Simulation of Differentiated Thermal Processing of Railway Rails by Compressed Air
V. D. Sarychev*, S. G. Molotkov**, V. E. Kormyshev*, S. A. Nevskii*, and E. V. Polevoi***

a Siberian State Industrial University, Novokuznetsk, Kemerovo oblast, Kuzbass, 654007 Russia
b AO “EVRAZ—Joint West Siberian Metallurgical Plant”, Novokuznetsk, Kemerovo oblast, Kuzbass, 654043 Russia

* e-mail: sarychev_vd@mail.ru
** e-mail: sgmol@yandex.ru
*** e-mail: 89236230000@mail.ru
**** e-mail: nevskiy sergei@yandex.ru
***** e-mail: Egor.Polevoj@evraz.com

Received December 23, 2019; revised June 22, 2020; accepted October 26, 2020

Abstract—Mathematical modeling of differentiated thermal processing of railway rails with air has been carried out. At the first stage, the one-dimensional heat conduction problem with boundary conditions of the third kind was solved analytically and numerically. The obtained temperature distributions at the rail head and at a depth of 20 mm from the rolling surface were compared with experimental data. As a result, the coefficient values of heat transfer and thermal conductivity of rail steel were determined. At the second stage, the mathematical model of temperature distribution in a rail template was created in conditions of forced cooling and subsequent cooling under natural convection. The proposed mathematical model is based on the Navier–Stokes and convective thermal conductivity equations for the quenching medium and thermal conductivity equation for rail steel. On the rail–air boundary, the condition of heat flow continuity was set. In conditions of spontaneous cooling, change in the temperature field was simulated by a heat conduction equation with conditions of the third kind. Analytical solution of a one-dimensional heat conduction equation has shown that calculated temperature values differ from the experimental data by 10%. When cooling duration is more than 30 s, the change of pace of temperature versus time curves occurs, which is associated with change in cooling mechanisms. Results of numerical analysis confirm this assumption. Analysis of the two-dimensional model of rail cooling by the finite element method has shown that surface temperature of the rail head decreases sharply both along the central axis and along the fillet at the initial cooling stage. When cooling duration is over 100 s, temperature stabilizes to 307 K. In the central zones of the rail head, the cooling process is slower than in the surface ones. After forced cooling is stopped, heating of the surface layers is observed, due to change in heat flow direction from the central zones to the surface of the rail head, and then cooling occurs at speeds significantly lower than at the first stage. The obtained results can be used to correct differential hardening modes.

Keywords: differentiated thermal processing, rail steel, cooling rate, mathematical modeling, thermal conductivity equation, boundary conditions of the third kind, finite element method

DOI: 10.3103/S096709122012013X

INTRODUCTION
The increase of consumer properties of rails in conditions during their exaggerated operation conditions is a crucial problem in the railroad industry. The main requirements to rail-rolling from customers are high durability, fatigue strength, resistance to brittle fracture, as well as high resistance to the formation and development of contact fatigue defects [1]. Fulfillment of these requirements is achieved by applying high-carbon (with steel content greater than 0.8–0.9%) steels of perlite and medium-carbon (0.2–0.6% of carbon) steels of bainite class. Presently, most of the rail steels applied in the world refer to perlite class. Mechanical properties of these steels depend on interlamellar distance, volume fraction of cementite in perlite, grain size, the presence of excessive phases, dispersivity and distribution of carbide particles [2, 3]. The final microstructure of rails subjected to thermal processing using residual heat of prerolling heating is formed under the influence of a series of technological factors of rolling and thermal processing [4]. Contemporary trends of thermal processing of rail steel are directed to the development and integration of differentiated hardening right after rolling of rails. Such a
the rail constitutes 4–8°C/s, while at distance of 10 mm from the surface of rolling it is 2.0–2.5°C/s. Different cooling rates of the surface and volume of the rails, as well as inhomogeneous distribution of temperature, are obvious reasons of the formation of gradient structural-phase states by the rail depth.

Searching for optimal regimes of thermal processing, which provide high mechanical properties of rails, is a complicated problem, whose solution requires not only experimental methods, but also mathematical modeling [10, 11]. Presently, the use of CAD systems for materials processing is common practice. For rails made of perlitic steel using physical and numerical modeling, a study of the influence of technological conditions on their properties was carried out. Typical problems of optimization of manufacturing processes are based on modeling various options according to the applied optimization methodology. To solve industrial problems, finite element (FE) modeling methods are usually applied to calculate the objective function, the arguments of which are the properties of the products used. For this purpose, the optimization problem’s solution is cost intensive and a search for alternative methods [12] is ongoing. In addition, when the objective function includes complicated microstructural parameters or material properties, it is necessary to apply multiscale modeling, which leads to further growth of computation efforts [13].

The aim of this work is to develop a mechanism and mathematical model, which would describe the process of controllable cooling of rails with a sufficient accuracy.

MECHANISM OF RAIL COOLING BY AIR

In order to reveal the mechanism of rail cooling by air, let us compare experimental and theoretical dependences of temperature on time on the surface and at depth of 20 mm. Assuming that heat exchange can be characterized by some average constant heat exchange coefficient $\alpha$ and constant temperature of cooling air $T_0$, we can consider a one-dimensional problem of heat conductivity with a boundary condition of the third kind. Temperature in rail on the symmetry axis as a function of longitudinal coordinate and time obeys a one-dimensional equation of heat conductivity with boundary conditions of the third kind, since transversal flow of heat is absent on the symmetry axis. Thus, the solution for the reverse one-dimensional problem of heat conductivity in order to determine the value ranges of heat exchange coefficient and air temperature is constitutive in revealing the mechanism of rail cooling by air. Experimental dependences of temperature on time on the surface and at depth of 20 mm from rail head are presented in work [9] for total cooling time $t_1 = 200$ s. Depth of heat flow penetration can be estimated as $s = \sqrt{a l_0}$ (where $\alpha$—coefficient of thermal diffusivity, for rail steel $\alpha = 6 \times 10^{-5}$ m$^2$/s, therefore $s = 35$ mm). Comparing this value with rail height (180 mm), the influence of cooling of the bottom on the head cooling process can be counted negligible. Thus, the one-dimensional boundary problem of heat conductivity for semi-infinite rod can be considered.

Let us consider cooling of rod ($v > 0$) with heat flux on its boundary ($v = 0$) [14]. The heat flux is conditioned by gas flow with temperature $T_c$ and different coefficients of heat exchange: at moments of time from zero to $t_1$ heat exchange coefficient equals to $\alpha_1$, at $t > t_1$, $\alpha_2$. Initial temperature of the rod—$T_0$. The mathematical problem is denoted as

$$\frac{\partial \Theta}{\partial \tau} = \frac{\partial^2 \Theta}{\partial \xi^2}; \quad 0 < \xi < \infty, \quad \tau > 0;$$

$$\xi = 0: \frac{\partial \Theta}{\partial \xi} = \Theta; \quad 0 < \tau < \tau_1; \quad \frac{\partial \Theta}{\partial \xi} = \kappa \Theta,$$

$$\tau_1 < \tau < \infty; \quad \Theta(0, \xi) = 1,$$

where

$$\tau = \frac{t}{l_0}, \quad \xi = \frac{y}{l_0}, \quad \Theta = \frac{T - T_c}{T_0 - T_c}, \quad \kappa = \frac{\alpha_2}{\alpha_1}, \quad t_0 = \frac{l_0^2}{\alpha}, \quad l_0 = \frac{\lambda}{\alpha_1},$$

and $\lambda$ is the thermal diffusivity of rail steel.
In case when the heat exchange coefficient does not change (\(\kappa = 1\)), the solution of equation (1) can be denoted as

\[
\Theta(t, \xi) = \Phi(\eta) + \exp(\xi + \tau)[1 - \Phi(\eta + \sqrt{\tau})];
\]

\[
\eta = \frac{\xi}{2\sqrt{\tau}}; \quad \Phi(z) = \frac{1}{\sqrt{\pi t_0}} \int_0^z \exp(-u^2) du.
\]  

(2)

Passing to dimensional variables, we obtain

\[
T(t, y) = T_c + \Theta \left( \frac{t}{t_0}, \frac{y}{l_0} \right) (T_0 - T_c).
\]  

(3)

To find the value of heat exchange coefficient for a range of surface temperatures, we introduce the following function:

\[
\Theta(\tau, \xi) = \Phi(\eta) + \xi + \tau - \Phi(\eta + \sqrt{\tau})
\]

\[
\lambda(\tau, \xi) = \frac{1}{\sqrt{\pi t_0}} \int_0^\xi \exp(-u^2) du.
\]

(4)

Using the least square method, we find that \(t_0 = 567\) s. Then equation (4) implies heat exchange coefficient

\[
\alpha = \frac{\lambda}{\sqrt{\pi t_0}}.
\]  

(7)

Heat exchange coefficient of rail steel changes from 42 to 25 W/(m K) at temperatures of 500–800°C [15]. On the surface of the rail head, temperature changes within the range of 600–400°C [9]. Thus, we will accept the value of heat exchange coefficient as the average value of 35 W/(m K). Then, the numeric value of the average heat exchange coefficient \(\alpha\) compressed air–steel equals to 600 W/(m^2 K). At a depth of 20 mm, temperature changes within the range of 700–800°C. Thus, we will accept heat exchange coefficient as 24 W/(m K); then \(l_0 \approx 40\) mm, \(\xi = 0.5\).

Figure 1 presents a comparison of computed and experimental values of dependences of temperature on time at constant exchange coefficient of 600 W/(m^2 K). In the first approximation, they differ by 10%. However, analysis of curve 1 shows that the curve is convex and falls quickly (cooling rate—7°C/s) until 30 s. At \(t > 30\) s, this curve is concave and cooling rate is significantly lower (2°C/s). This circumstance points at change of cooling mechanism due to polymorphous transformations conditioned by decomposition of austenite to ferrite-perlitic mixture.

It is necessary to account dependences of thermophysical constants of the material (heat capacity, density, and heat conductivity) and the hardening compound (heat exchange coefficient) on the temperature of the product. In this case [16], no simple analytic equation of heat conductivity exists. Therefore, we will refer to the numeric solution of the problem. The boundary problem for the heat conductivity equation considering the abovementioned facts will be denoted as

\[
\frac{\partial H}{\partial t} = \frac{\partial}{\partial y} \left( \lambda(T) \frac{\partial T}{\partial y} \right), \quad T(y, 0) = T_0;
\]

\[
\lambda \frac{\partial T}{\partial y} \bigg|_{y=0} = \alpha_i(T(0, t) - T_{ext});
\]

\[
\lambda \frac{\partial T}{\partial y} \bigg|_{y=t} = \alpha_j(T(t, t) - T_{ext}),
\]  

(8)

where \(H = c_p T\) is enthalpy; \(c\) is specific heat capacity; \(\rho\) is density of the material; \(T_{ext}\) is temperature of hardening compound.

The obtained set was solved by an implicit difference scheme using elimination method [17]. Figure 2 presents dependences of temperature on time.

Fig. 1. Dependence of temperature on time at surface of the rail head (1) and at a depth of 20 mm (2) (lines—dependences obtained by formula (3), points—experimental data).
FORMULATION OF THE MATHEMATICAL PROBLEM OF COOLING OF RAIL BY MOVING AIR FLUX

In this work, we will consider the cooling of rail flowing around by air from the side of head and bottom (Fig. 3). According to experimental data [9], thermal processing of rails in air medium takes 90–200 s, as further cooling takes place in conditions of natural convection. Therefore, the problem of temperature distribution must be split into two stages.

At first stage of forced cooling, the mathematical model will include equations of Navier–Stokes and convective heat conductivity for air flux and heat transfer in rail:

\[ \rho \frac{\partial \vec{u}}{\partial t} + \rho (\vec{u} \nabla) \vec{u} = \nabla [ -\rho I + \mu (\nabla \vec{u} + (\nabla \vec{u})^T)] ; \]

\[ \rho (\nabla \vec{u}) = 0 ; \]

\[ \rho_1 c_1 \frac{\partial T}{\partial t} + \rho_1 c_1 (\nabla \vec{u}) \nabla T + \nabla \vec{q} = -\lambda_1 \nabla T ; \]

\[ \rho_2 c_2 \frac{\partial T}{\partial t} + \rho_2 c_2 (\nabla \vec{u}) \nabla T + \nabla \vec{q} = -\lambda_2 \nabla T. \]

Conditions of heat flux continuity are fulfilled on the boundary between rail surface and air

\[ -\lambda_1 \frac{\partial T}{\partial n} = -\lambda_2 \frac{\partial T}{\partial n} ; \]

\[ n_a = 0 , \]

where \( \vec{u} \) is velocity vector of air; \( \lambda_1, \lambda_2 \) are heat conductivity coefficients of air and rail material; \( \rho_1 \) and \( \rho_2 \) are density of air and rail material; \( c_1 \) and \( c_2 \) are specific heat capacity of air and rail material; \( \nabla \) is differential operator nabla; \( \Delta \) is Laplacian operator.

At the second stage, the boundary problem of the third kind was formulated for heat conductivity equation (11), which is denoted as

\[ \vec{q} = \alpha(T - T_{ext}) , \]

where \( \alpha \) is heat exchange coefficient; \( T_{ext} \) is temperature of air.

Values \( \alpha_1, \alpha_2 \) and \( \alpha_3 \) were set on the surface of rail head, bottom and the rest surface correspondingly.

Equation sets (9)–(11) at all the stages were solved by the FE method using a scheme of adaptive grids [17, 18] in the Comsol Multiphysics package. In areas of large curvature grid step decreases to 0.2 mm, grid unevenness is characterized by compression parameter \( h = 1.2 \). For an iterative solution of the system, a generalized method of the second order of accuracy in time is used. Initial data on air flow and thermophysical characteristics of materials are given in Table 1.

RESULTS AND DISCUSSION

Figure 4 presents distribution of temperatures in rail at the stage of forced cooling at different moments of time.

At the initial stage of cooling, temperature of the rail head surface by the central axis and the fillet sharply decreases: if at the moment of time \( t = 0 \) s its
value constituted 1088 K, then at $t = 50$ and $t = 100$ s, 456 and 380 K correspondingly (fig. 4b, b). At the moments of time $t > 100$ s, temperature is stabilized to 307 K (200 s). Heat flux is directed from central parts of rail to its surface. In central areas, cooling process flows slower than in surface areas, which is confirmed by data of electron-microscopic researches \[7, 8\]. The surface layer of the researched samples of rail steel is characterized by comparatively more nonequilibrium state of the structure. A similar thermophysical situation was observed in works \[19, 20\] devoted to studying thermal-mechanical hardening of reinforcing bars.

Distribution of temperatures at the second stage of natural cooling is presented in Fig. 5.

At the stage of natural cooling (Fig. 5), first of all surface layers of rail are heated by the central axis and the fillet. This is conditioned by heat flux from the central areas to the surface. Then cooling with lower velocities than at the first stage takes place.
CONCLUSIONS

In this work, we modeled a thermophysical situation taking place at differentiated thermal processing of rails in an air medium. Distribution of temperature in rail gauges at different moments of time in areas of forced and self-induced cooling was obtained. It was established that decreasing of temperature of surface layers flows faster than in central parts. This fact provides a qualitative explanation for the formation of nonequilibrium structural-phase states in the given layers. The found dependences of temperature on coordinates and time can be used to correct regimes of differentiated thermal processing.

FUNDING

This study was supported by the Russian Foundation for Basic Research, grant no. 19-32-60001.

REFERENCES

1. Kuziak, R., Pidvyzots'kyi, V., Pernach, M., Rauch, Ł., Zygmunt, T., and Pietrzyk, M., Selection of the best phase transformation model for optimization of manufacturing processes of pearlitic steel rails, Arch. Civ. Mech. Eng., 2019, vol. 19, no. 2, pp. 535–546.
2. Yahyaoui, H., Sidhom, H., Braham, C., and Baczmannski, A., Effect of interlamellar spacing on the elastoplastic behavior of C70 pearlitic steel: experimental results and self-consistent modeling, Mater. Des., 2014, vol. 55, pp. 888–897.
3. Kapp, M.W., Hohenwarter, A., Wurster, S., Yang, B., and Pippin, R., Anisotropic deformation characteristics of an ultraline- and nanolamellar pearlitic steel, Acta Mater., 2016, vol. 106, pp. 239–248.
4. Borts, A.I., Shur, E.A., Reichart, V.A., and Bazanov, Yu.A., Results of tests of rails subjected to direct differential quenching. Influence of production technology on their properties, Prom. Transp. XXI Vek, 2009, no. 4, pp. 32–36.
5. Pavlov, V.V., Korneva, L.V., and Kozyrev, N.A., Selecting a thermal-hardening technology for rails, Steel Transl., 2007, vol. 37, no. 3, pp. 313–315.
6. Korneva, L.V., Yunin, G.N., Kozyrev, N.A., Atkona, O.P., and Polevoi, E.V., Quality comparison of OAO NKMK and imported rails, Steel Transl., 2010, vol. 40, no. 12, pp. 1047–1050.
7. Gromov, V.E., Volkov, K.V., Ivanov, Yu.F., Morozov, K.V., Alsarayeva, K.V., and Konovalov, S.V., Formation of structure, phase composition and faulty substructure in the bulk- and differentially-hard-tempered rails, Prog. Phys. Met., 2014, vol. 15, no. 1, pp. 1–33.
8. Gromov, V.E., Morozov, K.V., Ivanov, Yu.F., and Glezer, A.M., Analysis of structure-phase states in a-bulk hardened and a head-hardened rails, AIP Conf. Proc., 2014, vol. 1623, pp. 191–194.
9. Volkov, K.V., Polevoi, E.V., Temlyantsev, M.V., Atkona, O.P., Yunusov, A.M., and Syusyukin, A.Yu., Simulation of air jet hardening from furnace heating of railway rails, Vestn. Sib. Gos. Ind. Univ., 2014, no. 3 (9), pp. 17–23.
10. Sahay, S.S., Mohapatra, G., and Totten, G.E., Overview of pearlitic rail steel: Accelerated cooling, quenching, microstructure, and mechanical properties, J. ASTM Int., 2009, vol. 6, no. 7, pp. 1–26.
11. Pointner, P., High strength rail steels—the importance of material properties in contact mechanics problems, Wear, 2008, vol. 265, no. 9, pp. 1373–1379.
12. Behrens, B.-A., Denkena, B., Charlin, F., and Dannenberg, M., Model based optimization of forging process chains by the use of a genetic algorithm, Proc. 10th Int. Conf. on Technology of Plasticity (ICTP), Aachen, 2011, pp. 25–30.
13. Li, G., Liu, Z., Chen, L., and Hou, X., Numerical calculation of the comprehensive heat transfer coefficient on the surface of rail in the spray cooling process, J. Metall. Eng., 2015, vol. 4, pp. 13–17.
14. Carslaw, H.S. and Jaeger, J.C., Conduction of Heat in Solids, Oxford: Oxford Univ. Press, 1947.
15. Zubchenko, A.S., Koloskov, M.M., Kashirskii, Yu.V., et al., Marochchnik stalei i splavov (Grade of Steels and Alloys), Zubchenko, A.S., Ed., Moscow: Mashinostroenie, 2003.
16. Tikhonov, A.N., Kal’ner, V.D., and Glasko, V.B., Matematicheskoe modelirovanie tekhnologicheskikh protsessov i metod resheniya obratnykh zadach v mashinostroenii (Mathematical Modeling of Technological Pro-

Table 1. Thermophysical characteristics of the rail steel and air

| Characteristic                  | Value       |
|--------------------------------|-------------|
| Specific heat capacity, J/(kg K) |             |
| of steel                       | 1047        |
| of air                         | 716         |
| Density, kg/m³                 |             |
| of steel                       | 7911        |
| of air                         | 1.29        |
| Heat conductivity, W/(m K)     |             |
| of steel                       | 40          |
| of air                         | 24          |
| Pressure of air, mm H₂O (Pa)   | 1000 (10⁴)  |
| Initial temperature of rail, K | 1088        |
| Temperature of air, K          | 293         |
cesses and Method for Solving Inverse Problems in Mechanical Engineering), Moscow: Mashinostroenie, 1990.

17. Duda, P., A general method for solving transient multidimensional inverse heat transfer problems, *Int. J. Heat Mass Transfer*, 2016, vol. 93, pp. 665–673.

18. Samarskii, A.A. and Vabishchevich, P.N., *Vychislitel’naya teploperedacha* (Computational Heat Transfer), Moscow: URSS Editorial, 2003.

19. Sarychev, V.D., Nevskii, S.A., Granovskii, A.Yu., and Gromov, V.E., *Matematicheskie modeli i mehanizmy formirovaniya gradientnykh struktur v materialakh pri vneshnikh energeticheskikh vozdeistvijakh: monografiya* (Mathematical Models and Mechanisms of Formation of Gradient Structures in Materials under External Energy Influences: Monograph), Novokuznetsk: Sib. Gos. Ind. Univ., 2017.

20. Sarychev, V.D., Khaimzon, B.B., Nevskii, S.A., Il’yashchenko, A.V., and Grishunin, V.A., Mathematical models of mechanisms for rolled products accelerated cooling, *Izv. Vyssh. Uchebn. Zaved., Chern. Metall.*, 2018, vol. 61, no. 4, pp. 326–332.

Translated by K. Gumerov