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Stimulation of the Bainite Transformation Scenario by an External Magnetic Field

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Abstract

Introduction. It makes practical sense to change the properties of steels with a bainite structure, as with bainite transformation under the influence of a magnetic field, it is possible to improve the ductility of the steel while maintaining or even increasing its strength. Scientific research in this area has focused on the influence of the magnetic field on thermodynamics and on the change in the phase transformation scenario. However, there is no detailed description in open sources of the effect of a magnetic field on the structure and properties of the products of intermediate bainite transformation. The aim of the work is to study the peculiarities of the influence of an external magnetic field on the scenario and kinetics of phase transformation of steel.

Materials and Methods. The study was conducted using samples made of 65G steel. Their chemical composition was monitored using a Magellan Q8 optical emission spectrometer. Heat treatment (resistive heating) was carried out in an IMASH 20–75 installation for high-temperature research. The heating temperature was approximately 1000 degrees 1000°C, and the holding time was 10 minutes. The sample was cooled down using water-cooled electrical contacts. An external magnetic field with a strength of 400 kA/m and 800 kA/m was created by an electromagnet integrated into the vacuum chamber of the installation.

Results. The experiments confirmed the potential for altering the transformation pathway from pearlite into bainite in the presence of an external magnetic field of up to 1 MA/m. Images of the microstructure and surface relief of samples after cooling in a magnetic field were obtained. Kinetic changes and dependencies of the volumetric transformation rates on the duration of isothermal exposure were analyzed. It has been found that exposure to a constant magnetic field of 1.6 MA/m increased the volumetric transformation rate by 1.808 times (for 65G steel) and by 1.687 times (for 45Kh steel).

Discussion and Conclusion. The results of observations of changes in the surface relief during cooling in the absence of a magnetic field, and in magnetic fields of various strengths, were recorded. This has allowed us to draw the conclusion that the external magnetic field stimulates the bainitic transformation instead of the original pearlitic one. Microstructural changes can be explained by the influence of the magnetic field on the initial phase magnetic state.

Keywords: bainite transformation magnetic stimulation, pearlite transformation, improvement of steel properties, microstructural changes in steels, vacuum etching, magnetostrictive deformations

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Научная статья

Стимуляция бейнитного сценария превращения внешним магнитным полем

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Аннотация
Введение. Изменение свойств сталей с бейнитной структурой имеет практический смысл, т. к. при бейнитном превращении под воздействием магнитного поля возможно улучшение пластичности стали при сохранении или повышении ее прочностных показателей. Научные изыскания в этой сфере касались вопросов влияния магнитного поля на термодинамику и смену сценария фазового превращения. Однако в открытых источниках нет детального описания воздействия магнитного поля на структуру и свойства продуктов промежуточного бейнитного превращения. Цель работы — исследование особенности влияния внешнего магнитного поля на сценарий и кинетику фазового превращения стали.
Материалы и методы. Исследование проводилось на образцах из стали 65Г. Их химический состав контролировали при помощи оптико-эмиссионного спектрометра Magellan Q8. Термическую обработку (резистивный нагрев) проводили в установке для высокотемпературных исследований «ИМАШ 20–75». Температура нагрева — около 1000 °C, время выдержки — 10 минут. Образец охлаждали при помощи водоохлаждаемых электроконтактов. Внешнее магнитное поле напряженностью 400 кА/м и 800 кА/м создавалось электромагнитом, интегрированным в вакуумную камеру установки.
Результаты исследования. Эксперименты подтвердили возможность смены сценария превращения с перлитного на бейнитный при воздействии внешним магнитным полем до 1 МА/м. Получены изображения микроструктуры и поверхностного рельефа образцов после охлаждения в магнитном поле. Проанализированы кинетические изменения и зависимости объемных скоростей превращения от времени изотермической выдержки. Установлено, что действие постоянного магнитного поля напряженностью 1,6 МА/м увеличивает объемную скорость превращения в 1,808 раза (для стали 65Г) и в 1,687 раза (для стали 45Х).
Обсуждение и заключение. Зафиксированы результаты наблюдений за изменением поверхностного рельефа при охлаждении без магнитного поля и в магнитных полях различной напряженности. Это позволило сделать вывод о стимуляции внешним магнитным полем бейнитного превращения вместо исходного перлитного. Микроструктурные изменения объясняются влиянием поля на магнитное состояние исходной фазы.

Ключевые слова: магнитное стимулирование бейнитного превращения, перлитное превращение, улучшение свойств сталей, микроструктурные изменения сталей, вакуумное травление, магнитострикционные деформации

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Introduction. As it is known, the magnetic field affects thermodynamics [1], in particular, the equilibrium temperature of phase transitions [2]. A significant shift in critical temperatures can be achieved only when using sufficiently strong (pulsed) magnetic fields [3], which is associated with certain technical difficulties when implemented in production conditions. The experiments indicate the appearance of α-phase in structural and tool steels under the action of fields with strength of 1.6–2.4 MA/m [1]. These processes take place at temperatures that are much higher than equilibrium and do not fit into the shift assumed by thermodynamic estimates [4]. The influence of an external magnetic field during the heat treatment of steel is expressed in an increase in the rate [5] and dispersion of transformation products [6]. It is known from [7] that during intermediate (bainitic) transformation under the influence of a magnetic field with strength of up to 2 MA/m, structural changes allow for a greater margin of plasticity while maintaining or slightly increasing strength parameters.

The regions with a short-range magnetic order in the γ-phase undergo magnetostriction under the action of an external magnetic field. This is due to the magnetic inhomogeneity of austenite [8] and causes a change in the field of elastic forces of the lattice, and the energy of formation of the critical nucleus of the α-phase decreases. The external magnetic field increases the number and size of ferromagnetic clusters [1]. As a result, the number of nucleation centers multiplicatively increases during cooling in a magnetic field.

It is shown in [9] how the short-range magnetic order in austenite affects the change of the phase transformation scenario. It is known from [10] that the magnetic state of γ-phase determines the transformation of ferromagnetic α-phase into one or another product. It can be ferrite, perlite, bainite or martensite.

The aim of the presented work is to experimentally verify the possibility of changing the pearlite transformation scenario to a bainite one when exposed to an external magnetic field up to 1 MA/m. In addition, it is necessary to evaluate the change in the kinetics of bainite transformation when the field is applied.

Materials and Methods. Samples of one melting made of 65G steel were used. Their chemical composition was monitored using a Magellan Q8 optical emission spectrometer (Table 1).

Table 1

Average content of elements in the samples

Steel grade	Mass fraction, %							
	C	Si	Mn	Cr	S	P	Cu	Ni
65G	0.65	0.20	0.97	0.21	0.009	0.0012	0.08	0.13

Polished samples were placed in a vacuum chamber of an IMASH 20–75 high-temperature research facility. This equipment provided vacuum in the working chamber of $1.3 \cdot 10^{-5} \div 6.6 \cdot 10^{-6}$ Pa. This made it possible to implement the vacuum etching method. The structure was revealed as a result of evaporation in a vacuum at high temperature under the influence of surface tension. Upon cooling during phase transformations accompanied by shear processes, a corresponding relief appeared on the surface of the sample.

The samples were subjected to resistive heating to ~ 1000°C for 10 minutes and cooled with heat removal to water-cooled copper electrical contacts at a rate of ~28÷32 °C/s. In accordance with the diagram of the isothermal decomposition of austenite of 65G steel, the obtained cooling rate corresponded to the intersection of the nose of the area of the beginning of the pearlite transformation. The high heating temperature contributed to the growth of the austenitic grain and vacuum etching of its boundaries, which was required for video recording of surface relief changes during phase transformation.

To measure the temperature, thermal junctions were welded in the middle of the sample. During cooling, the processes occurring on the surface were recorded using an Eakins digital eyepiece. The obtained data on the microstructure of the surface relief and inside the sample were processed to determine the volume fraction of the structural components. For this purpose, SIAMS 800 analytical software was used in 16÷25 fields of vision.

External magnetic field was created by an electromagnet integrated into the vacuum chamber of the installation [11]. The experiments involved fields with a strength of 400 kA/m and 800 kA/m. Samples without a field were processed in the same way, but with an electromagnet removed from the vacuum chamber.

Results. With the bainitic or martensitic shear character of the transformation, a relief should appear on the surface of the polished sample. If this did not happen, we were talking about a pearlitic transformation. Under experimental conditions, the cooling rate was insufficient for quenching 65G steel with martensite. One could expect competition between pearlite and bainite transformations depending on the presence or absence of an external magnetic field during the cooling process.

Figure 1 shows screenshots of video frames of changes in the surface relief observed during the transformation of supercooled austenite at various points in time (τ). Each line in Figure 1 corresponds to the specified strength of the external magnetic field (H).

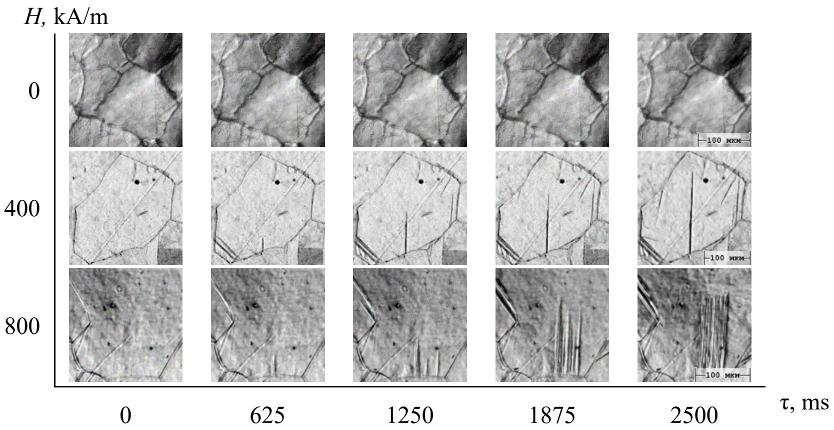


Fig. 1. Change in surface relief during cooling depending on strength of the external magnetic field (H, kA/m) and transformation time (τ, ms)

Figure 2 shows the microstructures of the surface relief and inside the samples after various processing modes.

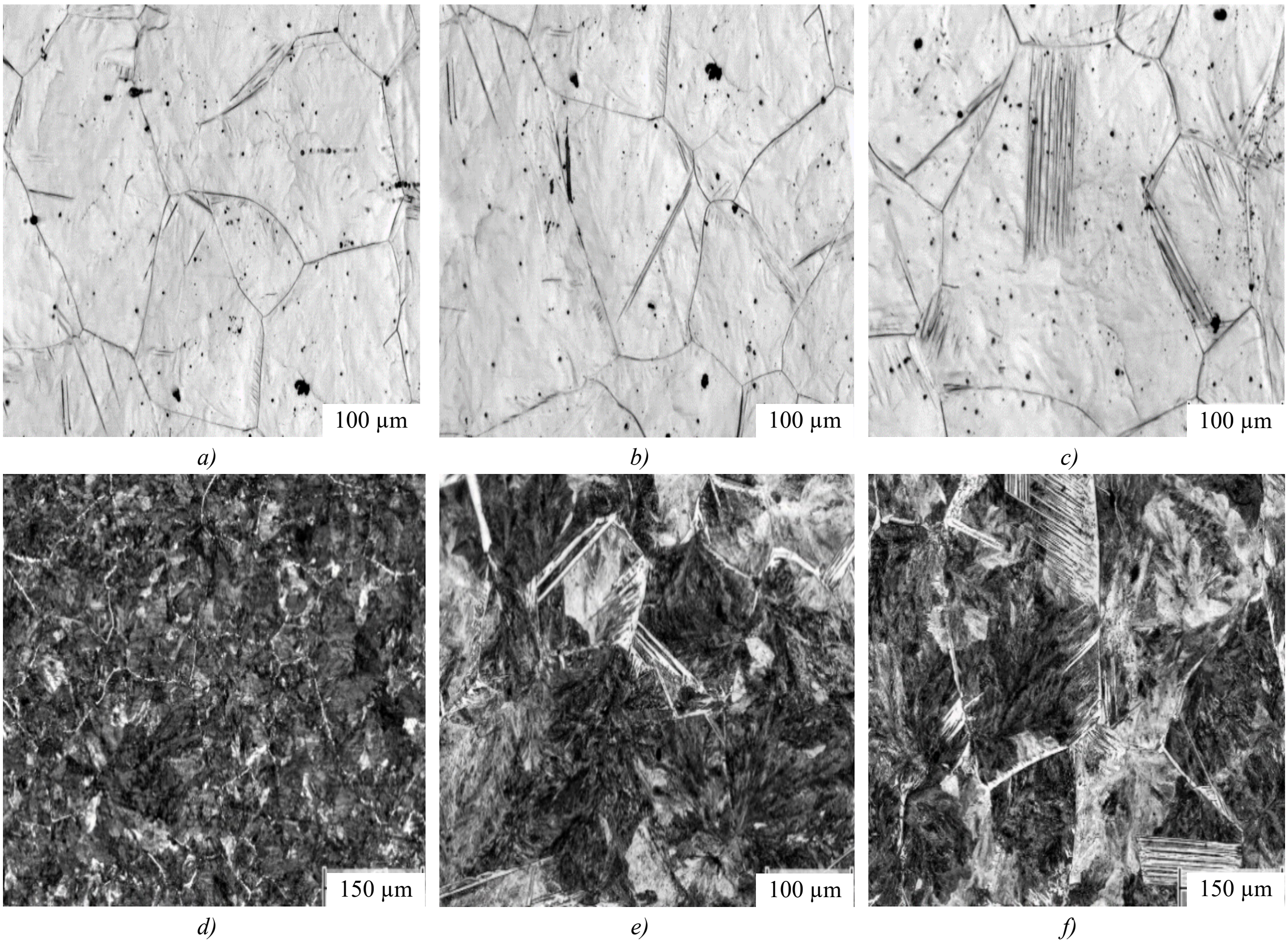


Fig. 2. Microstructure of the surface relief (*a, b, c*) and inside t he sample (*d, e, f*) after processing:
a, d — without a field; *b, e* — in a magnetic field with a strength of 400 kA/m;
e, f — in a magnetic field with a voltage of 800 kA/m

When processing without a field, changes in the surface relief were observed only in individual small formations (1st line of Fig. 1 and Fig. 2 *a*). On the video recording of austenite grain cooling, the propagation of the wave process over the surface was slightly noticeable. Apparently, this was a reflection of phase transformation. Microstructural analysis of the inner layers of the sample showed the presence of an overwhelming amount (98%) of the pearlitic structure (Fig. 2 *d*).

With the imposition of an external magnetic field, the surface relief was formed by nascent and growing bainite needles (the 2nd line of Fig. 1 and Fig. 2 *b*). These crystals could not be classified as martensitic because of their slow growth (Fig. 1). With increasing field strength, the intensity of shear transformation on the surface increased (Line 3 of Fig. 1 and Fig. 2 *c*), a batch bainite was formed.

Under the action of a magnetic field with a strength of 400 kA/m, the volume fraction of bainite increased three-fold — up to 6% (Fig. 2 *e*) compared with treatment without a field. In a magnetic field with a strength of 800 kAm, the volume fraction of bainite was already 8÷10%. This allowed us to conclude that it stimulated the change of the scenario of transformation from pearlite to bainite during processing in an external magnetic field.

If the initial phase (austenite) was kept as long as possible during cooling, then the short-range magnetic order (magnetic inhomogeneity), which increased in it with a decrease in temperature, would lead to an athermal martensitic transformation scenario to its critical extent. This was known from [9]. It was shown in [1] that the superposition of an external magnetic field during cooling of austenite led to additional, forced magnetic stratification of austenite due to an increase in the number, size and time of stable existence of ferromagnetic clusters. Under the conditions of the current experiment, artificially enhanced by an external field, the short-range magnetic order in the γ-phase promoted the bainite transformation instead of the pearlite one, which was natural for these cooling conditions without superposition of the field.

Under the influence of a magnetic field, the kinetics of the bainite transformation changed significantly. This was evidenced by the increase in the bainite reaction noted during the experiment with an increase in the magnetic field strength. In addition, [7] considered the imposition of an external magnetic field with a strength of 1.6 MA/m during isothermal exposure of various steels. The results of this work also confirmed the above statement about the kinetics of transformation.

To clarify the mechanism of the influence of an external magnetic field on the kinetics of an intermediate transformation, the following factors were taken into account:

– specifics of the growth of bainite crystals, which depended on the rate of removal of carbon atoms from the γ/α boundary;

– structural stresses arising during transformation due to changes in the specific volume of the transforming phases.

This approach was due to the fact that relaxation processes at the interface were strongly inhibited at low temperatures [12]. In such a situation, the stress gradient caused the drift of carbon atoms in spite of the concentration heterogeneity. This played a decisive role in the rate of growth of the lower bainite. The movement of C atoms led to a decrease in its concentration in the volumes of the γ-phase along the growth front of the bainite plates. As a result, a concentration gradient-controlled diffusion flow occurred. It was directed towards the growing crystal and reduced its growth rate. Dependencies describing these processes were found in the works of L.N. Alexandrov and B.Ya. Lyubov [13].

Magnetostrictive deformations occurred under the influence of an external magnetic field. Their elastic energy could make a certain contribution to the energy of interaction of diffusing atoms with the field of structural stresses. An increase in carbon drift and an increase in the growth rate of α-phase crystals should be expected. The rate of growth by the drift mechanism in accordance with the calculations of L.N. Alexandrov and B.Ya. Lyubov is described by the dependence:

$$V = \frac{2PD}{R_{кр}kT\left(1-\left(\frac{C_{н.ф}}{C_0}\right)^{\frac{4}{7}}\right)}. \quad (1)$$

Here D — carbon diffusion coefficient in austenite; $R_{кр}$ — radius of the critical nucleus under the supercooling; $C_{н.ф}$ and C_0 — carbon concentration in the α-phase and the initial austenite respectively. P characterizes the energy of interaction of diffusing atoms with the field of structural stresses caused by dilation of ε with a change in volume during the transformation process, and is found from the ratio:

$$P = \frac{8}{9}\pi r_a^3 \omega \frac{4\mu\varepsilon m}{(3-4v)(1-m)}, \quad (2)$$

where r_a — radius of the carbon atom; ω — parameter characterizing the dependence of the lattice constant on the concentration of atoms of the dissolved element in solid solutions; E — Young's modulus; ν — Poisson's ratio; $\mu = (E / 2) \cdot (1 - v)$ — Lame coefficient (shear modulus in the direction [100]); $m = (a - b) \cdot (a + b)$, where a and b — dimensions of the semi-axes of the crystal in the form of an ellipsoid of rotation.

The calculation according to formula (1) was carried out for carbon steel at: $C_0 = 0.7$; $m = 0.9$; $v = 0.3$; $\mu \approx 73.5$ hPa; $D = 0.0999\, exp\left(\frac{-131300\,\text{J/mol}}{RT}\right)\frac{\text{cm}^2}{\text{c}}$; $\varepsilon = 0.01$; $\omega = 0.02$. Value $R_{кр}$ was determined from the ratio $R_{кр} = 2\sigma / \Delta F_0$. Surface tension at the coherent boundary $\sigma = 0.2$ J/m^2; ΔF_0 at $T = 600$ K was 315 MJ/m^3. Value $C_{н.ф} = 0.4$ was determined as the concentration corresponding to the temperature of the beginning of the martensitic transformation (600 K). The growth rate of α-phase crystals found in this way was $\sim 8\cdot10^{-6}$ cm/s, i.e. it was a value of the same order as $V_{ср} \sim 10^{-6}$ cm/s, obtained experimentally for 65G steel when videotaping isothermal relief formation.

When the magnetic field was turned on, the measurement of the growth rate gave the same results, i.e. the effect of magnetostrictive stresses on the intensification of drift was not experimentally detected.

Let us suppose the elastic displacement was equal to the true magnetostriction of the paraprocess $\lambda \approx 0.5\cdot10^{-4}$ [14]. In this case, at $H = 1.6$ MA/m and $t = 400$°C the stresses from magnetostriction were $\sigma_\lambda = E_\lambda \approx 10$ MPa. They made a very small contribution to the energy of interaction of diffusing atoms with the field of structural stresses. This was explained by the fact that the magnitude of magnetostriction was two to three orders of magnitude less than the magnitude of dilation (0.01 ÷ 0.07 [15]) at a shear γ→α transition. For this reason, the estimation of the contribution of magnetostriction according to formula (1) gave a vanishingly small difference in the values of the growth rate during processing without a field and in a magnetic field.

The acceleration of the bainite formation process can actually be estimated using the A.N. Kolmogorov equation [16], which establishes a relationship between the degree of transformation, the rate of nucleation and the growth of the centers of a new phase. The change in the volumetric rate of transformation in a magnetic field due to a decrease in the formation of a ferromagnetic nucleus of critical size [1] can be found by formula:

$$\frac{\upsilon_H}{\upsilon_0} = exp\left[\frac{w}{kt}\left[1-\left(1+\frac{\Delta f^*}{\Delta f}\right)^{-4}\right]\right], \quad (3)$$

where υ — volumetric rate of transformation (indices *0* and *H*, respectively, indicate the processing conditions without a field and in an external magnetic field); W — energy of formation of an equilibrium nucleus; I — magnetization; H — magnetic field strength; Δf — specific "chemical" driving force; Δf^* — free energy of formation of one ferromagnetic cluster [1].

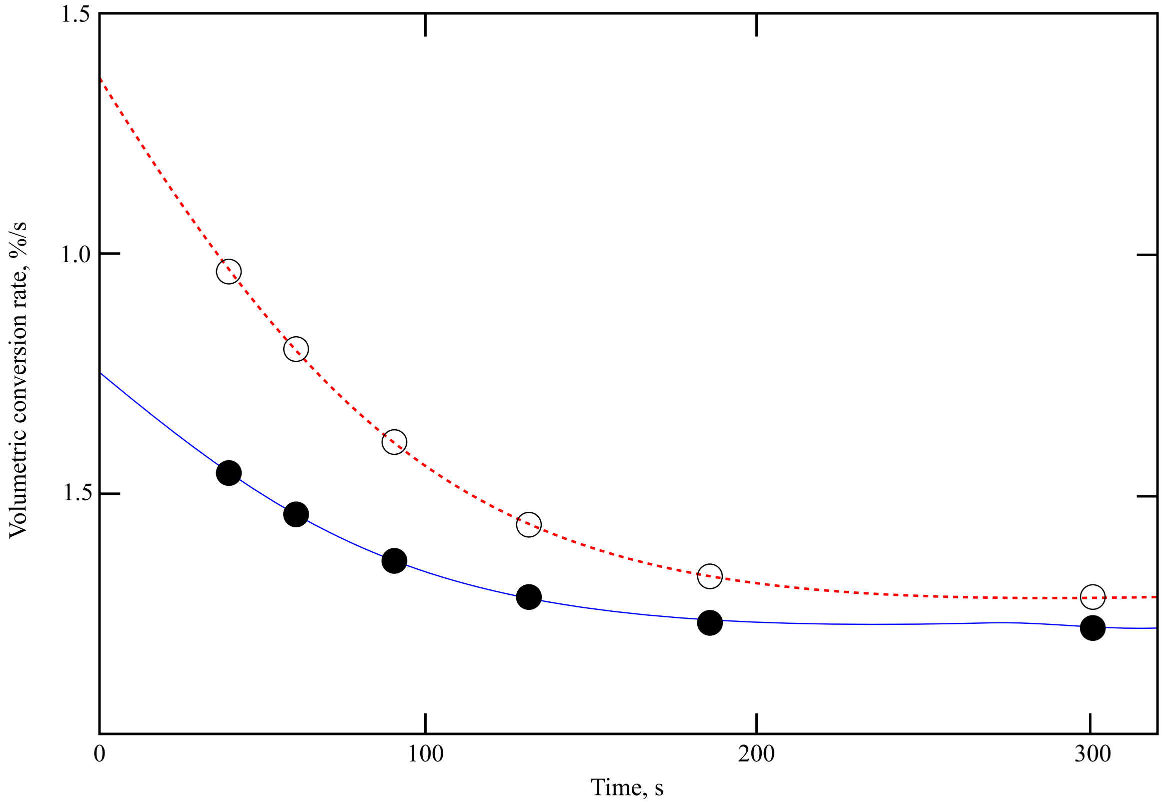
According to the classical theory of L. Kaufman and M. Cohen [17], the nucleation energy of the centers of new phases is equal to:

$$W = \frac{952{,}7 \cdot \theta^2 \sigma^2}{\left(\Delta f + \Delta f^*\right)^4}. \quad (4)$$

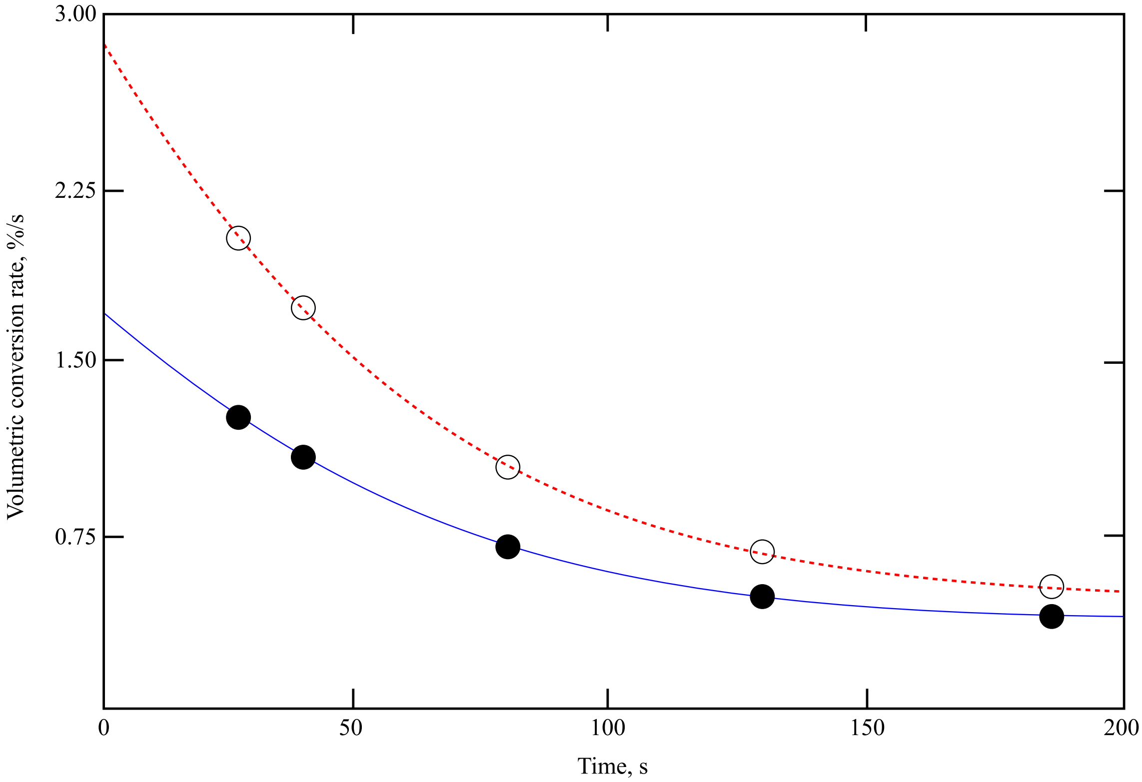
Here Δf^* — process of formation of ferromagnetically ordered clusters in austenite; θ — parameter that takes into account the influence of elastic deformation energy; σ — surface tension. It is known from [17] that $\theta^2\sigma^3 = 9.92 \cdot 10^{10}$ J^5/m^{12}.

Calculations were performed for temperatures of 543 K (65G steel) and 628 K (45Kh steel) at a magnetic field strength of H = 1.6 MA/m. Energy of formation of the equilibrium nucleus W was determined at a specific chemical driving force Δf = 150 MJ/m^3 taking into account the field strength and the average size of the ferromagnetic cluster ~ 1.8 nm [1], for which value Δf^* = 0.63 MJ/m^3 was obtained. Calculation by formula (3) gave for the bainitic transformation in 65G steel υ_H/υ_0 = 1.804, and in 45 Kh steel υ_H/υ_0 = 1.665.

Dependencies of the volumetric conversion rate (Fig. 3) were obtained using experimental data [7] on the degree of bainitic transformation in 65G and 45Kh steels at different times of isothermal exposure without a field and in a magnetic field with a strength of 1.6 MA/m.



a)



b)

Fig. 3. Dependencies of volumetric conversion rate (vertical axis, %/ s) on time of isothermal exposure: *a* — for 65G steel at a temperature of 375°C; *б* — for 45Kh steel at a temperature of 320°C. The blue curve reflects processing data without a field, the red one — in a magnetic field. Experimental points are marked on each line

Figure 3 allows us to consider the ratio of the volumetric conversion rate during processing in the field to processing without the field υ_H/υ_0 at the very beginning of the bainite reaction (extrapolated value in τ = 1 s). For 65G steel, it turns out to be 1.808, for 45Kh steel — 1.687. This is close to the theoretical estimates given above: 1.804 for 65G steel and 1.665 for 45Kh steel. In the process of transformation, the speeds change. If we consider the very first experimental points on the graphs, then:

– for 65G steel at τ = 40 s υ_H/υ = 1.75;

– for 45Kh steel at τ = 28 s υ_H/υ = 1.629.

As the isothermal exposure time increases, the volume velocities become less correlated with the calculated values.

Conclusion. It has been experimentally established that by using an external magnetic field, it is possible to change the transformation scenario from pearlite to bainite. This is explained by an increase in the degree of short-range magnetic order in austenite as a result of an increase in the number and size of ferromagnetic clusters in the gamma phase under the influence of a magnetic field. With an increase in its voltage, the magnetic heterogeneity of austenite increases. As a result, the rate of bainite transformation increases. The calculated values of the increase in the volumetric rate of transformation under the action of an external magnetic field are in good agreement with experimental data for the initial rates of bainite transformation.

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