3. The difference in the nitriding methods under the conditions of the experiment in question does not exert a significant influence on the strength characteristics of the steels that we investigated. The prevailing effect of the reduction in the resistance to brittle failure as a result of an increase in the size of the diffusion zone and its hardness over the increase in the resistance to plastic deformation due to nitrogen saturation of the solid solution and the formation of a nitride phase is observed during static-bending tests.

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GAS CARBURIZING PERFORMED WHILE HEATING WITH AN INTERNAL HEAT SOURCE

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A number of factors that contribute to the acceleration of case-hardening processes when specimens are heated by an internal heat source are pointed out in the literature [1]. Among them are the vigorous delivery of an active substance and the removal of reaction products in the "hot"-specimen/"cold"-medium system due to convective phenomena. However, no quantitative estimates of this factor have been made.

We investigated theoretically and experimentally the effect of this convective flux on the acceleration of the gas carburizing of steel heated by an internal heat source. If the heating is carried out with an external source (in ordinary furnaces used for gas carburizing), the temperatures of the specimen and gaseous medium will coincide. There is no temperature gradient in the gaseous phase. The mathematical model of gas carburizing for external heating is therefore a set of equations of Fick's second law with initial conditions and the equation for the mass-efficiency factor β, which depends only on the Reynolds number, the latter characterizing the flow across the surface of the specimen:

$$\partial C(x, t)/\partial t = D\partial^2 C(x, t)/\partial x^2; \quad t>0, \; x>0; \tag{1}$$

$$C(x, 0) = C_0; \quad x \geqslant 0; \tag{2}$$

$$-D\partial C(0, t)/\partial x = \beta[C_{atm} - C(0, t)]; \quad t>0; \tag{3}$$

$$C(\infty, t) = C_0; \quad \partial C(\infty, t)/\partial x = 0; \tag{4}$$

$$\beta = A(D/l)\text{Re}^a\text{Sc}^b, \tag{5}$$

where $C(x, t)$ is the concentration profile of carbon, D is the carbon-diffusion coefficient, C_0 is the initial carbon concentration, C_{atm} is the carbon potential of the atmosphere, $\text{Re} = wl/\nu$ is Reynolds number (w is the velocity of the gas flow, l is a specimen dimension, and ν is the coefficient of dynamic viscosity), $\text{Sc} = \nu/D$ is Schmidt's criterion, and A, a, and b are coefficients determined for the specific gaseous medium.

TABLE 1

x, mm	ΔC, %, at									
	w, m/sec				t, °C			τ, sec		
	0	0,5	1,5	2,5	900	950	1100	120	360	600
0,01	0,15	0,07	0,05	0,02	0,04	0,04	0,04	0,04	0,04	0,04
0,02	0,17	0,08	0,055	0,025	0,05	0,05	0,05	0,05	0,045	0,045
0,03	0,25	0,11	0,06	0,03	0,055	0,055	0,055	0,055	0,055	0,055
0,05	0,2	0,095	0,06	0,03	0,06	0,06	0,06	0,06	0,06	0,06

TABLE 2

| Method of heating	Method used to obtain results	$\Delta m \cdot 10^2$, kg/m², at															
		w, m/sec						t, °C					τ, sec				
		0	0,5	1,0	1,5	2,0	2,5	900	950	1100	1050	1100	60	120	240	360	480
External	Model	0,097	0,18	0,32	0,45	0,56	0,62	0,45	0,48	0,53	0,58	0,63	0,5	0,55	0,59	0,66	0,68
	Chroma-tography	—	0,16	0,30	0,44	0,55	—	—	0,47	—	0,59	—	—	0,53	—	0,65	—
	Gravi-metry	—	0,22	0,37	0,41	0,53	—	—	0,45	—	0,55	—	—	0,51	—	0,63	—
Internal	Model	0,18	0,29	0,39	0,49	0,58	0,63	0,48	0,51	0,56	0,61	0,66	0,52	0,58	0,62	0,69	0,71
	Chroma-tography	—	0,34	0,43	0,52	0,58	—	—	0,55	—	0,63	—	—	0,6	—	0,7	—
	Gravi-metry	—	0,32	0,47	0,49	0,62	—	—	0,53	—	0,62	—	—	0,62	—	0,68	—
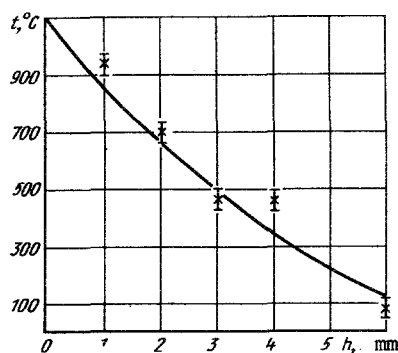
Fig. 1. Temperature field around heated flat specimen (h is distance from thermal converter to specimen).

If, however, the heating is accomplished by an internal heat source (for example, a direct electric heater), the temperatures of the specimen and gaseous medium will differ, i.e., a temperature gradient, which dicatates the presence of the medium's visible convective motion directed perpendicular to the surface of the specimen, exists in the gaseous phase. This motion changes the value of the mass-efficiency factor. The longitudinal and perpendicular flows are summed; in this case, the perpendicular flow is, in the theory of heat and mass exchange, characterized by Grashof's number [2], which is a function of the temperature gradient in the gaseous phase. Thus, the mathematical model for heating by an internal heat source includes equation (1) with conditions (2), (3), and (4) and the altered value of the mass-efficiency factor

$$\beta' = A(D/l)\,[\mathrm{Re} + \mathrm{Gr}]^a \mathrm{Sc}^b, \tag{6}$$

where $\mathrm{Gr} = (g\beta l^3/v^2)\dfrac{dT}{dh}$ is Grashof's number, g is the acceleration of free fall, β is the coefficient of the volume expansion of gas, and dT/dh is the temperature gradient in the gaseous phase.

Equation (6) is derived on the assumption that some summary criterion, which characterizes the motion of the gaseous atmosphere along and across the specimen simultaneously, exists during its heating by an internal heat source. Its effect on the mass-efficiency factor is similar to the effect of the Reynolds number for heating by an external heat source. For this representation of Eq. (6), moreover, the mass-transfer coefficient is not equal to zero as in Eq. (5), when the flow rate of gas $w = 0$; this corresponds to the physical pattern of the process (mass tranfer will take place by convective motion of the medium).

To calculate this model analytically on a computer, it is necessary to know the coefficients in the mass-efficiency equation and the temperature gradient in the gaseous phase. The coefficients were determined on the basis of the results of processing experimental data derived during external heating by the method of least squares. The temperature gradient was determined from theoretical nomograms [3] constructed by solving the corresponding differential equation, and was compared with experimental data obtained by introducing a Chromel–Alumel thermal converter, which was protected from the specimen's radiation by a titanium shield, in the reaction chamber during carburizing under an internal heat source. It is apparent from Fig. 1 that the temperature gradient is 1100°C on the surface of the specimen and 200°C at a distance of 6 mm from its surface. This value of the gradient was also introduced to the model. After this, Eq. (6) acquires the following form for a specific gaseous medium:

$$\beta' = 1.07 \cdot 10^{-4} (Re + Gr)^{0.15} Sc^{3.32}, \tag{7}$$

where determining the viscosity ν of the gas with allowance for the multicomponent nature of the gaseous medium and setting the coefficient of the medium's volume expansion β equal to the coefficient for an ideal gas, we have:

$$Re \cong 5 \cdot 10^3, \ Gr \cong 7 \cdot 10^2, \ Sc \cong 7 \cdot 10^{-2}$$

for the given gas-flow interval and temperature gradient.

When the velocity of the flow is increased, the Reynolds number increases and the contribution made by Grashof's number (i.e., the convective motion of the medium) to the mass-efficiency factor decreases. The resultant system of equations was solved on an ES-1033 computer by calculating the concentration profile of carbon in successive time intervals τ for various temperatures t and flow rates w. The calculation was performed for both methods of heating in accordance with the familiar solution of the equation of Fick's second law for a semi-infinite plate. The carburizing parameters were varied within the following limits: τ — from 60 to 720 sec; t — from 900 to 1100°C; w — from 0 to 3 m/sec; and, the distance x from the surface of the specimen — from 0 to 0.2 mm. The difference between the carbon contents in the surface layers of the specimen after carburizing in accordance with the two methods of heating as a function of the carburizing parameters under investigation is presented in Table 1.

It is obvious that this difference is maximum and is approximately 25% when there is no gas fed into the system. It decreases to 5% as the flow rate of gas is increased from 0.5 to 2.5 m/sec. With varying temperature and isothermal-holding time, the difference remains constant and is 10% at a flow rate of 2 m/sec.

The theoretical results were subjected to experimental confirmation on flat steel 10 specimens. The gaseous carburizing compound, which was a mixture of 25% of CH_4 and 75% of N_2, was purified of water with silica gel and of oxygen with magnesium chips heated to 500°C. The gas consumption (and, consequently, the flow rate) were regulated using rotameters.

The weight gained by the carburized specimens while heating them by internal and external heat sources for various carburizing parameters was measured by the gravimetric method. The limiting relative error of the measurements was ±4%.

The bulk content (in %) of hydrogen at the outlet from the reaction chamber, which was converted into an amount of diffusing carbon in accordance with the reaction $CH_4 \rightleftarrows C + 2H_2$, was determined by the method of gas-adsorption chromatography and by quantitative analysis of the hydrogen peaks [4]. The limiting relative error of the measurements taken in accordance with this method was ±6%. Moreover, the carbon content on the surface of the specimens after quenching from 950°C in water was determined by the radiographic method. It was established that a difference exists in the carbon contents at a flow rate of 2 m/sec, t = 950°C, and τ = 120 sec. The carbon content was 0.90% for "internal" heating, and 0.82% for "external" heating.

The experimental values obtained for the specific increase in mass (Δm) was compared with theoretical curves obtained after reconstruction of the carbon profiles for various carburizing parameters. The results of this comparison are presented in Table 2. The goodness of fit between the model and the experimental data was plotted with respect to Fisher's criterion, which had a smaller corresponding threshold value.

CONCLUSIONS

1. When a specimen is heated by an internal heat source, a temperature gradient from 1100 to 200°C exists in the gaseous medium at a distance h = 6 mm.

2. The model that we have constructed for gaseous carburizing takes into account the convective flow resulting from the presence of a temperature gradient for the case when a specimen is heated by an internal heat source.

3. When the flow rate of gas is lower than 3 m/sec, convective motion accelerates the carburizing process of steel during "internal" heating. The difference in the weight gain realized by the two methods of carburizing reaches 30%. An increase in the velocity of the gas flow (at a constant temperature and for a constant time) leads to a reduction in the difference in the carburizing rate.

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PROPERTIES OF NITRIDED ELECTRICAL STEELS

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The development of modern instrument and machine building raises a number of complex problems in the area of use of various materials and production operations. One of these problems is development of a method of production of magnetic circuits for the purpose of increasing their operating life as the result of their low surface hardness and wear resistance.

It is possible to obtain the optimum combination of magnetic and mechanical properties for magnetic circuit materials by chemicothermal treatment, particularly gas nitriding.

The steels É10-Sh and 12Kh13, which are widely used in electrical engineering, and special quality 16Kh steel were investigated.

The high-temperature nitriding was done in a dissociated ammonia (NH_3) atmosphere with a degree of dissociation of 50-95% at temperatures from 600 to 1000°C with an interval of 100°C, a hold of 1 and 3 h, and subsequent air cooling in the muffle. Carbon tetrachloride (CCl_4), which was added to the working space of the furnace in a mixture with ammonia at 480-500°C for 1-3 min, was used for depassivation of the surface.

The mechanical properties (σ_t, δ) were determined on 4-mm-diameter standard specimens on a UMM-5 tensile machine. The magnetic properties were determined by the ballistic method on a BU-3 instrument on toroidal specimens with an outer diameter of 22 mm, and inner of 18, and a height of 12 mm which were first annealed in vacuum at 900°C for 2 h.

To determine the life of parts produced from standard chemical nickel coated and nitrided magnetic circuits stand production tests were made.