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Study of the Influence of the Cutting Structure Design of a Cone Bit on the Load of tts Elements

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ABSTRACT

The article discusses the results of studies of the distribution of axial load along the crowns of bit cones with the carbide insert and milled cutting structure. The tests were carried out on a specially designed and manufactured bench. The study consists in the rotation of the bit under load along the metal face of a special measuring device. The results obtained made it possible to establish that the load on the crowns of the cones, individual teeth, and generally on the cones is distributed very unevenly. The unevenness persists with different designs of the cutting structure. However, the degree of uneven distribution of the axial load over the bit cones depends to a large extent on the design of the cutting structure and, mainly, on the nature of the arrangement of the crowns on the cones along the radius of the bit, which is associated with the design of the cone support assembly.

Key words : bit, cone cutting structure, drilling, load, roller cone.

1. INTRODUCTION

When drilling deep oil and gas wells, as well as blast holes in mining pits, cone bits are widely used. The bit cones loaded with axial force from the weight of the drill string or hydraulic force during its rotation roll over the rock and destroy it. The durability of the cutting structure and supports of cone drill bits depends on many factors, such as axial load on the bit, rotational speed, characteristics of the drilled rocks, properties and composition of the flushing fluid, the design of the bit, the quality of manufacture of its parts, and properties of materials. Roller cone bits work in severe conditions, being exposed to high static and dynamic loads, abrasive and corrosive environments, shocks and vibrations. The durability of the cutting structure of the cones directly destroying the rock largely determines the main indicators of the drilling efficiency. In this regard, a significant number of studies [1,2,3,4] are devoted to issues of depreciation and destruction of the cutting structure. In the process of drilling, the cone bits are rolling over the bottom, and the teeth successively come into contact with the rock, being subjected to a complex force. During the interaction of the tooth with the bottom, the forces acting on the tooth from the side of the destructible rock constantly change, changing the stress state of the tooth material. As a result of longitudinal oscillations of the bit, caused by a number of reasons, the interaction of the teeth with the rock is of shocking nature. In addition, the teeth of the cone cutting structure not only roll over, but also slip along the bottom, which leads to their wear. Analysis of the state of the carbide cutting structure of bits of various designs worked out under field conditions showed that in the process of work there are a wide variety of types of wear and tear [5,6,7,8]. The reliability and durability of the drilling tool depend on many design, technological and operational factors, including the magnitude of the forces acting on their elements during operation. A large number of experimental and analytical studies, for example, [9, 10, 11, 12], are devoted to determining the magnitude of the forces acting on the teeth of cones.

2. METHODS

In order to establish quantitative patterns of the influence of cone cutting structure design on the load on carbide cutting elements of the bits at a special bench [11,12] several batch of bits was tested III215,9K-PB, III215,9TKZ-CB-3 and III215,9T-CV. The tests were carried out using a device that allows measuring the forces perceived by each tooth of each cone of a real bit when it interacts with a non-destructible bottom. For separate registration of efforts acting on the crowns of each cone, the bottom is divided into two sectors, working (measured) sector I and non-working sector II (Figure 1). When the bit rotates along the bottom, the cones are in contact with the ring-shaped inserts of the working sector I of the bottom.

To implement this method, a special bench was designed and manufactured to rotate the test bit along the bottom of the measuring device. The axial load on the bit can smoothly vary from 0 to 200 kN, which allows testing bits of various sizes with axial loads close to or equal to the working loads, depending on the size of the bit under study. The drive of the bench provides a change in the angular velocity of the bit from 0.16 to 11.34 s^{-1}, thereby reproducing the conditions of rotary drilling.

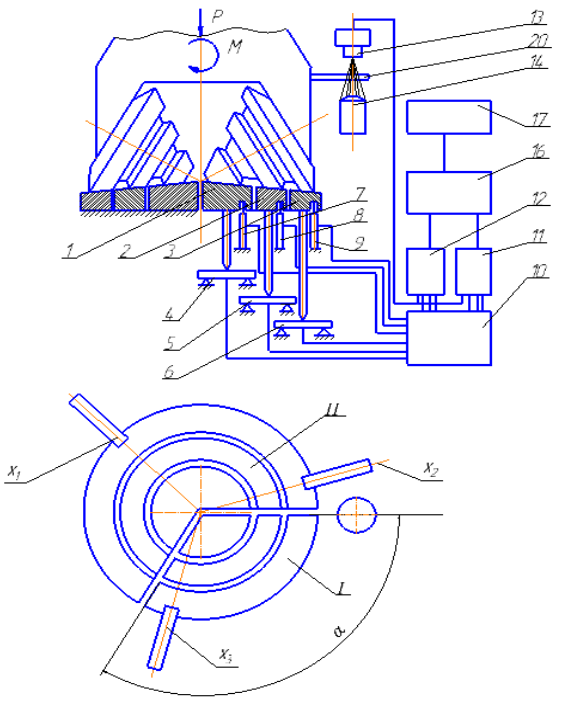

Figure 1: Schematic diagram of the measurement and registration of forces acting on the teeth of the cones: 1,2,3-ring-shaped bottom of the working sector; 4,5,6,7,-tensometric beams; 7,8,9-inserts; 10-amp; 11,12-oscilloscopes; 16,17- conversion equipment; X1.X2,X3 – axes of the cones.

3. RESULTS

The results of measuring the axial forces acting on the crowns of individual cones of the bit III215,9K-PB under different test conditions [14] showed that the average load of the cone crowns varies significantly. We consider how the axial load is distributed along the crowns of each cone. For convenience, we number all the crowns, starting from the peripheral crown of the first cone - crown 1, the middle crown of the first cone - crown 2, and so on. Table 1 provides results of measuring average axial forces in kN acting on each crown of each cone with an axial load on the bit of 80 kN and the bit angular velocity of 3.31 s-1. Here, for clarity, the average values of these forces in percent, the average values of maxima, minima, and amplitude of forces in kN are given. According to the data given in a diagram of the axial load distribution along the cone crowns of the bit III215,9K-PB is plotted, shown in Fig. 2. The results of studies of the distribution of axial load along the crowns of each cone of the bit III215,9K-PB allow us to conclude that the average loading of the crowns of various cones differs significantly.

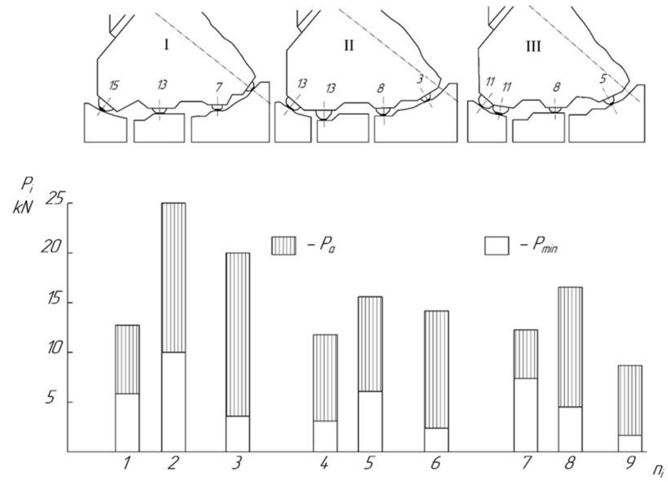

Figure 2: Diagram of the distribution of axial force Pi along the cone crowns of the bit III215,9K-PB with an axial load on the bit of 80 kN and the bit angular velocity of 3.31 s-1 (P_a – force amplitude; P_{min} – force minimum; n_i – crown number)

The highest proportion of the entire axial load acting on the bit is taken by the middle crown of the first cone. The relative load of this crown at a bit load of 80 kN and an angular bit velocity of 3.31 s^{-1} is 19.1% of the total axial load on the bit. This significantly exceeds the relative load of the neighboring peripheral and vertex crowns, which take, respectively, 10.6% and 13.4% of the total axial load on the bit. A similar picture is observed for other cones of the studied bit. Summing up the relative loads acting on the crowns of one cone, it can be established that the first cone is the most loaded, perceiving 43.1% of the total load on the bit, the second cone (30.4%) is in the second place and the third cone is least loaded (26.5%). Since the number of teeth on the individual crowns of various cones is not the same, it is apparently not enough to assess the load on the cutting structure of the individual crowns of cones only by the average axial load on the crown. The diagram (Fig. 2) shows the average values of the amplitudes of the axial forces acting on the crowns, as well as the average minimum values of the axial forces. The nature of the distribution of the maxima of forces along the crowns of individual cones corresponds approximately to the nature of the distribution of average values of forces, but the difference in the magnitude of the forces acting on the middle and adjacent crowns is even more significant. The maximum axial force exerted on the second crown of the bit III215,9K-PB is 25.03 kN, respectively. The amplitudes of changes in axial forces acting on the various crowns are also uneven. The amplitude of the force depends both on the maximum force acting on the crown and on the position of the crown on the cone. The amplitude of the force can be characterized by the dynamic coefficient of the load K_{di}, determined by the formula:

$$K_{di} = \frac{P_{i\max}}{P_{im}} \quad (1)$$

where P_{imax} - maximum force acting on the i-th crown, P_{im} – average value of force acting on the i-th crown.

Let us consider, for example, the peripheral crowns of bit cones, the maximum values of force on which are approximately the same, and the number of teeth is, respectively: $Z_1 = 15$; $Z_4 = 13$; $Z_7 = 22$. The dynamic factors of the load acting on these crowns are, respectively:

$K_{d1} = 1.375$; $K_{d4} = 1.569$; $K_{d7} = 1.253$. It follows that the dynamic load acting on the crown decreases with an increase in the number of teeth on the crown.

The technique we developed allows us to quickly and accurately determine the maximum value of the axial force acting on each tooth of each crown of all cones of the bit when the tooth passes through the vertical position. Since the cone rolling over the bottom hole makes a complex rotational movement, it is not possible to automate the process of marking the position of individual teeth relative to the measuring sector of the bottom. Therefore, to ensure a longer contact time of each tooth with the bottom, sufficient to mark its vertical position with a marker on the oscillogram during visual observation, a lower bit angular velocity of 0.157 s^{-1} was chosen, which, as can be seen from the above research results, does not lead to significant error in the measurement of forces. For this purpose, all teeth were numbered on the III2I5,9K-PB bit intended for research. On the oscillogram, the moment of transition through the vertical position of each tooth of the peripheral crown of each cone was noted. Knowing the pattern of the relative position of the teeth on different crowns along the cone generatrix and the moment of transition through the vertical position of the teeth of the peripheral crown, it is easy to determine the maximum load acting on the teeth of the middle and vertex crowns. Measurements showed that the axial load acting on individual teeth located on one crown differs significantly. So, for example, tooth No. 4 of the peripheral crown takes on an axial force of 22.1 kN, while the adjacent tooth No. 3 takes on an axial force of only 10.8 kN, i.e. two times less than tooth No. 4.

To explain the resulting picture of the load of individual teeth, the values of the radial run-out of the teeth relative to the axis of the cone bearing pin were measured. The reference level was the level of the position of the first tooth on the crown. Figure 3 shows a diagram of the radial run-out of the teeth of the peripheral crown of the first cone, combined with a diagram of the maximum load of these teeth. Comparing these two diagrams, it is easy to see that the uneven load of the teeth on the crown can be largely explained by the different values of the teeth protrusion from the cone body (run-out relative to the cone rotation axis). So, the difference in the position levels of the above teeth No. 3 and No. 4 is 0.51 mm, which explains their different load.

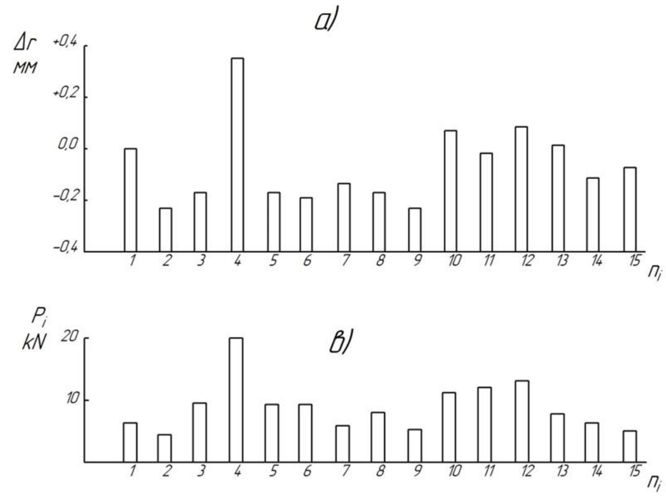

Figure 3: Diagram of radial run-outs Δr(a) and maximum load P_i(b) of the teeth of the peripheral crown of the cone I of the III215,9K-PB bit at P=80 kN, $\omega_g = 0{,}157\ s^{-1}$ (n_i – tooth number)

The greatest value of the axial force acts on the teeth of the middle crown of the first cone. For example, the maximum axial load acting on tooth No. 9 of the middle crown of the first cone is 39.5 kN, which is almost 50% of the total axial load on the bit. If we assume that the maximum permissible load of 850 kN will act on the III215,9K-PB bit, then individual teeth can take on a force of up to 120 kN, which can lead to breakage from overload.

It is known that the efficiency of the process of rock destruction by a cone bit, as well as the durability of the bit cutting structure, is influenced by the time of interaction of individual teeth with the rock. With the true rolling of an individual tooth crown along the indestructible bottom with an angular velocity ω, the contact time of each tooth with the bottom can be determined from the expression:

$$\tau = \frac{\pi}{30\omega * z} \quad (2)$$

where z - number of teeth on the crown.

In relation to the crown of the bit cone, expression (2) can be rewritten as:

$$\tau = \frac{\pi}{30\omega_g * I_\omega * z} \quad (3)$$

ω_g- bit angular velocity; i - bit to cone gear ratio.

Our experimental data allow us to determine the time of interaction with the bottom of almost every tooth of each bit cone. The oscillograms can also determine the gear ratios for all cones. So, for example, for the III215,9K-PB bit the gear ratios for individual cones were: i_1=1.572(first cone); i_2 = 1.590(second cone); i_3 = 1.525(third cone). Since the gear ratios of various cones differ insignificantly, the number of teeth on the crown will have the greatest influence on the time of interaction of the teeth of individual crowns with the bottom. Comparing the results of calculating the contact time of the teeth with the bottom, calculated by the formula (3) for $i_{av.}$=1.56 and ω_g=0.157 s^{-1} with the experimental data obtained when testing III215,9K-PB and III215,9TKZ-CV-3 bits with the same modes, it can be concluded that a significant difference in the actual contact time of individual teeth with the bottom from the calculated one is observed only for a small number of teeth, and with the number of teeth more than ten, the experimental points virtually fall on the calculated curve.

When cones are rolling along the bottom, not only the axial components of the reactions of interaction of the teeth of with the face P_i, but also the tangential components F_i, which also affect the stress state of the material of the teeth, change. In this regard, it is of interest to establish the nature of the change in the magnitude and direction of the tangential components of the forces acting on the teeth of various crowns of the bit cones, as well as the relationship between the axial and tangential components of the reactions. As measurements showed, the change in the tangential components of the force for the peripheral and especially for the vertex crowns is less stationary than the change in the axial components. For the middle crowns, this process is more stationary and here the relationship between the axial and tangential components is more clearly traced. The tangential components on individual crowns do not change direction in the process of rolling the crowns along the bottom. The tangential components acting on the teeth of the peripheral crowns of all cones have a negative sign, and on the teeth of the middle and vertex - a positive one.

Obviously, this can be explained by the different direction of the crowns slipping along the bottom caused by the imperfection of the shape of the crowns of the cones of the studied bits. As a result of a theoretical analysis of the interaction of the teeth of a single crown with a smooth bottom in the absence of slippage, it was established that the tangential component of the force acting on the tooth changes sign when the tooth moves through a vertical position [4]. But our results do not confirm this assumption. On the contrary, in most cases, at the moment of the transition of the tooth through the vertical position, the axial and tangential components of the reactions of the interaction of the tooth with the bottom have a maximum value. For peripheral and vertex crowns with the greatest sliding, the peaks of forces P_{max} and F_{max} do not always coincide, which can be explained by the non-smooth surface of the bottom. The values of the tangential components are quite small, compared with the axial components. The ratio of the maximum tangential component to the corresponding axial component in the teeth of the first cone varies from 0.03 - 0.06 for the vertex crowns to 0.08 - 0.12 for the peripheral crowns, and it is obvious that the influence of the tangential components on the durability of insert carbide bits under study will be small. However, for bits having a larger protrusion of teeth from the cone body and a greater depth of penetration of the teeth into the rock in one act of interaction, this effect can be very significant.

To study the influence of the cutting structure design on the distribution of axial load along the cones, tests of III215,9TKZ-CV-3 bits were carried out, which differ from III215,9K-PB bits by the location of the crowns on the cones and the shape and number of carbide teeth. The tests were carried out with an axial load on the bit P = 80 kN and an angular bit velocity of 3.31 s_{-1}. For bits of this type, the most loaded crown is the middle crown of the second cone.

The average value of force on this crown is 17.67 kN, which is 19% of the total axial load on the bit. For the III215,9TKZ-CV-3 bit, the loading of the middle crowns of each cone is also higher than the loading of the vertex and peripheral crowns, and the difference in the loading of the middle and adjacent crowns for bits of this type is more significant than for bits of the K-PB type. When comparing the relative loading of the cones of this type of bit, we can see that the most loaded cone in this bit, as well as in the III215,9K-PB bit, is the first cone, which takes 36.3% of the total axial load on the bit. The second cone occupies the second place in terms of loading, accounting for 34.7% of the total load and the least loaded is the third cone at 29.0%. The above results show that the uneven distribution of the axial load along the crowns is observed for both types of bits. However, the load distribution along the cone of the III215,9TKZ-CV-3 bit is much more uniform than over the cone of the III215,9K-PB bit. If we take the load acting on the least loaded third cone of the III215,9K-PB bit as 1, then the load on the first and second cones will be 1.63 and 1.15, respectively. At the same time, for the III215,9TKZ-CV-3 bit, the ratio of the axial load perceived by the first and second cones to the load perceived by the least loaded third cone will be only 1.25 and 1.20, respectively. Since the number of teeth on individual crowns of various cones is not the same, it is apparently not enough to assess the load on the cutting structure of the individual crowns of cones only by the average axial load on the crown.

Let us compare the results of testing bits of type TKZ with the previously given results of testing bits of type K-PB (Fig. 2). The nature of the distribution of the force maxima along the crowns of individual cones corresponds approximately to the nature of the distribution of average values of forces, but the difference in the magnitude of the forces acting on the middle and adjacent crowns is even more significant. The largest axial forces act on the second crown of the III215,9K-PB bit and on the fifth crown of the III215,9TKZ-CV-3 bit and are 25.03 kN and 26.96 kN, respectively.

The design of the support assembly of the cones of type K and TKZ bits is almost identical and these bits differ from each other mainly in the design of the cutting structure and the placement of crowns on the cones. In this regard, it seems advisable to try to establish the nature of the change in the magnitude of the maximum axial force acting on the crown, depending on the radius of the bit on which this crown is located. This dependence, combined with the scheme of the support assembly of the cone, is shown in Fig. 4. As can be seen from the figure, the scatter of points characterizing the loading of individual crowns is quite significant, however, a qualitative regularity is still traced. It lies in the fact that the dependence has a maximum lying close to the middle of the radius of the bit. When moving away from it both towards the axis of the bit and towards the periphery, the average value of the maximum force acting on the crown decreases. Moreover, the greatest axial force for both types of studied bits acts on the crowns the radius of location of which is approximately 70 mm. Comparison of the obtained experimental results (Fig. 4) with the previously obtained calculation results [9] allows us to establish that the experimental-theoretical values of forces on all crowns and theoretical values of forces on crowns located within radius R> 65 mm exceed the actual values of forces. This is due to the fact that in the calculations it was assumed that each cone is in contact with the bottom only with one tooth in its upright position. In fact, at each moment of time, along with the tooth under consideration, one or even several teeth interact with the bottom, taking part of the load attributable to the cone under consideration. The magnitude of the forces acting on various crowns, determined by the experimental-theoretical method, differ from the actual values of the forces determined experimentally by no more than 30 - 35%. Therefore, in our opinion, the use of the proposed experimental-theoretical method for assessing the magnitude of the forces acting on the crowns of the bits are quite acceptable for checking the optimal location of the cutting structure on the bit cones at the design stage.

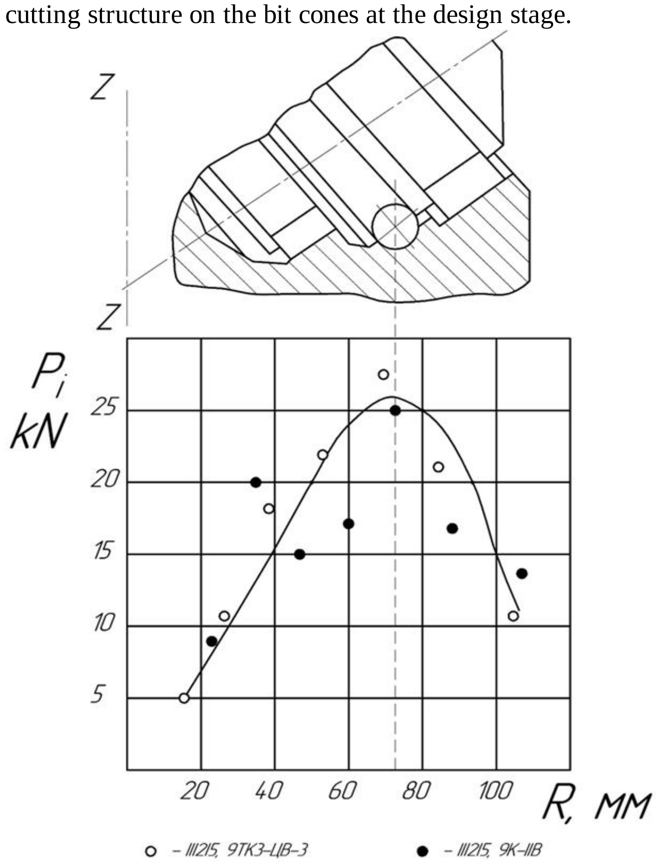

Figure 4: Dependence of the load on the crowns on their position along the radius of the bit (P_i – axial force on the crown, R – crown location radius)

To verify whether the pattern of axial load distribution along the crowns for milled tooth bits is preserved, tests of III215,9T-CV bits were carried out. In them, the second cone is the most loaded, perceiving about 40% of the entire axial load. Middle crowns are the most loaded crowns for all cones of type T bits, just like for insert carbide bits. However, this maximum is not so pronounced and the loading of the vertex crowns of the milled tooth bit comes close the loading of the middle crowns. So, for example, the average value of the maximum force acting on the middle crown of the second cone is 16.8 kN and on the vertex crown of the second cone is 15.7 kN. This can be explained by the following reasons. For insert carbide bits, the contact areas of the bottom and the teeth located on different crowns are approximately the same, since the diameters of the teeth differ slightly (8...10 mm on the vertex crowns and 10...12 mm on the peripheral and middle crowns). Therefore, the rigidity of the tooth-rock system for different crowns in this case can be considered almost identical and not affecting significantly the nature of the load distribution over the cones. For milled tooth bits, the size and shape of the blunting areas of the teeth located on different crowns vary quite significantly. Therefore, the nature of the load distribution along the crowns, along with the rigidity of the support assembly, is greatly affected by the rigidity of the tooth-rock system.

4. CONCLUSION

The results of the above studies of the distribution of axial load over the crowns of bit cones made it possible to establish that the load along the crowns of cones is distributed very unevenly, and the middle crowns of the cones are most loaded. Moreover, this unevenness persists with a different design of the cutting structure. The distribution of the axial load over the bit cone is also uneven, the maximum axial load is perceived by the first cone, the minimum - by the third one. However, the degree of uneven distribution of the axial load over the bit cone depends largely on the design of the cutting structure and, mainly, on the nature of the location of the crowns on the cones along the radius of the bit, which is especially noticeable in insert carbide drill bits.

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