DEVELOPMENT OF HIGH-STRENGTH DEEP-WELL PUMP RODS FOR OIL PRODUCTION BASED ON INNOVATIVE METALLURGICAL TECHNOLOGIES

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Abstract

In the world, including the Republic of Azerbaijan, oil production from 75-85% of wells is carried out by deep-well pumps. A deep-well pump located at the bottom of the well is connected to a pumping unit at the wellhead with rods. The pump brings oil to the surface of the wells either due to the reciprocating motion of the rod string or due to its rotation in one direction. In the first case, the rod string operates under a repetitive, variable tensile load with an asymmetric cycle, and in the second - under a torsional load. The chemical composition and design of the rods used in both cases are the same. Pump rods (Fig. 1) are long (8 m long) products of small diameter (16-25 mm) and are considered the weakest link in oil production by pumping. Shutdown of oil wells in most cases occurs as a result of rod breakage. Therefore, the level of oil production by this method depends on the strength and reliability of the pump rod. The aim of the research work is to obtain high-strength rods for deep-well pumps by using innovative metallurgical technologies. This is a pressing scientific and technical problem.

Keywords: sucker rod, steel, rolling, structure, sorbite, ingot, thermomechanical treatment, hardenability.

I. Introduction

The main factor determining the reliability and durability of deep well pump rods is the structural state of the rod metal after all operations. Unfortunately, many researchers have not paid due attention to this serious factor. For this reason, there is no significant information in the literature on the influence of steel structure on the operational properties of rods. Research shows that the most optimal working structure of the metal of pump rods operating in very difficult conditions should be sorbite (Fig. 6) [1].

In most cases, pump rods used in oil fields are rolled hot and cooled in air, i.e., normalized. In this case, excess ferrite grains appear in the metal structure. Even after heating the rod with high-frequency current, excess ferrite remains in the internal structure of the steel. To remove excess ferrite grains from the steel structure, prepare its structure for operating conditions and increase the steel's ability to elastic deformation, the pump rod must be hardened and tempered. For this purpose, the plant must have a workshop equipped with special equipment. In addition, the chemical composition of the rod steel should be selected so that the depth of hardening penetration (hardenability) fully ensures the cross-section of the product. However, many years of research show that this method is not suitable, since it causes problems when hardening long parts of small diameter (bending during hardening and cracking in the rods during the subsequent straightening process, etc.) [1].

II. Main part

It is known from the studies conducted on broken rods that the main reason for the failure of sucker rods after some time is the presence in their structure of excess ferrite grains with low mechanical properties (Fig. 2). Ferrite grains are subject to plastic deformation under stresses even below the yield strength ($\sigma_{0.2}$) of rod steel, soften and break under the action of forces periodically changing in direction (Fig.3). Since the yield strength of steel corresponds to the plastic and elastic region, irreversible plastic deformation develops significantly in the structure during operation. For this reason, the rod quickly breaks and fails. Therefore, the yield strength cannot fully characterize the quality of rod steel. Thus, steels used in the production of sucker rods should be characterized by the elastic limit at low residual deformation during measurement, that is, the limit of resistance at low deformations ($\sigma_{0.005}$).

Figure 1: *Head and transition zone of pump rods ShG-19 and ShG-22*

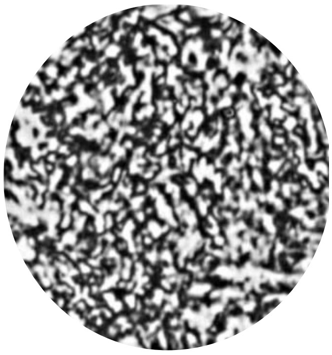

Figure 2: *Structure of rods made of 20NM steel after normalization ferrite + pearlite. x 400*

Figure 3: *Destroyed ferrite. x 2000*

In the Azerbaijan Republic and foreign literature, it is indicated that 77% of rods break in the body, including the transition zone at a distance of 120-160 mm from the rod head. In wells with a depth of 2000-2800 meters, this figure is 92%. Rod breakage: 42% occurs at the top, 35% in the middle, 23% at the bottom. According to literature, 62% of rods in the USA break in the upper part of the rod. The reason for this is that there is strong stress in the upper part of the rod. The reason for the breakage of rods in the lower part of the column is their bending and vibration along the length [1].

The steels tested and used in the Azerbaijan Republic and abroad for the manufacture of deep-well pump rods can be conditionally divided into three groups.

The first group includes low- and medium-carbon alloy steels 15NM, 20Cr, 20NM, 20CrGR, 35G, 35G2, 35GN, 35GCrM, 20Cr2M, 30CrMA, 40. Rods made of these steels are used mainly after normalization, the mechanical properties are at a fairly high level: $\sigma_в$=550-750 MPa; $\sigma_{0.2}$=300-480 MPa; δ=40-70%; φ=14-30%; a_H=0.6-1.6 MJ/m2. However, due to the presence of a large amount of structurally free ferrite in the structure, their elastic limit is very low ($\sigma_{0.005}$=150-220 MPa). Therefore, the use of some of them can be justified only if the deep well pump rods were hardened with sufficient stability of supercooled austenite and hardenability of steel.

The second group includes high-alloy steels 10Cr2GN4, 25CrGN3MD, 40CrGN3M, 35CrGN3M. Rods made of steels of this group are also delivered to the fields after normalization and tempering. They have high elastic mechanical properties: σ_B=600-900 MPa; $\sigma_{0.2}$=600-750 MPa; $\sigma_{0.005}$=350-450 MPa; δ=12-22%.

The third group includes low-carbon high-alloy nickel steels 03N4, 04N3M, 08N4M (σ_B=400-

500 MPa; σ_{02}=330-370 MPa). It should be noted that steels of the second and third groups are difficult to machine due to their high viscosity and contain (3-4%) scarce nickel. It is not advisable to use these steels for the production of rods.

In connection with the above, it was proposed [1] to use self-hardening steels for the manufacture of deep-well pump rods in such a way that duppring the cooling process after hot rolling or normalization, the rods are hardened in air along their entire length and cross-section. Subsequent tempering at optimal temperatures should ensure the receipt of a sorbitol structure and high values of the elastic limit. In this connection, 15X2NMFAl steel was developed, which after rolling or normalization with the corresponding rod diameter (16-22 mm) self-hardens in air along their entire cross-section to a bainitic structure. The chemical composition of this steel is given in table 1.

Table 1: *Chemical composition of steel*

Brand steel	Chemical composition of steel, %									
	C	Si	Mn	Cr	Mo	V	Ni	Al	S	P
15Cr2NMFAl	0,13-0,17	0,17-0,37	0,5-0,7	1,85 2,20	0,2-0,3	0,08-0,13	0,9-1,2	0,01-0,05	0,015	0,015

The steel was smelted in a 60-ton electric arc furnace. Deoxidation and alloying were performed during tapping into a steel-pouring ladle using liquid ligature and synthetic slag [2].

Aluminum for final deoxidation was introduced through a chute in small pieces weighing 0.5-1.0 kg in an amount of 0.6-1.0 kg/ton. The temperature in the ladle after tapping the metal was 1600-1620 °C. The smelted steel was poured in a continuous metal casting unit into billets with a cross-section of 280 x 280 mm. Ingots heated to 1150-1200 °C were rolled into intermediate billets with a diameter of Ø110 mm. The temperature of the metal at the beginning of rolling was 1120-1170 °C and at the end of rolling it was 850-950 °C. Intermediate blanks were rolled on a small-section mill 350 to a profile of Ø 19- and 22-mm. Steel grade 15Cr2NMFAl has high hardenability (Fig. 5), which makes it possible to use the heat of rolling heating during HTMT. This allows the strengthening of rods to be carried out in two ways:

1. after leaving the last stand with a deformation of 15%, the rods are cooled (table 2) in the air in the shop to obtain hardened rolled products with a bainite structure. Then the profile rolled products were cut to standard sizes and subjected to heating along the entire length in a furnace to a temperature of 630-650 ° C and cooled in air - tempering to obtain a sorbite structure. It was found that a rod with a hot rolling end temperature of 850-950 ° C before the onset of bainitic transformation (480 ° C) under shop conditions is cooled along the entire length in 90-100 sec., i.e., the cooling rate of the rods is 3-5 degrees / sec. These cooling rates of the rods under shop conditions correspond to the stability of supercooled austenite according to the diagram of isothermal and thermokinetic transformation in the range of 700-500 ° C (Fig. 4). The mechanical properties of deep-well pump rods made of 15Cr2NMFAl steel depending on the cooling rate from 860-920 °C are given in table 2.

Table 2: *Cooling rate after rolling and normalizing*

Cooling rate after rolling and normalizing, deg/sec.	$\sigma_{0,2}$, MPa	HRC/HB
0,1	540/260	25/248
1	720/760	29/248
3	740/680	32/248

6	820/780	34/248
500	110/740	41/248
Note: the numerator shows the properties of steel in the untampered state, the denominator shows the properties after tempering at 660-680 °C		

2. The presence of more than 3% alloying elements in the composition does not allow rapid cooling with water after deformation to the workshop temperature (i.e., quenching) during HTMT. For this reason, we manufactured pump rods from 15Cr2NMFAl steel using the high-temperature isothermal thermomechanical treatment method.

The 15Cr2NMFAl steel blanks were subjected to deformation by 15% upon exiting the last stand of the rolling mill and cooled according to the thermokinetic diagram (Fig. 4). After the rolled products with a diameter of 22 mm exited the last stand at a speed of 9 meters per second, they were cooled on 10 devices installed along the rolling with air under a pressure of 6-7 atm. to a temperature of 650-630 °C. In this case, the metal surface was cooled at a speed of 250 °C/sec. After the cooling by inertia ceases, the surface temperature of the rolled product decreases to 550-570°C. Then, due to the internal heat, the temperature of the rolled product rises to 630-650°C, i.e., it was subjected to isothermal thermomechanical treatment [3]. After that, the rolled product is cooled in the air in the shop conditions, i.e., the tempering process takes place. The deformed and supercooled austenite is transformed into a thin ferrite-cementite mixture – sorbite (Fig. 6). The structure of 20NM steel consists of pearlite, which is associated with low hardenability. The resulting profile was cut in a hot state and cooled in the air, obtaining rolled product hardened for sorbite.

The hardenability of steels was studied by the standard method [5,6] and is shown in fig. 5. As can be seen from the figure, the hardenability of steel grades 20NM, 15Cr2NMFAl, respectively, is 6, 34 mm.

The following mode of upsetting rod heads on a horizontal forging machine was developed: heating to 1150-1200 ° C upsetting, finishing upsetting at 1020-1060 ° C. The fibers on the rod head are located in the direction of deformation. No overheating was detected in the metal of the rod head (the fracture is matte).

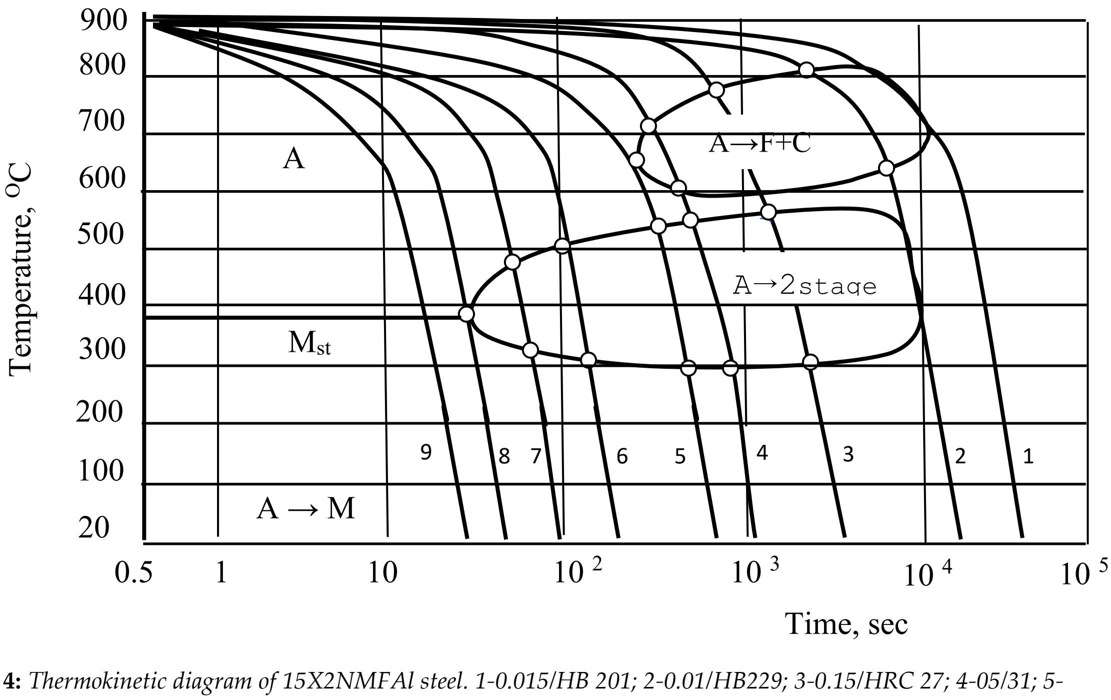

Figure 4: *Thermokinetic diagram of 15X2NMFAl steel. 1-0.015/HB 201; 2-0.01/HB229; 3-0.15/HRC 27; 4-05/31; 5-1/33; 6-9.5/36; 7-6.5/38; 8-13/41; 9-25/41. In the numerator - cooling rate in deg/sec. In the denominator - hardness - HB, HRC*

The results of the study of mechanical properties show that the transition zone in the steel under study after upsetting and tempering at 650 °C is practically absent. After upsetting the heads, one part of the rods was tempered, the other – normalized and tempered. In both cases, i.e., after hot rolling or normalization, the resulting structure in the deep-well pump rods was uniform and consisted of l ower baite. The hardness along the entire length of the rods was HB 235-240, the difference in hardness of the center of the section and the surface was HRC 0.5-0.8, which did not exceed the measurement error

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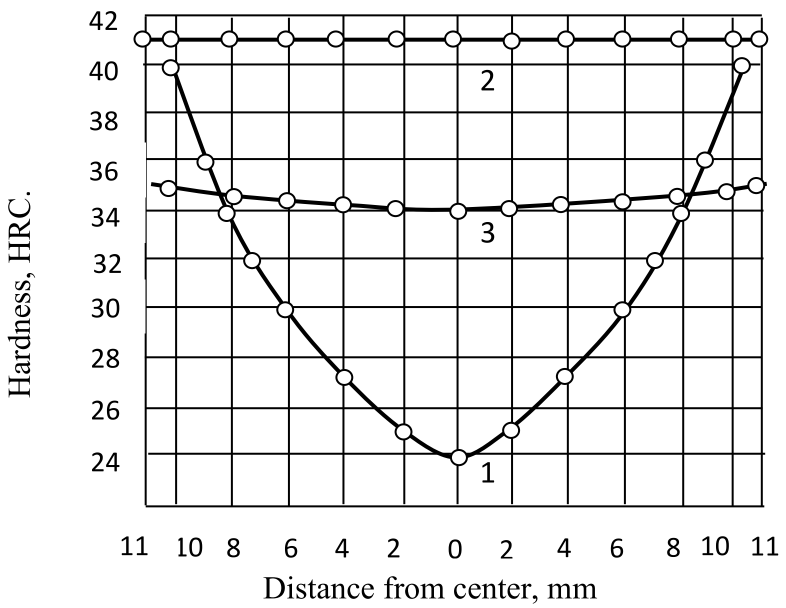

Figure 5: *Hardenability by cross-section of ShG-22 pump rods made of steels: 1-20NM and 2-15Cr2NMFAl after quenching in water, 3- after hot rolling, air cooling 15Cr2NMFAl*

Average data on mechanical properties of the transition zone and the rod body are presented in table 3. It is evident from the table that mechanical properties of deep-well pump rods made of 15Cr2NMFAl steel are higher than those of rods made of 20NM steel. And mechanical properties in the transition zone of rods made of 20NM steel are significantly lower than those in the rod body. The elastic limit of this steel (σ0.005) is within 53-57% of the yield strength (σ0.2), which is due to low hardenability of steel, the presence of ferrite in the structure and the coarse-grained transition zone.

Table 3: *Mechanical properties of the rods on the body and in the transition zone*

Brand steel	$\sigma_в$, MPa	$\sigma_{0,2}$, MPa	δ, %	φ, %	KV, J/cm2	$\sigma_{0,005}$, MPa
20NM* 15Cr2NMFAl *	600/530 810/760	390/320 730/685	21/17 21/18	56/42 76/70	120/80 165/152	210/178 643/618
* In the numerator the data in the body, in the denominator the data in the transition zone						

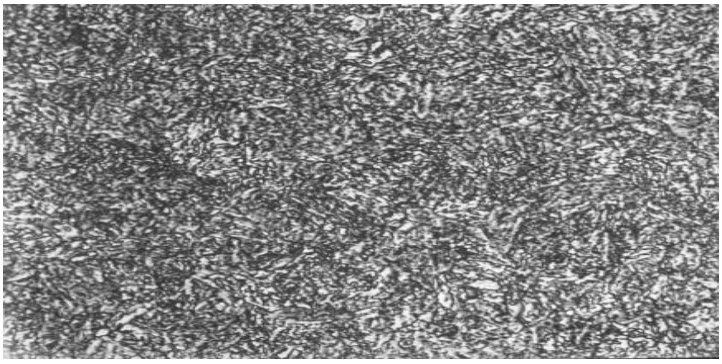

Figure 6: *Structure of steel rods 15Cr2NMFAl after VTMO and self- vacation. Sorbitol. x 400*

The presence of a small amount of molybdenum and vanadium in the composition of steel grade 15Cr2NMFAl contributes to increased hardenability and the formation of a fine-grained structure of the transition zone. Therefore, the mechanical properties of the transition zone and rod bodies made of steel grades 15Cr2NMFAl are high. The elastic limit of this steel ($\sigma_{0.005}$) is within 87-89% of the yield strength ($\sigma_{0.2}$). The mechanical properties of the transition zone of rods made of this steel are much higher than the indicators in the body of rods made of 20NM steels, provided for in GOSTs of the CIS and Russia [4].

Tests of pilot rods of all pilot heats were carried out in oil wells. Depending on the depth of the wells, 86-250 rods were used to assemble each column. The chemical composition of the pilot steel heats and test data are given in tables 4 and 5.

Table 4: *Chemical composition of experimental melts*

Number of compositions		Chemical composition of experimental melts, %									
		C	Cr	Mo	V	Ni	Al	Si	Mn	S	P
1		0,13	1,85	0,25	0,13	1,2	0,02	0,25	0,50	0,016	0,016
2		0,15	2,20	0,20	0,10	0,9	0,03	0,30	0,60	0,015	0,015
3		0,17	2,15	0,30	0,08	1,1	0,05	0,32	0,58	0,015	0,016

Table 5: Test data are given

Number of compositions	Tested bars, pcs.	Number of rod breaks		Durability of the bars	
		pcs	%	in hours	in work cycles x10-6
Rods ShG -19					
1	1086	3	0,3	16025	10,5
2	1672	3	02	18213	10,9
3	1893	6	0,2	19074	13,1
Rods ShG -22					
1	1242	4	0,3		10,3
2	1514	2	0,1	19008	11,6
3	1897	4	02	20716	12,6

III. Conclusion

According to the results of comparative tests, the probability of failure-free operation of rods made of 20NM and 15Cr2NMFAl steel is 0.974 and 0.995, respectively.

Tests of deep well pump rods made of 15Cr2NMFAl steel have shown that their use in oil production allows for an increase in the durability of the rod string by approximately 1.4-1.7 times and a decrease in the number of rod breaks by 6-8 times, thereby reducing well downtime for emergency rod replacements, reducing repair work and increasing oil production.

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