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Defect substructure change in 100-m differentially hardened rails in long-term operation

V.E. Gromov [a,*], A.A. Yuriev [b], Yu.F. Ivanov [c,d], A.M. Glezer [e], S.V. Konovalov [f], A.P. Semin [a], R.V. Sundeev [e,g]

[a] Siberian State Industrial University, 654007, Kirov str. 42, Novokuznetsk, Russia
[b] LTD Company «EVRAZ – Integrated West Siberian Metallurgical Combine», 654043, Kosmicheskoe av. 16, Novokuznetsk, Russia
[c] Institute of High Current Electronics, SD RAS, 634055, Akademicheskij av. 2/3, Tomsk, Russia
[d] National Research Tomsk Polytechnic University, 634050, Lenin av. 30, Tomsk, Russia
[e] National University of Science and Technology "MISIS", 119049, Leninskii av. 4, Moscow, Russia
[f] S.P. Korolev Samara National Research University, 443086, Moskovskoe sh. str. 34, Samara, Russia
[g] Moscow Technological University, "MIREA", 119454, Vernadskogo av. 78, Moscow, Russia

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By methods of optical and transmission electron diffraction microscopy the evolution in structural phase states of surface layers head of differentially hardened rails of DT 350 category to the depth up to 10 mm along the central axis after the passed tonnage of 691.8 mln. t brutto was studied. The formation of gradient substructure being expressed in regular change in scalar and excess density of dislocations, curvature-torsion amplitude of steel crystal lattice, degree of deformation transformation of lamellar pearlite structure was defected. The failure mechanisms of cementite plates were considered.

1. Introduction

In the modern conditions of high loads on the axis and movement speeds the surface layers of rails undergo the intensive plastic deformations leading to the damages in long-term operation, it may be the cause for the withdrawal of rails [1,2]. Even at a comparatively small operating load – 100–500 mln. t brutto – in the surface layers of rails the structural phase states with anomally high microhardness and ultrafine grain size in the interval from 20 to 500 nm are formed. The plates of cementite are either arched or fractured and on the interphase boundaries the extremely high density of dislocations is determined, and the cementite dissolution takes place as well [3–11].

One of the most important directions of development of notions of structural phase transformations is the determining of corresponding quantitative regularities along the rail cross-section. In this relation, the data on fine structure analysis, dislocations' substructures and extinction contour enabling to assess the level of internal long-range stress fields may be useful. For the initial state of bulk and differentially rails it is done in Refs. [9–11] and for bulk hardened rails after long-term operation it is done in Refs. [12–14]. The multi-stage process of dissolution of cementite particles of the initial state is observed in steel in operation.

As the production of 100-m differentially hardened rails by compressed air began comparatively recently the determination of nature and evolution regularities in long-term operation of fine structure in the head of these rails is of current concern and has the scientific and practical importance. The purpose of the research is the analysis of defect substructure being formed in long-term operation of DT 350 rails by methods of layer-by-layer transmission electron diffraction microscopy.

2. Materials and methods of investigation

The test materials were the samples of differentially hardened rails DT 350 from steel grade E76CrV manufactured at LTD company «EVRAZ-WSMC» after passed tonnage of 691.8 mln. t brutto in the process of testing on proving ground at experimental ring LTD «VNIIZhT» (Table 1).

The investigation of phase composition and defect substructure of rails was carried out by methods of diffraction electron microscopy [15–20]. The tests foils were manufactured by methods electrolytic of thinning of plates cut by electrospark method at 0, 2 and 10 mm distance from the tread surface along the central axis

* Corresponding author.
E-mail address: gromov@physics.sibsiu.ru (V.E. Gromov).

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Table 1
Chemical composition of rail steel (weight%).

C	Mn	Si	Cr	Ni	Al	V	S	P	N
0.76	0.85	0.35	0.8	0.05	0.02	0.10	0.025	0.025	0.010

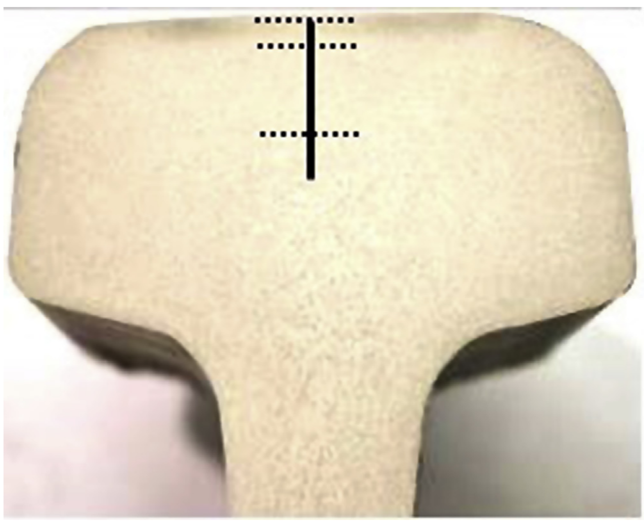

Fig. 1. The diagram of rail sample preparation in investigation of its structure by methods of electron diffraction microscopy. Dotted lines designate schematically the location of metal layers used for foil preparation.

(Fig. 1.). The assessment techniques of dislocation substructure parameters are presented in [21,22].

3. Results and discussion

The following structure components were detected in the rail head along the central axis: the colonies of lamellar pearlite (fractional content ≈ 0.7), the grains of ferrite-carbide mixture (≈ 0.25), the grains of structurally free ferrite (≈ 0.05). The similar values of structural components were obtained in bulk-hardened rails [1,9–11].

The operation of rails is accompanied by the transformation of material's defect substructure. Fig. 2a shows the results of research in dislocation substructure of rail steel along the central axis. The value of dislocation density reaches the maximum magnitude in the surface layer. As the distance from the tread surface increases the dislocation density decreases insignificantly, in this case the type of dislocation substructure is practically unchangeable. The structure of dislocation chaos or ball-cellular dislocation substructure is present in the ferrite component of pearlite colonies, in the grains of structurally free ferrite and in the grains of ferrite-carbide mixture.

The steel structure formed in the process of long-term operation is in the elastic-stressed state. This fact is detected by the presence of bend extinction contours on the structural images [12–14]. The characteristic electron-microscopy images of tested rail steel structure demonstrating the bend extinction contours are shown in Fig. 3 (the contours are designated by arrows in a–b). The presence of bend extinction contours in electron microscope images is indicative of the elastic-stressed distorsions of the material's crystal lattice and it may be caused by the mechanical effect on the rail metal in the process of operation [1,23]. The stress concentrators of the test steel are the intraphase (the interphase of ferrite grains and pearlite grains belong to them) and the interphase (interphase of ferrite and cementite) interfaces.

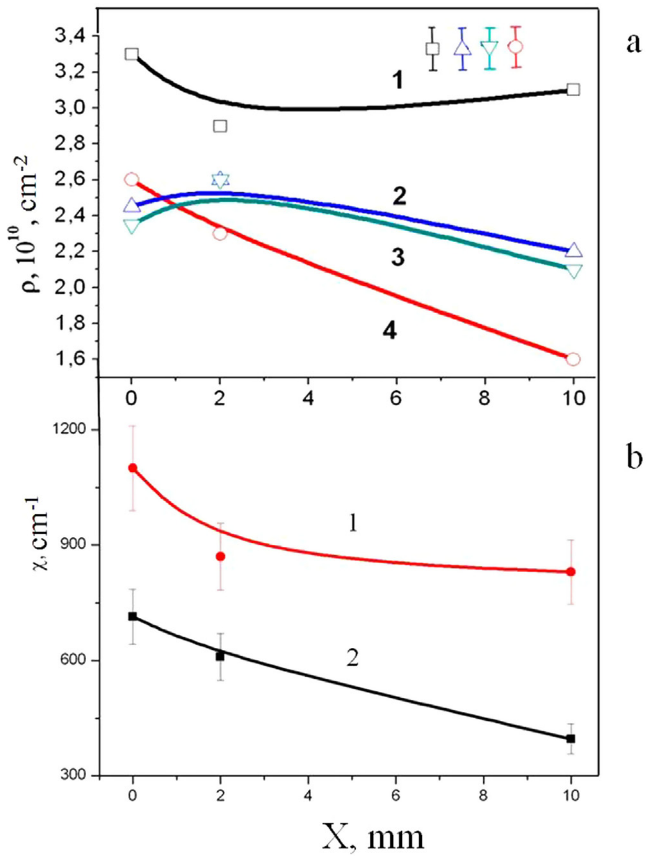

Fig. 2. Dependences of scalar (curves 1, 2) and excess (curves 3, 4) dislocation density of ferrite interlayers of pearlite colonies (curves 1, 4) and grains of structurally free ferrite (curves 2, 3) a) and curvature-torsion amplitude of crystal lattice of grains of structurally free ferrite (curve 1) and lamellar pearlite grains (curve 2); b) on the distance from the tread surface.

In the quantitative relation the value of elastic-plastic distortions of the material is characterized by curvature-torsion amplitude of its crystal lattice which is inversely proportional to the width of bend extinction contour [23]. Fig. 2b shows the dependences of curvature-torsion amplitude of the crystal lattice of the studied rail steel. The analysis of the results shown in Fig. 2b testifies the gradient character of stress fields being formed in steel. Namely, when the distance from the tread surface increases the curvature-torsion amplitude of the crystal lattice decreases.

All morphological constituents of steel (the lamellar pearlite grains, the ferrite-carbide mixture grains and the grains of structurally free ferrite) undergo the essential transformation in long-term operation of rails. At 10 mm distance from the tread surface the relative content of grains of structurally free ferrite amounted to 5% (note that the relative content of ferrite grains is practically independent of the distance to the tread surface); the grains of ferrite-carbide mixture – 5%; the balance-pearlite grains. At 2 mm distance from the tread surface the relative content of ferrite-carbide mixture grains increased up to 10%; in the surface layer (the layer adjacent to the tread surface) measured 35%. It is evident that these transformations of steel structure take place at the expense of failure of lamellar pearlite grains. The performed

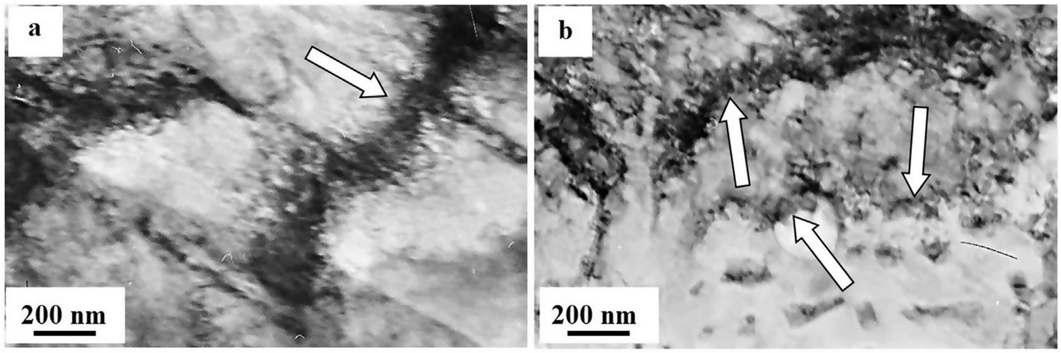

Fig. 3. Bend extinction contours (designated by allows) being observed in lamellar pearlite grains (a) and ferrite-carbide mixture grains (b).

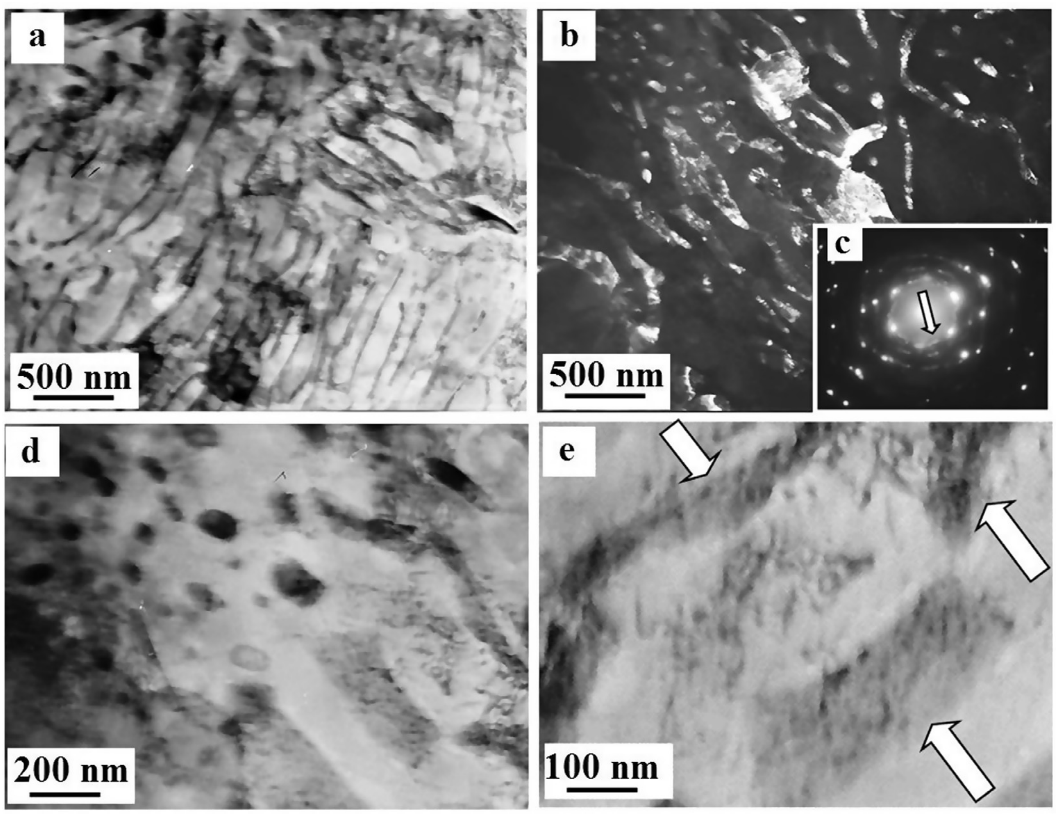

Fig. 4. Electron microscopy image of surface layer structure of rail steel; a, d, e – light field images, b – dark field obtained in reflection [2 0 1] Fe_3C + [1 1 0] α-Fe (the reflections are designated by the arrow in (c); c – microelectron diffraction pattern to (b).

studies of morphology of rail surface layer structure showed that the relative content of pearlite grains where the lamellar structure retained amounted to 25%; the balance – the pearlite grains in which the cementite plates are cut by gliding dislocations into separately located particles. These particles have globular shape, with their average dimensions being 30–50 nm.

For bulk hardened rails the formation of nanodimentional particles of carbide phase in steel ferrite constituent is observed after long-term operation. They are detected both in pearlite grains and in ferrite-carbide mixture grains and in grains of structurally free ferrite [1,12–14].

Fig. 4presents the images of lamellar pearlite structure of rail steel surface layer being formed in long-term operation. The analysis of the microelectron diffraction patterns shown in Fig. 4 is indicate of the two main transformation mechanisms of cementite plates taking place in rail steel operation. First, the mechanism of plate cutting by the moving dislocations. In this case some quantity of cementite particles of globular morphology is formed (Fig. 4a, b, d). Second, the mechanism of cementite plate dissolution caused by the departure of carbon atoms from cementite crystal lattice to dislocations (to Cottrell atmospheres and dislocation nuclei) (Fig. 4c) (the arrows designate the dissolving plates of cementite). Note that these mechanisms of pearlite structure transformation were considered in detail earlier in [1,23].

4. Conclusion

The studies of fine structure of differentially hardened rail metal depending on the distance to tread surface along the central axis of the head after passed tonnage of 691.8 mln. t brutto in the process of field testings were carried out by methods of electron transmission diffraction microscopy. The dependencies of change in scalar and excess dislocation density and curvature-torsion amplitude of crystal lattice on the distance of tread surface were established. When analyzing the deformation transformations of lamellar pearlite structure, it was shown that the failure of cementite plates of pearlite colonies proceeded mainly by two mechanisms: the cutting by glide dislocations and as a result of carbon atom departure from cementite crystal lattice to dislocations. The comparison with the data for bulk hardened rails was carried out.

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