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Deformation Transformation of the Structure and Phase Composition of the Rail Surface during Long-Term Operation

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Abstract—The structure—phase state of the tread surface and the fillet of differentially quenched 100-m rails after long-term operation (tonnage of 1770 mln t). The transformation of the pearlite structure on the tread surface is found to be slower in comparison with the fillet surface. The distribution of carbon atoms in rail structure has been estimated.

Keywords: structure, phase composition, rails, surface, operation

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INTRODUCTION

An analysis of the causes of rail structure degradation during long-term operation, leading to their disposal, attracts significant scientific and practical interest due to continuous increase in the requirements to reliability of rails under conditions of high loads on axles and motion speeds. Prolonged intense deformation was found to lead to abnormal microhardness of tread surface of rails, herewith, destruction of cementite, stable under normal conditions, was detected which was induced by deformation [1, 2].

The processes of structure degradation, strengthening, and wear begin from the surface layers after accumulation of certain level of plastic deformation [3–9]. The features of deformation transformation of structure, phase composition and properties of Russian 25 meter through hardened rails after handled weight of 500 and 1000 mln t are studied in details and summarized elsewhere [1, 10]. Concerning differentially quenched 100-m rails, the data bank was formed about the regularities of formation of structure phase states, defect structure, and distribution of carbon atoms after a tonnage of 691.8 and 1411 mln t [2, 11].

The operation of a batch of differentially quenched 100-m DT350 rails produced in 2013 reached 1.77 bln t gross weight, which is twice as much as the specified resource. Currently, the target is to increase the guaranteed operation of rails to 2.5 bln t. The solution to this problem is substantially related to acquisition of information about the structure—phase state and the nature of strengthening of such rails during long-term operation.

This work is aimed at studying the evolution of the structure and phase composition of the rail surface during long-term operation.

EXPERIMENTAL

Specimens of differentially hardened 100-m rails of type R65, grade DT350, and E76KhF steel were studied after a tonnage of 1770 mln t. The metal meets the requirements of Specifications TU 0921-276-01124323–2012 (wt %): 0.73 C, 0.75 Mn, 0.58 Si, 0.012 P, 0.007 S, 0.42 Cr, 0.07 Ni, 0.13 Cu, 0.002 Al, 0.003 Ti, 0.006 Mo, and 0.04 V.

The structure and defect substructure of the tread surface and the fillet of the rail head were analyzed by transmission electron microscopy (TEM, EM-125 microscope) [12–14], and X-ray diffraction analysis (XRD-7000S X-ray diffractometer, Shimadzu). Plates for foils were cut out from the rail surface.

RESULTS AND DISCUSSION

The structure of the steel is represented by pearlite grains of laminar morphology, structurally free ferrite grains (ferrite grains not contained in the bulk of particles of carbide phase), and ferrite grains with inclu-

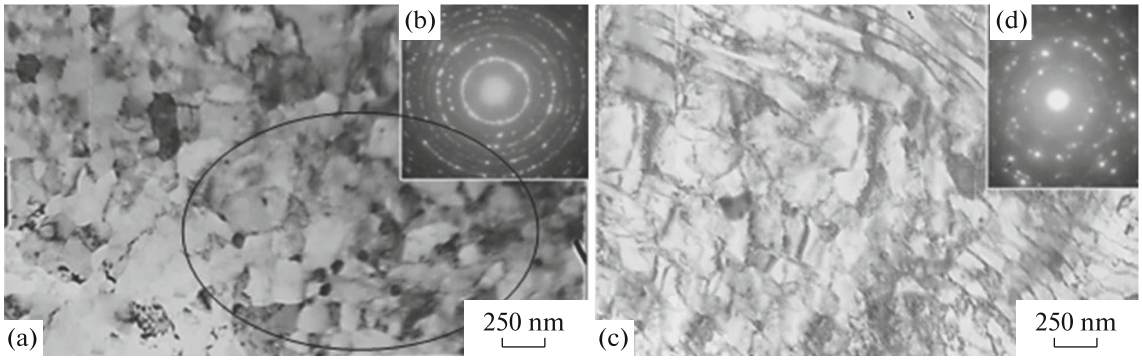

Fig. 1. Submicrocrystalline structure of (a, b) fillet and (c, d) tread surface of the rail head; ova in (a) indicates a region with a subgrain structure (ferrite grainsare bright, cementite particles are dark).

sions of cementite particles mainly in the form of short plates and particles of globular shape [1].

Long-term operation leads to significant changes in the structure of rail head surface, in particular, to transformation of pearlite. Three main structural constituents were revealed. They are comprised of grains with preserved structure of lamellar pearlite, where dark-field analysis detected fragmentation of ferrite plates into fragments separated from each other by low-angle boundaries. The transversal sizes of the fragments correspond to the transversal sizes of ferrite plates, and the longitudinal sizes exceed them by 1.5–2 times. The second characteristic structural constituent is comprised of pearlite grains, in which cementite plates are subdivided into regions (fragments) 25–35 nm in size. In addition, ferrite grains with subgrain structure were detected (Fig. 1). The electron diffraction patterns of this structure have a ring structure evidencing submicron size of crystals (150–250 nm). The diffraction rings are formed by individual point reflections, which evidence high-angle misorientation of crystals. Nanoscale particles of carbide phase were detected at the boundaries (25–75 nm).

The contents of the aforementioned structures determined from the relative surface area are different in different segments of the rail head surface. For example, the content of pearlite grains preserving a lamellar structure on the tread surface is 25%, and that on the surface of fillet is 15%. The content of pearlite grains, in which the ferrite lamellar structure is preserved and cementite plates are subdivided into separately positioned particles, is 70% on the tread surface and 60% on the surface of fillet. The content of regions with subgrain structure (see Fig. 1) is 5% on the tread surface and 25% on the surface of fillet. The obtained results evidence a higher level of deformation transformation of a lamellar pearlite structure in the surface layer of the fillet in comparison with the structure of the tread surface.

Table 1. Qualitative characteristics of the surface structure of the rail head

Parameters	Tread surface	Fillet
$\langle\rho\rangle \times 10^{-10}$, cm^{-2}	4.43	4.23
$\rho_{\pm} \times 10^{-10}$, cm^{-2}	3.12	3.84
Fe_3C content, vol %	4.5	3.1
Carbon content, wt %	0.32	0.22

The defect substructure of the ferrite constituent of pearlite is characterized by a dislocation substructure. It is usually characterized by scalar dislocations density $\langle\rho\rangle$, which was determined by the random intercept method [15]. SEM analysis revealed bend extinction contours in structure images, which indicates lattice bending/torsion (formation of internal stress fields).

The sources of foil curvature/torsion are the interfaces between cementite and ferrite plates (Fig. 2a), subgrain interfaces (Fig. 2b), the interfaces of globular particles located at the boundaries (Fig. 2c) and in the bulk (Fig. 2d) of subgrains.

A quantitative characteristic of internal stress fields is excessive density of dislocations $\rho_{\pm}$ (determined by the procedure described in [2, 12–14]). It should be mentioned that $\rho_{\pm}$ is lower than $\langle\rho\rangle$ (Table 1), which indicates at elastic pattern of foil bending/torsion.

Carbon in steel structure is known to exist in a solid solution based on α or γ iron (in the position of interstitial elements), on dislocations (Cottrell and Maxwell atmospheres), at interphase (carbide–matrix) and intraphase boundaries (grain and pack boundaries, and crystals pf massive and lamellar martensite), in particles of carbide phase. The carbon content in a solid solution based on α or γ iron is usually estimated from the relative changes in the lattice parameters of these phases [16]. The carbon content in carbide particles is estimated on the basis of carbide chemical composition, the type of crystalline lattice, and the

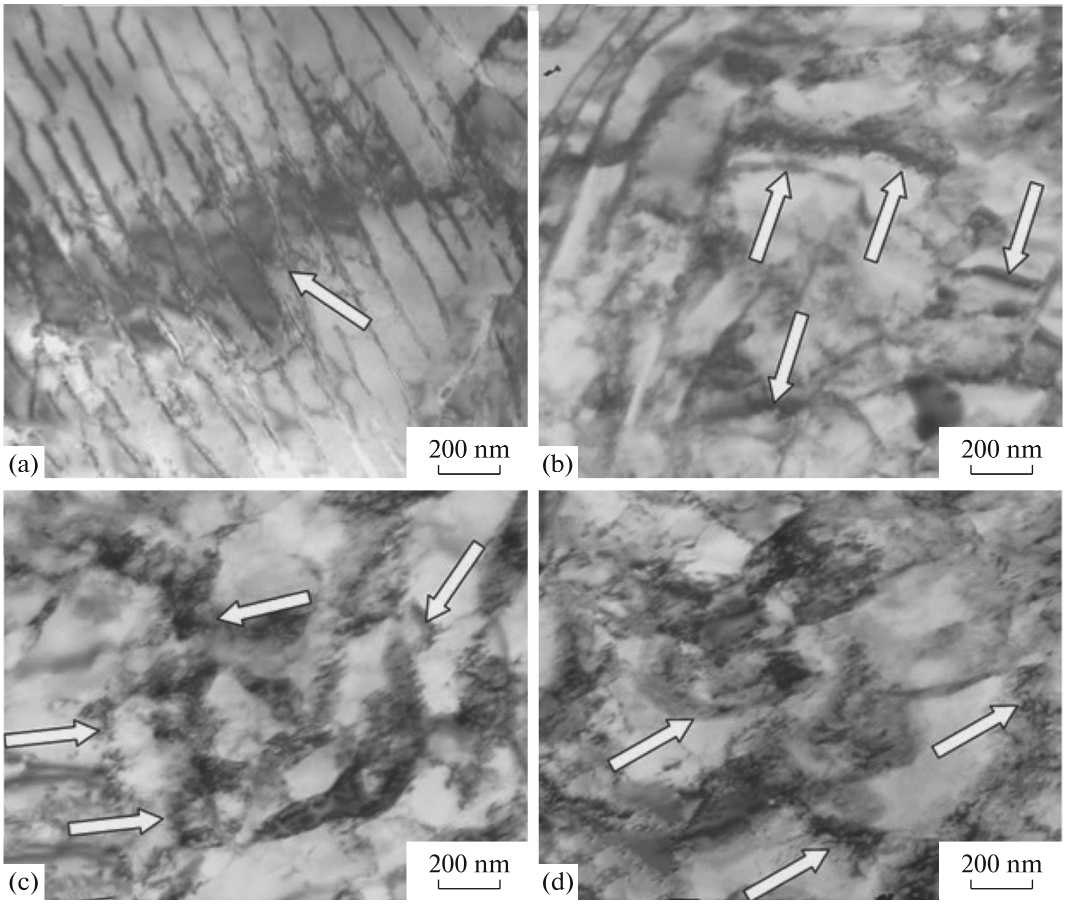

Fig. 2. Microstructure of the surface layer of the fillet (extinction bend contours are marked with arrows).

volumetric portion of particles of carbide phase in steel [2]. The carbon content on defects is estimated by indirect methods (internal friction, X-ray spectral microanalysis). The carbon content on structural elements was estimated by equations in Table 2.

According to the obtained results, the long-term operation of rails is accompanied by noticeable changes in the carbon concentration in the surface layer of rails, which was detected by transmission electron microscopy (see Table 1).

The revealed carbon loss can be stipulated by both the decarburization of the surface layer of rails during long-term operation and the deposition of carbon atoms onto structure defects, namely, dislocations, grain and subgrain boundaries, that is, by occurrence of dynamic aging of steel. The interaction between dislocations and interstitial atoms leads to fixation of dislocations, preventing their further movement, promoting significant strengthening of material, and finally resulting in its embrittlement [18, 19]. The

Table 2. Analysis of carbon distribution in steel

Carbon locations	Estimating equations	Reference
α-Fe-based solid solution	$\delta C_\alpha = \delta V_\alpha \frac{a_\alpha - a_\alpha^0}{39 \pm 4} \times 10^3$	[2, 16]
Particles of carbide phases	$\delta C\ (Fe_3C) = 0.07\delta V$	[2, 17]
Defect structure elements	$\delta C_{def} = C_0 - \delta C_\alpha - \delta C\ (Fe_3C)$	[2, 17]

δV_α, δV volumetric portions of α-Fe and carbide phases; a_α = 0.28782 nm—α-Fe lattice parameter; a_α^0 =0.28668 nm—initial lattice parameter; C_0— average carbon content in steel.

embrittlement of the surface layer manifests itself in the formation of numerous micro- and macrocracks in the rail head.

The role of rotational plastic deformation mode forming local curvature of a lattice was considered in [20–22]. It can be assumed that it is responsible for the displacement of carbon atoms during cementite destruction. The authors believe that such a mechanism can be reversible due to cyclic pattern of load application, allowing the rearrangement of elements of internal structure without formation of discontinuities. This process is not diffusive, since it is developed at moderate temperatures and a load is applied irregularly but cyclically.

The increase in the tonnage to 1770 mln t is accompanied by significant fragmentation of grain structure and leads to the formation of local segments not capable to provide development of relaxation processes: a so-called critical structure is formed [23]. Such a structure is the center of subsequent nucleation of regions of viscous destruction of material.

The obtained results allow us to assume that the destruction of rails will occur first exactly in the surface layer of the fillet, where already after a tonnage of 1700 mln t a nanosized subgrain structure forms and the density of accumulated defects reaches critical value, which inhibits development of reversible elastic deformation and involvement (development) of the mechanism of plastic distortion. The formation of such a critical structure will be finished by nucleation of microcracks according to fatigue mechanism and failure of rails.

Therefore, an increase in the life of the rail can be promoted by the most prolonged preservation of the structure capable of developing reversible deformation processes excluding cementite destruction with subsequent displacement of carbon atoms to lattice defects.

CONCLUSIONS

Long-term operation of rails is accompanied by deformation transformation of the structure and phase composition of the rail head comprised of fragmentation of ferrite plates, destruction of cementite plates, and repeated precipitation of carbide phase nanoparticles. The level of structure transformation in the surface layer of the fillet is higher than that on the tread surface. This finding can be attributed to both surface decarburization and the deposition of carbon on structure defects, namely, dislocations, grain boundaries, and subgrain boundaries.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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