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CONVECTIVE HEAT TRANSFER IN ACCELERATED COOLING OF ROLLED STOCK

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An engineering technique for calculation of convective heat transfer in accelerated cooling of hot rolled stock in a co-current water flow is considered. Experimental values of the heat-transfer coefficient are given. The energy-saving regime of cooling of the reinforcing rolled stock at the "Krivorozhstal'" Joint Stock Company Krivoi Rog Integrated Mining-Metallurgical Works is presented.

The main problems of the technology of accelerated cooling of rolled stock under the conditions of small-section and wire-rod mills are the reduction of metal losses to scale and the obtaining of the required microstructure and mechanical properties of the product.

The facilities for cooling rolled stock of round cross section are represented by a number of cylindrical chambers into which the cooling water is fed under pressure and where metal moves along the axis at the velocity of rolling (Fig. 1).

The fact is that-rolled stock strengthening on modern domestic mills is carried out with an unsoundly large reserve relative to mechanical characteristics [1]. By virtue of this, improvement of the technological modes of cooling in order to obtain a complex of the required mechanical properties and microstructure of the rolled stock with minimum energy consumption of the process is a potential source of savings of energy and resources.

Attempts to study the influence of some design and technological parameters of the cooling process on the heat-transfer rate are known [2–5]. However, the results of these studies do not allow a complex approach to the choice of such initial parameters as pressure and flow rate of the cooling water and the number and length of the cooling chambers as a function of the input data (initial temperature of metal, velocity of rolled-stock motion, chemical composition of steel) in order to minimize the flow rate of energy carriers reaching the necessary level of the mechanical properties of the rolled stock.

At present, when a reduction of the cost of metal products is the main trend in the improvement of its competitiveness in the world market, the development of this approach undoubtedly is an urgent problem.

Theory. Accelerated cooling of metal is a complex thermophysical process that is characterized by a number of specific features: straight- or cross flow of metal and the cooling-water movement at a velocity up to 100 m/sec and 20–40 m/sec, respectively; conjugate temperature fields of the rolled stock and water; high values of the heat-transfer coefficient (up to 100,000 W/(m^2·K)), Biot number (up to 25), and cooling rates (4000–5000 K/sec).

The temperature of rolling on modern equipment is 1050–1100^{o}C, and the initial temperature of the cooling water is 20–45^{o}C. As the hot metal enters the cooling chamber, a high temperature head arises between its surface and the cooling water, as a result of which the water boils up and is displaced from the layer bounding with the rolled stock.

However, the value of the heat-transfer coefficient of 80,000–100,000 W/(m^2·K) that is obtained at this stage of cooling indicates that intense break-up of the vapor boundary layer occurs on the metal surface under the action of turbulent motion of the cooling water, which results in a direct contact between the hot rolled stock and the liquid. The tendency toward formation of the vapor interlayer decreases with a decrease of the temperature of the metal surface.

Since the mass-mean temperature of the liquid is lower than the temperature of boiling, boiling can take place in the boundary layer, whereas beyond the boundary layer, in the bulk of the water, condensation of the vapor formed

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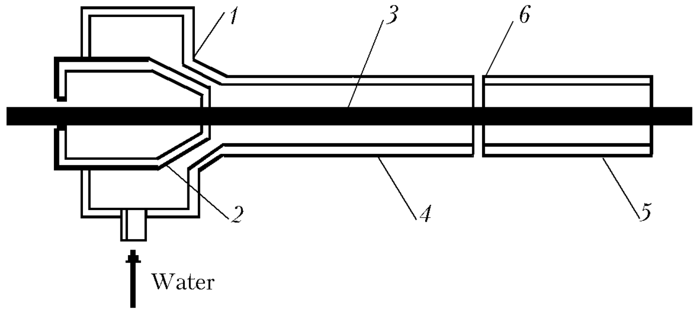


Fig. 1. Schematic diagram of the facility for accelerated cooling: 1) injector body; 2) injector nozzle; 3) cooled rolled stock; 4) first cooling chamber; 5) second cooling chamber; 6) discontinuity for drop of static pressure.

on the heating surface occurs. However, some researchers note that at high pressures and a large velocity of water flow the process of nucleate boiling can be absent and most of the energy is transferred directly to the cooling water [6, 7].

This study is aimed at construction and substantiation of a reliable technique for calculation of convective heat transfer and mechanical properties of strengthened metal, which can be used in engineering-technical calculations.

Calculation of the process of accelerated cooling includes determination of the coefficient of heat transfer from hot metal to the cooling water and the temperature field of the rolled stock and prediction of the formation of the microstructure and the mechanical properties of the ready product.

One method of calculation of the heat-transfer coefficient in cooling of the rolled stock is the employment of the empirical dimensionless relations of the following form [8]:

$$\mathrm{Nu} = p\mathrm{Pr}^m \left(\sqrt{\mathrm{Re}_\mathrm{a}^2 + \mathrm{Re}_\mathrm{rel}^2}\right)^n , \tag{1}$$

where $\mathrm{Nu} = \alpha d_{\mathrm{r.s}}/\lambda_\mathrm{w}$; $\mathrm{Re_a} = \overline{W}d/\nu_\mathrm{w}$; $\mathrm{Re_{rel}} = (\overline{W} \pm W_{\mathrm{r.s}})d_{\mathrm{r.s}}/\nu_{\mathrm{sat}}$; p, m, and n are the coefficients determined experimentally.

However, the possibility of using relations similar to (1) is limited by the narrow range of values of the Pr, Re, Fo, and Bi numbers at which the experiments were conducted. In connection with this, difficulties in the choice of an adequate dimensionless relation can arise in calculation of convective heat transfer in one facility of accelerated cooling or another.

Calculation of the temperature field of the rolled stock is based on numerical solution of the differential equation of heat conduction for an infinite cylinder at boundary conditions of the third kind

$$c_\mathrm{m}\rho_\mathrm{m} \frac{\partial t}{\partial \tau} = \frac{\partial}{\partial r}\left(\lambda_\mathrm{m} \frac{\partial t}{\partial r}\right) + \frac{\lambda_\mathrm{m}}{r}\frac{\partial t}{\partial r} , \tag{2}$$

which are given in the form

$$-\lambda_\mathrm{m} \frac{\partial t\,(R_{\mathrm{r.s}}, \tau)}{\partial r} = \alpha\,(t\,(R_{\mathrm{r.s}}, \tau) - t_{\mathrm{sur}}) . \tag{3}$$

The initial condition, written as $t(r, 0) = f(r)$, is a function of the initial temperature distribution over the radius of the rolled stock.

Determination of the volume fractions of structural phases in the microstructure of strengthened metal is based on the knowledge of the temperature field of the metal at the end of the cooling process and the temperatures of the onset of phase conversions for the considered grade of steel [9].

Calculation of the mechanical properties of the rolled stock is based on the assumption that a linear relation between the properties (especially strength) and the volume fraction of structural phases is often reduced to an ideal-

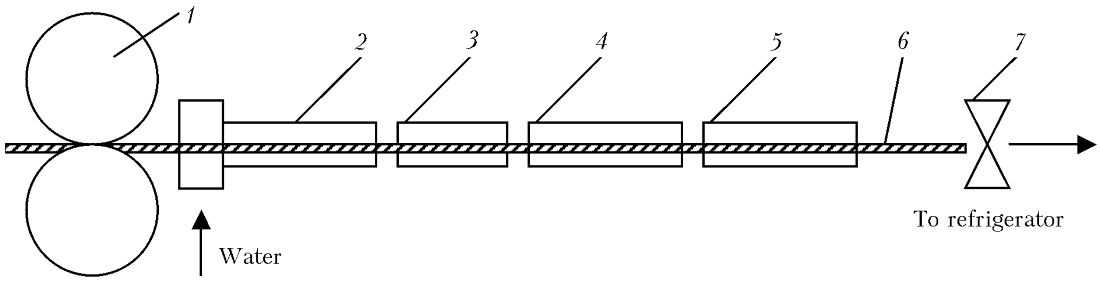


Fig. 2. Schematic of the facility for accelerated cooling under the conditions of the 250-4 mill of the "Krivorozhstal’" Integrated Mining-Metallurgical Works: 1) finishing stand; 2–5) cooling chambers; 6) reinforcing rolled stock; 7) scissors.

ized law of mixing [10]. Due to this fact, the strength properties of steel as a natural composite were calculated by the rule of mixing:

$$\sigma = \sigma_{mt}V_{mt} + \sigma_b V_b + \sigma_s V_s + \sigma_{pt}V_{pt} . \tag{4}$$

Experimental Studies. Based on the considered technique, we developed a computer program for thermal engineering optimization of the facilities of accelerated cooling of rolled stock that allows minimization of the consumption of electric energy and recycled water in the process of thermal strengthening [11]. The program was tested under the conditions of the 250-4 small-section mill of the "Krivorozhstal’" Integrated Mining-Metallurgical Works.

The reinforcing rolled stock with a diameter 12 mm is manufactured on the 250-4 small-section mill from St3ps steel (carbon content not less than 0.17%) of grades A400S and A500S and BS 4449.

The facility for accelerated cooling consists of four successive chambers and is located behind the finishing stand of the rolling mill (Fig. 2). Under the operating conditions of the facility, we took samples of the reinforcing rolled stock with a diameter of 12 mm of grade A500S ($\sigma_y \geq 500$ MPa, $\sigma_t \geq 600$–900 MPa) cooled with acceleration at different values of pressure and temperature of the cooling water and temperature and velocity of motion of the metal.

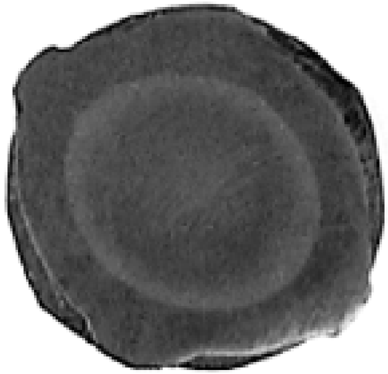
Metallographic studies of the microsections of the samples of the reinforcing rolled stock showed that a ring with a depth of 1.4–1.8 mm and a structure of the tempered martensite is present on all the samples (Fig. 3). This ring with a martensite structure is followed by a 0.15–0.25-mm-wide transient region having the structure of the lower bainite. The metal structure mainly consists of the upper bainite. Due to the small fraction of the transient region in the total microstructure of the metal (less than 6%), the fraction of the formed lower bainite was neglected and combined with the fraction of the upper bainite. In this case, the volume fractions of the phases were calculated as follows:

$$V_b = \frac{(R_{r.s} - S_{mt})^2}{R_{r.s}^2}, \quad V_{mt} = 1 - V_b \frac{R_{r.s}^2 - (R_{r.s} - S_{mt})^2}{R_{r.s}^2} . \tag{5}$$

The quantity S_{mt} is calculated by the known temperature field of the rolled stock at the end of the cooling process and the temperature of the onset of martensite conversion for the given grade of steel t_{mt} (Fig. 4).

By processing the results of the investigation of the strength characteristics of the samples of the reinforcing rolled stock we determined values of the mechanical properties of the formed structural phases, i.e., yield strength of martensite σ_y^{mt} = 940 MPa, ultimate strength of martensite σ_t^{mt} = 1100 MPa, yield strength of bainite σ_y^b = 354 MPa, and ultimate strength of bainite σ_t^b = 395 MPa.

Thus, the calculation technique is adapted for calculation of the mechanical properties of the thermally strengthened reinforcing rolled stock with a diameter of 12 mm manufactured from St3ps steel on the basis of the value of the quenched layer.



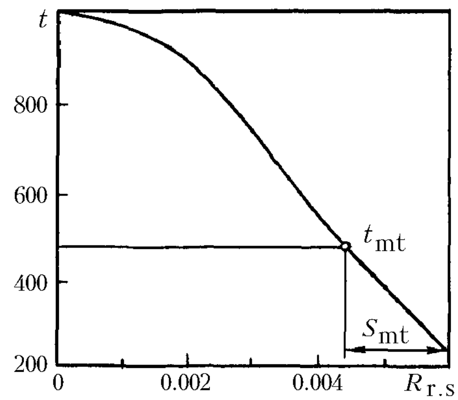


Fig. 3. Macrostructure of the strengthened reinforcing rolled stock with a diameter of 12 mm of grade A500S.

Fig. 4. Temperature distribution over the rolled-stock cross section.

TABLE 1. Experimental Values of the Coefficient of Convective Heat Transfer

No. of the cooling chamber	$t_{w,in}$, °C	$t_{w,f}$, °C	Fo	$Re_a \cdot 10^{-6}$	$Re_{rel} \cdot 10^{-6}$	$\alpha \cdot 10^{-3}$, W/(m^2·K)	Bi	Nu
1	38	68	0.037	2.095	1.340	95,000	21	2940
2	68	77	0.015	3.120	0.370	75,000	20	4485
3	77	84	0.027	2.480	0.080	30,000	7	1795
4	84	87	0.015	2.150	0.040	20,000	5	1200

In the commercial tests on the 250-4 small-section mill, the temperature of the cooling water was measured at the outlet from each cooling chamber at the known parameters of the process: initial temperature of the metal 1080°C, velocity of metal motion 13.6 m/sec, pressure of the cooling water in front of the injector 2.6 MPa, and initial temperature of the cooling water 38°C.

Values of the heat-transfer coefficient in each cooling chamber were calculated by the measured values of the temperature of the cooling water (see Table 1).

In order to complete the process of adaptation of the technique of calculation to the conditions of the 250-4 small-section mill at the "Krivorozhstal'" Integrated Mining-Metallurgical Works, it is necessary to select a dimensionless relation of a set of known ones Nu = *f*(Pr, Re) with the use of which the calculated values of the heat-transfer coefficient will be the closest to the experimental values.

An acceptable accuracy of the calculation of heat transfer was obtained by the formula based on the Nusselt–Crawssold relation, which allows for the effect of both an absolute velocity of motion of the cooling water and the velocity of water relative to the surface of the cooled metal on the heat-transfer rate, in the form of the total Reynolds number:

$$\mathrm{Nu} = 0.023\,\mathrm{Pr}^{0.4}\left(\sqrt{\mathrm{Re}_a^2 + \mathrm{Re}_{rel}^2}\right)^{0.8}. \tag{6}$$

Thus, the conclusion suggests itself that the above-described technique based on dimensionless relation (6) can be used for reliable engineering-technical calculation of the process of accelerated cooling of the reinforcing rolled stock. The results of the adaptation calculations showed that the use of relation (6) allows determination of the mechanical properties of the strengthened metal with an average error on the yield strength of up to 20.6 MPa (or 3.3%) and on the ultimate strength of up to 18.7 MPa (or 2.6%).

An Energy-Saving Regime of Cooling of the Reinforcing Rolled Stock. Using the developed technique of calculation, we studied the dependence of the mechanical properties of the strengthened metal on the pressure of the cooling water in front of the injector ranging from 1.0 to 3.0 MPa. Variation of pressure within this limit did not sub-

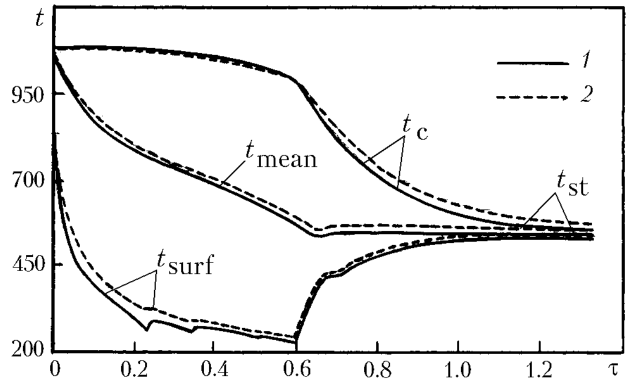


Fig. 5. Temperature graphs of the process of rolled-stock cooling at different pressures of the cooling water: 1) 3; 2) 1 MPa.

stantially affect the value of the mechanical properties of the strengthened metal. As the water pressure changed from 1.0 to 3.0 MPa, the yield strength changed by 28 MPa and the ultimate strength by 21 MPa.

Figure 5 presents the calculated temperature graphs of the process of cooling under the indicated values of pressure of the cooling water in front of the injector.

According to the technological specification of the 250-4 small-section mill at the "Krivorozhstal'" Integrated Mining-Metallurgical Works, in manufacture of the reinforcing rolled stock with a diameter of 12 mm of grade A500S the pressure of water in front of the injector is equal to 3.2 ± 0.3 MPa. The results of the modeling showed that obtaining of the complex of necessary mechanical properties is possible at a water pressure of 1.0 MPa.

In order to confirm the results of the modeling experimental, cooling of the rolled stock was conducted at a water pressure of 1.0, 1.5, and 2.0 MPa. The following values of the mechanical properties of metal were obtained: P_{inj} = 2.0 MPa: σ_y = 635 MPa, σ_t = 705 MPa; P_{inj} = 1.5 MPa: σ_y = 605 MPa, σ_t = 690 MPa; and P_{inj} = 1.0 MPa: σ_y = 580 MPa, σ_t = 660 MPa.

Thus, the conclusion on the possibility of manufacturing strengthened reinforcing rolled stock at a water pressure of 1.0 MPa is substantiated. It is also shown that variation of the water pressure by 0.1 MPa leads to changes in the yield strength of the metal by 5–6 MPa and the ultimate strength by 3–6 MPa.

The required level of mechanical properties of the rolled stock with a minimum flow rate of energy carriers can be provided by establishing a rational ratio between the water pressure in front of the injector and the lengths of the cooling chambers. For the 250-4 small-section mill this ratio was obtained by the above-described technique on the basis of expression (6).

As a result, an energy-saving regime of cooling, which envisages a decrease of water pressure from 3.2 to 1.5 MPa and elimination of the third cooling chamber from the facility, was suggested. Calculation of the economic efficiency showed that a decrease of pressure of the cooling pressure allows one to decrease energy consumption on the pump drive by $4.4 \cdot 10^6$ kW/h and water consumption by 830,000 m^3/year, which in money terms is 130,000 U.S. dollars. In this case, mechanical properties of the strengthened reinforcing rolled stock are in full correspondence with the requirements of the A500S grade.

At present, the developed energy-saving regime has been successfully adopted on the 250-4 small-section mill of the "Krivorozhstal'" Integrated Mining-Metallurgical Works.

NOTATION

Bi, Biot number; c, specific heat capacity, J/(kg·K); d, inner diameter of the cooling chamber, m; $d_{r.s}$, nominal diameter of rolled stock, m; Fo, Fourier number; Nu, Nusselt number; Pr, Prandtl number; P_{inj}, water pressure in front of the injector, Pa; r, current radius, m; Re_a, Reynolds number for absolute velocity of water flow; Re_{rel}, Reynolds number for relative velocity of water flow; $R_{r.s}$, rolled-stock radius, m; S_{mt}, thickness of the quenched surface layer, m; t, temperature, ^oC; t_{mt}, temperature of the onset of martensite conversion, ^oC; V, volume fraction of structural phases; $\overline{W}$, mean velocity of water flow, m/sec; $W_{r.s}$, velocity of rolling, m/sec; α, heat-transfer coefficient, W/(m^2·K);

λ, thermal conductivity, W/(m·K); ν, kinematic viscosity, m^2/sec; ρ, density, kg/m^2; σ, strength characteristic, Pa; σ_y, yield strength, Pa; σ_t, ultimate strength, Pa; τ, time, sec. Indices: a, absolute value; b, bainite; t, temporal rupture strength (ultimate strength); w, water; f, final value of a parameter; m, metal; mt, martensite; in, initial value of the parameter; sat, parameter on the line of saturation; rel, relative value of the quantity; sur, surrounding medium, surf, surface, pt, perlite; s, sorbite; st, self-tempering; mean, mean value of the quantity; y, yield; inj, injector; c, center; r.s, rolled stock.

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