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Featured Letter

Structural phase states and properties of rails after long-term operation

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ABSTRACT

The investigations into structural phase states and properties of differentiatedly quenched 100-m rails of DT 350 category after extremely long-term operation (passed tonnage of 1411 mln. t brutto) were performed by the methods of modern physical material science. It has been established that rail operation results in the essential strengthening of surface layer up to 80–100 μm in thickness independent of the studied area of rail head. The microhardness of rail surface is 1.5–2-fold higher in comparison with volume and it decreases with the distance from the surface. A 7-fold increase in wear resistance of tread surface and 1.3-fold increase in friction coefficient with respect to volume have been revealed. The values of α-Fe crystal lattice parameter of tread surface (a = 0.28699 nm), the distortions of cementite crystal lattice ($\Delta d/d = 2.37 \cdot 10^{-3}$) are higher but the relative content of cementite (3.31 mas. %) and the size of coherent-scattering region (D = 20.6 nm) are lower than the corresponding values in volume. The long-term operation of rails is accompanied by the failure of cementite plates and carbon being liberated goes into solid solution and precipitates on the defects of crystal structure (dislocations, interphase and intraphase interfaces).

1. Introduction

A substantial increase in the traffic intensity of railway transport and the density of freight traffic has been observed in recent years that requires the application of rails with high operation resistance [1,2]. From 2013 the manufacture of 100-m differentiatedly quenched rails by pressed air on rolling mills had been started in Russia at JSC 'Evraz – integrated West Siberian metallurgical combine'. The improvement of quenching technology is largely connected with obtaining the information on structural phase states and operation properties of rails in long-term operation. The importance of information in this field is determined by the depth of understanding of fundamental problems of solid-state physics, on the one hand and the practical importance of the problem, on the other hand.

Analysis of literary data [3–8] shows that already at a comparatively moderate passed tonnage up to 300 mln. tons a severe change in structure is observed, the atypically high value of microhardness and cementite decay phenomenon are noted. The segregation, relaxation, homogenization and recrystallization processes and phase transitions are induced that may be accompanied by the deterioration of physical and mechanical properties and be responsible for rail failure [3–8].

At the same volumes of passed tonnage a 'white' layer leading to the contact fatigue, crack formation and rails' failure [9–13] is formed in surface layers. In the Russian bulk-quenched rails with the passed tonnage of 500–1000 mln. tons a formation of nanodimensional multiphase structure in the metal layer adjacent to working surface (fillet and tread surface) was revealed. It is characterized by total failure of lamellar pearlite colonies (surface layer), the proceeding of the initial stage of dynamic recrystallization of structurally free ferrite grains (layer not less than 2 mm thick), the fragmentation of ferrite-carbide mixture grains with formation of the structure in which the particles of carbide phase are mainly located along subgrains' boundaries [12–15].

For the Russian 100-m differentiatedly quenched rails after passed tonnage of 691.8 mln. t. brutto the theoretical estimates of metal additive yield point along central axis and fillet on the

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basis of multifactor strengthening analysis were made [16–18]. It has been shown that the change in fine structure parameters of ferrite constituent of pearlite colonies along the central axis and fillet has a gradient character. The change in structural phase states of rails in long-term operation is similar to Fe – C alloy behavior under severe plastic deformation [1,2,19].

The purpose of the research is to study the structural phase states and properties being formed on the tread surface and fillet in the head of 100-m differentiatedly quenched rails after passed tonnage of 1411 mln. t. brutto and the comparative analysis with volume parameters of rail steel.

2. Materials and methods

The samples of 100-m rails of DT 350 category taken from the railway on experimental testing ring after passed tonnage of 1411 mln. t. brutto were used as material under study. The rails of the certified batch were manufactured at OJSC 'Evraz WSMC' in 2013 from vacuum steel (Table 1) and differentiatedly heat quenched.

The metal macrostructure was determined by deep etching method in 50% hot water solution of hydrochloric acid on incomplete transverse template (head, fillet). The macrostructure estimation was done in accordance with 'Classificator of macrostructure defects of rails rolled from continuously cast billets of electric steel'. Metal microstructure was studied on metallographic sections cut out from the top part of the head (fillet and tread surface) after etching in 4% alcoholic solution of nitric acid. The investigations into steel structure were performed using the methods of optical microscopy (device Olimpus GX 51) and scanning electron microscopy (device MIRA 3 Tescan).

The steel properties were characterized by determining the microhardness, wear parameter (the value reciprocal to wear resistance) and friction coefficient. Microhardness was tested with the device PMT-3 by Vickers method at indenter load of 0.5 N along vertical axis of tread symmetry and fillet surface at 10–110 μm interval with 10 μm spacing (two tracks), at depth of 2 mm and 10 mm from the surface at the site of both fillets and the central zone of head tread surface according to 4 measurements in each zone. The tribological studies (determination of wear parameter and friction coefficient) were carried out on tribometer Pin-on-Disc and Oscillating TRIBOtester (TRIBOtechnic, France) at the following parameters: a 6 mm diameter ball made of roll bearing steel ShKh15, 4 mm track radius, 12 N indenter load, rotation speed of sample 25.0 mm/s, at room temperature. The material wear degree was detected by the results of profilometry of track formed in tests.

3. Results and discussion

The microhardness profiles presented in Fig. 1 testify that rail operation is accompanied by the essential strengthening of the near-surface steel layer up to 80–100 μm thick independent of the rail area under study (zone of tread surface or working fillet). In this case the steel hardness is 1.5–2 – fold higher at rail surface as compared with the volume and it decreases with a greater distance from the working surface.

The strengthening of steel surface layer is accompanied by the increase in material wear resistance. The results shown in Table 2 testify that wear resistance of tread surface increased ≈ 7 – fold in relation to volume.

The increase in steel wear resistance is accompanied by the friction coefficient growth (by ≈ 1.3 times) (Table 2). The character of friction coefficient dependence on test time is different for steel volume located at 15 mm depth from tread surface and the one forming the tread surface. In the first case the change in friction coefficient returns to the standard level after 100 s running-in; in the second case - after 400 s. The latter evidently is indicative of the change in structural phase of steel in the surface layer in the

Table 2
Tribological characteristics of DT350 rails after passed tonnage of 1411 mln. t. brutto.

Steel state	μ	k, 10^{-5}, mm^3/H*m
Tread surface	0.76	0.3
At 15 mm distance from surface	0.6	2.0

μ - friction coefficient, k - wear parameter

Table 1
Chemical composition of DT350 rails.

Content of chemical elements, wt. %										
C	Mn	Si	P	S	Cr	Ni	Cu	V	Al	Ti
0.72	0.77	0.61	0.010	0.009	0.42	0.07	0.14	0.038	0.003	0.003

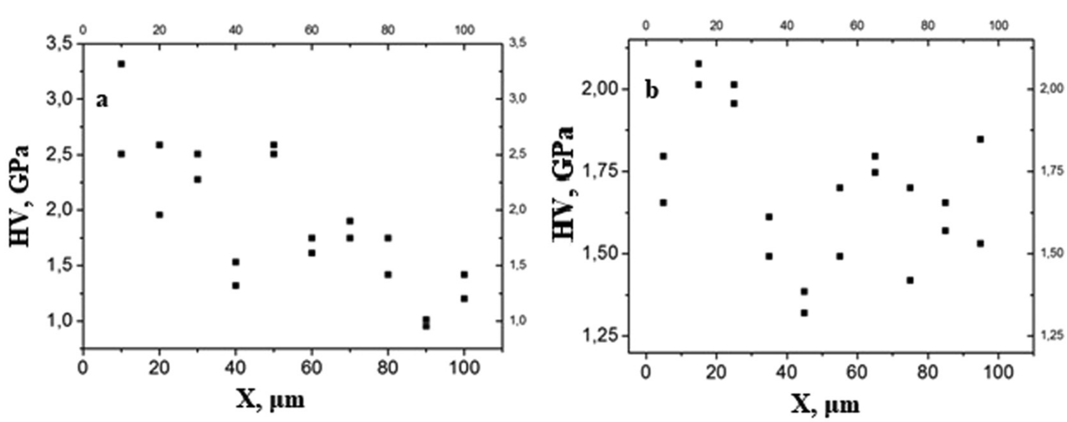

Fig. 1. Dependence of microhardness on distance from tread surface (a) and fillet surface (b). Steel microhardness at distance of 2 mm – 1.48 GPa, 10 mm – 1.21 GPa.

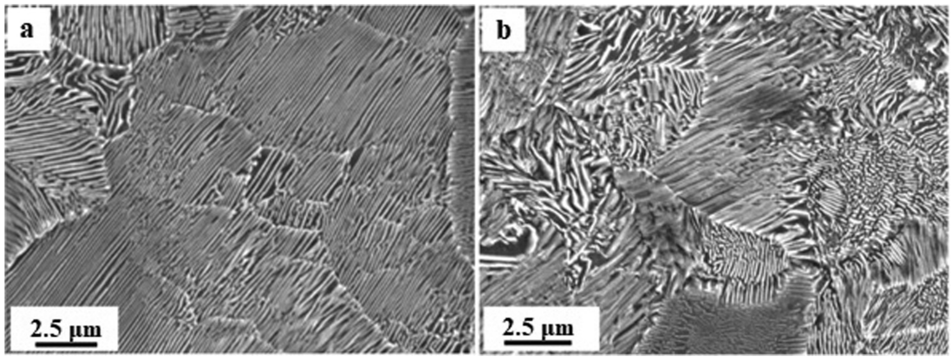

Fig. 2. Electron microscopic image of rail pearlite colony structure at 0.5–1.0 mm depth from tread surface.

Table 3
X-ray structural analysis results of rails after long-term operation.

Parameter Steel state	Cementite content, mas. %	a (Fe), nm	$\frac{\Delta d}{d}$	D_{csr}, nm
Tread surface	3.31	0.28699	$2.37 \cdot 10^{-3}$	20.6
At 15 mm distance from surface	3.39	0.28693	$1.26 \cdot 10^{-3}$	36.5

a - parameter of Fe crystal lattice; Δd/d - microglides of cementite crystal lattice; D_{scr} - size of coherent scattering regions.

process of rails' operation. The friction track obtained in tribological tests of rail tread surface has a smoother profile that is indicative of a more equistrength state of surface layer of friction track as compared with the rail volume material.

The metallographic studies enabled one to detect a sandwich structure of surface layer with layers' location in parallel to tread surface. The layers are formed by microvolume dimensions (1.5–2 μm). The thickness of the transformed layer of tread surface amounts to ≈ 35 μm. With a greater distance from tread surface the sizes of etching volume increase.

In rail head the steel microstructure is formed by lamellar pearlite with average grain size of 29.8 μm (the size of real grains varies within the limits from 15.0 μm to 51.2 μm). Along the pearlite grain boundaries the comparatively fine grains of excess ferrite are detected, they are estimated by 1.5 number of scale № 7 of Russian State Standard 8233. Bainite in the sample metal microstructure is not revealed by the metallography methods.

By the methods of scanning electron microscopy of the etched metallographic sections of fillet and head tread surface at 0.5–1.0 mm depth it has been stated that steel structure is presented by fine-grained pearlite of lamellar morphology (Fig. 2a). In the pearlite structure in addition to the regular colonies with cementite plates located in parallel the colonies in which the cementite plates are failed or located in random fashion (Fig. 2b) are detected.

Analysis of the revealed structure has shown that the value of steel pearlite colonies varies in the limits from 2.7 μm to 12.2 μm at average value of 6.2 μm. The distance between plates (the distance between the boundaries of neighboring plates of cementite) varies in the limits from 73 nm to 256 nm at the average value of 132 nm and practically is independent of the location of area under analysis relative to fillet and tread surface.

By the methods of X-ray structural analysis it has been determined that the main phases of steel under study are the solid solution based on α-iron (bcc crystal lattice) and carbide of iron (Fe_3C, cementite). Examination of X-ray structural analysis results presented in Table 3 shows that the cementite located in steel volume forming the tread surface is in the essentially higher stress state in comparison with volume cementite.

Supposing that the increase in α-iron crystal lattice parameter is connected with cementite dissolution and escape of carbon atoms to solid solution, let's estimate the carbon concentration in solid solution based on α-Fe, using the offered relations in [20]. The performed estimates show that the detected increase in α-iron crystal lattice parameter may correspond to the transition of 0.0015 wt% carbon into solid solution. Using Fe-C phase diagram [20] it may be possible to estimate the amount of liberated carbon corresponding to the detected change in relative content of cementite in steel. The performed estimates show that the liberated carbon concentration amounts to 0.0052 wt%. By employing the results of estimate calculations it can be concluded that the main amount of carbon atoms being liberated in cementite failure in rail operation process precipitates on crystal lattice defects (dislocations, interphase and intraphase interfaces). Therefore, on the basis of the performed studies and estimate calculations it can be concluded that thermodeformation effect taking place in long-term operation of rails is accompanied by the cementite failure of steel surface layer, the liberation of carbon atoms which embed partly into α-iron crystal lattice (implantation positions) and precipitate on defects of steel crystal structure. Both processes, without doubt, lead to strengthening of steel [21–23].

4. Conclusion

It has been shown that rail operation is accompanied by the essential (1.5–2-fold) strengthening of steel near-surface layer up to 80–100 μm thick independent of rail area under study (tread surface zone or working fillet). It has been revealed that wear resistance of tread surface increased ≈ 7 – fold in relation to volume of the product. It has been shown that rail operation is accompanied by the lamellar structure formation of surface layer ≈ 35 μm thick with layer location in parallel to tread surface. The layers are formed by microvolumes with 1.5–2 μm in size. It has been established that the long-term operation of rails is accompanied by cementite failure, the carbon being liberated goes into solid solution based on α-iron crystal lattice and precipitates on the defects of steel crystal structure.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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