Structure-phase state evolution of 100-m differentially hardened rails in long-term usage

A A Yuriev¹, B E Gromov², K V Morozov¹, Yu F Ivanov³,⁴, S V Konovalov⁵ and A P Semin²

¹EVRAZ Consolidated West Siberian Metallurgical Plant, 16 Kosmicheskoye shosse, 654043, Russia
²Siberian State Industrial University, 42 Kirova street, Novokuznetsk, 654007, Russia
³Institute of High-Current Electronics of Siberian Branch of Russian Academy of Sciences, 2/3, Academicheskii ave, Tomsk, 654052 Russia
⁴National Research Tomsk State University, 36 Lenina ave, Tomsk, 634050, Russia
⁵Academician S.P. Korolev Samara National Research University, 34 Moskovskoye shosse, Samara, 443086, Russia

E-mail: gromov@physics.sibsiu.ru

Abstract. By methods of optic and transmission electron diffraction microscopy the structure-phase states evolution of surface layers’ head of differentially hardened rails to the depth up to 10 mm along the fillet after the passed tonnage of 691.8 mln. t. brutto was examined.

1. Introduction
The long-term usage of rails is accompanied by the considerable change in structure and properties of the surface layer [1-3]. The structure-phase states with anomalous high values of microhardness are formed in the surface layers even at a comparatively small operating load of 100-500 mln.t. of passed tonnage.

Under this surface intensive plastic deformation the cementite plates are either arched or fractured at interfaces. The dissolution of cementite and austenite formation is noted at the expense of the reverse $\gamma \rightarrow \alpha$ transformation [4-6]. The understanding of the processes running in steel in this case is one of the essential conditions of material state control making possible to predict the operating of rails.

The purpose of the research is a comparative layer-by-layer analysts of surface structure and phase composition of differentially hardened rails in long-term usage.

2. Materials and methods
The test materials were the samples of differentially hardened rails of E76CrV steel of DT 350 category fabricated at open joint-stock company “Evraz ZSMK” after operating load tonnage of 691.8 mln.t. brutto in the processes of field-tests at experimental ring “VNIIZhT”.

The chemical composition of rail material meet the State Standard requirements P51685-2013 for E76CrV steel. The microstructure of rails’ metal was tested according to the requirements the of State Standard P51685-2013 at templet cut from rails in transverse direction, after etching in 50% water solution of hydrochloric acid. The microstructure analysis was done after electrolytic polishing of micro metallographic section in 5% acetic solution of perchloric acid followed by etching in 4%
alcoholic solution of nitric acid. The investigation of phase composition and defect substructure of rails was carried out by methods of diffraction electron microscopy. The foils for testing were manufactured by method of electrolyte thinning of plates cut by electro-spark method from the fillet region at 2 mm and 10 mm distance and near the fillet surface according to figure 1.

![Fig. 1. Diagram of rail sample preparing on testing its structure by methods of electron diffraction microscopy. The direction along the fillet is designated with solid line; the regions of metal layers’ location used for foil preparation are designated with dotted lines.](image)

3. Results and discussion

By methods of metallography it is established that a considerably deformed structure to depth up to 200 µm is observed on the etched metallographic sections from the surface of the working fillet. The decarbonized layer value from the surface along the solid ferrite network does not exceed 0.25 µm. In the initial state (before the usage) the following structural constituents were marked out by the morphologic feature by methods of electron diffraction microscopy: the lamellar pearlite, the grains of ferrite-carbide mixture and the grains of structurally free ferrite. The main structural types of the tested steel are the grains of lamellar pearlite with their relative content in the material being 0.7; the relative content of grains of ferrite-carbide mixture is 0.25; the balance is the grains of structurally free ferrite.

After the passed tonnage of 691.8 mln.t. this state is conserved only at 10 mm depth from the fillet surface. The distinctive feature of the structure at this distance is a large number of bend extinction contours being indicative of the elastic-plastic distortions of the material’s crystal lattice caused by the intensive mechanical effect on rails’ material in the process of usage.

The stress concentrators of the tested steel are the intraphase and interphase interfaces (1) of ferrite and pearlite grains (figure 2, a); (2) plates of cementite and ferrite of pearlite colonies (figure 2, b, c); (3) particles of globular cementite and ferrite (figure 2, d).

The multiple changes in rail metal structure at the microlevel are manifested in the formation of small crack network of the contact-fatigue origin being revealed on the tread surface of rail’s head after etching. At the region of defects of contact-fatigue origin the continuity violations filled with corrosion products passing at an acute angle to the surface to the depth up to 140 µm are observed. The distance between the defects measures 700-110 µm.

Figure 3 shows the image of cementite plates of pearlite colony located in the surface layer of rail head fillet after usage. The studies performed by the methods of dark field analysis show that the usage is accompanied by the fragmentation of cementite plates followed by their destruction. The carbide phase reflections in microelectron diffraction pattern obtained from the plates have both the radial and azimuthal spreading indicative of the high level of cementite crystal lattice imperfection and the change in crystal lattice parameter due to the escape of carbon atom as well.
Figure 2. Bend extinction contours (designated by the arrows) in grains of ferrite (a); plastic (b, c) and ferrite-carbide mixture (d).

Rail operation is accompanied by significant changes in the defect substructure of the structure-free ferrite grains, within which band substructure is observed. The distance between the bands is 30-40 nm. At the band structure, we see carbide particles in the range of 5-10 nm. These findings may indicate that two competing processes occur in rail operation: (1) fragmentation of the cementite particles, with their subsequent entrainment in the ferrite grains or plates (in the pearlite structure); (2) fragmentation and subsequent solution of the cementite particles, with transfer of the carbon particles to dislocations (Cottrell atmospheres) and transportation of carbon atoms by dislocations within the ferrite grains (or plates), culminating in the formation of cementite nanoparticles.

Figure 3. Electron microscopy image of surface layer structure of fillet metal of rail head after usage: a, b – light field images; c – dark field obtained in the reflection [130] Fe₃Cr; d – microelectron diffraction pattern, the arrow designates the reflection in which the dark field was obtained.

4. Conclusion
By methods of optic and electron diffraction microscopy the studies of phase composition, macro- and microdefect structure of fillet metal of differentially hardened rails of category DT 350 from E76CrV
steel after the passed tonnage of 691.8 mln.t. brutto in the process of field tests at experimental ring of open joint- stock company “VNIIZhT” were performed. It is shown that rails usage is accompanied by the multiple transformation of steel structure. At the macrolevel it is manifested in the formation of microcracks passing at an acute angle to the surface to the depth up to 140 µm, and the formation of decarbonized layer; at the microlevel – in the formation of elastic-plastic stress fields and the cementite plate destruction of pearlite colonies. In the grains of structurally free ferrite the fragmentation of cementite particles and their dissolution is observed.

Acknowledgements
The research is financially supported by the Russian research fund, project № 15-12-00010.

References
[1] Sheinman E and Friction J 2012 Wear 33(4) 308–314
[2] Gromov V E, Peregovodov O A, Ivanov Y F, Morozov K V, Alsaraeva K V and Semina O A 2016 Surf J Investig X-ray Synchrotron Neutron Techniq 10(1) 76–82
[3] Gromov V E, Yur’ev A B, Morozov K V and Ivanov Yu F 2016 Microstructure of Quenched Rails (Cambridge Int. Sci. Publ., Cambridge)
[4] Ivanisenko Yu and Fecht H J 2008 Steel Tech. 19–23
[5] Ivanisenko Yu, Maclaren I, Souvage X, Valiev R Z and Fecht H J 2006 Acta Mater. 54 1659–69
[6] Gavriljuk V G 2003 Mater. Sci. and Eng. A 345 81–89