KINETICS OF HARDENED LAYER FORMATION WITH INDUCTION HARDENING

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The kinetics of martensitic transformation of roll steels with induction heating by a current of industrial frequency are studied. It is shown that martensitic transformation proceeds autocatalytically. The time dependence of the amount of martensite with decomposition of supercooled austenite is established. Critical nuclei dimensions during phase transformation are determined. Martensite crystal growth may be described by a quasidiffusion equation.

Key words: roll steels, martensitic transformation, induction hardening, phonon.

INTRODUCTION

The most important production factor that affects the operating properties of a steel roll is heat treatment. In order to provide the required hardness for the roll barrel as final heat treatment there is use of induction hardening with current of industrial frequency (CIF). Hardening is the most critical heat treatment operation. With rapid cooling there is phase transformation of austenite into martensite, that has very marked hardness. Hardening is sued for increasing surface hardness of a component, and improving wear and fatigue resistance. The aim of this work is to describe quantitatively the mechanism of martensitic transformation with induction hardening of rolls.

METHODS OF STUDY

There are numerous factors that affect induction heating kinetics, that may be considered as a special form of transient thermal conductivity with internal positive and negative sources of energy. A positive source is an inductive electric current, and a negative source is thermal effects of exothermic reactions of phase and magnetic transformations. Thermal energy released with induction heating has a direct effect on temperature distribution only through a section of a surface layer. The thickness of this layer (or the depth of induc-tion heating penetration) may be determined by the equation [1]:

$$\Delta = 503 \sqrt{\frac{\rho}{f\mu}}, \qquad (1)$$

where Δ is heated surface layer thickness, m; ρ is specific resistance, $\mu\Omega \cdot$ m; f is current frequency, Hz; μ is relative magnetic constant.

Steel specific electrical resistance in the temperature range $20 – 1000$ºC varies within the limits $0.3 – 1.3\ \mu\Omega \cdot$ m, and magnetic permeability depends weakly on temperature up to the Curie point ($700 – 750$°C) and is mainly determined by magnetic field intensity. Magnetic permeability close to 700°C varies within the range $\mu = 5 – 25$. With heating above the Curie point μ takes a value differing little from one. The rate of inductor movement is determined by the time required for reaching a required maximum temperature of $910 – 950$°C. The depth of induction current penetration is within the limits $50 – 70$ mm.

In MK ORMETO-YuUMZ JSC five-pass induction hardening of rolls in a TPCh-700 unit is used with vertical inductor travel. Roll heating is accomplished for the first four passes. In the fifth, the hardening pass, water is fed under pressure for 60 min to the barrel surface from a sprayer connected to the inductor. Here the inductor stops in the upper position after passing the roll working surface. the main production parameters of induction hardening are provided in Table 1.

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TABLE 1. Production Parameters of IFC Induction Hardening

Pass number	v, mm/sec	I, A	U, V	t_b, °C	t_{max}, °C	Δ, mm
1	2	1500	360	420	79	7
2	2	1600	360	660	217	7
3	2	1800	380	780	316	21
4	2	2000	380	840	436	44
5	1	2000	380	940	587	70

Notations: v is inductor movement speed; I is inductor current; U is voltage; t_b is barrel temperature beneath inductor; t_{max} is roll axis maximum temperature; Δ is depth of induction heating penetration.

Working and supporting rolls were selected for study. The roll material was steel grades 72Kh2SGF, 9Kh2MF, 9Kh3MF, 9Kh5MF. The chemical composition of the test steels, roll types and dimensions are provided in Tables 2 and 3.

Specimens with a size of $20 \times 20 \times 20$ mm were cut from a transverse template of a roll billet after forging and cooling to room temperature. Induction hardening of specimens was performed from 850, 950 and 1050°C. After hardening specimens were tempered in oil at 120, 150 and 180°C. Brinell and Rockwell hardness was measured and also by using a small programmed TÉMP-2 hardness meter.

The original roll structure is pearlite. On heating for hardening the pearlite is transformed into austenite, that depending on cooling rate is transformed into pearlite, bainite and martensite. An isothermal diagram for austenite decomposition is shown in Fig. 1 for steel 9Kh2MF. Similar decomposition curves were plotted for steels 9Kh3MF and 9Kh5MF. An isothermal diagram for austenite decomposition in steel 72Kh2SGF is given in Fig. 2. In the case of steels 9Kh2MF, 9Kh3MF, and 9Kh5MF the temperature for the start of martensitic transformation is below 200°C, and for steel 72Kh2SGF it is a little higher. Isothermal diagrams for these steels were plotted by a procedure proposed in [2].

Analysis of experimental results made it possible to obtain the following regression equations, expressing the dependence of hardness on heating temperature for hardening T_h and tempering T_0:

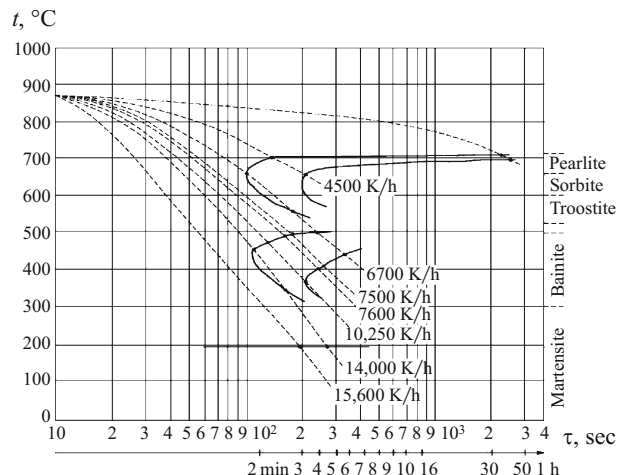| Steel	Equation
9Kh3MF	$HB = -858 + 1.45T_h - 0.03T_0,$
9Kh3MF	$HB = -863 + 1.44T_h - 0.03T_0,$ (2)
75Kh2SGF	$HB = -869 + 1.45T_h - 0.03T_0.$

Fig. 1. Isothermal diagram of steel 9Kh2MF supercooled austenite with different rates (numbers on curves, K/h).

It may be seen from expression (2) that with this form of heat treatment a decisive role in obtaining hardness is the heating temperature for hardening, and tempering temperature does not have a marked effect on it. During tempering at 180°C there is a reduction in the degree of martensite lattice distortion due to a reduction of carbon within it, that commences to precipitate in the form of carbide, close in composition to Fe_2C. This carbide is still insufficiently isolated, and its lattice is closely connected with that of martensite. Calculations have made it possible to confirm the optimum production regime, i.e. quenching from 960 – 1000°C and tempering at 140°C. Tempering in an oil bath at 140°C for 50 h makes it possible to obtain tempered martensite, that has the most finely dispersed structure and is not so brittle as untempered martensite. Roll hardness here is not markedly altered.

RESULTS AND DISCUSSION

Martensite transformation at low temperature is an autocatalytic process. It proceeds rapidly with continuous cooling. With high levels of supercooling there is an increase in the thermodynamic instability of austenite, and the rate of carbon diffusion is reduced. Here there is only a change in the type of lattice: $\gamma \rightarrow \alpha$. All of the carbon, previously dissolved within the austenite lattice remains within the ferrite lattice. As a result of this there is formation of supersaturated
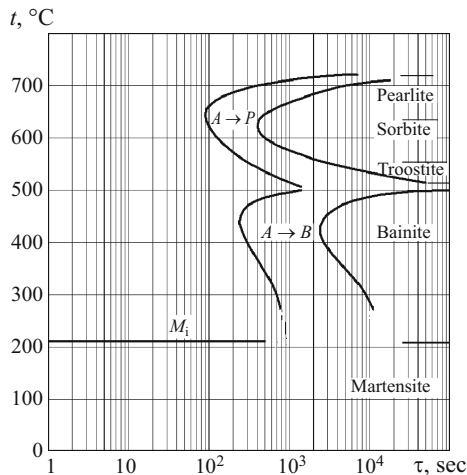
TABLE 2. Steel Chemical Composition

Steel	Element content, %										
	C	Cr	Mn	Si	Mo	V	Ni	Cu	Ae	P	S
75Kh2SGF	0.75	2.11	0.55	0.50	0.03	0.07	0.21	0.14	0.020	0.020	0.018
9Kh2MF	0.91	1.89	0.41	0.31	0.22	0.13	0.28	0.12	0.022	0.019	0.010
9Kh3MF	0.90	3.10	0.41	0.31	0.22	0.13	0.28	0.12	0.022	0.019	0.010
9Kh5MF	0.92	4.97	0.53	0.6	0.2	0.10	0.23	0.15	0.033	0.021	0.005

t, °C

Fig. 2. Isothermal diagram of steel 75Kh2SGF supercooled austenite.

solid solution of interstitial carbon in iron. Due to supersaturation with carbon the α-phase lattice is distorted and instead of cubic it acquires a tetragonal form. In this case martensite formation leads to an increase in phase interface and an increase in conversion rate. We designate the volume of a growing martensite crystal V and its surface S. Since $S \sim V^{2/3}$, we find that the rate of martensitic transformation is proportional to its amount to a power of 2/3. Changing to concentration, we will have

$$dC/dt = KX^{-2/3}, \qquad (3)$$

where X is concentration, t is time, K is martensitic transformation rate constant.

After integrating Eq. (3) we obtain

$$\Delta X = Kt^{0.6}. \qquad (4)$$

The amount of martensite in steel varies more rapidly in time than the amount of austenite decomposition by a diffusion mechanism. Expression (4) was used in order to describe the time dependence of this change [3]. Calculated values coincide with experiments.

The value of K in Eq. (4) depends on carbon content. In order to calculate it is possible to use a Kolmogorov –

Avrami equation [4, 5]

$$K = K(t)[1 - \exp(-\varepsilon\omega)], \qquad (5)$$

$$\varepsilon = \frac{2\beta}{dCr}, \qquad (6)$$

$$\omega = \frac{1}{T_s - T_f} \frac{dT}{dt}, \qquad (7)$$

where K is proportion of decomposition; ω is cooling rate; T_s and T_f far temperatures for the start and finish of martensitic transformation respectively; ε is Newton cooling coefficient; β is thermal conductivity coefficient; d is steel density; r is roll radius; C is specific heat capacity. In order to determine C it is possible to use the Dulong – Petit equation:

$$C = \frac{3R}{A}. \qquad (8)$$

where A is atomic weight; R is universal gas constant.

Martensitic transformation only occurs with continuous cooling. As the temperature ceases to change $\omega = 0$, $\Delta X = 0$, i.e. the amount of martensite is unchanged.

Solid phase reactions are built up from a number of stages, whose kinetics are described by different features. For phase transformations by diffusion mechanism the following equation has been obtained [6]

$$\frac{dZ}{dt} = D\frac{X_0}{Z}, \qquad (9)$$

where $dZ/dt = V$ is new phase growth rate; D is diffusion coefficient; Z is phase boundary movement in the direction of its growth; X_0 is concentration at a phase boundary.

Martensitic transformation occurs in an elastic isotropic medium at low temperature, when movement of atoms is very difficult. Elastic stress arise with cooling or deformation of metals. The elastic wave energy is a quantum value. This quantum is called a phonon. Local phonon oscillations are connected with point and linear defects of a crystal lattice and the surface of a crystal.

A consequence of the high value of characteristic temperature θ for iron is that the phonon energy at temperatures close to 300 K exceeds the energy for random thermal move-

TABLE 3. Dimensions and Weight of Cold Rolling Working and Supporting Rolls

Steel	Roll	Roll diameter and length ($d \times l$), mm, in sections:			m, kg
		barrel	conical neck	cylindrical neck	
9Kh2MF	Working	600 × 1420	406 × 188	343 × 805	4865
9Kh3MF	Supporting	1350 × 1420	1000 × 134	820 × 1386	24,600
75Kh2SGF	Working	500 × 2500	360 × 170	280 × 865	4700
9Kh5MF	Supporting	1000 × 2100	595 × 760	339 × 535	17,300

ment of atoms. The value of θ may be estimated by the Lindeman equation:

$$\theta = 137(T_3/A\,(A/d)^{2/3})^{1/2}, \qquad (10)$$

where for iron: $T_3 = 1808$ K; $A = 55.847$; $d = 7.9$ g/cm³; θ = 406 K.

Phonon energy $W = k\theta$ equals 0.04 eV and in order of value it corresponds to experimental values of activation energy with martensitic transformation [7]. This conformity points to its phonon mechanism. Here elastic energy is converted into phase transformation energy. Equilibrium distribution of phonons at a prescribed temperature is combined with movement of crystal atoms, and here no thermal resistance arises [8].

Martensitic transformation is connected with formation of crystallization centers and growth of crystals around them. A characteristic of austenite transformation into martensite consists of the fact that crystals of a new phase form by simultaneous (cooperative) movement of atoms, i.e. bases of the old phase, with respect to each other by very small distances, not exceeding the crystal lattice spacing. This movement of atoms in some areas of old phase leads to microscopic changes, expressed in formation of new phase crystals, moving with respect to neighbors. Neighbors of any atom in the original phase remain its neighbors in the new martensitic phase.

The process of martensite crystal growth, as for any phase transformation, should proceed by fluctuation generation of crystallization centers of a new phase within the old phase, and subsequent growth, if the size of a nucleus is not less than critical. Critical radius r may be estimated as follows:

$$r = \frac{2\sigma A}{\Delta F d}, \qquad (11)$$

where σ is surface tension coefficient (for steel it is possible to adopt σ = 29.7 J/m²; ΔF is the change in free energy) Gibbs energy); d is steel density. Since the mechanism of martensitic transformation has a phonon character, $\Delta F \approx 0.04$ eV. Then the critical martensite nucleus radius $r_0 = 110$ nm.

The idea of a radius is purely conditional. Martensite has an acicular structure. The size of needles is determined by the size of an original austenite grain. With rapid cooling at the martensitic transformation temperature the size of austenite grains is 90 – 100 nm, that in order of magnitude corresponds to the value obtained.

At the boundary of martensite in the original phase there is rapid movement of a boundary in the direction of the matrix even at very low temperature, since for this movement diffusion is not required with migration of atoms by a distance exceeding interatomic.

With martensitic, as with any phase transformation, there is crystal growth. This process of diffusionless growth may be called quasidiffusion. Then from Eq. (9) it follows that

$$D^* = \frac{1}{Z_0}\frac{\mathrm{d}Z}{\mathrm{d}t} = \frac{1}{Z_0}V, \qquad (12)$$

where D^* is quasidiffusion movement coefficient; $Z = a$, where a is crystal lattice spacing; V is elastic wave velocity; according to Debye, the wave propagation rate for longitudinal transverse waves V_l and V_τ are different. They are connected by a relationship [9]:

$$\frac{3}{V^3} = \frac{1}{V_l^3} + \frac{2}{V_\tau^3}, \qquad (13)$$

$$V_l = \sqrt{\frac{E}{d}}, \quad V_\tau = \sqrt{\frac{c}{d}}, \qquad (14)$$

where E is Young's modulus; G is shear modulus; d is density.

By substituting expression (14) in Eq. (13) we obtain an equation for martensitic transformation rate:

$$V = \sqrt{\frac{EG}{d}}\,\sqrt[3]{\frac{3}{2E^{3/2} + G^{3/2}}}. \qquad (15)$$

If it is assumed that $E = 200$ GPa, $G = 76$ GPa, steel density $d = 7900$ kg/m³, then martensite growth rate $V = 3500$ m/sec. The rate of martensite formation is high. This is due to continuous transition from an austenite crystal lattice to a martensite lattice. Depending on composition and temperature, martensite crystal formation may have different morphology and substructure. At a prescribed temperature the quasidiffusion coefficient, as for the diffusion coefficient, is a constant value. Thus, in order to explain martensitic transformation kinetics it is possible to use a Fick diffusion equation, replacing coefficient D by D^*. Considering martensitic transformation as a first order reaction, we obtain:

$$D^* \frac{\partial^2 X}{\partial Z^2} = \varepsilon X. \qquad (16)$$

In order to explain martensite phase growth by a diffusionless mechanism in [10] a mass transfer coefficient was introduced whose value appeared to be different depending on the method of action on austenite. It should be noted that with martensitic transformation the chemical composition of steel is unchanged, and consequently in relationship (9) X_0 is a constant value, differing little from one. A solution of Eq. (16) will be the following expression [11]:

$$X = X_0\, e^{-\sqrt{\frac{\varepsilon}{D^*}}\,Z}. \qquad (17)$$

Whence the effective hardened layer thickness

$$L = \sqrt{\frac{D^*}{\varepsilon}}. \qquad (18)$$

Taking account of Eqs. (14), (15), and (6) expression (18) may be written as follows:

$$L = 0.85 \left(\frac{3Rra}{\beta A} \right)^{1/2} \frac{(EGd)^{1/4}}{(2E^{3/2} + G^{3/2})^{1/6}}, \qquad (19)$$

where R is universal gas constant; a is crystal lattice spacing; b is heat transfer coefficient; A is atomic weight; E is Young's modulus; G is shear modulus; d is density.

For a metal – water boundary according [12], $\beta = 1600 \text{ W/(m}^2 \cdot \text{K})$. Lattice spacing [13] $a = 0.25$ nm, $E = 200$ GPa, $G = 76$ GPa, then for rolls with a diameter of 500 and 1350 mm the thickness of the hardened layer $L = 14$ and 22 mm, respectively.

During cooling the value of the heat transfer coefficient will decrease [12], as a result of which the thickness of the hardened layer will be somewhat greater.

The thickness of a hardened layer depends on cooling intensity and roll dimensions. The greater the roll dimensions, the greater are thermal inertia properties. For the same cooling technology and different roll sizes the thickness of the hardened layer is different [14]. Values of hardened layer thickness obtained by calculation are in qualitative agreement with the data of other authors [14] and they are not contradicted by experimental results. It should be noted that thickness L may be measured by experiment only after roll destruction.

After induction hardening the surface of rolls acquires a hardness of $98 – 102$ HSD, that is greater by $5 – 10$ HSD than with volumetric hardening. The variation of hardness does not exceed $2 – 3$ HSD. The thickness of the hardened layer is within the limits of $20 – 40$ mm.

CONCLUSIONS

1. It has been established that martensitic transformation of austenite decomposition is a autocatalytic process. Time dependence has been determined for the new phase growth rate.

2. Crystal growth during martensitic transformation may be considered as a quasidiffusion process, and the formation mechanism is due to spreading of phonons.

3. The dimensions of a critical nucleus of a martensite grain are very significant, of the order of 100 nm.

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