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Short report
Краткое сообщение

Evolution of structural-phase state and properties of hypereutectoid steel rails at long-term operation

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Abstract. The methods of modern physical materials science were used to analyze the evolution of microhardness, tribological properties, dislocation substructure and phase composition of the rails with increased wear resistance and contact endurance of DT 400 IR category after missed tonnage of 187 million gross tons on the experimental ring of Russian Railways. It is shown that extremely long-term operation of the rails is accompanied by a decrease (3.1 times) in wear parameter of the rolling surface and an increase (1.4 times) in microhardness, scalar dislocation density (1.5 times) and Fe_3C carbide content (1.24 times). Operation of the rails led to a decrease in the crystal lattice parameter, which correlates with an increase in the content of iron carbide. We made the assumptions about physical causes of the change in parameters.

Keywords: special purpose rails, structure, microhardness, phase composition, tribological properties

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Эволюция структурно-фазового состояния и свойств рельсов из заэвтектоидной стали при длительной эксплуатации

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Аннотация. Методами современного физического материаловедения выполнен анализ эволюции микротвердости, трибологических свойств, дислокационной субструктуры и фазового состава рельсов повышенной износостойкости и контактной выносливости категории ДТ 400 ИК после пропущенного тоннажа 187 млн т брутто на экспериментальном кольце РЖД. Экстремально длительная эксплуатация рельсов сопровождается уменьшением параметра износа поверхности катания (в 3,1 раза), увеличением микротвердости (в 1,4 раза), скалярной плотности дислокаций (в 1,5 раза) и содержания карбида Fe_3C (в 1,24 раза). Эксплуатация рельсов привела к уменьшению параметра кристаллической решетки, что коррелирует с ростом содержания карбида железа. Высказаны предположения о физических причинах изменения параметров.

Ключевые слова: рельсы специального назначения, структура, микротвердость, фазовый состав, трибологические свойства

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Introduction

The continuous rise in the demand for rail reliability under high axle loads and high speeds necessitates ensuring their operational stability and analyzing potential causes of rail withdrawals [1]. Understanding the patterns in the formation of structural-phase states and the properties of specialized rail types is essential for enhancing production techniques and predicting their performance during operation.

In Russia, the production of differentially hardened special purpose rails with enhanced wear resistance and contact endurance has been ongoing for over three years. These rails, categorized as DT 400 IK, are designed for use on straight track sections with speeds up to 200 km/h and on curved sections without traffic density limitations. The significance of information on the structural-phase state, strength, and tribological properties of these new rail types arises from the profound challenges in physical materials science, as well as the practical importance of the issue [2 – 4]. As per the development program of Russian Railways, there are plans to increase the service life of rails up to 2.0 billion tons of passed tonnage. According to Russian Railways, up to 75 % of rail withdrawals in 2020 were attributed to reaching the limit state for wear and contact fatigue defects.

The objective of this study is to analyze the change in phase composition, dislocation substructure, and properties of special-purpose rails following long-term operation.

Experimental

Samples of hypereutectoid steel E90KhAF, which comply with the properties and elemental composition regulated by State Standard GOST 51685–2013 and Specifications TU 24.10.75111-298-05757676.2017 RZhD, were utilized as the material for this study. The analysis was conducted on the rails after undergoing differential hardening and subsequent operation on the experimental track of the Russian Railways, with a total tonnage was 187 million gross tons).

The microhardness of the steel was determined using a PMT-3 instrument, employing the Vickers method with an indenter load of 0.5 N. The tribological properties were evaluated by measuring the wear parameter and friction coefficient. Dry friction conditions were maintained during the tests, employing the Pin-on-Disc and Oscillating layout, with a TRIBOtester tribometer (TRIBOtechnic, France). The test parameters included a VK8 hard alloy 6 mm ball, a wear track radius of 2 mm, a 50 m path traveled by the counterbody, a sample rotation speed of 25 mm/s, a 2 N load on the indenter, and ambient temperature. The wear groove profile and its parameters were examined using a contact nanoprofilometer (refer to the figure provided)). The wear parameter κ was calculated using the following equation:

$$\kappa = \frac{2\sigma RA}{FL},$$

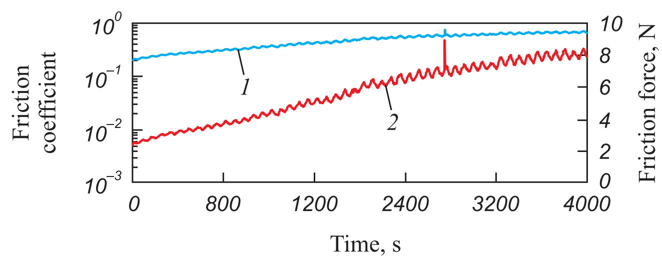
where R represents the track radius, mm; A denotes the surface area of the transversal cross-section of the wear tread, mm^2; F signifies the applied load, N; L represents the path passed by the ball counterbody, m [5].

The dislocation substructure was analyzed using transmission electron microscopy (JEOLJEM 2100 F) [6; 7]. The investigation of the phase composition and structural parameters was carried out using an XRD-600 diffractometer with CuK_α radiation. The RDK 4+ databases and the POWDERCELL 2/4 full-profile analysis program were utilized for the analysis.

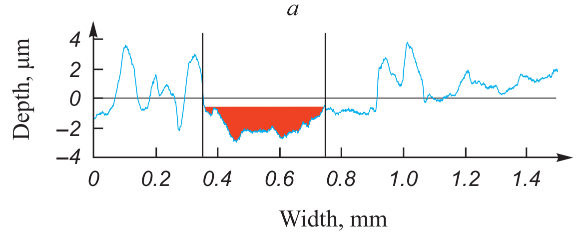
Results and discussion

After the operation of DT 400 IK rail, the microhardness of the tread surface increased by 1.4 times, from 5.5 to 7.7 GPa, while the scalar dislocation density increased by 1.5 times, from $5.0 \cdot 10^{10}$ to $7.5 \cdot 10^{10}$ cm^{-2}. These changes in parameters are attributed to the development of a complex stress-strain state of the rail tread surface during long-term operation [1]. These factors likely contribute to the more than threefold increase in the wear resistance of the tread surface. Initially, the wear parameter was $7.7 \cdot 10^{-6}$ mn^3/(N·m), which reduced to $2.5 \cdot 10^{-6}$ mn^3/(N·m) after operation. The friction coefficient exhibited a slight decrease from 0.43 to 0.35. However, these results do not provide sufficient grounds for extrapolation wear behavior during subsequent operation. To obtain a comprehensive understanding, additional values of this parameter at different carried tonnage levels, as presented in [1], are required.

X-ray phase analysis of DT 400 IK rails revealed that the primary phases present in the steel are α-Fe and iron carbide Fe_3C. In the initial state, the phase content



a



b

Dependence of friction coefficient (*1*) and friction force (*2*) on time of tribological testing of DT 400 IR rails after missed tonnage of 187 million tons (*a*) and profile of friction track (*b*)

Зависимость коэффициента трения (*1*) и силы трения (*2*) от времени трибологических испытаний рельсов ДТ 400 ИК после пропущенного тоннажа 187 млн т (*a*) и профиль дорожки трения (*b*) is 95.83 wt. % and 4.17 wt. %, respectively. The crystal lattice constants: for α-Fe a = 2.8736 Å, for Fe_3C carbide a = 4.7313 Å, b = 4.3299 Å, c = 2.8330 Å.

After the rails have undergone cargo operation, the content of α-Fe and Fe_3C phases changes to 94.84 wt. % and 5.16 wt. %, respectively. Additionally, the crystal lattice constants become: for α-Fe a = 2.8713 Å; for iron carbide a = 4.3057 Å, b = 4.3057 Å, c = 2.8342 Å. These findings indicate that the rails operation resulted in a 1.24-fold increase in the content of Fe_3C carbide, by a factor of, accompanied by changes in its crystal lattice constants, suggesting a potential presence of structural defects. Furthermore, the crystal lattice constant of α-Fe decreased, which corresponds to the increased content of iron carbide and indicates the release of carbon from the α-Fe crystal lattice during operation, leading to the formation of a carbide phase.

Conclusions

Overall, the operation of DT 400 IK rails contributes to an enhancement in wear resistance, microhardness, scalar dislocation density, and Fe_3C carbide content.

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M. A. Porfir'ev – conducting experiments, writing the text.

V. E. Gromov – formation of the work concept, editing the text.

R. E. Kryukov – preparation of the samples, discussion of the results, literature review.

М. А. Порфирьев – проведение экспериментов, составление текста.
В. Е. Громов – формирование концепции работы, редактирование текста.
Р. Е. Крюков – подготовка образцов, обсуждение результатов, обзор литературы.

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