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Theoretical study of dependence of screwing of drilling-pipe connector on thread-process cutting tool profile

Screwing is one of the main parameters of the quality of a drill string tapered thread tool joint. It indicates the number of screwing operations that can be applied to this tool joint during drilling. Tool joints that have undergone rejection (determined by a specific criterion – the distance between the end faces of the pin and the box before they are start the screwing) are not permitted to screw. The value of this criterion is proportional to the working height of the threadprofile, which decreases during operation. In this article, it is offered to increase the initial value of the criterion of rejection due to the increase of the work height of the thread profile. This can be done without violating the standard but with the use of a modernized profile of the tool for thread turning. This profile makes it possible to increase the crest diameter of the thread and at the same time ensure sufficient tool life. Due to its usage, the resource of the tool joint can increase by 9–14.5%, while the cutter's tool life and cost remain unchanged.

Key words: *drill pipe, tool joint, box, pin, screwing, turning tool, tool life*

1. INTRODUCTION

The structure of a drill string includes elements that combine drilling pipes with between each other as well as with other objects. These connectors are called as tool joints for drill string elements.

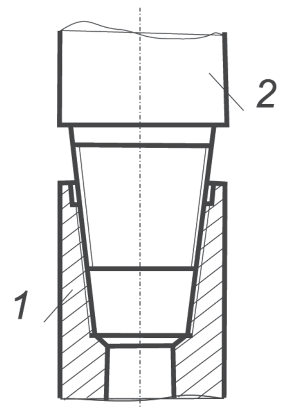

Fig. 1. Scheme of drill string connector: 1 – box, 2 – pin

They consist of two parts (Fig. 1): a box (1), which is the female end of the connection, and a pin (2), which is the male end of the connection. One of the quality indicators of a tool joint is its screwing, which is the value that indicates the number of unobstructed screwing and unscrewing processes in it. Such operations always accompany the lowering and lifting process of a drill string. Typically, this value is up to 8–10 screwing and unscrewing operations for new drill pipes; after this, the tool joints are discarded.

2. GAP IN THREADED CONNECTION OF DRILL STRING TOOL JOINT

A tool joint's tapered thread profile according to standards [1] and API 7 (American Petroleum Institute) is schematically presented in Figure 2.

Here are the tool joint tapered thread parameters: h_1 is the height of the thread profile [mm], h – the working height of the thread profile [mm], P – the pitch of the thread [mm], a – the width of the thread crest [mm], and $\alpha/2$ – half of the thread profile angle.

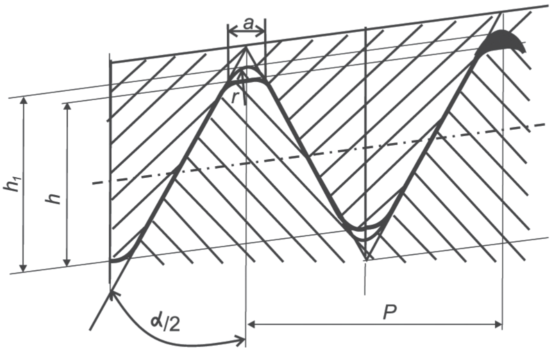

Fig. 2. Scheme of tool joint tapered thread according to API 7 standard

According to this standard, there is always a structural gap between the pin and the box; the width of this is indicated by a. In the right part of the diagram, the specified gap is tinted black for clarity. This gap according to the standard has a technological purpose. The values of h, h_1, and a are optional and are intended for the design of a cutting tool for thread manufacturing. According to the author of [2], the existence of this gap is one of the most important reasons for the loss of tightness in a cut, especially after 3–4 operations of screwing – unscrewing. In the article [3], it is said that the speed of the duct of drilling mud decreases from 30–50 m/min to 1 m/min when the value of a decreases from the standard value of 1.6 mm to the of 1-mm value offered by the author. In paper [4], it is offered to reduce the height of the gap from 0.45 mm to 0.15 mm. However, turning to the full depth of the workpiece will be sharply reduced and the technological stability will decrease accordingly to the cutter.

To ensure long tool life, it is suggested to use a cutter with a non-zero value of the back-rake angle, although no known companies show any thread cutting tool with positive or negative values of this angle at the tool nosein their catalogs [5].

3. ANALYSIS OF VARIANTS OF INITIAL CONTACT OF THREADS OF SCREW AT MOMENT OF INSTALLATION OF PIN INTO BOX

The process of inserting the pin into the box precedes the process of their screwing. In publication [6], four variants of the initial contact of the threads of the drill string screw at the pin-installation moment into the box are considered. Figure 3 shows these four options. Option a illustrates Position I. In this position (as in Positions II and III [Options b and c]), the contact between the threads occurs at the crests of the thread screw. In Variant d, Position IV illustrates the contact between the pin and the box by the thread flanks.

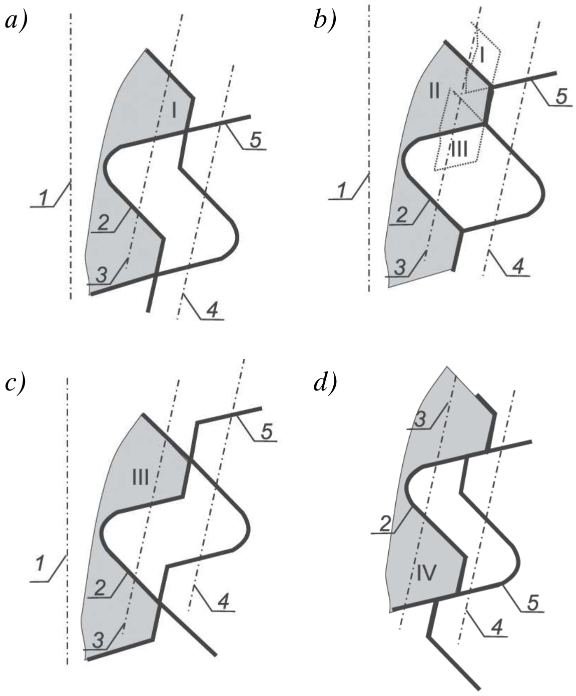

Fig. 3. Schemes of initial contact of threads of tapered screw at moment of pin installation into box: 1 – axis of screw thread, 2 – contour of pin thread, 3 – pitch diameter of pin thread, 4 – pitch diameter of box thread, 5 – contour of box thread

At the time of the installation of the box under the influence of the weight of all string grid-screwed elements, pressure is created, which depends on the weight of the drill string and the area of contact between the pin and the box. So, the greatest pressure corresponds to the smallest area, which is obviously in Positions I and III (Variants a and c in Fig. 3). As lightly larger area of contact can be seen in Position II (Option b). Option d provides the greatest contact area and, accordingly, the least amount of pressure created by the weight of the drill string. The wearing intensity of the thread-screw surface depends on the pressure; i.e., Option d illustrates the position of IV, which provides the least intense action when the pin insertion into the box is repeatedly applied for their further repeated screwing.

4. CRITERION OF TOOL JOINT TAPERED THREAD

By the criterion of rejection of the tool joint tapered thread most often in the practice of drilling the value *H* (Fig. 4) is applied. This value defined between the pin end face and box end face at the moment of the pin setting into the box before their screwing start [6]. This method is sufficiently operational, however it does not allow us to control the thread-screw separately for the pin and the box. For the purpose of analyzing the state of the pin thread separately from the box thread, templates are used. The application of the *H* criterion and the special template for the pin are shown in Figure 5. The pin is displayed with the number "1" on it and the template is displayed with the number "2". The value of *H* decreases due to the thread flank wearing (value of *e*) and thread height wearing (value of *b*) and, in theory, the value of *H* can approach zero. This can be achieved by the following formula:

$$H = \frac{2h}{K} \quad [\text{mm}] \tag{1}$$

where:

- h – working height of thread profile [mm],
- K – thread taper.

The number of revolutions (m) that must be carried out for the complete screwing-in of the elements of the tapered thread tool joint also depends on the work height of profile h and thread taper K [6]. This can be achieved by the following formula:

$$m = \frac{2h}{KP} \quad [\text{mm}] \tag{2}$$

where P – thread pitch.

Formulas 1 and 2 correspond to the definition of rejection criterion *H* for the schemes of the initial contact of the pin with Boxes I, II, and III (Fig. 3).

Figure 6 schematically illustrates the box thread contour of the *ABCDEFH* as well as the contour of the crest of the pin thread in its initial variants of Contacts I, II, and III. Parameter x indicates the position of the pin thread crest in the process of screwing from the initial contact and until line *LF* on the pin crest coincides with line *DE* on the root of the box. The value of x can be determined by the following formula:

$$x = \frac{KP_1}{2} m = P\frac{K}{2}\left(1 - \frac{K}{2}\tan\alpha\right)m \quad [\text{mm}]$$

where:

- K – thread taper,
- P_1 – thread pitch between bigger flanks (corresponds to segment *GK* on axis),
- M – number of revolutions,
- a – thread profile angle.

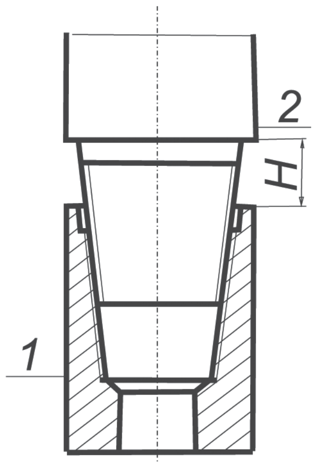

Fig. 4. Scheme for determining H criterion of rejection of tapered thread

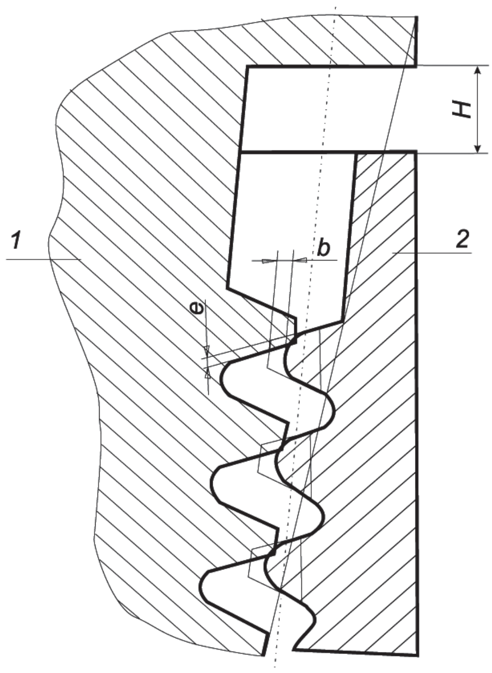

Fig. 5. Scheme for determining rejection criterion H for tapered thread elements and template

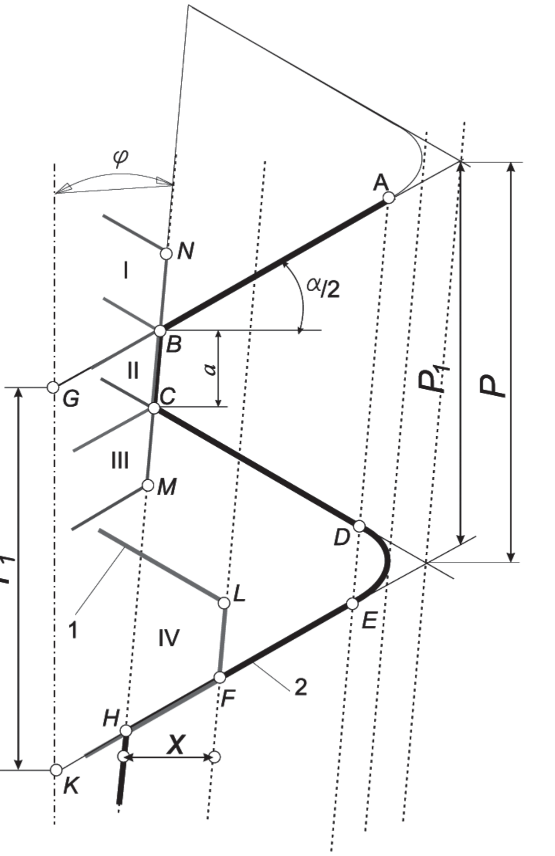

Fig. 6. Scheme of variants of contact of threads at time of installation of pin into box and in process of screwing

In this case, the distance between the end faces of the box and the pin in the process of their interconnection will be changed according to the following formula:

$$H_m = \frac{2(h-x)}{K} \quad [\text{mm}]$$

Figure 7 illustrates the position of the pin that comes in contact with the box by the flank surface. The dark gray color corresponds to the position of the pin at the initial moment of contact (as in Position IV in Fig. 3). In order to improve the perception of the initial position in the scheme, the straight-line segment *CL* that is parallel to the thread-screw axis is applied. This position is characterized by parameter x_0 – the maximum value of which can be determined by the following formula:

$$x_0 = \frac{K}{2}(P-2a)\left(1-\frac{K}{2}\tan\alpha\right) \quad [\text{mm}]$$

where *a* – crest flat width [mm], which in Figure 6 corresponds to length of straight-line segment *BC*.

In accordance to the specified position of the pin, one can find the value of rejection criterion $H_{\min}$, which corresponds to the position of IV by the following formula:

$$H_{\min} = \frac{2(h-x_0)}{K} = \frac{2h}{K} - (P-2a)\left(1-\frac{K}{2}\tan\alpha\right) \quad [\text{mm}] \tag{3}$$

The light gray color illustrates the schematic position of the pin at the time of completing its screw-in into the box. The number of revolutions ($m_{\min}$) required to complete the screw-down of the tool joint's tapered thread after the moment of pin insertion into the box or the template corresponding to Position IV are determined by the following formula:

$$m_{\min} = \frac{2(h-x_0)}{KP} = \frac{2h}{KP} - \left(1-\frac{2a}{P}\right)\left(1-\frac{K}{2}\tan\alpha\right) \quad [\text{mm}] \tag{4}$$

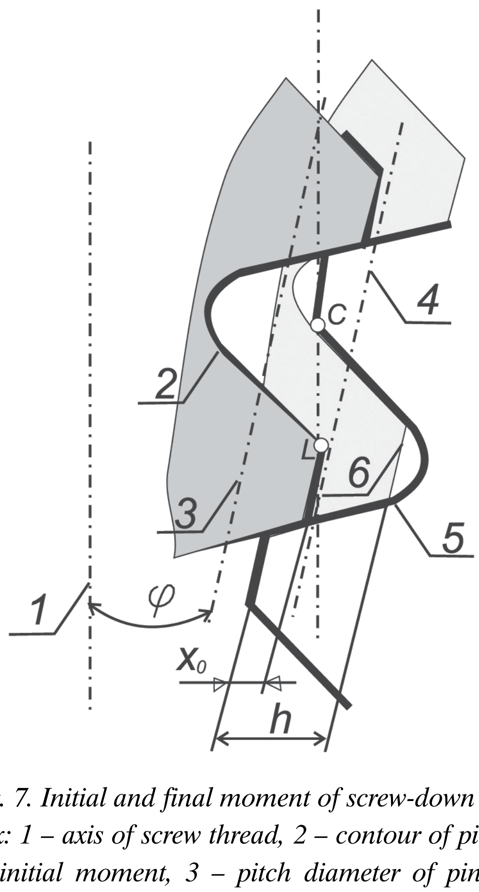

Fig. 7. Initial and final moment of screw-down pin with box: 1 – axis of screw thread, 2 – contour of pin thread at initial moment, 3 – pitch diameter of pin thread, 4 – pitch diameter of box thread, 5 – contour of boxthread, 6 – contour of pin thread at final moment

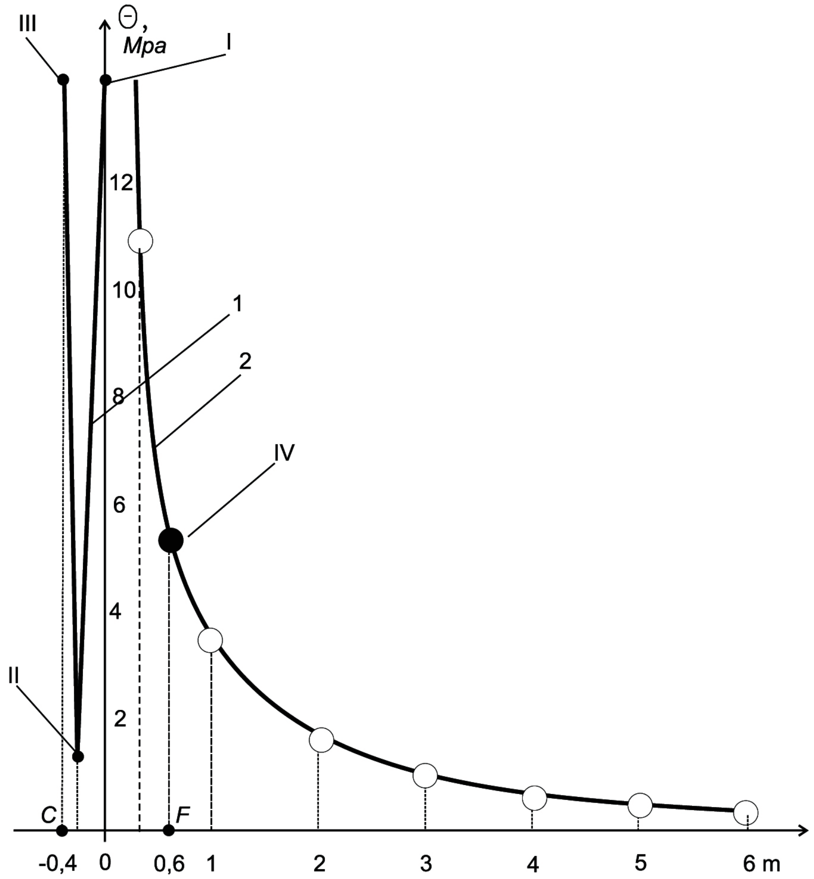

Fig. 8. Pressure changing in tool joint tapered thread 5" FH under action of weight of drill string in process of screwing in different schemes of initial contact of threads: 1 – at initial contact of pin and box only on thread crest (Provisions I, II, III), 2 – at initial contact of pin and box only on thread flanks

Figure 8 shows the graph of the pressure change on the thread surface under the action of the drill string weight, which depends on the position of the pin at its initial moment of contact with the box before screwdriving and in the process from the beginning to the end of the screwing-in [6]. Points C and F limit the stage of setting the pin into the box from the next stage – the actual screw-in. The graph indicates that the initial pin position before the screwing is subjected to pressure values that are greater than (Positions I, II, and III) or similar to the pressure that occurs during the screwing process itself.

The maximum value of the criterion of rejection can actually be determined by the same Formula (1):

$$H_{\max} = \frac{2h}{K} \quad [\text{mm}] \tag{5}$$

The maximum value of the number of revolutions can actually be determined by the same Formula (2):

$$m_{\max} = \frac{2h}{KP} \quad [\text{mm}] \tag{6}$$

5. PROFILE OF CUTTING EDGE OF THREADING TURNING CUTTER WITH NON-ZERO VALUE OF BACK-RAKE STATIC ANGLE AT ITS NOSE

Article [7] states that the special application for determining the profile half angle of the thread cutter for the manufacture of all standard sizes of the tool joint's tapered threads is createdon the basis of algorithm [8]. The obtained results allow us to design the technological process of the tool joint's tapered thread turning in which the cutter with the calculated cutting-edge profile is executed with a significant static back-rake angle at the its nose and, at the same time, the thread profile formed by it has an initial deviation of within 10–15% of the permissible deviation of the thread profile half angle. Article [9] proves that the value of the deviation of the thread profile half-angle does not exceed 0.16° if the value of the static back-rake angle at the nose lies within a range of –5° to 5°, while the profile of the cutting edge of the tool remains the same as the profile of the thread. According to the authors of [10], the tool life with a value of the static back-rake angle of –5° can increase considerably; thus, it can provide increased productivity of the process of turning the closed surfaces of the thread roots.

6. PURPOSE OF WORK

The purpose of this work is to upgrade the profile's cutting edge in order to improve the screw-in process of the tool joint's tapered thread and simultaneously increase its tightness while providing the necessary value of the tool life of the cutter.

7. METHOD TO ACHIEVE PURPOSE

Graphically and analytically the dependence of the value of the criteria for the rejection of H_{min} and H_{max}, and the number of revolutions (m_{min} and m_{max}) from the cutter's profile is obtained by changing its optional sizes and applying a non-zero value of the static back-rake angle at the nose.

8. GRAPHICAL ANALYSIS OF NATURE OF WEAR OF TOOL JOINT'S TAPERED THREAD

Figure 9 shows a diagram illustrating the nature of the operation of the tool joint tapered thread, which occurs as a result of multiple repetitions of the following processes:

1 – installation of pin into box,
2 – their screw-up,
3 – their further screwing with interference fit.

Process 1 corresponds to the schemes of the initial contact of the pin with the box. In Figure 8, this is a graphical representation, where the argument is the number of revolutions of the screw (m) between points C and F. As a result of this process, thread wear occurs primarily on the crest in accordance with the schemes of the initial Contacts I, II, and III (see Figs. 3a–c). Figure 9 illustrates the reduction of the working height of the profile on the thread by a value of Δh. Graphically, this value seems larger than the thread flank deviation from their standard shapes, which are shown in black.

In Process 1, the installation can also be on the thread flank, which means that the initial contact occurs according to Scheme IV. This corresponds to the part of the graph where the values of the arguments correspond to the points that are located left of Point F but to the right of 0 (see Fig. 8).

Since the pin contact with the box is exactly the larger thread flank, the diagram graphically emphasizes a greater deviation from the face value of the larger thread flank (Area 3) than the smaller one (Section 5).

Process 2 involves the screw-in, during which there is moving contact with the large thread flanks of the pin and the box as well as their operation due to friction under pressure from the weight of the drill string.

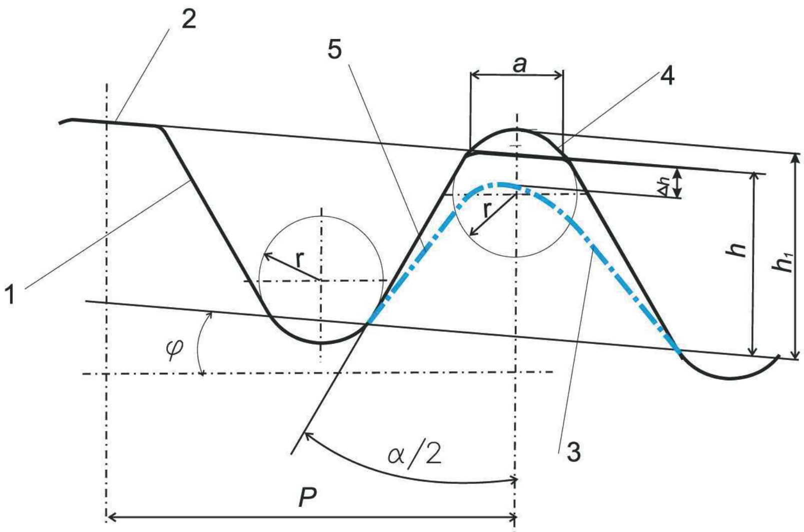

Fig. 9. Diagram graphically illustrating shape of worn thread due to contact pressures and friction of its surfaces as result of installation of pin into box and their screwing: 1 – larger standard flank profile of thread, 2 – crest according to standard, 3 – profile of larger flank profile after prolonged exploitation, 4 – standard root of thread, 5 – profile of lower thread flank after prolonged exploitation

This process corresponds to that part of the graph in Figure 8, where the arguments are represented by the points that are located right of Point *F*. Figure 9 shows that the thread profile long flank deviates more significantly from the initial profile (corresponding to Section 5) than the short one (corresponding to Section 3) in this process.

Process 3 – screwing-in with an interference fit occurs when the pin and box are in contact at the short flanks, accompanied by significant deformations in this thread section. It is not the screwing under pressure created by the weight of the drill string but under the tension created by the deformation; therefore, it is not considered within the limits of this article.

Figure 9 illustrates the worn thread crest, but the thread root remains relatively natural (in accordance with the drilling practice and special bench surveys [6]).

9. RESEARCH OF CUTTING-EDGE PROFILE OF TOOL FOR MANUFACTURE OF TOOL JOINT TAPERED THREAD

Figure 10 shows a 20-fold increase in the photo of the cutting edge of the new turning tool for the manufacture of the tool joint tapered thread of the Form IV profile, which is used most in drilling practice.

Figure 11 shows a 20-fold increase in the photo of the cutting edge of the turning tool for the manufacture of the tool joint tapered thread of the Form IV profile after prolonged operation.

Figure 12 shows a diagram that combines the contours of the profile of the new cutter from Figure 10 (solid black line) and of the worn out one from Figure 11 (dotted red line). If you compare these lines, it becomes clear that the cutting edge of the turning tool is the most intensively worn out in the part that forms the thread root.

Fig. 10. Photo of cutting part of carbide insert of tool for turning of tool joint tapered thread Form IV (executed at 20-fold increase)

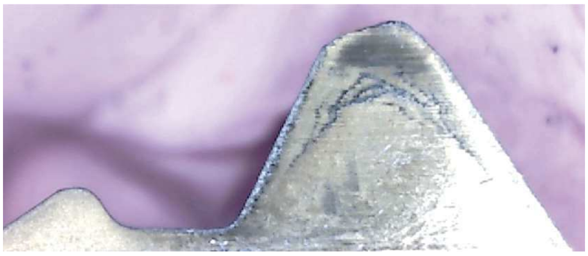

Fig. 11. Photo of cutting part of carbide insert of tool for turning of tool joint tapered thread Form IV after prolonged exploitation (executed at 20-fold increase)

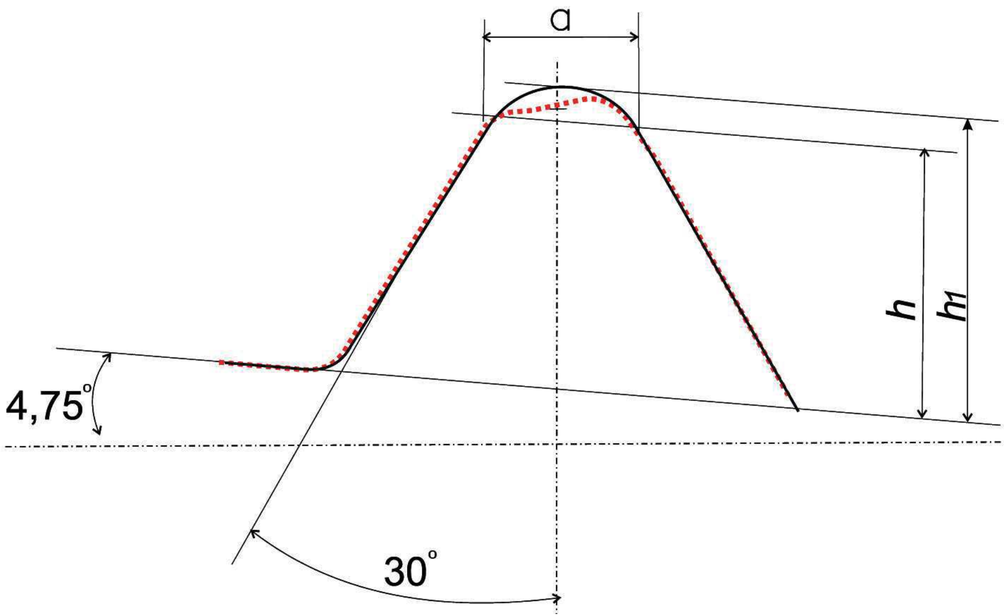

Fig. 12. Scheme of combined contours of new tool cutting edge profile (black line) and cutting edge with worn profile (dotted red line) of turning tools for tool joint tapered thread manufacture

From Figure 12, it can be concluded that the further operation of the worn cutter does the red line below the top line, which will result in the fact that the pin cannot be screwed into the box due to the interference of their thread surfaces.

9.1. Ensuring increase in tightness due to reduction of technological GAP

To reduce the initial value of the height of the gap (which is determined by the previously adopted $h_1 - h$ formula), it is more expedient to increase the value of h rather than reduce the value of h_1. This is due to the fact that the part of the cutting edge that wears out most intensively forms the thread root; therefore, it is inappropriate to reduce it.

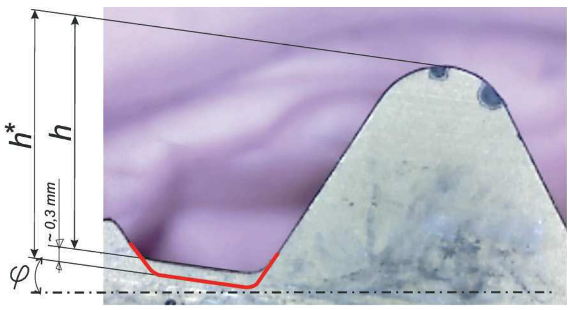

Fig. 13. Similar photo to Figure 10, but only with corrected section of cutting edge that forms crest of tool joint's tapered thread

However, it is quite reasonable to increase the value of h (i.e., it is reasonable to increase the appropriate section of the cutting edge of the tool. Figure 13 shows a cutting-edge photo that is similar to Figure 10, but an additionally modernized profile (red line) is imposed, which confirms that an increase in size h to value h^* is due to the transfer of the cutting edge that forms the crest of the thread at 0.3 mm in accordance with the recommendations [4].

9.2. Ensuring drill string tooljoint threading tool life

Figure 14 illustrates the scheme of obtaining the reduced technological gap of $h_1 - h^*$, which can be executed using a turning tool with an adjusted cutting edge (as shown in Fig. 13).

The dotted red line in Figure 14 indicates the view of the worn cutting edge of the cutter at the time of the completion of its working ability.

It is obvious that the value of h^* cannot be provided with such an edge, since it has gone beyond the boundary of the figure placed between the dimensions of h_1 and h^*. In this case, it is true to ensure the tool's life by adjusting its geometric parameters: in the first place, the back-rake static angle at the nose of the cutter – for example, within a range of –5° as recommended [9, 10].

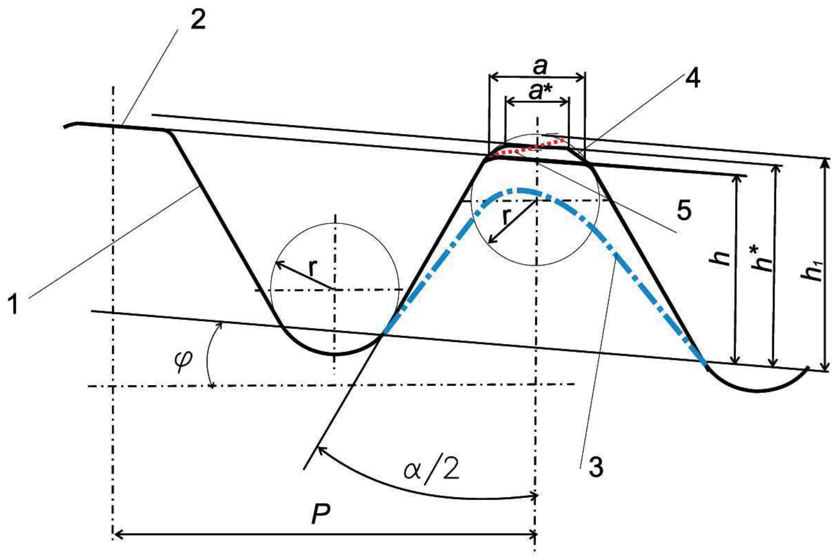

Fig. 14. Diagram illustrates reduction of initial gap as consequence of reducing theoretical limit of cutting edge of tool by increasing value of h to size h. Digits are indicated as follows: 1 – long thread flank of profile according to standard, 2 – thread crest according to standard, 3 – thread profile after prolonged operation, 4 – crest of thread that is executed by using corrected cutting edge, 5 – cutting edge of threading tool after prolonged operation*

10. INCREASING VALUE OF CRITERION OF REJECTION *H* AND VALUE OF NUMBER OF REVOLUTIONS *m*

Figures 13 and 14 show that the value of h can be increased to the size of h^*; accordingly, the value of a decreases to the size of a^*. Using Formulas (1)–(4), the value of the criterion of rejection H and the value of number of revolutions m should be calculated for the purpose of obtaining the results, which confirm the idea that the modernized cutter increases the specified parameters according to Figure 13 and recommendations [9, 10].

10.1. Example of calculation of criterion *H* and value of *m* for tool joint tapered thread with form of Profile IV

Input parameters: value of pitch $P = 6.35$ mm; value of work height $h = 2.633$ mm; value of taper K 1:6.

According to works [3, 4], the decrease in value a from a value of 1.65 mm to a value of 1 mm can be achieved by increasing the value of h to $\Delta = 0.328$ mm. At the same time, the speed of the duct of the drilling mud through the gap will drop 30–50 times according to [3], which means that the abrasive wears lows down sharply. We put these values in Formula 1 and carry out two calculations at $h = 2.633$ mm and at h^*:

$$h^* = 2.633 + 0.328 = 2.961 \text{ mm}.$$

Thus, at a value of $h = 2.633$ mm, criterion $H = 30.98$ mm is obtained, and at a value of $h^* = 2.961$ mm, a value of $H = 34.84$ mm is obtained. Thus, Formula 1 actually indicates the functional dependence on the screwing of the drill string tool joint from the profile of the cutting edge. In the numerical dimension on the example of Profile IV, we have the following relative increase in criterion $H_{\%}$:

$$H_{\%} = \frac{H^* - H}{H} = \frac{34.68 - 30.98}{30.98} 100 = 11.94\%$$

where H^* is the criterion of rejection at $h^* =$ $= 2.961$ mm.

Thus, an increase of working height h by 0.328 mm leads to an increase in the criterion of the rejection by almost 12%.

We put the values obtained above into Formula (2) and carry out two calculations at the values of $h = 2.633$ mm and $h^* = 2.633 + 0.328 = 2.961$ mm. Thus, at the values of $h = 2.633$ mm, $m = 4.88$, and $h^* = 2.961$ mm, the value of $m^* = 5.49$. Thus, Formula (2) also indicates the functional dependence on the screwdriving of the drill string tool joint from the profile of the cutting edge. In the numerical dimension on the example of Profile IV, we have the following relative increase in criterion $m_{\%}$:

$$m_{\%} = \frac{m^* - m}{m} = \frac{5.49 - 4.88}{4.88} 100 = 12.5\%$$

where m^* is the value of the number of revolutions at $h^* = 2.961$ mm.

Thus, an increase of 0.328 mm in the working height of profile h leads to an increase of 12.5% in the value of the number of revolutions of the tapered tool joint.

10.2. Comparison of calculated criteria of rejection *H* and number of revolutions to full screw *m* of upgraded tapered tool joints and standard ones with IV form of profile

On the basis of these examples (and after applying Formulas (3) and (5), Table 1 is offered. This includes the calculation of the criteria of rejection for both standard parameters H_{max} and H_{min} of Form IV as well as that which is executed by the help of the tool with the modernized profile for the same form.

On the basis of this example, and after application of the Formulas (4) and (6), Table 2 is offered. It includes the calculation of the numbers of revolutions for both standard parameters m_{max} and m_{min} of Form IV as well as that which is executed by the help of the tool with the modernized profile for the same form.

Table 1

Results of calculating criteria of rejection for standard and upgraded execution of tool joint tapered thread (IV form profile)

Name of parameter	Standard value			Upgraded values			Relative increase	
	Parameter value	H_{min} [mm]	H_{max} [mm]	Parameter value	H^*_{min} [mm]	H^*_{max} [mm]	$H_{min\%}$ [%]	$H_{max\%}$ [%]
P	6.35			6.35				
K	1 : 6			1 : 6				
a	1.65	28.08	30.98	1	30.74	34.84	9.4	11.94
h	2.63			2.96				
a	30			30				

Table 2

Results of calculating number of revolutions for standard and upgraded execution of tool joint tapered thread (IV form profile)

Name of parameter	Standard value			Upgraded values			Relative increase	
	Parameter value	m_{min} [rev]	m_{max} [rev]	Parameter value	m_{min} [rev]	m_{max} [rev]	$m_{min\%}$ [%]	$m_{max\%}$ [%]
P	6.35			6.35				
K	1 : 6			1 : 6				
a	1.65	4.42	4.88	1	4.84	5.49	14.5	12.5
h	2.63			2.96				
a	30			30				

11. CONCLUSIONS

On the basis of the practice of the rejection criteria application and the theoretical research of the cutting-edge profile of the thread tool, the following conclusions have been made:

1. An increase in the work height of thread profile *h* and *a* decrease in the crest flat width of a thread profile simultaneously lead to an increase in the tightness of a tool joint tapered thread and the criterion of its rejection *H* by 9–12%.
2. Increasing the work height of thread profile *h* and reducing crest flat width *a* of the thread profile leads to an increase of 12.5–14.5% in the number of revolutions from the moment of installing the pin into the box until the moment of the full screwing-in.
3. Increasing the work height of thread profile *h* and reducing the crest flat width of thread profile *a* do not lead to violations of the standards, as these represent its optional values GOST 28407-90 and API 7.

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