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SELECTION OF THE CHEMICAL COMPOSITION OF STEELS AND THEIR THERMAL HARDENING MODE USING A COMPUTER PROGRAM

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Abstract. The relationships between the parameters of the structure of heat-treated steels and their abrasive wear resistance are established. At all temperatures of the final tempering of hardened steel, there is a direct relationship between its structure parameters and wear resistance when sliding friction against loose abrasive particles.

Keywords: heat treatment, dislocation density, extreme temperature, low-alloy steel, computer program.

Introduction. Abrasive wear is the main cause of failure of metal parts. The manufacture of parts from high-wear material is often not justified and, as a rule, is due to the inertia of production [1]. In the repair industry, this trend is often associated with the absence or lack of the necessary wear-resistant steel grades, which can lead to premature failure during the operation of repaired units. The choice of steels for the manufacture of critical parts should be based on their wear resistance [2].

The objectives of this study are: to perform preparatory heat treatment under extreme conditions with final heat treatment; establishment of relationships between the parameters of the structure of steels and their abrasive wear resistance; creation of a program for selecting materials and hardening methods to achieve the required wear resistance of manufactured parts.

Methods. We studied carbon steels (from technical iron to U8) and low-alloy steel 65G [3]. To create different structures in the studied steels, the samples were subjected to heat treatment. The processing modes were selected in such a way as to ensure the study of the effect on wear resistance of one structural parameter of steel with the relative stability of other parameters.

Materials were tested for abrasive wear on a PV-7 device, which destroys the sample surface as a result of friction [4]. Metallographic analysis was performed using a MIM-8M microscope with a magnification of ×100 and ×1000 [5]. The intercement spacing in quenched and tempered steels was determined from microphotographs obtained from carbon replicas on an UMV-100L electron microscope, as well as from thin sections using light microscopes. The surveys were performed at an accelerating voltage of up to 75 kV and a magnification of 17,000–27,000 times [5].

X-ray diffraction analysis was carried out on a DRON-2.0 diffractometer [6]. The state of the fine structure of steel (density of dislocations), the amount of residual austenite, the period of the crystal lattice, the amount of carbon in the phases of hardened steel were determined.

Results and Discussion. To determine patterns of structure formation, preliminary normalization of steels was carried out at different temperatures (above Ac_3 (or Ac_1) + 30÷50 °C up to 1200 °C). An extreme normalization temperature (1100 °C) was established, at which, after the (γ-α) transformation, a ferrite phase with a maximum dislocation density is formed.

Wear tests showed that, despite a slight increase in hardness and non-equilibrium structure, with an increase in the heating temperature for normalization, the least wear is observed at a temperature of 1100 °C. The increase in wear resistance compared to the wear resistance of traditionally normalized specimens (higher Ac_3 (or Ac_1) + 30–50 °C) is the greater, the higher the carbon content in the steel [7].

During quenching followed by tempering at a temperature of 350 °C and above, the structures of carbon and low-alloy steels are a ferrite-cementite mixture, however, depending on the alloying, ferrite has an increased amount of carbon in its composition. In this case, wear is affected by solid-solution hardening of ferrite with carbon.

The degree of this influence can be established from the difference ΔQ of wear, i.e., between the wear of technical iron quenched and tempered at a temperature of 200 °C (carbon content $C_C = 0.15\%$) and the wear of iron in the normalized state with equal dislocation density. The difference in wear as a result of solid-solution hardening of ferrite with carbon was $\Delta Q_{\text{solid.s}} = \xi C_C$ [7] (C_C, % is the carbon content in the solid solution of the α-phase; ξ, mg/% is the coefficient of hardening and wear reduction when carbon atoms are introduced into the solid solution of ferrite ($\xi = 6.2$ mg/%).

The wear of steels in the annealed state (at a minimum dislocation density) depends only on the amount of the pearlite component of the structure, then the difference in wear is $\Delta Q_p = Q_0 - \text{P}$, where $Q_0 = 7.5$ mg is the wear of commercial iron after annealing; P = 0.047% - percentage of the pearlite component in the structure of the annealed steel.

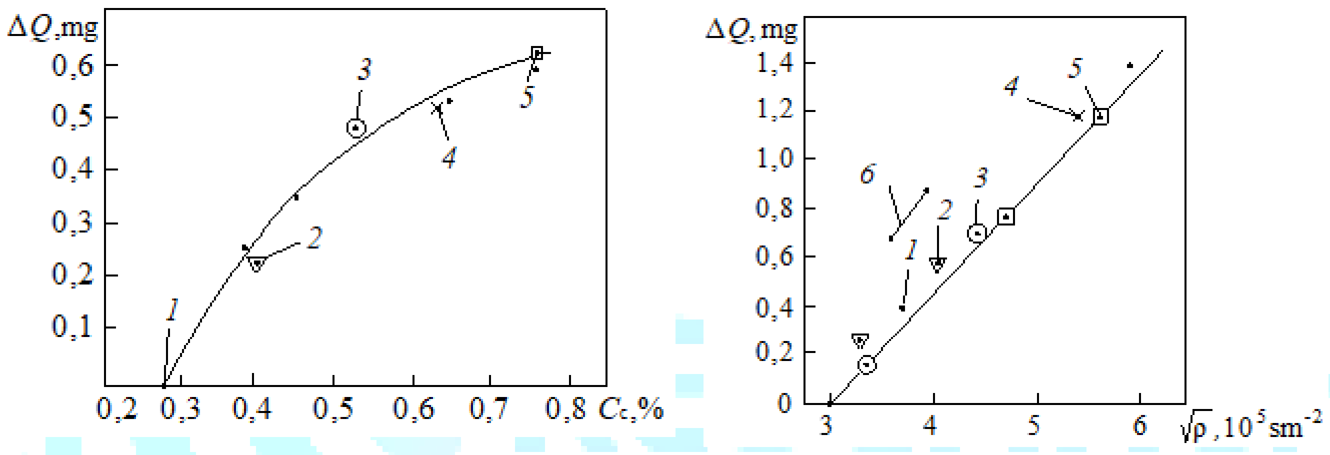
Repeated phase recrystallization was carried out by heating to the temperature adopted for each steel grade during hardening. Carbon steels (steel 30) were quenched in water or in a 10% NaCl aqueous solution, alloyed steel 65G was quenched in oil. After quenching, the samples were subjected to tempering at a temperature of 200 °C; some of the samples made of steel 30 were left without tempering.

Studies have shown [7] that after repeated phase recrystallization, the austenite grains of steels were approximately the same, regardless of the preliminary normalization temperature, the amount of residual austenite was minimal. However, the state of the fine structure, depending on the temperature of preliminary normalization, changed according to an extremal law. The dislocation density was maximum if preliminary normalization was carried out at a temperature of 1100 °C, which indicates the inheritance of elements of the original submicrostructure during repeated phase recrystallization. During repeated quenching, a significant part of the carbon atoms goes to dislocations, therefore, at the extreme temperature of preliminary normalization, the tetragonality of the martensite lattice is minimal. Similar results were obtained with direct quenching at a temperature of 1100 °C. In particular, steel 30 (carbon content $C_C = 0.28\%$) after a sharp quenching cooling had a martensite structure, but the carbon content in the tetragonal lattice did not exceed 0.15%, and when quenched at temperatures of 1100 and 1150 °C in the tetragonal carbon lattice was not found.

The increased density of dislocations in hardened steel, which is observed during preliminary normalization with extreme temperature, significantly affects the wear resistance of steel during sliding friction against loose abrasive particles [7].

The results of the study [7] showed that it is possible to establish the dependence of the difference in wear ΔQ of samples from low-tempered steels 30, 45, 55, U8 and 65G on the relative density $\sqrt{(\rho)}$ of dislocations. The obtained dependencies are linear. For all investigated steels, the dependence $\Delta Q_d = \alpha \Delta \sqrt{\rho}$ is valid, where $\alpha = 0.4$. However, each steel has a distinctive feature due to an additional structural parameter. For a single-phase martensitic structure, this can only be solid-solution strengthening. If we consider the solid solution hardening of martensite with carbon, then it can be found at one reduced dislocation density $\sqrt{\rho}$. Extrapolating the dependencies $Q = f(\sqrt{\rho})$ to the y-axis, we determine the degree of wear reduction as a result of solid-solution hardening of martensite with carbon.

On fig. 1, a shows the values of relative wear ΔQ of steels 30, 45, 55, 65G and U8 on the content of C_C carbon in martensite and the curve approximating them, which has a nonlinear character and is described by the equation $y = ax^b$, i.e. $\Delta Q = a(\Delta C_C)^b$. By setting the carbon content in steel and having the experimental values of ΔQ, we can find the coefficients a and b, then we get: $\Delta Q_{solid.s} = 1{,}06\Delta C_C^{0{,}78}$.



a *b*

Fig. 1. Values of wear differences ΔQ for steels 30 (1), 45 (2), 55 (3), 65G (4), U8 (5) and steel 30 without tempering (6) depending on the content of C_C carbon in martensite (*a*) and on the density $\sqrt{\rho}$ of dislocations (*b*), as well as their approximating curves

For carbon and low-alloy hypo-eutectoid and eutectoid steels, hardened to martensite and low-tempered, it is possible to write down the generalized dependence of wear on the structure parameters:

$$Q = Q_{0St30} - 0.4\Delta\sqrt{\rho} - 1.06\Delta C_C^{0{,}78}, \qquad (1)$$

where $Q_{0St30} = 2.2$ mg – is the wear of a reference specimen made of steel 30 with $C_C = 0.28\%$ after hardening from a temperature of 890÷900 °C and tempering at a temperature of 200 °C;

$\Delta\sqrt{\rho}$ – is the difference between the dislocation densities in the studied and reference steels; ΔC_C – is the difference between the carbon contents in the studied and reference steels.

Formula (1) reflects the additive effect of structure parameters on wear resistance. It was obtained for steels with maximum hardening, while the coefficients of structural parameters remain constant. Experiments have shown that the introduction of manganese as an alloying element into steel in small amounts did not affect the wear resistance of steels with a martensitic structure.

In expression (1), a significant factor is the density of dislocations. The maximum reduction in wear for martensite-hardened steel as a result of an increase in the dislocation density was 1.5 mg, and for solid-solution hardening of martensite with carbon, it was 0.62 mg.

The reduction in wear as a result of dislocation hardening was determined after subtracting the wear of the reference steel (steel 30, pre-normalization at 900 °C, reheating to 900 °C, quenching and tempering at 200 °C), the analysis showed a decrease in wear as a result of solid solution hardening.

The data presented in fig. 1*b* indicate that the decrease in wear as a result of dislocation hardening generally corresponds to expression (1), however, the data for steel 30 after quenching without tempering are missing:

$$Q = Q_{0St30} - 0{,}4\Delta\sqrt{\rho} - \Delta Q_{s.h} - 1{,}06\Delta C_C^{\,0{,}78} = 2{,}2 - 0{,}4\Delta\sqrt{\rho} - 0{,}5 - 1{,}06\Delta C_C^{\,0{,}78},$$

where $\Delta Q_{s.h}$ – wear difference due to work hardening, due to the friction process, of untempered steel.

A significant decrease in the wear of steel 30 in the state of quenching without tempering cannot be explained only by an increase in the dislocation density (see Fig. 1, *b*), since the dislocation density changes little compared to tempered steel at a temperature of 200 °C.

At deformation $\varepsilon > 2\%$ of untempered steel, more new dislocations are retained in martensite. The initial dislocation structure is rearranged. X-ray analysis showed a decrease in the X-ray line width. The redistribution of carbon causes a decrease in the width of the x-ray lines. The formation of Cottrell atmospheres [8] also helps to reduce crystal lattice distortions. However, this means an intensive course of strain aging in the process of abrasive wear.

It is impossible to use hardening without tempering for medium and high carbon steels, from which high-wear parts are made, since the probability of brittle fracture increases. However, brittle fracture of the hardened low carbon steel 30 is unlikely even in the untempered state. Therefore, in studies of hardening without tempering, they limited themselves to steel 30.

The maximum dislocation density and minimum wear (at tempering temperatures of 350, 450, and 600 °C) are observed at a preliminary normalization temperature of 1100 °C. At all final tempering temperatures, a linear relationship is observed between the decrease in wear and the increase in dislocation density. The effect of cementite particles on wear during tempering of steel at a temperature of 600 °C is shown in Table. 2.

Table 2

Influence of cementite particles on wear during tempering of steels at a temperature of 600 °C

Материал	Q, mg	ΔQ, mg	λ, μm	1/λ, μm^{-1}
Technical Fe	7.5	0	-	0
Steel 45	3.1	4.4	0.90	1.04
Steel 55	2.9	4.6	0.83	1.20
Steel У8	3.3	5.2	0.68	1.47

Thus, with an increase in the strength of steel (a decrease in the tempering temperature of hardened steel), the effect of strengthening structural parameters on its wear resistance decreases.

If we assume an additive effect of structure parameters on wear resistance, then wear in these cases (after tempering at temperatures of 350 °C and above) can be determined by the expression

$$Q = Q_{0Fe} - \alpha\sqrt{\rho} - K\lambda^{-1} - \xi C_C, \tag{2}$$

where $Q_{0Fe} = 7.5$ mg – wear of annealed technical iron;
ρ – ferrite matrix dislocation density;
α – hardening coefficient of steel and wear reduction with increasing dislocation density;
λ – distance between cementite particles of hardened and tempered steel;
K – hardening coefficient and wear reduction as a result of dispersion in the structure of the second phase;
C_C – the carbon content in the solid solution of the α-phase, i.e., in ferrite, when, after tempering, part of the carbon has not yet separated from the solid solution;
ξ – coefficient of hardening and wear reduction when carbon atoms are introduced into the ferrite solid solution.

The carbon content in the tempered steel ferrite composition is not large, therefore, the expression found from the results of experiments with technical iron will be common for all steels with a ferritic-based structure.

Since it was found that $\xi = 6.2$, then for alloyed steels $\Delta Q_{solid.s} = 6.2C_C$ [9].

In general, we write:

$$Q = Q_{0Fe} - \Delta Q_d - \Delta Q_f - \Delta Q_{solid.s}, \tag{3}$$

where $Q_{0Fe} = 7.5$ mg – wear of annealed technical iron under accepted conditions;
ΔQ_d – wear difference due to increased dislocation density;
ΔQ_f – wear difference due to the presence of dispersed cementite particles in the ferrite matrix;
$\Delta Q_{solid.s}$ – wear difference due to the presence of carbon atoms in the tempered alloy steel ferrite.

When quenching with low tempering of low-alloy steels, the influence of alloying chemical elements in the composition of martensite (for example, *Mn*) on wear resistance was not revealed, which cannot be attributed to quenching with tempering at temperatures of 350 ° C and above. In this case, the amount of the alloying chemical element and carbon in the ferrite depends on the tempering temperature, so the effect of solid solution hardening on wear resistance can be significant, then the expression will be valid:

$$Q = Q_{0Fe} - \Delta Q_d - \Delta Q_f - \Delta Q_{solid.s} - \Delta Q_{allo} = 7.5 - \alpha\sqrt{\rho} - K\frac{1}{\lambda} - \eta M - 6.2C_C, \tag{4}$$

where M – the amount of alloying chemical element in the α-phase solid solution;
η – hardening coefficient of ferrite alloying element.

Thus, for low-tempered steels with a martensitic structure, wear can be determined by formula (1), and for steels after quenching and tempering at temperatures of 350 ° C and above - by formula (4).

In formula (1), only the dislocation density and carbon content are variables. In steels with a martensitic structure, the carbon content can vary from 0.28% (steel 30) to 0.82% (steel U8). In this case, it is easy to calculate the dislocation density (or $\sqrt{\rho}$) for a given wear at a given carbon content.

In expression (4), the variables depending on the tempering temperature are the coefficients α, ε, η, as well as the carbon content SS and the amount M of the alloying chemical element in the ferrite. These data can be entered into a computer program in the form of discrete values, using the above results, as well as data from [9].

The program for the selection of materials and hardening technology is designed to determine only one indicator - relative wear resistance: $E = Q_{0Fe}/Q$, where Q_{0Fe} – wear of reference steel (annealed technical iron); Q – calculated wear.

The sequence (without restrictions on the area of existence and combinations of structural parameters) of the choice of material and methods of its hardening to ensure the required wear resistance:

data input;

cycle-1 on the dislocation density of quenched and tempered 350 °C steels;

calculation of intercementite distances λ by relation (4);

cycle-2 on the content of cementite in steel;

calculation of the average diameter of cementite particles d from the intercementite distance and the amount of cementite f;

finding the tempering temperature of hardened steel with a known amount of carbon and an average diameter of cementite particles;

cycle-3 on the carbon content in steel after martensite quenching and low tempering;

calculation of the density of dislocations by relation (1) and reconciliation of data with the intervals of their existence, including heat treatment with preliminary preparation of the structure;

With the help of the developed program, it is possible to determine the composition of steel and the mode of thermal hardening, depending on the required wear resistance.

To verify the results obtained, full-scale tests of plow shares made of steel 30 were carried out, the blades of which were hardened from a heating temperature to 1100 °C without tempering. As control samples, a plow share made of steel L53 manufactured by JSC Bakhtselmash was used.

Tests have shown that the wear resistance of serial shares slightly exceeds the wear resistance of shares made of steel 30, the blades of which are hardened from a temperature of 1100 ° C without tempering.

Conclusions

1. Quantitative relationships between the parameters of the structure of heat-treated steel and its abrasive wear resistance during sliding friction against loose abrasive particles are established.

2. There is an interdependence between the amount of wear during friction against loose abrasive materials (quartz sand) and the density of dislocations of quenched and tempered steels.

3. It has been established that at all temperatures of the final tempering of hardened steel, there is a direct relationship between its structural parameters (the number of elements in the solid solution, dislocation density, cementite particle size and intercementite distance) and wear resistance during sliding friction against loose abrasive particles.

4. An algorithm and a calculation program have been developed for finding the composition of steels, their thermal hardening regimes depending on the required level of relative wear resistance during sliding friction against loose abrasive particles.

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