Influence of deep cryogenic treatment on structure and wear resistance of materials of hydraulic breaker chisels

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Abstract. It is shown that shallow cryogenic treatment at -75°C (SCT) of the materials of hydraulic breaker chisels - P20, 1080 and D2 steels leads to a decrease (44÷82%) in the amount of retained austenite and an increase (26÷99%) in the amount of carbides in the structure of hardened steel, which is accompanied by an increase in its hardness (1.4÷2.1%) and abrasive wear resistance (10÷31%) with a simultaneous decrease in impact toughness (19÷24%). Deep cryogenic treatment at -196°C (DCT) and subsequent low-temperature tempering of D2 steel leads to a significant increase in its wear resistance (98%) and impact toughness (32%).

1. Introduction
When operating the breaker, especially on strong and abrasive rocks, its chisel is subjected to considerable stresses, impact loads and intense abrasive wear [1]. For this reason, the chisel should be made of a material having increased strength, hardness and wear resistance with sufficient resistance to influence loads. Typically, medium and high carbon steels of various degrees of alloying are used for this purpose after conventional heat treatment (CHT), including austenitization, quenching in oil, and low-temperature tempering. The structure of steel after CHT is martensite with a certain amount of retained austenite and carbides. Preservation of austenite in the structure of quenched steel is due to lower martensite finish temperature \( M_f \) in comparison with the temperature of quenching medium used. The presence of "soft" austenite in the structure of the material of chisel reduces its hardness, strength and wear resistance. On the other hand, under the effect of high impact loads acting on the chisel during the operation of the hydraulic breaker, a part of the retained austenite of steel transforms into martensite. Since the specific volume of martensite is by 4.3% larger than that of austenite, the course of this transformation leads to a distortion in the dimensions of the chisel, which affects the trajectory of the breaker.

In order to reduce the amount of retained austenite and increase the amount of carbide in these steels, SCT or DCT, widely used to increase the hardness and wear resistance of tool steels, can be used as an additional operation in heat treatment [2-8]. This present paper is devoted to the study of the influence of these types of treatment on the structure, mechanical properties and abrasive wear resistance of P20, 1080 and D2 steels as materials of hydraulic breaker chisels.

2. Experimental methods
Cylindrical samples of steels (diameter = 8 mm) after quenching in oil were placed in a cryostat with a
cooling liquid \( T = -75^\circ C \) or with liquid nitrogen \( T = -196^\circ C \), where it was held for 5 or 72 hours, respectively, tempering at 200°C. Determination of the amount of carbides and retained austenite in the steel structure (with a sensitivity threshold of 0.1%) was carried out using microscope Axioplan-2 and program KS 300 3.0. The values of \( KCV, HV \) were determined on pendulum copra Zwick/Roell RKP450 and universal hardness tester Zwick/Roell ZHU.

Tests for abrasive wear were carried out according to procedure [9] in the installation, the diagram of which is shown in Fig. 1, with the rotation frequency of machine spindle of 7.5 \( s^{-1} \). Granite I was used as an abrasive medium, as the rock is most often destroyed by hydraulic breakers. At constant static load (100 N), the end surface of steel sample 2 was worn for 50 minutes with mass measurement (weighing accuracy 1.0 mg) every 10 minutes and calculation of its loss \( \Delta m \). After each measurement, the plate of abrasive material was displaced relative to the sample, which ensured contact of metal with fresh surface of abrasive in each cycle.

![Diagram of the installation for abrasive wear testing samples](image)

**Figure 1.** Installation diagram for abrasive wear testing samples: 1 - plate of abrasive material; 2 - test sample; 3 - holder; 4 - spindle of vertical drilling machine; 5 - water supply device.

Dependency of total loss of sample mass was plotted on duration \( t \) of abrasive action of the medium. Through experimental points, an extrapolation straight line was made, the tangent of the slope, which was taken as wear rate \( K \), and magnitude of it was reversed for wear resistance of material I.

3. Experimental results

Results of studies are presented in Table 1, Table 2, Fig. 2 and Fig. 3.

**Table 1.** Effect of SCT and DCT on amount of retained austenite and carbides in structure of steels

| Steels | Amount of retained austenite, % | Amount of carbides, % |
|--------|---------------------------------|-----------------------|
|        | CHT at -75°C | SCT at -196°C | DCT at -196°C | CHT at -75°C | SCT at -196°C | DCT at -196°C |
| P20    | \( \leq 0.10 \) | \( \leq 0.10 \) | \( \leq 0.10 \) | 0.17 | 0.33 | 0.58 |
|        | \((-43.8\%)\) | \((-61.9\%)\) | \((-10.4\%)\) | \(+98.9\%) | \(+243.2\%) | \(+100.4\%) |
| 1080   | 2.21 | 1.24 | 0.84 | \( \leq 0.10 \) | \( \leq 0.10 \) | \( \leq 0.10 \) |
|        | \((-43.8\%)\) | \((-61.9\%)\) | \((-10.4\%)\) | \(+98.9\%) | \(+243.2\%) | \(+100.4\%) |
| D2     | 15.65 | 2.78 | 0.50 | 5.41 | 6.80 | 10.84 |
|        | \((-82.3\%)\) | \((-96.8\%)\) | \(+25.7\%) | \(+100.4\%) | \(+100.4\%) | \(+100.4\%) |

As follows from data in Table 1, SCT and DCT lead to a substantial decrease in the amount of retained austenite in high-carbon steels 1080 \((-0.8\% \text{ C})\) and D2 \((-1.5\% \text{ C})\), where it remained after quenching in significant quantities. It also leads to the increase in carbide number in quenched alloyed steels (P20, D2). Moreover, the lower the temperature of cryogenic treatment, the higher its efficiency.

As the results of experiments on abrasive wear have shown, for all tested steel samples, the wear process is described by a linear dependence (Fig. 2): \( \Sigma \Delta m = K t \), where \( K \) is wear rate depending on a
steel grade and a type of heat treatment.

Figure 2. Approximating curves of dependence $\Sigma \Delta m = f(t)$ for P20 (a), 1080 (b) and D2 (c) steels subjected to CHT (1) and additional SCT at -75°C (2) and DCT at -196°C (3)

Established values of wear resistance ($I = I/K$), impact strength and hardness of steels, as the arithmetic mean of results of three experiments, are presented in Table 2 and Fig. 3.

Table 2. Results of physical and mechanical tests and experiments on wear of steels subjected to CHT and cryogenic treatment

| Steels | Type of treatment | Parameter value |
|--------|------------------|-----------------|
|        |                  | KCV, J/cm$^2$   | HV   | I, min./mg |
| P20    | CHT              | 40.6            | 529   | 0.50       |
|        | CHT + SCT (-75°C) | 33.0          | 536   | 0.61       |
|        |                  | (-18.7%)        | (+1.4%) | (+23.2%) |
|        | CHT + DCT (-196°C) | 35.0          | 539   | 0.67       |
|        |                  | (-13.8%)        | (+2.0%) | (+34.7%) |
| 1080   | CHT              | 5.1             | 707   | 0.63       |
|        | CHT + SCT (-75°C) | 3.9            | 717   | 0.68       |
|        |                  | (-23.5%)        | (+1.4%) | (+9.6%)   |
|        | CHT + DCT (-196°C) | 5.1            | 730   | 0.76       |
|        |                  | (+0.0%)         | (+3.2%) | (+21.2%)  |
| D2     | CHT              | 3.1             | 694   | 1.12       |
|        | CHT + SCT (-75°C) | 2.5            | 708   | 1.47       |
|        |                  | (-19.4%)        | (+2.1%) | (+30.9%)  |
|        | CHT + DCT (-196°C) | 4.1            | 750   | 2.22       |
|        |                  | (+32.3%)        | (+8.2%) | (+97.8%)  |
Figure 3. Effect of cryogenic treatment temperature on mechanical properties and wear resistance of materials of hydraulic breaker chisels - P20 (1), 1080 (2) and D2 (3) steels

4. Discussion of results
As follows from data in Table 2, with a decrease in temperature of cryogenic treatment, the hardness of all grades of steel increases (Fig. 3, a), the most noticeable for D2 steel (8.2% at -196°C). For the same material, the greatest increase in wear resistance is observed (97.8%) (Fig. 3, c.). Impact toughness of all materials as result of cryogenic treatment at -75°C decreases, and at -196°C increases (Fig. 3, b), exceeding the value of $KCV$ after CHT for D2 steel (4.1 compared to 3.1 J/cm$^2$).

The difference in the degree of influence of cryogenic treatment on wear resistance of steels is explained by the fact that this characteristic depends not only on the hardness of the steel, but also on the type, size, and amount of the carbides present in it.

D2 steel demonstrates the most noticeable improvement in hardness and wear resistance since it contains a significant amount of retained austenite after quenching (more than 15%), almost completely transformed to martensite after DCT at -196°C. In addition, it has the biggest carbon content (~1.5%) and alloying elements (~13%) from the analyzed steels, which provides after DCT an increase to 10.8% of fine carbide particles.

P20 steel does not show such a noticeable improvement in hardness (only 2.0%) and wear resistance (by 34.7%) due to the practical absence of retained austenite in its structure after quenching. Increase as a result of treatment is due only to an increase in the amount of small particles of carbides. Although an increase in wear resistance of 1.35 times is also significant.

In 1080 steel, increase in hardness (3.2%) and wear resistance (21.2%) as a result of treatment, on the contrary, is associated with the transformation of retained austenite to martensite in the steel structure.

SCT at -75°C reduces impact toughness of all steels to approximately the same extent (from 18.7 to 23.5%). At the same time, a decrease in treatment temperature to -196°C leads to an increase in $KCV$ for all steels compared to at -75°C, whereby for 1080 steel impact toughness reaches the value of $KCV$ of original hardened steel, and for D2 steel even exceeds it (by 32.3%).

Improvement of impact toughness as a result of DCT can be explained by the uniform distribution of released homogeneous and fine carbides in matrix [10] or is associated with microstructural changes occurring inside the martensite itself [5].
5. Conclusion
From the presented results, it can be concluded that cryogenic treatment can be considered as a promising additional operation for heat treatment of hydraulic breaker chisels to increase their wear resistance. In this case, the most preferred treatment temperature should be -196°C, in which, along with the increase in hardness and wear resistance, impact toughness of chisel material also increases.

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