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DEVELOPMENT OF A MODEL FOR CALCULATING CHANGES IN K76F RAIL STEEL TEMPERATURE TO DETERMINE THE HEAT TREATMENT PARAMETERS

Introduction. *The conditions of operation of the railways of Ukraine and the prospects for their entry into the international system of transport corridors require the development and modernization of railway tracks, including rails.*

Problem Statement. *Given the necessity to ensure the main operational parameter of the rails (wear resistance), regulatory and technical documents standardize hardness. The most progressive European standard EN 13674-1-2011 establishes that the hardness of the rail head at a depth of 20 mm shall be, at least, 321 HB, while DSTU 4344:2004 requires, at least, 321 HB at a depth of 11 mm. At the same time, according to EN 13674-1-2011, the rail surface hardness without the formation of needle structures shall be, at least, 405 HB.*

Purpose. *To determine the possibility of achieving hardness without needle structures for rail head made of steel 0,80% C, 0,25% Si, 0,97% Mn, 0,055% V (hereinafter referred to as K76F), which complies with the world requirements, based on the calcination experiment and calculations with the use of the model; to determine the rational cooling rate for K76F steel during heat treatment.*

Materials and Methods. *K76F rail steel with 0.80% C, 0.25% Si, 0.97% Mn, 0.055% V. Techniques: metallographic studies, hardness measurements, determination of calcination by end quenching, modeling by means of mathematical calculation with the use of QForm heat treatment software package.*

Results. *The change in temperature, the formation of structure and hardness across the section of a K76F steel sample for calcination tests according to GOST5657 has been modeled. The changes in the hardness and microstructure has been experimentally established, depending on the distance to the heat sink surface; the cooling rate in the points where the hardness meets the requirements of EN 13674-1-2011 for rails has been determined.*

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Conclusions. *The analysis of the model has shown a high accuracy of the model and the convergence of the experimental results with the calculated ones. It has been established that the requirements of EN 13674-1-2011 can be achieved up to a hardness of 405 HB without the formation of needle structures on steel that meets the chemical composition of K76F according to DSTU 4344: 2004.*

Keywords: railway rail, hardness, calcination, mathematical model, and cooling rate.

Today, the operating conditions of Ukrainian railways and the prospects of their entry into the Europe-Asia international system of transport corridors require the development and modernization of the railway tracks, the use of new energy and resource-saving technologies both in production and operation of track superstructure elements, including rails. The comparison of the quality of domestic rails with foreign samples has displayed the leadership of the latter. The studies have shown that the train-handling capacity of domestic rails is equal to 0.5 billion tons of gross cargo. Under the same operating conditions, the rails manufactured in Russia, Japan, and France have a capacity of 1 billion tons of gross cargo. Today, the problem of raising the efficiency of rails becomes even more relevant in connection with intensifying traffic on the country's railways, increasing the track rigidity due to the use of reinforced concrete cross-sleepers, and growing traffic load [2, 4].

To ensure high efficiency of operation of railway rails, it is necessary to increase their quality, reliability and stability, which determine the smooth and trouble-free operation of railway transport [1—3]. The quality of rails, the train-handling capacity, and the safety of railway transport depend on the requirements of regulative documents. Given the necessity to ensure the main operational parameter of the rails (wear resistance), in all countries, regulatory and technical documents standardize hardness. A feature of the requirements for this parameter is a rigid framework for its level on the rolled surface. According to DSTU 4344: 2004, the hardness on the rail head surface is regulated both by the upper limit (401 HB) that shall not be exceeded in order to prevent the formation of intermediate transformation structures (bainite) and by the lower limit (374 HB). Similarly, the hardness on the surface shall range from 352 to 405 HB, according to GOST R 51685-2013, and from 370 to 410 HB, according to EN 13674-1: 2011 [2].

The rather progressive European standard EN 13674-1-2011 establishes that the hardness of the rail head at a depth of 20 mm shall be, at least, 321 HB, which is unattainable for Ukrainian manufacturers under the current conditions (According to the DSTU, the deepest hardness measurement point is 11 mm, and the hardness here shall be, at least, 321 HB for the highest category rails); deeper, the hardness is not standardized.

Therefore, for the enterprises of Ukraine, it is very relevant to solve the problem, i.e. to obtain a high hardness at a depth of 20 mm with strict restrictions on the maximum value for the head surface. The hardness of rail steel is known to be determined by its structural state that, in turn, depends on the cooling rate along the cross section of the rail head in the course of differentiated quenching.

In terms of industrial production, to reduce material consumption and time resources is especially important while developing new technologies, new range of products, and new steels. For heat treatment of steel products, these issues may be solved with the use of modern methods of modeling and calculations, which with minimal time and material resources allow us to study various

Table 1. **Chemical Composition of Rail Steel, weight %**

C	Si	Mn	P	S	Cr	Ni	Cu	Al	Ti	Mo	V
0.80	0.25	0.97	0.011	0.007	0.04	0.03	0.03	0.006	0.005	≤0.01	0.055

technological processes, to develop and to optimize them for different materials for obtaining specific solutions.

The purpose of this research is to determine the possibility of achieving hardness without needle structures for rail head made of steel 0.80% C, 0.25% Si, 0.97% Mn, 0.055% V (hereinafter referred to as K76F), which complies with the world requirements, based on the calcination experiment (the Jominy technique) and calculations with the use of the model and to find the rational cooling rate for K76F steel in the course of heat treatment.

Metallographic studies have been done with the use of light microscopes *Neophot-32* and *Axiovert200 M MAT*. Hardness measurements have been conducted with the use of a TK-2M hardness tester.

For the research purpose, a full-profile sample of the P65 type rail manufactured by PJSC MMK *Azovstal* is used. The width of rail head is 75 mm, its height along the axis is 45 mm. The chemical composition of rail steel is presented in Table 1.

According to the mass fraction of elements, this steel may be classified as K76F steel with increased carbon and reduced silicon content.

The experiment is simulated with the use of the *QForm* heat treatment software package. This method allows us to reduce the solution of the system of equations to the system of the simplest algebraic equations while entering data. The sample quenching process has been analyzed in the following stages:

1. Construction of geometric objects of the quenching process. The geometry of the sample is constructed with the use of the КОМПАС program. The drawing is exported in *.stp format to *QForm*.

2. Initial conditions. Types of operations (heat treatment calculations, thermo-elastic-plastic problem) are set as initial conditions. The initial temperature before quenching is set at 880 °C.

3. Boundary conditions. In the physical sense, the boundary conditions are water as cooler fed in the form of a jet directed from the bottom upwards to the end surface. It is characterized by heat transfer coefficient and coolant temperature. The heat transfer coefficient is set based on the steel surface temperature.

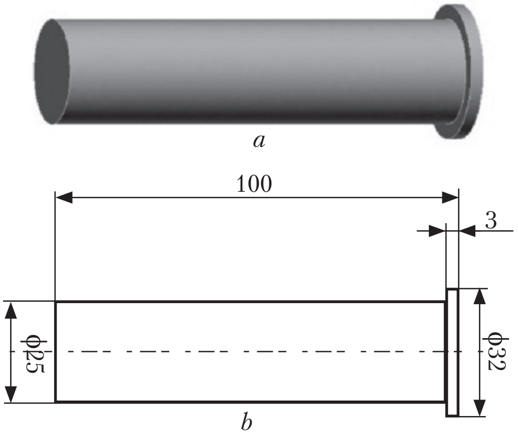

Fig. 1. Sample for steel calcination test: *a* — *Qform* environment, *b* — as per GOST 5657

4. Modeling is done for K76F steel. For this steel grade, the dependence of the heat transfer coefficient on temperature is determined by the trial method.

5. At the last stage of modeling, the model is adapted to the real process (comparison of the experimental data at reference points with the numerical results, further adjustment of the model), and optimal modeling results are analyzed. The simulation results (temperature in the nodes of the sample model at different depths) are compared with the experimental data and, in the case of significant discrepancy, the numerical model is adjusted through varying the heat transfer coefficient of the cooler.

Research results. Rails at the enterprises of Ukraine are subjected to differentiated heat treatment: as only the rail head are heated with subsequent accelerated cooling. To solve this problem, it is necessary to determine the cooling rate (for steel 76F DSTU 4344) that provide the required hardness according to EN 13674-1-2011 along the cross section of the rail head. An experiment has been made in the laboratory to determine the cooling rate that provides hardness at a given level and the absence of needle structures.

At the first stage of research, a 3D model has been developed (Fig. 1, *a*) in the *Qform* environ-

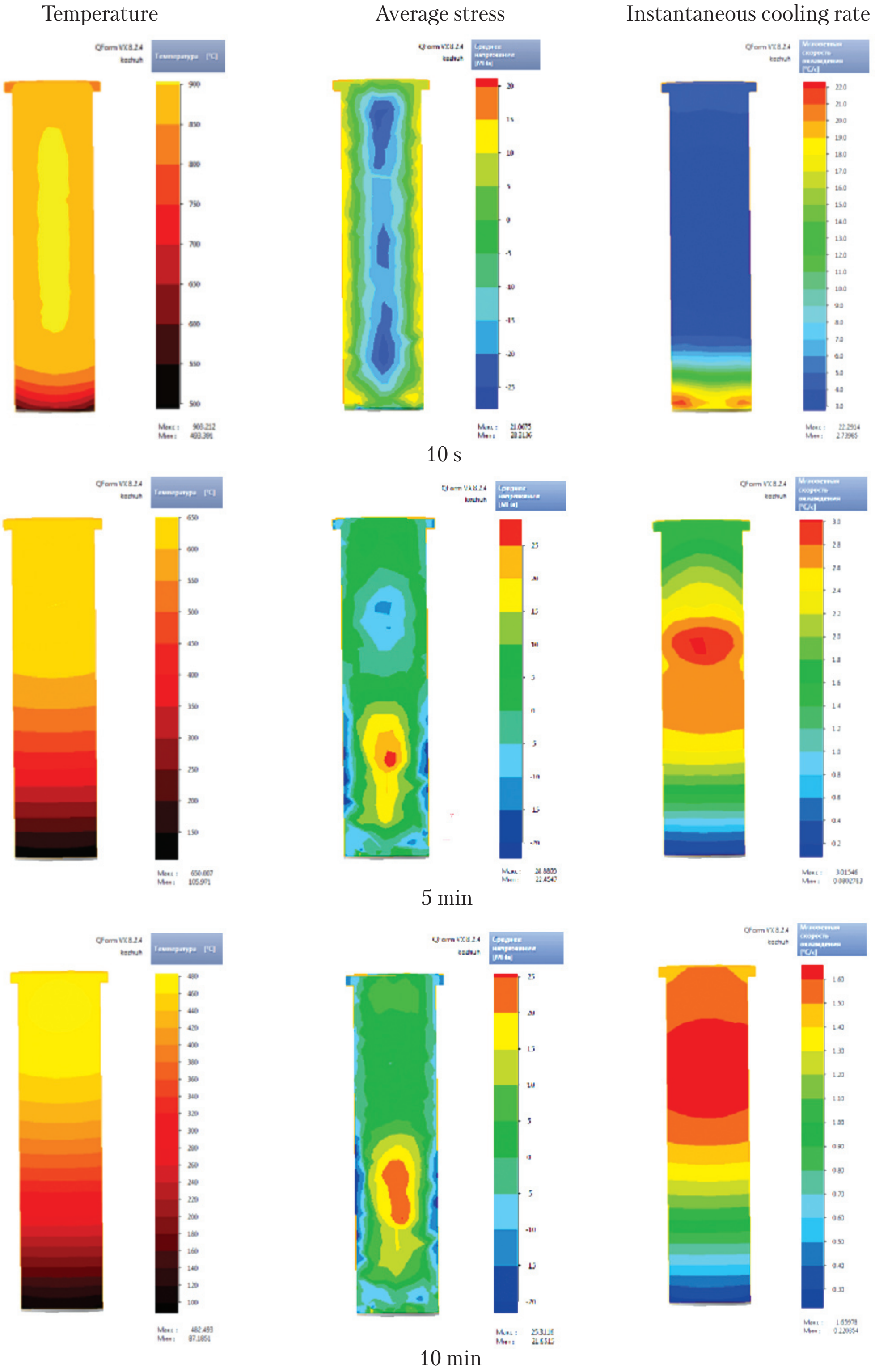

Fig. 2. The results of modeling a sample for determining K76F steel calcination by the Jominy method in the *QForm* software package

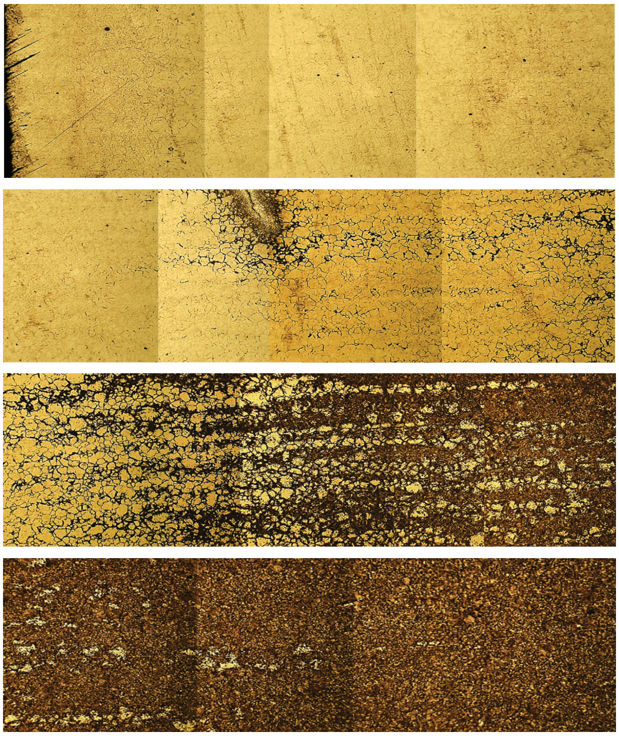

Fig. 3. K76F rail steel microstructure after end quench. ×50

ment. At the second stage of research, to adapt and to verify the adequacy of the model, two samples are made of the steel studied, according to the scheme presented in Fig. 1, *b*, and an experiment is conducted to determine changes in the structure and hardness after cooling by the Jominy technique for determining the steel calcination, according to GOST 5657.

Calcination is the ability of steel to harden. It is characterized by the depth of penetration of the quenched (martensitic or semi-martensitic) layer into the volume of quenched product. The calcination is determined by the critical quenching rate that depends on the steel composition. Due to higher resistance of supercooled austenite and, accordingly, lower critical cooling rate the alloy steels are calcined deeper than the carbon steels. Mn, Mo, Cr, Ni and small additives of B strongly increase calcination. Calcinability grows especially with the simultaneous introduction of several alloying elements, such as Cr and Ni into steel. There are several methods for estimating calcination, the most widely used among them is the end quench method that determines the hardness of steel as a function of distance from the end of cylinder with insulated side surface, which is cooled by hardening fluid jet.

A mathematical model has been developed to predict changes in temperature, instantaneous cooling rate, and average cross-section stress of the sample for calcination tests with continuous one-sided cooling. This model may be used to determine the required cooling parameters in the thermal quenching process in order to obtain the desired structural state and set of properties. This allows selecting the optimal modes of differentiated heat treatment to obtain a homogeneous structural state and, consequently, the cross-sectional properties of the rail head.

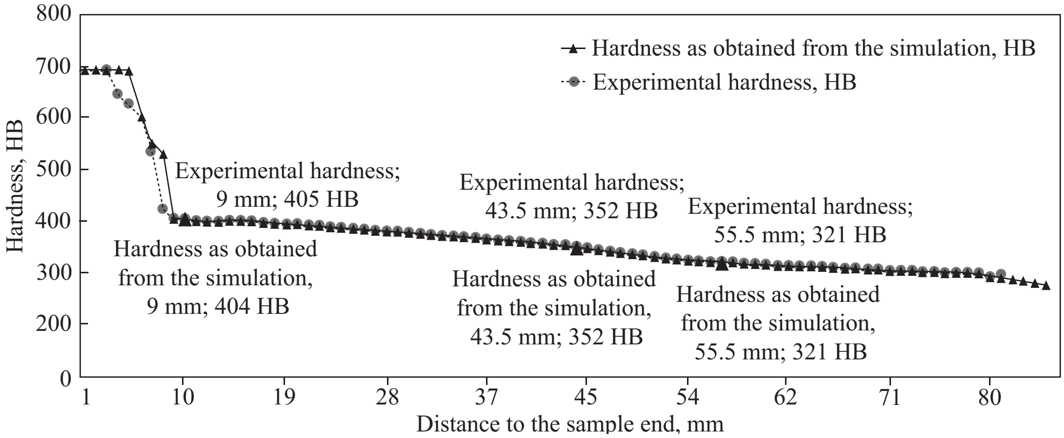

Fig. 4. Change in hardness depending on distance to the end after Jominy end-quench tests

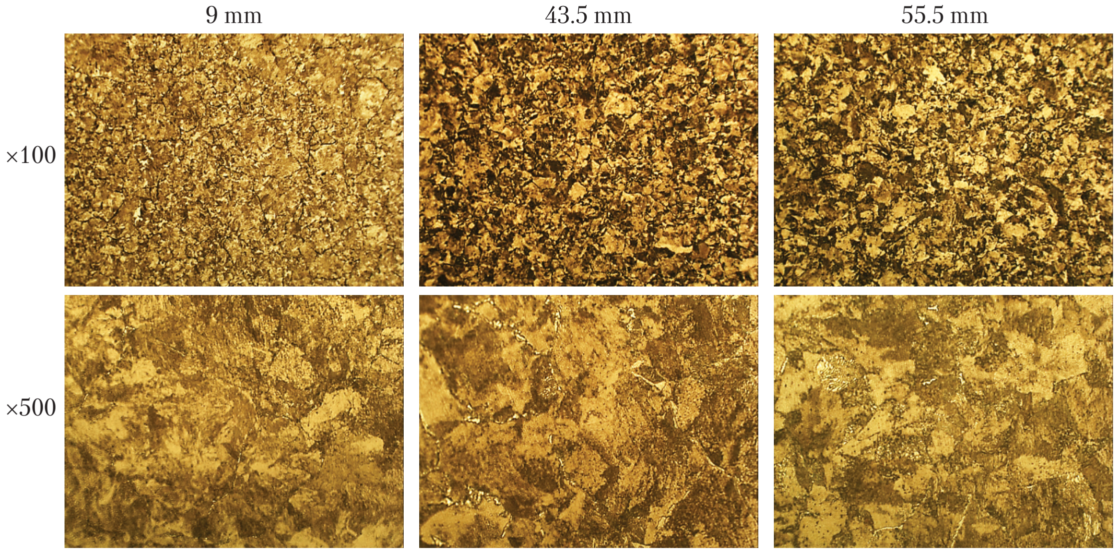

Fig. 5. Microstructure at a distance of 9 mm; 43.5 mm, and 55.5 mm from the end of the sample

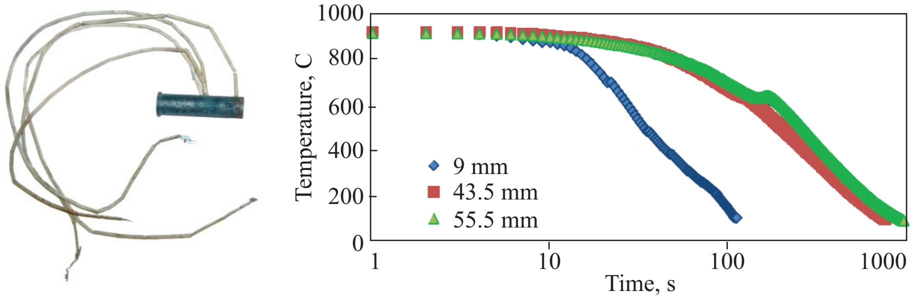

Fig. 6. Sample (*a*) and cooling curves (*b*) at points with a hardness level: 9 mm — 405 HB, 43.5 mm — 352 HB, 55.5 mm — 321 HB

The results of this simulation are presented in Figs. 2 and 4.

To verify the model adequacy, a laboratory experiment has been conducted with the use of samples of K76F rail steel. The test blanks are made of rail head. Before cutting the samples, the blanks are subjected to normalization given the steel chemical composition at a temperature of 880 °C for a holding time of 30 min. The installation for determining the calcination by the end quench method and test conditions meet the requirements of GOST 5657. Change in hardness depending on the distance to the cooling end has been measured. Additionally, the sample structural state has been studied from the surface towards increasing the distance from the cooling end (Fig. 6). It has been shown that as the distance from the end increases, the structure changes from needle structures to pearlite, and at a distance of 9 mm, there is no martensite is formed; different levels of hardness at the reference points are achieved by varying the dispersion of perlite.

The places where the hardness meets the requirements of world standards and at the same time there is no formation of needle structures have been determined (Figs. 3, 5).

At the next stage of research, thermocouples are chased at certain points (Fig. 6, *a*) and cooling curves are recorded. This allows us to determine cooling rates (Fig. 6, *b*): the maximum cooling rate allowable for the rail head rolling surface, which does not lead to the formation of martensite (9 mm: average V_{cool} ranges within 900... 20 °C ~ 8 °C/s); the minimum cooling rate required for axial sections at a depth of ≥ 20 mm to achieve hardness at the level of world analogs (43.5 mm: average V_{cool}. ranges of 900... 20 °C ~ 1.5 °C/s); the minimum cooling rate required for axial sections at a depth of 11 mm to achieve hardness at the level of the Ukrainian standard requirements (55.5 mm: average V_{cool}. ranges of 900... 20 °C ~ 1 °C/s).

As a result of simulation, it has been found that the instantaneous cooling rate, in particular at points of 9 mm, 43.5 mm, and 55.5 mm correspond to the experimental data. When comparing the experimental data and the results of the calculation with the use of the proposed model, it has been found that the change in hardness (Fig. 4) and the change in cooling rate (Fig. 2), depending on the distance to the end of the sample during the tests, have similar values. The analysis of the model adequacy has shown a high accuracy of the model and the convergence of the experimental results with the calculated ones. The model may be used to determine the conditions of heat treatment in the case when it is necessary to achieve a certain level of hardness for a certain structural state.

Conclusions. It is possible to achieve the requirements of EN 13674-1-2011 for the hardness of the rail head at a depth of 20 mm without the formation of needle structures on the surface of the rail head made of steel that corresponds to the chemical composition K76F according to DSTU 4344: 2004.

A mathematical model that allows predicting the change in temperature, the average instantaneous rate, and the average stress across the cross section of sample for calcination tests according to GOST5657, in the process of continuous one-sided cooling has been developed. The model may be used to determine the required parameters of rail quench in order to obtain the desired structural condition and hardness.

With the use of the Jominy method, the regularities of the changes in hardness and microstructure of K76F steel, depending on the distance from the heat sink, have been established. It has been found that at a cooling rate of ~ 8 °C/s, the hardness is 405 HB, and no martensite structure is formed, i.e. the structural state and hardness correspond to the European standard EN 13674-1-2011 established.

REFERENCES

1. Podolskyi, R. V., Deineko, L. N. (2019, May). Determination of ways to increase the operational stability of the railway track. *Proceedings of the All-Ukrainian Scientific and Technical Conference of Students and Young Scientists "Young Academy 2019" (May 18, 2019, Dnipro),* 82. Dnipro [in Russian].
2. Podolskyi, R. V., Safronova, O. A., Babachenko, O. I., Kononenko, G. A. (2020, March). Investigation of the influence of heat treatment on the formation of the microstructure and hardness of experimental rail steels. *Proceedings of the XI All-Ukrainian Conference of Young Scientists "Young Scientists — 2020" (March 16, 2020, Dnipro)*, 53—56. Dnipro [in Ukrainian].
3. Podolskyi, R. V., Deineko, L. M. (2020, May). Determination of further areas to increase the operational reliability of the new generation of railway tracks. *Proceedings of the All-Ukrainian Scientific and Technical Conference of Students and Young Scientists "Young Academy 2020" (May 12, 2020, Dnipro)*, 59. Dnipro [in Ukrainian].
4. Babachenko, O. I., Kononenko, G. A., Filonenko, N. Yu., Khulin, A. Yu. (2018). Development of a mathematical model for calculating the thermal field at the cross section of the railway rail during heat treatment. *Construction, materials science, mechanical engineering*, 100, 31—35 [in Ukrainian].
5. DSTU 4344: 2004. Rails are common for wide gauge railways. General technical conditions. Kyiv, 2005. 31 p. [in Ukrainian].
6. GOST R 51685-2013. Railway rails. General technical conditions (EN 13674-1: 2011, NEQ). Moscow, 2014. 96 p. [in Russian].

7. EN 13674-1: 2011 (E). Railway applications — Track — Rail — Part 1: Vignole railway rails 46 kg / m and above. Brussels, 2011. 108 p.

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РОЗРОБКА РОЗРАХУНКОВОЇ МОДЕЛІ ЗМІНИ ТЕМПЕРАТУРИ РЕЙКОВОЇ СТАЛІ К76Ф ДЛЯ ВИЗНАЧЕННЯ ПАРАМЕТРІВ ТЕРМІЧНОЇ ОБРОБКИ

Вступ. Умови експлуатації залізниць України, перспектива входження їх до міжнародної системи транспортних коридорів, вимагають розвитку та модернізації залізничної колії, зокрема й рейок.

Проблематика. З огляду забезпечення основної експлуатаційної характеристики рейок — зносостійкості, нормативно-технічна документація регламентує твердість. Найпрогресивніший Європейський стандарт EN 13674-1-2011 визначає рівень твердості головки рейки на глибині 20 мм не менше 321 НВ, а ДСТУ 4344:2004 — мінімум 321 НВ на глибині 11. При цьому, згідно з EN 13674-1-2011, на поверхні рейки твердість має бути не менше 405 НВ без утворення структур гарту.

Мета. Визначити можливості досягнення твердості без структур гартування в головці рейки зі сталі 0,80 % С, 0,25 % Si, 0,97 % Mn, 0,055 % V (далі К76Ф) рівня світових вимог на підставі експерименту на прожарюваність (за Джоміні, ГОСТ5657) та розрахунків за допомогою моделі; визначення раціональної швидкості охолодження сталі К76Ф при термічній обробці.

Матеріали й методи. Матеріал: рейкова сталь К76Ф з 0,80 % С, 0,25 % Si, 0,97 % Mn, 0,055 % V. Методики: металографічні дослідження, вимірювання твердості, визначення прожарюваності методом торцевого загартування, моделювання за допомогою математичного розрахунку в середовищі програмного комплексу термообробки QForm.

Результати. Змодельовано зміну температури, формування структури та твердості по перерізу зразка для випробувань на прожарюваність за ГОСТ5657 зі сталі К76Ф. Експериментально встановлено зміну твердості та мікроструктури залежно від відстані до поверхні тепловідводу, визначено швидкість охолодження у точках, твердість у яких відповідає вимогам EN 13674-1-2011 до рейок.

Висновки. Аналіз адекватності моделі показав її високу точність та збіжність експериментальних результатів з розрахунковими. Встановлено можливість досягнення вимог EN 13674-1-2011 до рівня твердості 405 НВ без утворення голчастих структур на сталі, яка відповідає за хімічним складом К76Ф згідно ДСТУ 4344: 2004.

Ключові слова: залізнична рейка, твердість, прожарюваність, математична модель, швидкість охолодження.