

DIRECT MARTENSITIC TRANSFORMATIONS OF LOW-CARBON STEELS

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The proposed model is based on the use of the principle of detailed equilibrium, which occurs during phase transitions of the crystal lattice. This theory complements the theory of Landau phase transitions in crystalline media, as well as the theory of crystallization of matter by Kolmogorov and Avrami. In the proposed theory, martensitic transformations are described by equations of induced transitions between two energy levels, which correspond to the number of particles of the original phase with low energy (austenite) and the number of particles of the transformed phase with higher energy (martensite). The source of transformations are particles of the third kind – phonons, the number of which is related to the induced transitions of particles between energy levels and depends on the transformation temperature. The conclusions of the proposed theory quantitatively correspond to the experimental data for phase transformations of low-carbon steels.

Nowadays, various steel products and structures are used in almost all industries. The choice of steel as the main material for the manufacture of parts is due, first of all, to the best combination of such technological properties as strength, wear resistance, reliability and durability, as well as a wide variety of steel alloys and low cost. Iron ore gives a huge advantage when using this material.

In order to improve the mechanical properties of steel products, they are alloyed and subjected to preliminary treatment. Depending on the operating conditions and required properties of the steel, pre-treatment is carried out by various methods.

Heat treatment of metal products is a very complex technological process, which consists in heating the metal (alloy) to a certain temperature, holding it at this temperature for a given time and further cooling in order to obtain the necessary microstructure and, accordingly, the necessary properties of the product for use in specific conditions.

The topic is not new, as the phase transformation theories of L. Landau and the crystallization theories of A. Kolmogorov and J. Christian are known. However, not all of them can always be used to describe experimental results.

FORMULATION OF THE PURPOSE OF THE RESEARCH

The huge variety of metal alloys makes the task of heat treatment a very individual process, which requires careful selection of temperature regimes, methods of heating and cooling, exposure time depending on the chemical composition of a specific material.

The purpose of this work was to consider the previous theories of phase transformations of carbon steels, to analyze the discrepancies of experiments with analytical data, and to propose a new model for describing phase transformations.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

The theory of phase transitions in crystalline media, formulated as a description of a change in their symmetry (for example, the transition of a crystal from a phase from cubic to tetragonal symmetry), was first proposed by Landau in [1]. In the Landau theory, for the quantitative description of the change in symmetry, the concept of an order parameter is introduced, which is chosen as a quantity that is linearly transformed under the action of the symmetry group of the medium. This phenomenological approach, which consists in assuming the expansion of thermodynamic potentials in a series by degrees of this parameter, made it possible to describe changes in heat capacity near the phase transformation temperature. In particular, it was shown that if there is no jump in the state of the body at the point of symmetry change (there is no transition heat), then such transitions are accompanied by a jump in heat capacity.

To describe the PMP of metals and alloys based on Landau's phenomenological theory, such a thermodynamic quantity as shear strain is used as an order parameter [6]. In this case, the summation of the Gibbs free energy is carried out in powers of this quantity. However, in some cases, such decomposition does not describe the experimental results [7].

Another approach in the description of direct martensitic transformations (DMR) is to use a strict solution to the problem of crystallization of a substance, which is obtained under some schematic and rather general assumptions in the paper [7]. In particular, this work shows that the fraction of the transformed volume f is determined by the expression $f = 1 - \exp(-Kt^4)$, where t is the time of crystallization, K is the kinetic coefficient.

In a more complicated case, to describe the isothermal kinetics of the three-dimensional nucleation and growth of a new phase, Avrami suggested using the general relationship that bears his name [3]: $f = 1 - \exp(-Kt^n)$, where n is the kinetic coefficient.

This equation at $3 \leq n \leq 4$ must cover all cases in which the conversion rate is some decreasing function of time, up to its constant value.

However, calculations of the kinetics of phase transformations based on the Avrami equation do not always lead to correct results, since the value varies discretely during the transformation, depending on the carbon content and possibly the austenitizing temperature.

PRESENTATION OF THE MAIN RESEARCH MATERIAL

Discrepancies between the theoretical description of PMP and the experimental data described above require the continuation of the search for a theory that would more adequately describe phase transformations in metals and alloys.

Therefore, the physical model of martensitic transformations in crystalline media based on the principle of detailed equilibrium, which was described in [5] for martensitic transformations in nickel steel, is adopted in this work. Next, the model itself and its use in manganese steels will be described.

MARTENSITIC TRANSFORMATIONS IN NICKEL STEELS

Considering the above-mentioned discrepancy between theoretical models and experimental results of martensitic transformations in steels, it is advisable to put forward another physical model. As such, consider the model of induced transitions of quasiparticles between energy levels developed by A. Einstein [9].

The general appearance of the model of induced transitions is schematically depicted in Fig. 1, a.

Phase transformations in crystalline media are described using a simplified model schematically shown in Fig. 1, b of the two-level system (TLS).

Let's describe the TLS parameters.

When the temperature decreases from T_H to T_K , the structural transition of steel A to M can be characterized as an induced transition from the stable state A (level A) to the metastable state M (level M), and the probability of induced transitions can be attributed to this transition w_{AM} (see Fig. 1, b). We will assume that the stable state is characterized by energy \mathcal{E}_A and temperature T_A and the metastable state by \mathcal{E}_M and T_M accordingly.

Moreover, the following inequalities are valid: $\mathcal{E}_A < \mathcal{E}_M$, $T_A > T_M$. In Fig. 1, b the directions of transitions are indicated by arrows indicating the magnitude of the probability: μ_{MA} – the probability of a spontaneous transition; w_{MA} and w_{AM} – probabilities of induced transitions from the upper level of M to the lower level of A and vice versa, respectively.

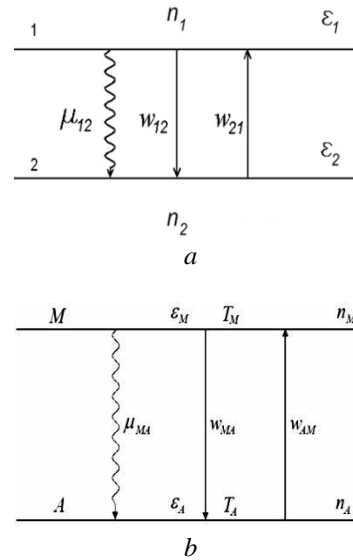


Fig. 1. General view of the model of induced processes in two-level systems (a); two-level AM system of carbon steel (b): n_A – number of elementary cells of phase A; n_M – the number of elementary cells of phase M

Based on the principle of detailed equilibrium, the solution of the system of equations (1) was obtained, which describes both athermal and isothermal direct martensitic transformations of manganese steels.

The system of equations describing the induced transition of phase A, M and phonons between energy levels has the following form:

$$\begin{cases} \frac{dn_1}{dt} = -\mu_{12}(1+N)n_1 + \mu_{12}Nn_2 = -\mu_{12}n_1 + \mu_{12}(n_2 - n_1)N; \\ \frac{dn_2}{dt} = -\frac{dn_1}{dt} = \mu_{12}n_1 - \mu_{12}(n_2 - n_1)N; \\ \frac{dN}{dt} = \mu_{12}(1+N)n_1 - \mu_{12}Nn_2 = \mu_{12}n_1 - \mu_{12}(n_2 - n_1)N; \end{cases} \quad (1)$$

In the region of high temperatures $T_K \leq T(t) \leq T_H^*$

for a large number of phonons $N_0 \gg n_{A0}, n_{M0} \gg 1$, the obtained equations are used to describe the isothermal direct martensitic transformation of nickel steel (Fe + 7%Cr + 2%Ni [5]).

The results of the comparison of the normalized experimental curves [2] and the analytical solution (2) in the area of high temperatures for nickel steel demonstrated in Table 1 and Fig. 2. The results of the comparison of the normalized experimental curves [2] and the analytical solution (2) in the area of low temperatures for nickel steel – in Table 2 and Fig. 3.

MARTENSITIC TRANSFORMATIONS OF MANGANESE STEELS

To confirm the expediency of using this model to describe phase transformations of steels, it was decided to check the analytical solutions by describing martensitic transformations in manganese steels.

The results of the experiment were taken for comparison data from work [2], which showed the dependence of the percentage content of martensite on time for manganese steel (Fe + 0.7% C + 6.5% Mn).

Table 1

Values of the parameters of the curves that describe the experimental data of nickel steel [2]

$T, ^\circ\text{C}$	580	600	620	635	650	680	725
A	2.51163	525.61394	104.40626	167.51094	106.07279	104.30425	130.9397
B	0.0227	9.2989E-4	0.44776	0.02168	0.14735	0.16748	0.04159
C	0.0168	1.5202E-4	0.002	0.05163	0.08818	0.15926	0.06849
k	1.73072	2.50219	0.86837	1.21282	0.80822	1.53915	1.2088
t_{AM}^*	10.602	33.566	$1.283 \cdot 10^3$	11.514	20.178	3.299	9.189

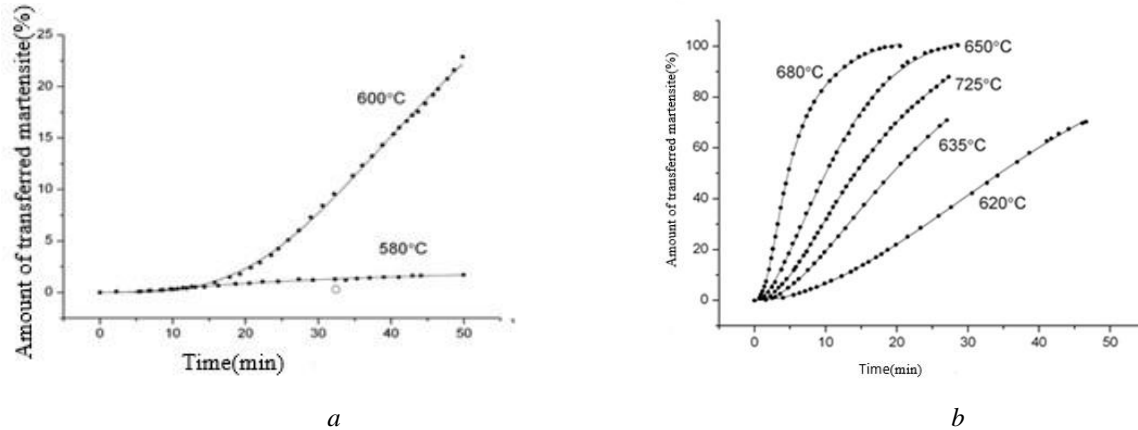


Fig. 2. Comparison of normalized experimental data (dark circles) with analytical solutions (2) (solid lines) for different temperatures of isothermal PMP of nickel steels

Table 2

Values of the parameters of the curves that describe the experimental data of nickel steel [2]

$T, ^\circ\text{C}$	A'	B'	B	C'	D
415	10.39448	12.54669	1.67272	0	0
400	32.02108	6.86054	0.93142	59.43278	6.12407
375	50.19302	85.35374	6.10650	11.05937	0.83587

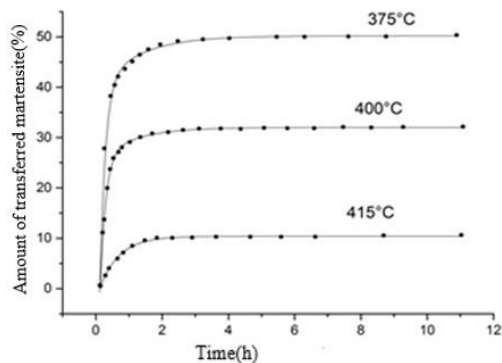


Fig. 3. Isothermal PMP in the region of low temperatures for nickel steel

The model proposed in [5] should demonstrate quantitative correspondence in manganese steels as well. Analytical solutions obtained from the original equations

$$\frac{n_{AS}}{n_{A0}} = \left(1 + \frac{n_{M0}}{n_{A0}}\right) \cdot 100 \cdot \left(1 - \exp\left(-2\mu' N_{eq} \xi(t, T)\right)\right) = A \cdot 100 \cdot \left(1 - \exp\left(-Bt \left(1 - \exp\left(-Ct^k\right)\right)\right)\right), \quad (2)$$

where $A = 1 + \frac{n_{M0}}{n_{A0}}$, $B = 2\mu' N_{eq}$, $C = (t_{AM}^*)^{-k}$.

The dependence of the reduced amount of martensite on time is shown in Fig. 4, and the values of the parameters of the curves are shown in Table 3.

include four constant coefficients, the value of which depends on the transformation temperature and is determined experimentally.

A comparison of the analytical dependences describing the isothermal PMP with the experimental data of the same process for one type of alloy steel shows a good quantitative agreement. Below is a graphic material that confirms the validity of the proposed model in the area of high temperatures and a large number of phonons.

We compare the theoretical dependence of the isothermal PMP of carbon and manganese steels with experimental data, using the dependence of the percentage content of the amount of transformed phase A on time in the region of high temperatures:

Table 3

Values of the parameters of the curves that describe the experimental data of manganese steel [2]

$T, ^\circ\text{C}$	A	B	C	t_a	k
-90	1.001101	0.198880	0.440417	0.255	0.6001
-103	1.000791	0.194365	17.27953	3809.098	0.3456

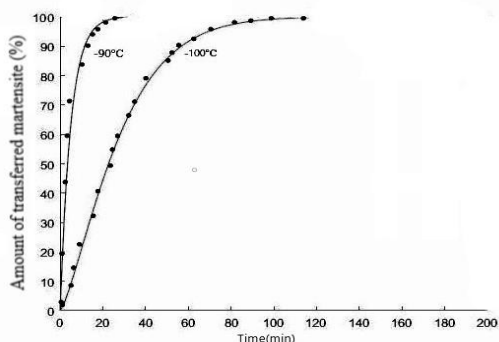


Fig. 4. Isothermal PMP in the region of high temperatures for manganese steel

$$\frac{n_{MS}(t)}{n_{A0}} = 100 \left(1 - \frac{n_{M0}}{n_{A0}} \right) \left(A(1 - \exp(-Bt)) + C(1 - \exp(-Dt)) \right) - 100 \frac{n'_{M0}}{n_{A0}} =$$

$$= A' - B' \exp(-Bt) - C' \exp(-Dt), \quad (3)$$

where

$$A' = 100 \left(1 - \frac{n_{M0}}{n_{A0}} - \frac{n'_{M0}}{n_{A0}} \right), \quad B' = 100 \left(1 - \frac{n_{M0}}{n_{A0}} \right) A, \quad C' = 100 \left(1 - \frac{n_{M0}}{n_{A0}} \right) C.$$

Table 4

Values of the parameters of the curves that describe the experimental data of manganese steel [2]

$T, ^\circ\text{C}$	A'	B'	B	C'	D
-165	97.39448	35.54669	0.00567272	50.3	0.0492
-183	80.4158	44.6179	0.00961965	33.3	0.03952
-195	72.4158	68.6179	0.00861965	5.33455	0.8852

The results of the comparison of the normalized experimental curves [2] and the analytical solution (2) in the region of high temperatures for nickel steel – Table 4, Fig. 5.

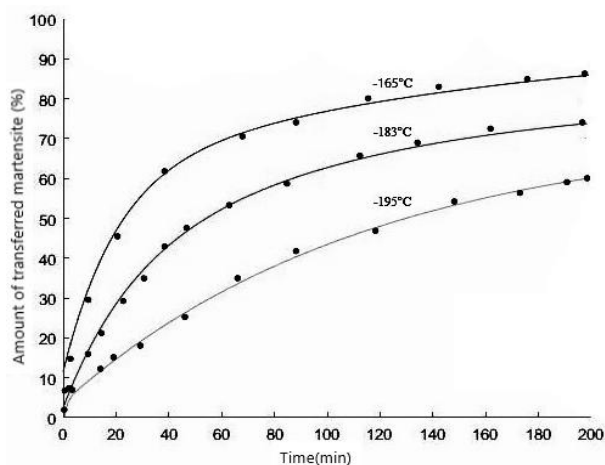


Fig. 5. Isothermal PMP in the region of low temperatures for manganese steel

CONCLUSIONS

A comparison of the analytical dependences describing the isothermal PMP of one type of manganese steel with experimental data in the region of high and low temperatures shows a good quantitative agreement. Such correspondence indicates the possibility of using the PMP model, based on the principle of detailed equilibrium, to describe the PMP processes of manganese steels in the region of high and low temperatures.

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ПРЯМІ МАРТЕНСИТНІ ПЕРЕТВОРЕННЯ НИЗЬКОВУГЛЕЦЕВИХ СТАЛЕЙ

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Запропонована модель базується на використанні принципу детальної рівноваги, яка виникає при фазових переходах кристалічної решітки. Теорія доповнює теорію фазових переходів Ландау в кристалічних середовищах і теорію кристалізації речовини Колмогорова і Аврамі. У запропонованій теорії мартенситні перетворення описуються рівняннями індукованих переходів між двома енергетичними рівнями, які відповідають кількості частинок вихідної фази з низькою енергією (аустеніт) і кількості частинок трансформованої фази з більшою енергією (мартенсит). Джерелом перетворень є фонони, кількість яких пов'язана з індукованими переходами частинок між енергетичними рівнями і залежить від температури перетворення. Висновки кількісно відповідають експериментальним даним для перетворень низьковуглецевих сталей.