Extending Rail Life by Creating Compressive Stress in the Crown

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Safe train operation depends largely on the composition and life of the rails. Improvement in rail performance is a continuing concern. Premature rail failure on account of production defects is a problem at OAO Rossiiskie Zheleznye Dorogi: the purchase of replacement rails costs around 10 billion rubles each year.

A literature review shows that many foreign firms produce rails that exceed the life of Russian rails by a factor of 1.5—2.

That superiority may be largely attributed to flexibility in selecting the chemical composition of rail steel and to the introduction of new thermal-strengthening techniques.

Note, in particular, their ability to ensure the required hardness of the rail crown without increasing the carbon content and hence without the associated loss in welding properties of the steel.

As an example, consider the production of rails of elevated strength by Thyssen Steel (Germany) [1]. The rails are based on bainitic steel with 0.35—0.40% C, 1.5% Si, 0.7% Mn, 1.1% Cr, 0.8% Mo, and 0.1% V.

Isothermal quenching of such rails forms a structure consisting of finely acicular (lower) bainite, with hardness around 400 HV and relative elongation of about 9%.

Additional 1-h tempering at 550°C yields the following characteristics: strength 1400—1450 N/mm²; relative elongation 13—15%; hardness up to 440 HV; fracture strength no less than 40 MPa/m°. These values considerably exceed those for Russian steel with plate-pearlite structure [2].

Note that increasing the strength of bainitic steel components (including rails) is currently a priority in Russian metallurgy.

The mechanical properties of 30XГCA and 40XHMA steel, whose composition resembles that of rail steel, in thermal strengthening were considered in [3—5]. Two methods were employed: 1) quenching in oil with subsequent tempering; 2) isothermal quenching in a salt bath at 325°C for 15—30 min. In both cases, the strength of the steel reaches 140—160 kgf/mm², whereas the impact strength is 1.5—2 times greater in salt quenching than in oil quenching.

For example, the strength of 40XHMA steel (0.40% C, 0.21% Mo, 0.72% Cr, 1.34% Ni) on quenching from 850°C in oil is σ = 160 kgf/mm²; the impact strength σc = 2 kgf m/cm² (2-h tempering at 300°C after quenching).

For 30-min isothermal quenching in a salt bath at 325°C, the impact strength is 3.4 kgf m/cm², while σB = 165 kgf/mm².

Industrial experiments confirm that rail strength may be increased to σB = 140—150 kgf/mm² with high plasticity [6, 7]. The rails are strengthened by isothermal quenching to lower bainite with 30-min holding in a NaNO3 + KNO3 salt bath at 320—340°C.

Tensometry has shown that, in rails quenched to lower bainite, the crown’s contact surface is characterized by residual compressive stress (12—15 kgf/mm²) [7]. That increases the contact life of the metal and correspondingly must extend rail life [7].

Note that the favorable influence of residual compressive stress on the life of steel components was established later, in [8]. The reduction in warping of rails quenched to lower bainite is of interest here [7].

The isothermal quenching of steel rails in a mixture of molten salts has not been widely adopted, despite the results in [6, 7]. That may be attributed to the practical difficulties in the industrial use of aggressive quenching media. There are few references to the isothermal quenching of rails to lower bainite in the foreign literature: only the use of compressed air is mentioned.

In the present work, we propose isothermal quenching of rails to lower bainite in an environmentally safe quenching fluid: industrial-grade water at the shop temperature. The rolled rails are cooled by means of centrifugal water-droplet sprayers, so that the flow rate and correspondingly the cooling rate of the rail surface may be regulated over a broad range.

The quenching system must permit differential (separate) regulation of the water flow rates to individual sections of the rail (the crown, the neck, and the base).

Using cold water as the quenching fluid represents a radical change in the technology and entails the solution of numerous problems, including the identi-
fication of the best cooling conditions and the development of designs for the quenching system and an automatic coolant-control system.

In the present work, we focus on the rational conditions for isothermal quenching of the rails and on the residual stress distribution in the crown of rails quenched to lower bainite.

**ISOTHERMAL QUENCHING OF RAILS BY WATER**

Isothermal quenching of rails in the bainitic-transformation range (300–400°C) by means of cold water requires reduction in the cooling properties of water.

We know that immersing rails in cold water results in quenching of the steel to martensite and often leads to cracking, on account of extreme embrittlement.

The cooling properties of water may be reduced by pulsed water supply, with partial heating of the surface by the heat accumulated in the rail prior to quenching—that is, by self-tempering [9].

In Fig. 1, we show experimental data for the cooling of a nickel sample (a cylinder with diameter 60 mm and height 180 mm) by means of a water–air sprayer with regulation (by a microcomputer) of the water and air supply so as to ensure specified variation in surface temperature [10]. Analog–digital converters connect the computer and the sprayer.

The sample temperature (measured by a thermocouple welded to the sample) is sent to the input of the control system, and the required water and air pressures (calculated by the computer) appear at its output. The computer memory contains the analytical expression for the initial sample temperature \( T_0 = 800°C \) and the specified surface temperature in four successive time intervals (shown by the dashed line in Fig. 1).

The mathematical model of the sample cooling in the computer memory permits prediction of the required external cooling rate and the pulsed water and air pressure in the sprayer system.

The variation in water and air pressure corresponding to the specified sample cooling is illustrated in Fig. 1. The interval from 40 to 60 s is of most interest; it corresponds to specified metal temperatures of 370–390°C.

As follows from Fig. 1, such isothermal holding of the metal is ensured by shutting the water sprayers off completely and reducing the air pressure almost to zero. Radiant heat transfer results in only slight (3–5°C) decrease in surface temperature over the 20-s interval. We may assume that the isothermal holding in this interval is satisfactory.

This example of microcomputer control of pulsed cooling serves as the prototype for isothermal quenching of rails to lower bainite by means of water.

The rail cooling in isothermal quenching is regulated by means of the mathematical model in [11, 12]. That model takes account of the kinetics of austenite transformation and also of the appearance of thermal and structural stress in the rail cross section on cooling. The model in [11] is modified in terms of the method of determining the temperature field in the rail cross section when pulsed heat transfer to the surface is taken into account and ensuring the required time for isothermal transformation of austenite to lower bainite \((A \rightarrow B)\). We know that, for 30XFCA and 40XHMA steel, \(A \rightarrow B\) transformation takes no more than 25–30 min [3, 4].

In the subsequent calculations, we assume that \(A \rightarrow B\) transformation takes 30 min and the rate of bainitic transformation is greatest in the range 300–400°C.

Isothermal holding of samples at 390°C for 10 s requires limiting reduction in the external cooling rate, according to [10]. Analogously, in isothermal holding during the quenching of the rail crown, the external cooling rate must be minimized for a certain time. A temperature considerably higher than water’s boiling point (350°C) is maintained by the supply of heat stored in the upper section of the rail to the cooled surface. The cooling time of the rail crown to the isothermal holding temperatures (from 400 to 300°C) depends on the initial rail temperature prior to quenching (no more than 900–950°C).

Since the heat stored within the rail prior to quenching is limited, it is not obvious that it will be sufficient to maintain the temperature at the crown surface within the range of \(A \rightarrow B\) transformation for 30 min.

That must be ensured in specifying the pulsed cooling of the rail surface.
The temperature field in the rails is determined by numerical solution of the equation
\[ \rho C \frac{\partial T}{\partial t} = \text{div}(\lambda \text{grad} T) + Q(x, y, z, t) \] (1)
and by taking account of the initial condition \( T(t_0) = T_i \), when \( t = 0 \) and the boundary condition at the rail surface
\[ \lambda \frac{\partial T}{\partial n} \bigg|_{\text{sur}} = \alpha (T_{\text{sur}} - T_i), \] (2)
where \( T \) is the temperature; \( t \) is the time; \( \rho \) is the density of the metal; \( \lambda, C \) are the thermal conductivity and specific heat of the metal, respectively; \( Q \) is the density of the heat source associated with the phase transitions; \( T_i \) is the coolant temperature; \( T_i \) is the initial rail temperature; \( n \) is the normal to rail surface; \( \alpha \) is the effective (mean) heat-transfer coefficient at the rail surface.

The density of the heat source associated with the phase transitions takes the form
\[ Q = \rho L \frac{\partial \Psi}{\partial t}, \]
where \( \Psi(x, y, t) \) is the proportion of transformed austenite; \( L \) is the specific heat of the phase transitions.

Isothermal quenching of the rail crown in the temperature range corresponding to \( A \rightarrow B \) transformation may be ensured by strict enforcement of the specified time dependence of the heat-transfer coefficient at the rail surface.

On the basis of numerous calculations of the rail’s temperature field, we may divide the total cooling time in rail quenching into three periods:

1. initial cooling of the rail crown and subsequent low tempering (120 s);
2. isothermal quenching of the rail crown for 1800 s, with pulsed (periodic over time) variation in the heat-transfer coefficient;
3. the final stage of rail cooling, in air or with a low rate of sprayer action.

The initial cooling of the rail crown reduces the temperature nonuniformity along the vertical axis of the rail, with corresponding improvement in the stress distribution in subsequent quenching.

The specified variation in heat-transfer coefficient during the first period is as follows
\[ \alpha = AK_1 + (A01 - AK_1) \exp\left(-\frac{20 - L}{tk}\right), \text{ when } t \rightarrow t_0; \]
(3)
\[ \alpha = A_S, \text{ when } t = t_0 \rightarrow t_1. \] (4)
Here \( A01 = 3000 \text{ W/(m}^2\text{ °C}) \); \( AK_1 = 1500 \text{ W/(m}^2\text{ °C}) \); \( A_S = 50 \text{ W/(m}^2\text{ °C}) \); \( tk = 5000 \text{ s}; t_0 = 15 \text{ s}; t_1 = 120 \text{ s}. \)

The second cooling period (isothermal quenching) is associated with specification of the effective heat-transfer coefficient as a periodic step function (Fig. 2). In selecting the maximum heat-transfer coefficient in this period, we take account of the heat-transfer coefficients in isothermal quenching of steel components in salt melt: 400–600 W/(m\(^2\) °C) [13].

The peak heat-transfer coefficient \( \alpha \) in this period is assumed to gradually decline from 1000 to 50 W/(m\(^2\) °C). The interval between peak values of \( \alpha \) is assumed to be 20 s.

In the intervals between peak values, \( \alpha \) is assumed to be zero. That is associated with local increase in temperature of the rail crown on account of heat from the interior.

In Fig. 4a, we show the calculated temperatures at some representative points of the rail cross section (identified in Fig. 3).

The calculation is based on the model in [11, 12]. The following thermophysical properties of the steel
are assumed: \( \rho = 7500 \text{ kg/m}^3; \lambda = 30 \text{ W/m deg}; C = 628 \text{ J/kg deg}; T_s = 20^\circ \text{C}; L = 75.8 \text{ kJ/kgf} \) (for transformation from austenite to pearlite); \( L = 20 \text{ kJ/kgf} \) (for transformation from austenite to lower bainite).

If we specify \( \alpha \) as a step (pulsed) function with gradually declining amplitude, we may maintain the temperature at the rail’s contact surface within the range of bainitic transformation (300–400\(^\circ\)C) for 1800 s, which is sufficient for transformation of 60% of the initial austenite to lower bainite, as we see in Fig. 4a. With 60% \( A \rightarrow B \) transformation, as we show later, the surface layer of the rail is characterized by residual compressive stress, with improvement in its wear resistance.

Our results indicate that, if the heat-transfer coefficient is specified as a pulsed function, isothermal quenching may be investigated on the basis of the model in [11, 12]. The purely thermal stress depends on the linear expansion coefficient \( \alpha_f \).

In calculating the structural stress due to phase transformations in the metal, we replace the thermal-expansion coefficient by the equivalent expansion coefficient \( \beta \), assumed to be additive

\[
\beta = \beta_A + \beta_P + \beta_B = A(t)\beta_A^n + P(t)\beta_P^n + B(t)\beta_B^n,
\]

where \( \beta_A^n, \beta_P^n, \beta_B^n \) are the maximum expansion coefficients for the austenite, pearlite, and bainite phases, respectively; \( A(t), P(t), B(t) \) are the proportions of the individual phases, which increase over time.

For the transformation of austenite to lower bainite

\[
B(t) = B_s\{1 - \exp[-kB(t-tB)^n]\},
\]

where \( tB \) is the incubation period for the given steel; \( B_s \) is the limiting proportion of austenite, which depends on the transformation temperature; and \( kB \) is calculated as [14]

\[
kB = \frac{0.693}{A\exp\left(\frac{Q}{RT}\right)^n}.
\]

Here \( Q \) is the activation energy; \( R \) is the gas constant; \( T \) is the absolute transformation temperature; \( A = 0.086 \) = const.

We assume that \( Q = 11700 \text{ cal/mol} \) and \( n = 4.8 \) [14]. Then we calculate \( kB \) from Eq. (7) at \( T = T_B = 623 \text{ K (350}^\circ\text{C)} \): \( kB = 1.75 \times 10^{-15} \text{ s}^{-n} \).

We assume that \( \beta_A^n = 2.08 \times 10^{-5}, \beta_P^n = -1.52 \times 10^{-5}, \beta_B^n = -2.25 \times 10^{-5} \text{ deg}^{-1} \).

In Figs. 4–6, we plot the calculated quantity of bainite and the corresponding longitudinal stress at characteristic points.

It follows from Fig. 5b that, for pulsed heat supply, the stress at the rail’s contact surface (point 1) varies

**STRESS DISTRIBUTION AT THE RAIL CROWN ON ISOTHERMAL QUenchING**

The stress distribution at the rail crown associated with isothermal quenching may be investigated on the basis of the model in [11, 12]. The purely thermal stress depends on the linear expansion coefficient \( \alpha_f \).
The amplitude of longitudinal-stress variation is 100–110 MPa at \( t = 250–300 \) s and gradually declines at \( t > 1000 \) s.

In Fig. 6, we note synchronous increase in the quantity \( B(t) \) of lower bainite at the rail crown and decrease in longitudinal stress \( \sigma_Z(t) \) at the rail’s contact surface (point 1) and also at a distance of 10 mm (point 2).

Typically, the stress reduction in the upper section of the rail is only seen at points 1 and 2—that is, within the hardenability zone (15 mm).

At the thermal center of the rail’s upper section (at a distance of 30 mm from the contact surface), tensile stress predominates, as seen in Figs. 4b and 5b.

Note again that the compressive stress is confined to the hardenability zone of the metal, close to the rail’s contact surface. In Fig. 7, we show the distribution of longitudinal-stress along the axis of the rail cross section for different times. We see that compressive stress is confined to a band of no more than 15 mm. At a distance of 26–27 mm from the rail’s contact surface, we observe tensile stress, with a maximum value of 500–510 MPa.

On that basis, we conclude that isothermal quenching to produce lower bainite by pulsed cooling may increase the wear resistance of rails. The appearance of compressive stress at the rail’s contact surface increases the contact strength of the metal with lower bainite structure.

The practical introduction of this method will require experimental determination and refinement of numerous parameters.
In particular, the linear expansion coefficient of lower bainite must be refined, as well as various pulsed-cooling parameters: the amplitude of the heat-transfer coefficient $\alpha(t)$ and the time interval $Dt$ between successive coolant (cold water) pulses.

**CONCLUSIONS**

In isothermal quenching of R65 rails, we may produce lower bainite structure at the rail’s contact surface by pulsed cooling with cold water for 25–30 min. The total quenching time of the rail may be divided into three stages: initial cooling of the upper section of the rail (100–120 s); pulsed cooling (1800 s); and final air cooling.

The lower bainite zone at the rail’s contact surface significantly strengthens the metal in comparison with the plate pearlite formed by traditional oil quenching.

In the proposed method, compressive stress is formed within the band of metal quenched to lower bainite, with corresponding increase in the contact strength and rail life.

**REFERENCES**

OJSC Scientific-Research Institute of Metallurgical Heat Engineering (VNIIMT) established in 1930 as Ural Division of All-Union Heat Engineering Institute is widely known in Russia and the CIS. The Institute focuses on development of high-technology heat engineering units, energy efficient and ecologically friendly technologies in ferrous and non-ferrous metallurgy, machine-building and other fuel-consuming branches of industry.

Highly-qualified academic researchers, unique experimental and production facilities and own research and design centre enable efficient scientific-and-research, design-and-experimental, engineering and project works, delivery of equipment, designer's supervision and commissioning works including execution of turnkey contracts in the following areas:

**Sintering:**
- development of techniques and modes of metal raw material heat treatment;
- design of energy-efficient agglomeration hearths and agglomeration gas heat recovery circuits allowing to reduce energy consumption and dust and gas emissions.

**Pellet production:**
- optimal traveling grate pelletizing furnaces for heat treatment of iron-ore pellets from various concentrates (hematite, magnetite, etc.) with optimal automatic process control system.

**Preparation of metallic and nonmetallic raw materials:**
- technique of iron-ore raw material dephosphorization by roasting and leaching;
- installations for drying high-moisture dispersive materials of various designs;
- efficient techniques of magnetizing roasting and subsequent dressing;
- technique of rare-earth element extraction (for example, germanium from germanium iron ores).

**Blast-furnace ironmaking:**
- explosion-proof near-furnace systems of blast furnace slag granulation giving a high-quality product for cement production;
- optimal control system for hot blast stoves;
- an innovative bench for drying hot metal and steel-smelting ladles;
- copper coolers and tuyeres of blast furnaces.

**DRI (direct reduction of iron)**
- improvement of the reduction technique in shaft furnaces for radical improvement of technical and economic indicators of their operation (productivity is increased twice);
- technique of raw material reduction in rotary furnaces using coal as the reductant.

**Lime production:** development of the technique and increase of lime production process efficiency:
- in shaft furnaces;
- in double-shaft furnaces;
- in rotary furnaces;
- in “stacked-tower preheater - rotary furnace” installations;
- in “shaft calciner - rotary furnace” installations (VNIIMT innovative technology).

**Granulation of metal melts:**
- development of technologies and designs of explosion-proof plants for near-furnace granulation of metallurgical slag, molten metal, etc., including heat recovery;
Reheating furnaces:
- development of new and update of the existing designs of furnaces for stock heating;
- high-performance systems of reheating furnace firing with recovery and regeneration firing systems based on the innovative burner units designed by VNIIMT;
- switching the furnace firing systems to cheaper fuel types;
- development and implementation of optimal furnace operating parameters.

Heat-treatment furnaces development of techniques and equipment for heat treatment of roll stock and metal products including those with protective atmospheres:
- thermochemical treatment conditions ensuring retention or directional change in chemical composition of metal surface;
- gas dampers for heat-treatment furnaces;
- spray quenching units and other elements of convective cooling systems;

Furnaces with protective atmosphere and gas treatment units:
- development of the furnace structure, design, manufacture, delivery and commissioning works;
- development of a technology for treatment of articles and devices for protective gas generation;
- calculation, development and manufacture of endogas and exogas atmosphere generators for metal product thermochemical treatment units;
- gas analysis systems for monitoring and control of physico-chemical properties of protective process atmospheres.

Reheating, heat-treatment and drying furnaces with convection heat transfer:
- development, design and manufacture using industrial heat-resistant (up to 900 °C) furnace fans designed by VNIIMT.

Rolled products:
- techniques and units for controlled high-speed air-to-water cooling (quenching) of rolled ferrous and non-ferrous metal products including thick plate on mill 5000;
- replacement of oil quenching technology with VNIIMT's eco-friendly air-to-water technique;
- innovative technique of oily mill scale processing;
- line of wire rod accelerated air cooling with process improvement.

Manufacturing manufacture and delivery of:
- high-performance burner units;
- heat-resistant (furnace) fans (up to 900 °C);
- copper coolers for blast furnaces and nonferrous furnaces based on VNIIMT technology;
- Pitot tubes for measuring flow rates and pressures.

OJSC VNIIMT developments are widely used in metallurgical enterprises of Russia, Ukraine, Kazakhstan, China, India and others.

For detailed information on institute developments, please visit OJSC VNIIMT site at www.vniimt.ru

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