and having done the transformation, we will obtain:

$$s = H \cdot (ctg\varphi + ctg\varphi`)^2 \cdot tg\varphi . \quad (2)$$

Having plotted the straight line through the points $N_2$ and *B* (the point of crossing of the straight line parallel to the axis *Ox* through the point *A* from the PRC PCG at the moment of the revolution completion), we will obtain the SRC PCB position, corrected value of the angle $\varphi_{2K}$, as well as the segment $N_1'N_2$, the length of which corresponds to the feed value on the PRC correspondingly $s_1$ (Figure 2).

The PRC feed – $s_1$ can be found from $\Delta N'_1N_2C$:

$$s_1 = N'_1N_2 = H_1 / tg\varphi' . \quad (3)$$

From $\Delta N'_1N_2C$ the value $H_1$ is found from the dependence:

$$H_1 = s_2 \cdot tg\varphi . \quad (4)$$

Having substituted in (4) instead of $s_2$ its value from (1), we will obtain:

$$H_1 = H \cdot (ctg\varphi + ctg\varphi') \cdot tg\varphi . \quad (5)$$

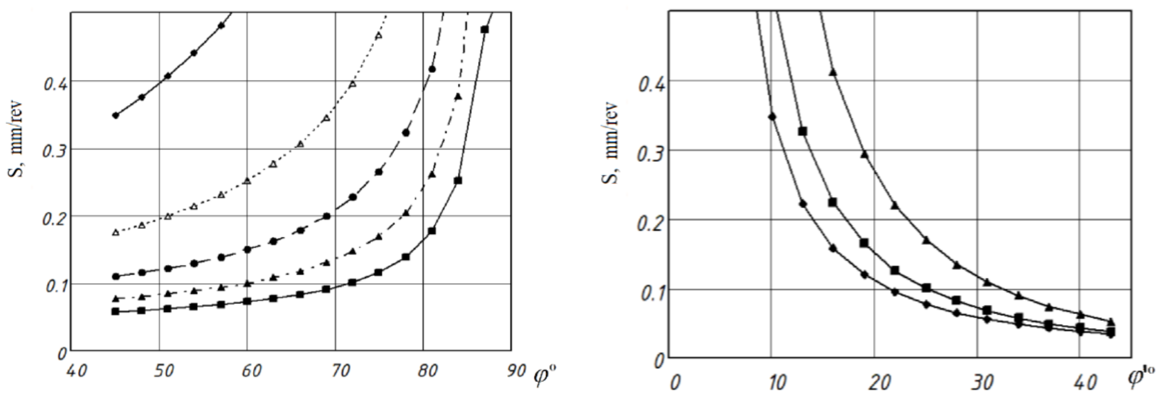
The feed value on PRC was obtained having substituted the $H_1$ value from (5) in (3). We will obtain:

$$s_1 = \frac{H + H \cdot tg\varphi \cdot ctg\varphi'}{tg\varphi'} . \quad (6)$$

Having analyzed $\Delta N'_1N_2B$, we will find the corrected value $\varphi_{2K}$ on SRC: $\varphi_{2K} = arcctg\left((s_1 - H \cdot ctg\varphi')/H\right)$. Having simplified this equation and having substituted the value $s_2$ from (1), we will obtain:

$$\varphi_{2K} = arcctg\left(tg\varphi / tg^2\varphi'\right). \quad (7)$$

The analysis of $\varphi$ and $\varphi'$ effect on the feed *s* (2) is performed using the dependence schemes of *s* from the primary and secondary angles in the plane presented in Figure 3.

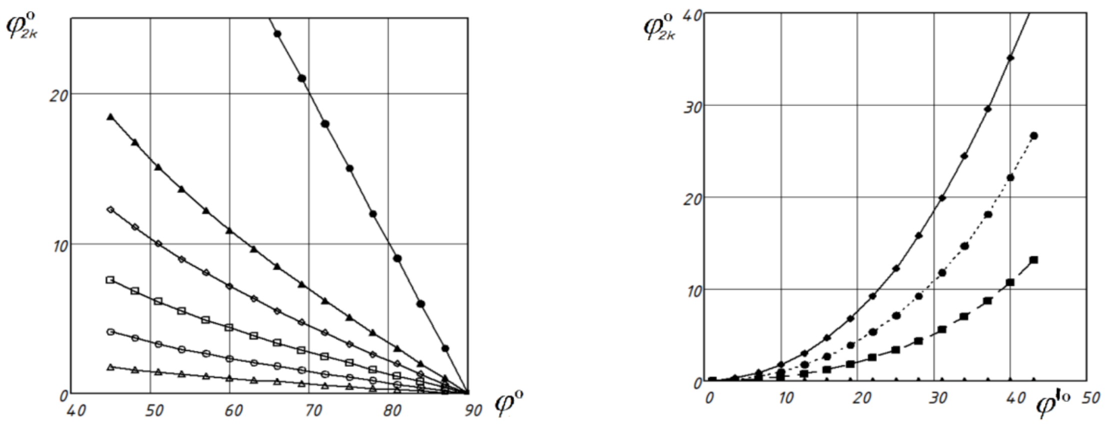



a) b)

**Figure 3**. Scheme of the TBH *s* dependence on $\varphi$ and $\varphi'$ at $H = const$ : a) $s = f(\varphi)$ at different values $\varphi'$ ◆—◆—◆ – $\varphi' = 10^0$ △—△—△ – $\varphi' = 15^0$ ●—●—● – $\varphi' = 20^0$ ▲—▲—▲ – $\varphi' = 25^0$ ■—■—■ – $\varphi = 30^0$ b) $s = \psi(\varphi')$ at different values $\varphi$ : ◆—◆—◆ – $\varphi = 45^0$ ; ■—■—■ – $\varphi = 60^0$ ; ▲—▲—▲ – $\varphi = 75^0$

The analysis of schemes presented in Figure 3 a shows, that when $\varphi$ increases, the general value of the TBH feed increases under the proposed position of cutters and the provided $H \approx Rz = const$ . When the secondary angle $\varphi'$ increases in the plane (Figure 3 b), the value *s* decreases. Here we can conclude, that in order to increase the feed under the given cutters position and the condition $H \approx Rz = const$ , it is worth increasingly $\varphi$ and decreasing $\varphi'$ on the cutters.

Graphical presentation of the dependences of the primary and secondary angles effect in the plane I and II of the finishing cutters on the value of the corrected primary angle in the SFC plane at $H \approx Rz = const$ is presented in Figure 4.




a) b)

**Figure 4.** Schemes of dependences of the primary corrected angle in the SRC plane on values $\varphi$ and $\varphi'$ : a) $\varphi_{2K} = \upsilon(\varphi')$ at different $\varphi'$ : △—△—△ – $\varphi' = 10^0$ ; ○—○—○ – $\varphi' = 15^0$ ; □—□—□ – $\varphi' = 20^0$ ; ◇—◇—◇ – $\varphi' = 25^0$ ; ▲—▲—▲ – $\varphi' = 30^0$ ; ●—●—● – $\varphi' = 45^0$ ; b) $\varphi_{K2} = \varsigma(\varphi')$ at different $\varphi$ : ◆—◆—◆ – $\varphi = 45^0$ ; ●—●—● – $\varphi = 60^0$ ; ■—■—■ – $\varphi = 75^0$

The analysis of these graphic dependences shows, that when $\varphi$ increases, the value of the corrected primary angle in the plane on the SRC $\varphi_{2K}$ decreases, and when $\varphi'$ increases

$\varphi_{2K}$ increases too. In this case the nature of the $\varphi$ effect and $\varphi'$ on $\varphi_{2K}$ is opposite of that on the feed, that is, engineering contradiction takes place, the solution of which while taking into account some restrictions was made by optimization of the geometric parameters I and II of the finishing cutters. Some engineering restrictions are opposed because of the following:

I. The value of the primary angle in the plane having some restrictions and can not be less than some minimum $\varphi_{2\min}$, the inequality must be provided $\varphi_{2\min} \le \varphi_2$. Then the first restriction will be expressed by the following dependences: $\varphi_{2K\min} \le arcctg\left(tg\varphi / \left(tg\varphi'\right)^2\right)$, or $\varphi \le arctg\left(\left(tg\varphi'\right)^2 \cdot ctg\varphi_{2K\min}\right)$.

II. Taking into account the fact, that two finishing cutters at such position must provide the treatment roughness being not lower than that of the three-cutter head with the symmetric position of cutters, the feed $s_2$ at the second finishing cutter is $s_2/s \le 1/3$. Having substituted (1) and (2) in this inequality and having simplified it, we will obtain the second restriction: $\varphi \le arctg\left(2 \cdot tg\varphi'\right)$.

III. As the value $\varphi_{2K}$ is always less than $\varphi$, then $\varphi_2 \le \varphi$. Having substituted its value from (7) instead of $\varphi_{2K}$, we will have: $arcctg\left(tg\varphi / \left(tg\varphi'\right)^2\right) \le \varphi$. Having solved this inequality relatively $\varphi$ we will obtain: $\varphi \ge arcctg\left(\sqrt{1/\left(tg\varphi'\right)^2}\right)$.

Let us add the following restrictions:

IV. $\varphi \ge \varphi_{\min}$.

V. $\varphi \le \varphi_{\max}$.

VI. $\varphi' \ge \varphi'_{\min}$.

VII. $\varphi' \le \varphi'_{\max}$.

Being provided with the target function, which deals with the fact that the treatment efficiency providing the given roughness must be maximum, that is, $s \to \max$, or taking into account that (2) $(ctg\varphi + ctg\varphi')^2 \cdot tg\varphi \to \max$, we will obtain the equations system being the mathematic model of geometric parameters (angles in the plane) of the head cutters.

$$\left.\begin{array}{l} \varphi \le arctg\left(\left(tg\varphi'\right)^2 \cdot ctg\varphi_{2K\min}\right) \\ \varphi \le arctg(2 \cdot tg\varphi') \\ \varphi \ge arctg\left(\sqrt{1/\left(ctg\varphi'\right)^2}\right) \\ \varphi \ge \varphi_{\min} \\ \varphi \le \varphi_{\max} \\ \varphi' \le \varphi'_{\max} \\ \varphi' \ge \varphi'_{\min} \end{array}\right\} H \approx Rz = const; \quad (ctg\varphi + ctg\varphi')^2 \cdot tg\varphi \to \max$$

The solution of the obtained system will be illustrated graphically (Figure 5). In the coordinate system $\varphi O \varphi'$ the restrictions are shown, the schemes of which are signed by corresponding Roman numerals.

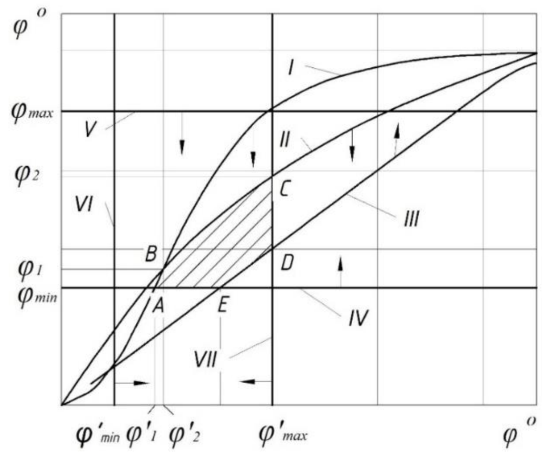



**Figure 5.** Graphic illustration of the maximum values $\varphi$ and $\varphi'$ restrictions for the first version of the TCH design

The analysis of the presented schemes showed (Figure 5), that the set of maximum values $\varphi = \varphi_{onm}$ and $\varphi' = \varphi'_{onm}$, which can be used while designing the presented above boring heads, is in the middle of the quazi-convex polyhedron ABCDE (hatched area).

Having taken into account the target function – $(ctg\varphi + ctg\varphi')^2 \cdot tg\varphi \to \max$, the roughness values being provided, and Figure 4a, b, and having assumed that, for example, $\varphi'_1 \le \varphi'_{onm} \le \varphi'_{\max}$, the $\varphi_{onm}$ value must be chosen on the line ABC, which restricts the maximum values of the angles in the plane. The equation of the line ABC will be determined by the system:

$$\varphi_{onm} = \begin{cases} \varphi \le arctg\left(\left(tg\varphi'\right)^2 \cdot ctg\varphi_{2K\min}\right) & \text{при} \quad \varphi'_1 \le \varphi'_{onm} \le \varphi'_2 \\ arctg(2 \cdot tg\varphi') & \text{при} \quad \varphi'_2 \le \varphi'_{onm} \le \varphi'_{\max} \end{cases} \tag{8}$$

Let us analyze the scheme of the finishing cutters position and forming the rough surface according to the second version of the TBH design. (Figure 6)

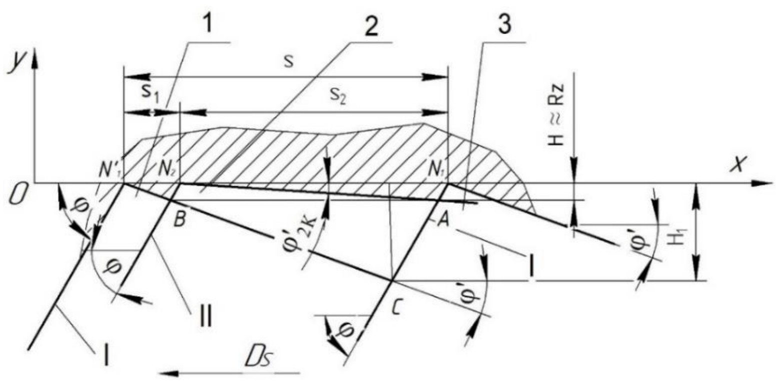



**Figure 6.** Scheme of the finishing cutters position and roughness forming of the surface according to the second version: 1 – is position of the 1-st finishing cutter at the moment of the revolution beginning; 2 – is the position of the 2-nd finishing cutter being replaced relatively the 1-st in the angle $\theta_1$; 3 – is the position of the 1-st cutter at the moment of the revolution completion

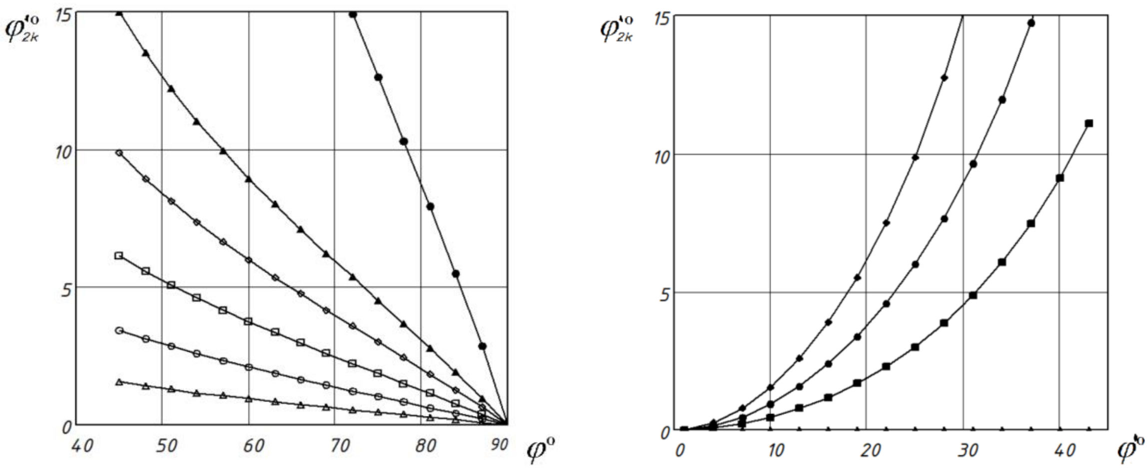
To determine technological parameters, such as feed values on the finishing cutters, let us introduce the coordinates system *yOx*. The principle of the PFC position at the moment of the revolution beginning and after its completion is 1 and 3 correspondingly, similar to that of the 1-st TBH version. The SRC is placed so, that the micro-roughnesses height formed as the result of the SRC PCE and PRC SCE contacts is equal to $H \approx Rz = const$ . While correcting the value of the secondary angle in the plane on SRC – $\varphi'_{2K}$, we make so, that the theoretical micro-roughnesses hight as the result of the PRC PCE and SRC SCE contact is also equal to the given $H \approx Rz = const$ . In this case the feed value *s* is found according to the formula (2) and the feeds at the first and second finishing cutters – from the dependencies (1) and (6) correspondingly.

The corrected value $\varphi'_{2K}$ is found according to the formula:

$$\varphi'_{2K} = arcctg\left(ctg\varphi' + tg\varphi \cdot \left(ctg\varphi'\right)^2 - ctg\varphi\right) \qquad (9)$$

The nature of the $\varphi$ and $\varphi'$ effect on *s* will be similar to that in the 1-st version of the TBH design.

The graphic dependences of the primary $\varphi$ and secondary $\varphi'$ angles effect in the plane on the value of the corrected secondary angle on SRC $\varphi'_{2K}$ are presented in Figure 7, a, b. respectively.




a) b)

**Figure 7.** Dependences schemes of the corrected secondary angle in the SRC plane on the values of the primary and secondary angles in the plane a) $\varphi'_{2K} = \rho(\varphi)$ at different $\varphi'$ : △——△——△ – $\varphi' = 10^0$ ; ○——○——○ – $\varphi' = 15^0$ ; □——□——□ – $\varphi' = 20^0$ ; ◇——◇——◇ – $\varphi' = 25^0$ ; ▲——▲——▲ – $\varphi' = 30^0$ ; ●——●——● – $\varphi' = 45^0$ ; b) $\varphi'_{2K} = \sigma(\varphi')$ at different $\varphi$ : ◆——◆——◆ – $\varphi = 45^0$ ; ●——●——● – $\varphi = 60^0$ ; ■——■——■ – $\varphi = 75^0$

It is seen from the schemes (Figure 7, a, b), that when the value $\varphi$ increases, the corrected value of the secondary SRC angle decreases, and when $\varphi'$ increases, the value of corrected secondary SRC angle increases. According to the effect of $\varphi$ and $\varphi'$ on $\varphi'_{2K}$, let us optimize the geometric parameters of the finishing cutters. Some engineering restrictions are because of the following:

I. $\varphi'_{2K}$ must be greater than that of the minimal admissible value, that is, $\varphi'_{2K} > \varphi'_{\min}$.

II. $\varphi'_{2K}$ can not be greater than $\varphi'$, that is, $\varphi' \geq \varphi'_{2K}$, then $\varphi' \geq arcctg\left(ctg\varphi' + tg\varphi \cdot (ctg\varphi')^2 - ctg\varphi\right)$. Having expresses $\varphi$ as $\varphi'$, we will obtain: $\varphi \geq arctg\left(\frac{1+\sqrt{1+4(ctg\varphi')^2}}{2(ctg\varphi')^2}\right)$.

III. Having taken into account, that two finishing cutters being in such position must provide the roughness being not less than the three-cutter head with the symmetric location, the feed $s_2$ on SFC is $s_2/s \leq 1/3$. Having substituted $s_2$ and $s$ by their values from (1) and (2) correspondingly, and having solved them relatively $\varphi$, we will obtain: $\varphi \leq arctg(2 \cdot tg\varphi')$.

The other restrictions and the target function are similar to the restrictions and the target function of the TBH design according to the 1-st version.

We will obtain the equations system being the mathematic model of the geometric parameters (angles in the plane) of the head cutters.

$$\left.\begin{array}{l} \varphi'_{2K} > \varphi'_{\min} \\ \varphi \geq arctg\left(\frac{1+\sqrt{1+4(ctg\varphi')^2}}{2(ctg\varphi')^2}\right) \\ \varphi \leq arctg(2 \cdot tg\varphi') \\ \varphi \geq \varphi_{\min} \\ \varphi \leq \varphi_{\max} \\ \varphi' \geq \varphi'_{\min} \\ \varphi' \leq \varphi'_{\max} \end{array}\right\} H \approx Rz = const; \quad (ctg\varphi + ctg\varphi')^2 \cdot tg\varphi \to \max$$

The solution of the obtained system is illustrated graphically (Figure 8). In the coordinates system $\varphi O \varphi'$ the restrictions, the schemes of which are signed by the corresponding Roman numbers, are presented.

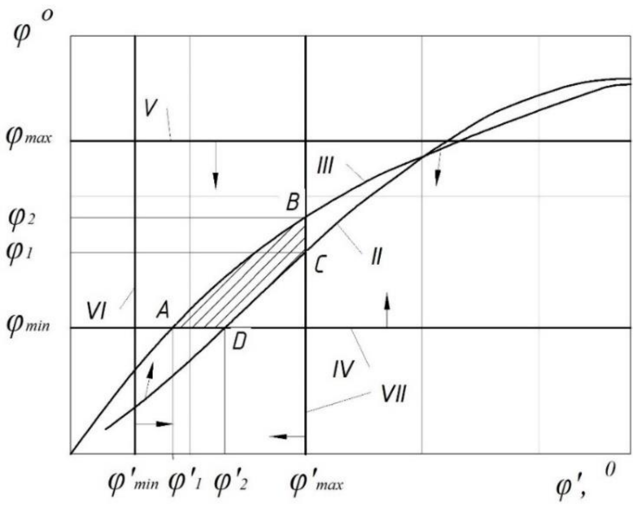



**Figure 8.** Graphic illustration of the restrictions for the maximum values $\varphi$ and $\varphi'$ for the 2-nd version of the TCH design

Having analyzed the results of schemes (Figure 8), we can conclude, that the values set $\varphi$ and $\varphi'$, which can be used for the TCH design of this type, are inside the quazi-convex polyhedron ABCD (hatched area).

Taking into account the target function – $(ctg\varphi + ctg\varphi')^2 \cdot tg\varphi \to \max$ ,the given roughness value being provided, and having assumed, for example, that $\varphi'_1 \le \varphi'_{onm} \le \varphi'_{\max}$ $\varphi_{onm}$, it is necessary to choose on the line AB, restricting the angle values, which satisfy the conditions of all restrictions.

The equation of the line AB will look like:

$$\varphi \le arctg\left(2 \cdot tg\varphi'\right) \text{ при } \varphi'_1 \le \varphi'_{onm} \le \varphi'_{\max} \qquad (10)$$

The value $\varphi_1'$, will be found as the abscissa of the point A coordinates, which are formed as the result of the restriction lines III and IV crossing. We will obtain $\varphi'_1 = arctg\left(tg\varphi_{\min}/2\right)$

Knowing the feed values of the 1-st and 2-nd versions, such design parameters of the head as the angles of cutters location can be found.

Such TBH design parameters as the central angles, which regulate the circular position (location) of the cutters, are found using Figure 9 a.

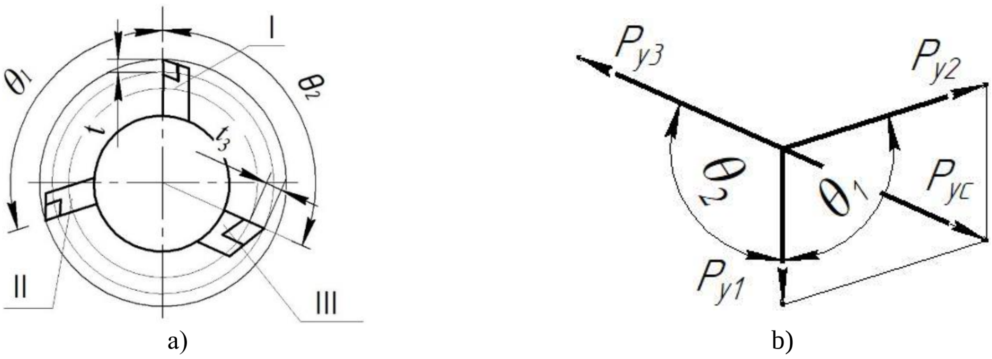



**Figure 9.** Scheme of the roughing and finishing cutters position and calculation scheme for finding the angle positions of the cutters: I, II and III – are the PRC, SRC and the roughing cutter correspondingly

The values of the angle $\theta_1$, which provide the SRC angle displacement relatively PRC, will be found according to the formula:

$$\theta_1 = 2\pi \cdot s_2 / s \, , \qquad (11)$$

Having used the Figure 9 b, as well as taking into account [15, 19], the angle $\theta_2$ is found from the dependence:

$$\theta_2 = arctg\left[(1-\cos\theta_1)/\sin\theta_1\right] + \pi/2 \, . \qquad (12)$$

The radial sweep (the cutting depth) on the roughing cutter is found being based on the balancing condition of the radial cutting forces on the roughing and finishing cutters. The total radial component of the cutting force on the finishing cutters, which must be balanced with the radial component of the cutting force on the head roughing cutter, the cutting depth being $t_r$ and the feed *s*, will be found according to the theorem of cosines (Figure 9 b)

$$P_{yc} = \sqrt{P_{y1}^2 + P_{y1}^2 - 2P_{y1}P_{y2}\cos\theta_1} \, , \qquad (13)$$

where $P_{y1}$ $P_{y2}$ – are the radial components of cutting forces at the 1-st and 2-nd finishing cutters correspondingly, *H*.

Having taken into account the dependence [20] $P_y = 10C_5 t^{x_2} s^{y_2} HB^{n_2} K_\varphi$ for finding the radial components of the cutting forces, the formulas for finding the radial components of the cutting forces at the 1-st and 2-nd finishing, as well as on the roughing cutter, will look like:

$$P_{y1} = 10C_5 t^{x_2} s_1^{y_2} HB^{n_2} K_{\varphi 1}, \tag{14}$$

$$P_{y2} = 10C_5 t^{x_2} s_2^{y_2} HB^{n_2} K_{\varphi 2}, \tag{15}$$

$$P_{y3} = 10C_5 t_r^{x_2} s^{y_2} HB^{n_2} K_{\varphi 3}. \tag{16}$$

where $C_5$ – is the proportional factor taking into account the physical-mechanical properties of the treated material while finding the cutting forces; $HB$ – is the Brinell hardness; $K_\varphi$ – is the presented correction coefficient on the principle angle in the plane; $x_2$, $y_2$, $n_2$ – are the power values specifying the effect of $t$, $s$ and $HB$ correspondingly on $P_y$;

Having substituted (14), (15), (16) in (13) and having solved it relatively $t$, as well as taking into account, that $t_r + t = p$, where $p$ – is the treatment allowance, we will obtain the dependence for finding cutters basing on the balancing condition of the radial components of the cutting forces.

$$t = \frac{p}{2}\left(\frac{\sqrt{s_1^{2y_2} K_{\varphi 1}^2 + s_2^{2y_2} K_{\varphi 2}^2 - 2 s_1^{y_2} s_2^{y_2} K_{\varphi 1} K_{\varphi 2} \cdot \cos\theta_1}}{s^{y_2} \cdot K_{\varphi 3}}\right)^{1/x_2}. \tag{17}$$

**Conclusions.** The method for finding the three-cutter boring head parameters providing the simultaneous allowance and feed distribution while cutting was developed. Two possible versions for manufacturing TBH were analyzed basing on the geometric and design parameters. The dependences for the design of such TBH were obtained, which make possible to determine their technological (feed on the revolution and on a single finishing cutter as well as the cutting depth on the roughing and finishing cutters) and design (the cutters interrelated position) parameters. The optimization of the geometric parameters of the finishing cutters was performed providing the maximum treatment efficiency. The graphical dependences, according to which the feed of the head revolution can be found depending on the parameters of the treated surface roughness and the angle values in the plane, were presented. The substantiation of the TBH makes possible to design their construction for the special treatment conditions under the given initial parameters.

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# ОБГРУНТУВАННЯ ПАРАМЕТРІВ ТРИРІЗЦЕВИХ РОЗТОЧУВАЛЬНИХ ГОЛОВОК З ПОДІЛОМ ПРИПУСКУ І ПОДАЧІ ТА АСИМЕТРИЧНИМ РОЗМІЩЕННЯМ РІЗЦІВ

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***Резюме.*** *Проведено аналіз конструкцій, а також рекомендацій для призначення конструкторських і технологічних параметрів розточувальних інструментів. Розроблено методику проектування трирізцевих розточувальних головок, що працюють за методом одночасного поділу припуску та подачі й містять один чорновий та два чистові різці, причому другий чистовий різець встановлений у точці максимальної мікронерівності профілю, створеної проходом першого чистового. За способом розміщення другого чистового різця запропоновано два варіанти конструкторського виконання головки, в яких здійснюється коригування або головного, або допоміжного кута в плані на другому чистовому різці. Для обох варіантів конструкторського виконання на основі схем обробки наведено залежності для визначення подач на різець і на оберт головки, коригованих головного та допоміжного кутів у плані на другому чистовому різці залежно від початкових геометричних параметрів чистових різців, а також заданої висоти мікронерівностей профілю. Внаслідок аналізу залежностей впливу зміни головного та допоміжного кутів у плані на подачу виявлені технічні протиріччя, розв'язок яких, врахувавши певні обмеження, здійснювали шляхом оптимізації геометричних параметрів чистових різців. Оптимізацію кутів у плані для обох варіантів конструкторського виконання головок здійснено на основі розроблених технологічних обмежень, що враховують особливості елементів конструкції розточувальних головок, а також забезпечення заданої висоти мікронерівностей профілю обробленої поверхні. Запропоновано залежність для функції мети, що полягає у забезпеченні максимальної продуктивності оброблення. Наведено залежності для визначення центральних кутів, які регламентують кругове положення різців головки (другого чистового та чорнового відносно першого чистового). Отримано формулу для визначення глибини різання та чистових різців залежно від припуску на оброблення та з умови зрівноваження всіх радіальних складових сил різання. Запропонована методика дасть можливість розробляти конструкції трирізцевих розточувальних головок підвищеної продуктивності оброблення.*

***Ключові слова:*** *розточувальна головка, різець, висота мікронерівностей профілю, подача на різець, подача на оберт, глибина різання, радіальна складова сили різання, кут у плані, оптимізація кутів у плані.*

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