

MARTENSITIC TRANSFORMATION IN LOW-CARBON STEELS

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Translated from *Metallovedenie i Termicheskaya Obrabotka Metallov*, No. 8, pp. 8–14, August, 2017.

Isothermal and thermokinetic martensitic transformations in low-carbon martensitic steels have been studied. A model is proposed that relates the mechanical state of the austenite, as dependent on the parameters of thermal treatment and the law of the grain size distribution, to the volume fraction of transformed martensite. Physical constants of the transformation are determined.

Key words: isothermal martensitic transformation, lath martensite, austenite, grain size distribution.

INTRODUCTION

According to notions of the martensitic transformation, which have been developed by the middle of the 20th century, the main features of this phenomenon are the existence of a critical cooling rate, lack of dependence of the transformation start temperature (M_s) on the cooling rate (v_{cool}) varied in a broad range (for the same steel composition), relationship between the volume fraction of martensite and the cooling rate, weak influence of the exposure duration on the amount of retained austenite, instantaneous growth of steel grains, and absence of changes in the phase composition. However, already at the end of 1950–1960s, new data appeared that proved the possibility of isothermal martensitic transformation at low temperatures. It was shown that the martensitic transformation should be considered as a usual phase transition in a single-component system [1, 2].

At present, some issues are still not completely clear, including the mechanisms of nucleation of the martensite phase [3], martensite crystal geometry and morphology [4–14], and possibility of predicting the martensite forma-

tion kinetics [15–17]. The transformation kinetics can be described using equations of the Avrami type [18, 19] derived assuming validity of the first-order reaction kinetics, according to which the elementary event involves only one particle (molecule, atom, ion). An alternative approach is based on the transformation kinetics described assuming a functional relationship between T_0 (temperature of thermodynamic equilibrium of the austenite–martensite transformation) or M_s (martensite start temperature) and T_{tr} (transformation temperature) [20–22].

The present work was aimed at studying and modeling the thermokinetic and isothermal martensitic transformations in low-carbon steels of the martensite class.

METHODS OF STUDY

The experiments were performed with low-carbon martensitic steel (LMS) grades 07Kh3GNM and 15Kh2G2NMF with lath martensite structure obtained upon austenitizing and cooling in air (austenitization temperature, 950°C), the elemental compositions of which are given in Table 1. The microstructure of steel specimens was studied by optical and electron microscopy, magnetometry, and dilatometry techniques. The extent of shear-induced $\gamma \rightarrow \alpha$ transformation was estimated isometrically in 240–500°C temperature in-

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TABLE 1. Chemical Composition of Steels Studied

Steel grade	Content of element, wt. %										
	C	Si	Mn	Cr	Ni	V	Nb	Mo	Cu	S	P
07Kh3GNM	0.07–0.09	0.27	0.92	3.20	1.06	–	–	0.20	–	0.009	0.008
15Kh2G2NMF	0.15	0.31	2.07	2.39	1.48	0.14	0.07	0.53	0.19	0.008	0.016

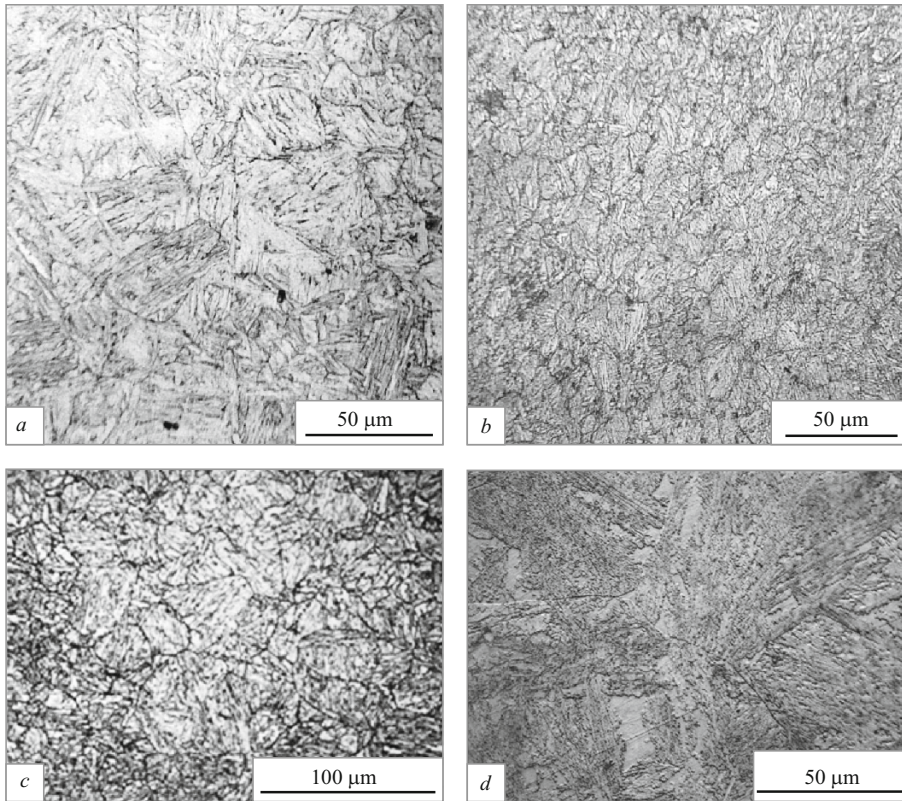


Fig. 1. Structure of 07Kh3GNM (*a, c*) and 15Kh2G2NMFB (*b, d*) low-carbon martensite steels in initial state (*a, b*) and upon isothermal exposure at 499 and 360°C, respectively (*c, d*).

terval. The true size of austenite grains was determined by the intercept method [23].

The microstructure of specimens was analyzed using a Neophot-32 microscope at $\times 100 - 400$ magnification and FEI Quanta 200 (Philips) scanning electron microscope. The amount of martensite formed during isothermal exposure and on cooling was determined by magnetometry on a modified Akulov type anisometer with automatically controlled experimental parameters.

RESULTS AND DISCUSSION

The initial structures of LMS grades studied, as obtained upon quenching in air from rolling temperatures, are presented in Fig. 1*a* and *b*. According to electron-microscopic data for 07Kh3GNM and 15Kh2G2NMFB steels, the most probable grain sizes were 26 and 6.5 μm and the corresponding lath widths were $h \sim 460$ and 300 nm, respectively.

Taking into account the right-hand asymmetry of the observed austenite grain size distributions (Fig. 2) and the results of previous investigations, it was suggested that these distributions obey a lognormal law [23]. The hypothesis of lognormal distribution of austenite grain sizes was checked according to the Pearson criterion (χ^2) [24] at $p = 0.05$ confidence level (Table 2). Previously, the lognormal size distribution of LMS structure constituents was confirmed in [25, 26].

The most important factor determining the transformation kinetics is the particle (grain) size [22, 27]. The steel

structure in specimens upon isothermal exposures represents lath martensite (Fig. 1*c* and *d*), the distinctive features of which are small values of the lath width and misorientation angle and different directions of carbide axes [28].

Martensite formation takes place provided that the difference of free energies (ΔG) of the austenite–martensite transformation becomes equal to the temperature-dependent specific work of conversion [22]. The free energy of martensitic transformation can be calculated as a product of the austenite yield stress and specific coefficient of the mechanical equivalent of heat, according to which [22]

$$\sigma_{0.2T} = b(T_0 - T), \quad (1)$$

where $\sigma_{0.2T}$ is the austenite yield stress (with allowance for the phase hardening [22]) at cooling temperature $T < T_0$; T_0 is

TABLE 2. Verification of the Hypothesis of Lognormal Distribution of Austenite Grain Sizes According to the Pearson Criterion (χ^2) in Steels Studied

Steel grade	χ^2	p	n
07Kh3GNM	12.8/12.6	0.05	6
15Kh2G2NMFB	12.7/11.4	0.05	5

Notations: p is the confidence level; n is the number of degrees of freedom; Pearson criterion χ^2 in numerator and denominator represents the obtained experimental values and published reference data, respectively.

the temperature of thermodynamic equilibrium of the austenite–martensite transformation; and $b = 1.3 - 1.4$ (for steels with Mo and W) and $b = 1$ (in the absence of these elements). The values of constant coefficient b were determined for lath martensite formation in LMS under conditions of continuous cooling [22]. In this work, it was assumed that these steels admit the dependence of b on the chemical composition. Each particular steel grade was characterized by its own value of this constant, which was the same for all temperatures of isothermal exposure.

As is known [3, 17, 22], growth of the grain size is accompanied by increase in the martensite start temperature and decrease in the austenite yield stress, which is also valid for LNSs [29]. The values of yield stress $\sigma_{0.2T}$ and grain size d in a broad range (from meso- to nanoscale) obey the Hall–Petch relationship [30]

$$\sigma_{0.2T} = \sigma_0 + kd^{-0.5}, \quad (2)$$

where σ_0 is the stress characterizing resistance to the propagation of dislocations in the grain body [30] and k is the coefficient describing hindered slip transfer through the grain boundary [30]. Grains of various sizes contribute differently to the austenite yield stress: large grains produce lower hardening than smaller ones. Therefore, it is necessary to take into account the influence of grain size distribution.

The characteristic stress σ_0 consists of the temperature-dependent (σ_0^{**}) and temperature-independent (σ_0^*) parts [31]:

$$\sigma_0 = \sigma_0^* + \sigma_0^{**}. \quad (3)$$

The temperature-independent component σ_0^* is related with resistance to the motion of dislocations from disordered solute atoms, disperse precipitates, and lattice defects.

The austenite yield stress at transformation temperatures close to zero was estimated from data on the temperature dependence of $\sigma_{0.2}$ [32] by interpolating it to 0 K. The corresponding $\sigma_{0.2}$ value for the austenite grain size within 40 – 50 μm was about 510 MPa. The value of coefficient k in formula (2), which characterizes the resistance of grain boundaries, is independent of the temperature [33] and amounts to $k = 0.46 \text{ MPa} \cdot \text{m}^{1/2}$ for austenitic steels [27].

The temperature-dependent component σ_0^{**} (related to the Peierls–Nabarro stress) obeys according to N. J. Petch data [31] the following relation:

$$\sigma_0^{**} = \beta \exp(-\alpha T), \quad (4)$$

where α and β are constant coefficients. For austenite at room temperature, $\sigma_0^{**} = 2 \cdot 10^{-4}G$ and amounts to about 38 MPa. As the temperature is reduced to nearly 0 K, the σ_0^{**} value exhibits more than tenfold growth [31] and reaches a level of about 380 MPa. Then, by jointly solving Eqs. (2) and (3), one can estimate the temperature-independent component as σ_0^* at about 60 MPa.

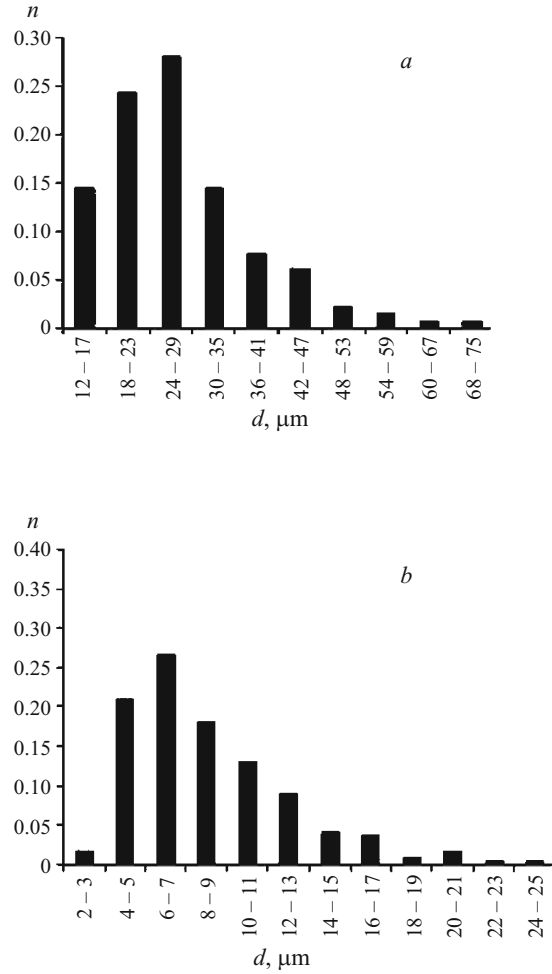


Fig. 2. Histograms of the distribution of austenite grain size d in LMS of 07Kh3GNM (a) and 15Kh2G2NMFB (b) grades (ordinate n is the probability density).

The minimum size d_i of austenite grain capable of transforming into martensite at a given temperature T is found by jointly solving Eqs. (1) and (2):

$$d_i = \frac{k^2}{(b(T_0 - T) - \sigma_0)^2}. \quad (5)$$

Then, the resulting volume fraction f_m of martensite can be determined by substituting formula (5) into the grain size distribution function expressed by formula (6) below. In all cases, the lognormal distribution law was found to be valid. It was assumed that the transformation of austenite begins with largest grains and ends by the austenite–martensite transformation in finest grains. The volume fraction of martensite corresponding to the distribution of grain sizes is expressed as

$$f_m = 0.5 \operatorname{erfc} \left(\frac{\ln(d_i) - \mu}{s\sqrt{2}} \right), \quad (6)$$

where μ and s are parameters of the lognormal distribution function. The use of error function $\operatorname{erfc} = 1 - \operatorname{erf}$ is related to

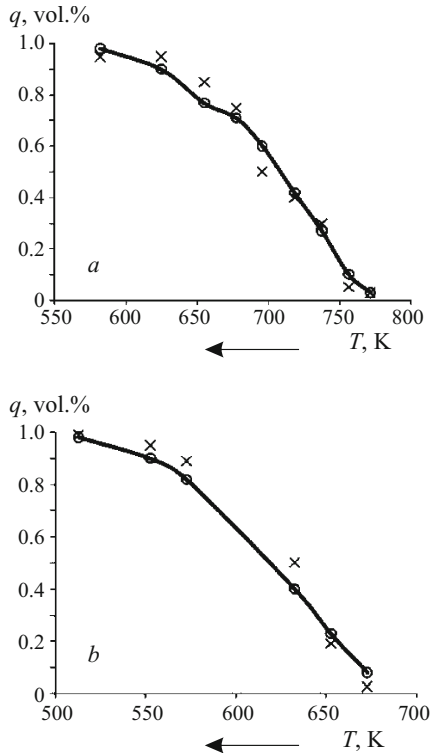


Fig. 3. Temperature dependences of austenite fraction q transformed into martensite in 07Kh3GNM (a) and 15Kh2G2NMFB (b) steel during continuous cooling in air from 1273 K (950°C).

the aforementioned fact that the transformation begins in largest grains and terminates in small ones (Table 3).

The values of constants α and β calculated by least squares are presented in Table 3. A decrease in the temperature of thermodynamic equilibrium with increasing content of carbon is consistent with published results [22].

Parameters of the grain size distribution according to Eq. (6) were used to construct the temperature dependence of the maximum fraction of transformed austenite during continuous cooling (Fig. 3). Thus, the kinetics of supercooled austenite transformation in LMSs on continuous cooling strongly depends on the grain size distribution.

In order to describe the kinetics of isothermal transformation, it is necessary to study the volume fraction of martensite as function of the duration of exposure. The fraction of transformed austenite determines the yield stress of a steel with the given grain size. During the isothermal exposure, the strength of austenite decreases due to stress relaxation, which allows the transformation volume to grow. However, another factor to be taken into account is the hardening of austenite, which suppresses its transformation. Since this hardening linearly depends on the transformed volume and proceeds in a narrow interval, variation of the mechanical state of γ -phase was described by the following relation [34]:

$$\sigma_{0.2T} = \sigma_{0.2T}^{\tau} \exp(-p\tau), \quad (7)$$

TABLE 3. Relationship between Grain Size d and Volume Fraction f_m of Martensite Formed under Isothermal Conditions

Steel grade, HT regime	T , K	d , μm	f_m	Constants
07Kh3GNM, $T = 866$ K, quenching from 950°C (30 min)	772	55/54	0.03/0.03	$\alpha = 0.89$; $\beta = 1.15$; $\mu = 2.31$; $s = 0.97$
	757	48/32	0.10/0.05	
	738	39/19	0.27/0.3	
	719	32/12	0.42/0.40	
	696	23/8.16	0.6/0.5	
	678	16/6.22	0.71/0.75	
	655	19/5	0.77/0.85	
	625	10/3.29	0.90/0.95	
15Kh2G2NMFB, $T = 780^\circ\text{C}$, forg- ing + quenching from 950°C (30 min)	582	7/2.21	0.98/0.95	$\alpha = 0.95$; $\beta = 1.15$; $\mu = 2.24$; $s = 0.93$
	673	33/36	0.080/0.025	
	653	19/20	0.23/0.19	
	633	12/13	0.4/0.5	
	573	4.0/5.08	0.82/0.89	
	553	3/4	0.90/0.95	
	513	2/2.68	0.98/0.99	

Notations: HT) heat treatment; μ and s) parameters of the lognormal distribution function; T_0) temperature of thermodynamic equilibrium of the steels; T) transformation temperature; α and β) constant coefficients in Eq. (5); d) grain size of austenite transformed into martensite; f_m) volume fraction of martensite.

Note. d and f_m values in numerator and denominator represent calculated and experimental data, respectively.

where $\sigma_{0.2T}^{\tau}$ is the yield stress upon exposure at temperature T for time τ , p is a constant coefficient, and τ_0 is the time to stabilization of the transformation at temperature T ($\tau_0 > \tau$).

Kinetic curves of the isothermal transformation of supercooled austenite presented in Figs. 4 and 5 were obtained by calculations in which $\sigma_{0.2T}$ was replaced by $\sigma_{0.2T}^{\tau}$. The calculated values of the volume fraction of transformed austenite did not deviate from experimental data by more than 15%.

CONCLUSIONS

1. It is established that the distribution of austenite grain sizes is the main factor that determined the volume of martensitic transformation of low-carbon austenite in LMSs.

2. A model is proposed that relates the mechanical state of low-carbon austenite with lognormal law of austenite grain size distribution to the thermodynamic and kinetic parameters of martensitic transformation. This model allows the volume fraction of lath martensite formed during continuous cooling of LMSs under isothermal conditions to be predicted.

This work was supported by the Ministry of Education and Science of the Russian Federation (Agreement

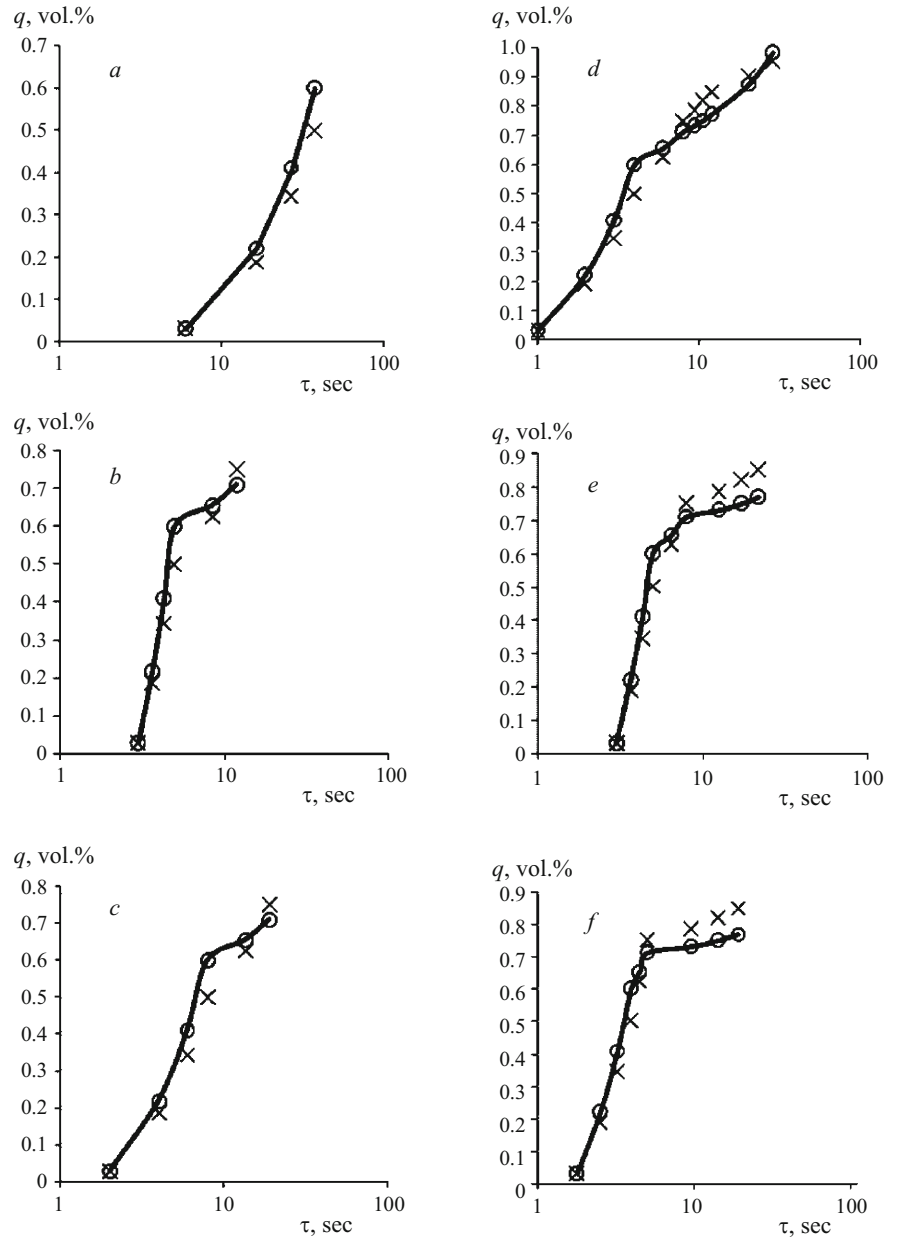


Fig. 4. Plots of the fraction q of austenite transformed into martensite in 07Kh3GNM steel vs. duration τ of isothermal exposure at temperatures: a) 465°C; b) 446°C; c) 423°C; d) 382°C; e) 352°C; f) 309°C; x) experiment; o) calculation.

No. 02.G25.31.0068 of 23.05.2013) in the framework of investigations according to Governmental Order No. 218.

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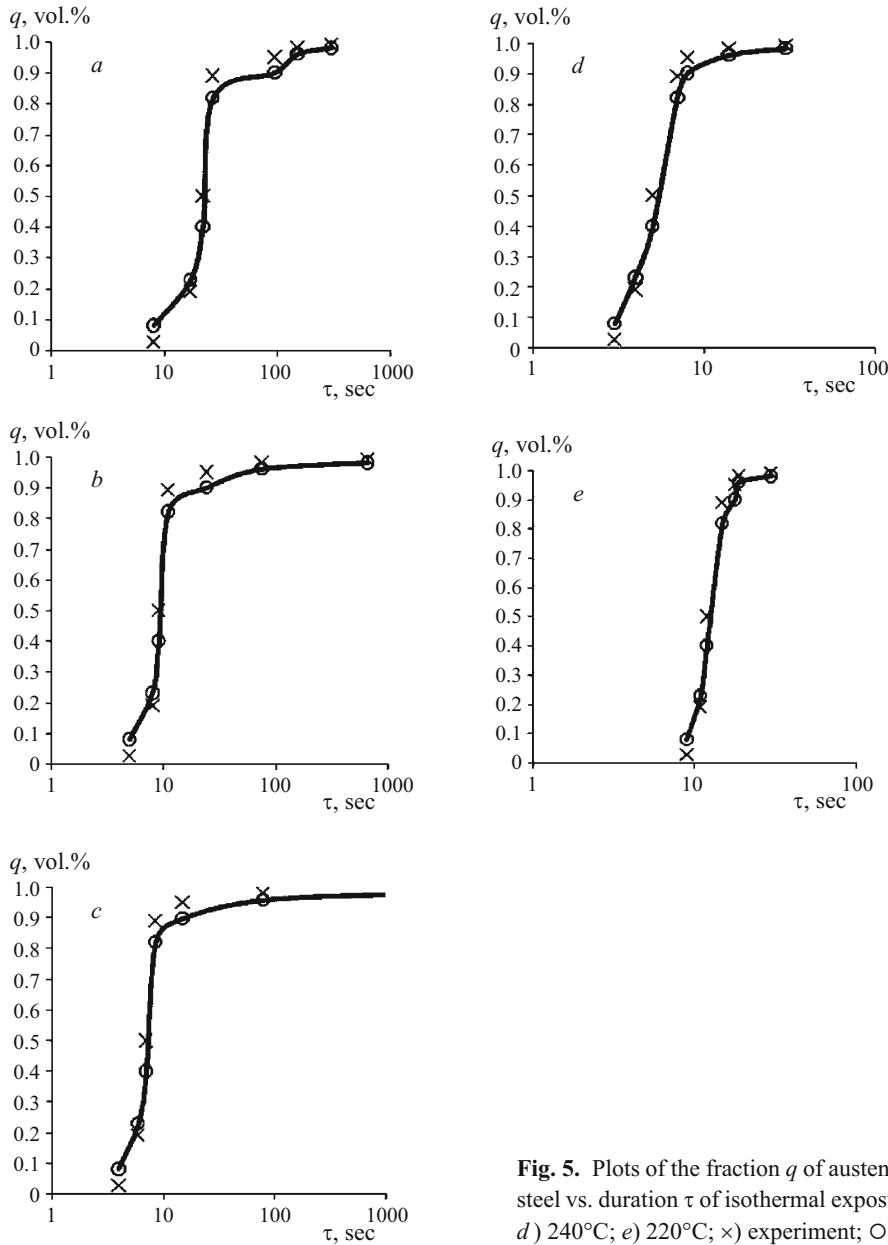


Fig. 5. Plots of the fraction q of austenite transformed into martensite in 15Kh2G2NMFB steel vs. duration τ of isothermal exposure at temperatures: a) 360°C; b) 300°C; c) 280°C; d) 240°C; e) 220°C; x) experiment; o) calculation.

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