INTRODUCTION

The processes of formation and evolution of structural phase state and properties of rail surface layers under long service conditions represent a complicated complex of interrelated scientific and technical problems. 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.

In the modern condition of high loads on axis and speeds of movement the rail surface layers undergo the severe plastic deformations under long service conditions resulting in the formation of structural phase states with atypically high microhardness and nanoscale grain sizes. In a relatively small number of papers [1–6] it is shown that already after the passed tonnage of 100–300 mln.t the cementite plates are either bent or fractured, and at the interphase boundaries the extremely high dislocation density is observed, cementite dissolution and austenite formation occur at the expense of the reverse \( \gamma \rightarrow \alpha \) transformation [1–6]. These processes result in the redistribution of carbon and it is finally reflected on the level of mechanical properties [7–10].

As the mass production of 100m differentially hardened rails began only 4 years ago in Russia, the determination of nature and evolution laws of carbide phase, fine structure and carbon atoms
distribution in the head of these rails under long service conditions is of high priority and practical importance. The majority of the used techniques of cementite phase evolution analysis lack the enough degree of locality. It does not permit to follow the evolution of the plate taken individually. Electron diffraction microscopy is the most developed method of aiming analysis of structural phase state of a material to date. This method enables to carry out simultaneously the complex analysis of the morphology and defect structure (the light field image method), phase composition (dark field method combined with imaging and indexing of electron-diffraction patterns) with the enough (for the problem being analyzed in the paper) degree of locality [11]. Carbon quantity in \( \alpha \)- and \( \gamma \) – base solid solutions is usually estimated by the relative change in crystal lattice parameter of these phases [12]. The estimates of carbon quantity in carbide particles are made on the basis of the chemical composition of the carbide, the type of crystal lattice and the volume fraction of carbide phase particles in steel.

The purpose of the research is the determining and analyzing of the evolution mechanisms of carbide phase, fine structure and carbon atoms redistribution in rails under long service conditions by methods of layer-by-layer transmission electron diffraction microscopy [TEM] and X-ray phase analysis.

Materials and methods of study

The samples of differentially hardened rails DT 350 manufactured at the joint stock company «EVRAZ–WSMC» after the passed tonnage of 691.8 mln. t brutto at the experimental ring JSC «VNIIZhT» were used as the test material. According to the classification given in the paper [13] it corresponds to the severe plastic deformation. In the content of all chemical elements revealed as a result of the verifying analysis of chemical composition of rails metal it satisfies the requirements of Russian Standard R 51685–2013. The study of phase composition and defect substructure of rails were performed by methods of electron diffraction microscopy [14–19]. The test foils were manufactured by methods of electrolytic thinning of plates cut out by electric spark method at the distance of 0.2 and 10mm from the tread surface along the central axis and along the fillet (Fig.1). The study of crystal lattice state was realized by method of X-ray phase analysis.

Results and Discussion

The estimation of quality after long service conditions showed that by the level of mechanical properties (Table 1), content by nonmetallic inclusions, macro- and microstructure the quality of metal satisfied the requirements of Russian Standard R 51685–2013 for rails of DT 350 category. The main morphological components of rail steel are the lamellar pearlite grains, the grains of ferrite-pearlite mixture and the grains of structurally – free ferrite.

The relative grain content 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) at 10 mm distance from tread surface; the grains of ferrite-carbide mixture – 5%; the balance - pearlite grains. At 2 mm distance from tread surface the relative content of grains of ferrite-carbide mixture increased by 10% in the surface layer (the layer adjacent to tread surface) it amounted to 35%. It is evident that these transformations of the structure were realized at the expense of fracture of lamellar pearlite grains. The studies of structural morphology of rails’ surface layer showed that the relative content of pearlite grains, where the lamellar structure retained, amounted to 25%; the balance – pearlite grains in which the cementite plates were cut into separately located particles by the sliding dislocations. These particles have the globular shape and their average sizes range within 30–50nm.

Two mechanisms of cementite plate fracture under deformation of pearlite structure steel are mainly discussed in scientific literature [20–28]. The first mechanism consists in the cutting of the plates by moving dislocations and carrying out the carbon atoms by them to ferrite to the field of stress dislocations. Estimations given in the research [20] show that in this case the maximum effect of cementite disintegration can not increase the tenth parts of a percent from the available quantity of cementite.
The second mechanism consists in the pulling of carbon atoms by dislocations from the carbide phase lattice with the formation of Cottrell atmospheres due to the substantial difference of average energy of carbon atom bonds with dislocations (0.6eV) and atoms of iron in cementite lattice (0.4eV) in the plastic deformation process. The diffusion of carbon occurs in the stress field formed by dislocation substructure that is formed around cementite plates. In this case the degree of cementite disintegration must be determined by the value of dislocation density and the type of substructure. So, according to the author’s opinion [20, 21] the model of cementite disintegration may be presented in the following way. The plastic deformation of pearlite steel causes the formation of cellular substructure with cell’ boundaries located near the interphase boundary «cementite-ferrite». With the presence of thermodynamic stimulus (the bonding energy of carbon atoms with dislocations is higher than that with iron atoms in cementite) the carbon atoms, whose mobility is initiated by plastic deformation, are transferred from the cementite surface layers to the dislocations localized at the interphase boundary.

The first process occurring by the mechanism of carbide particles cutting and pulling their fragments apart is accompanied only by the change in their linear sizes and morphology (Fig.2). The change in elemental composition of cementite in the process of fragmentation is minimal. During the occurrence of the second process (the action of the mechanism of dissolution «at the site») quite a different picture is observed. At the initial stage of transformation the cementite plates of pearlite colony are entangled by the sliding dislocations (Fig.3). It is accompanied by breaking the cementite plates into separate weakly disoriented fragments. Then, with the increase in the degree of plastic deformation of the material the change in the carbide structure may occur due to the pulling of the carbon atoms out of cementite lattice.

The second transformation stage of cementite plates of pearlite colony being realized by the mechanism of dissolution at the site and consisting in the pulling the carbon atoms out the cementite crystal lattice is accompanied by the change in defect substructure of carbide that is caused by the penetration of sliding dislocations from the ferrite crystal lattice to the cementite crystal lattice (Fig.4). Therefore, at this stage of cementite plates dissolution the interphase boundaries «α-phase / cementite» play a particular role. The coherent and half-coherent boundary [22] facilitate the penetration of dislocations from α-phase into cementite and inversely, and thereby it favours the fracture and dissolution of carbide. The large-angle incoherent interphase boundary stabilizes the carbide structure and leaves the possibility only for diffusion mass transfer. That is why the cementite plates in pearlite colony break down and the spherical particles of cementite retain at the boundaries of grains and subgrains.

The revealed quantitative regularities of change in the parameters of tread surface structure in the center of the head enabled us to analyze the carbon distribution in the structure of steel. The estimates concerning the content of carbon atoms on the structural elements of steel were made on the basis of the expressions generalized in Table 2. The results of the estimates made are presented in Table 3.

The estimates made showed that the operation of rail steel was accompanied by the essential redistribution of carbon atoms in the surface layer of rails. If in the initial state the main quantity of carbon atoms was concentrated in cementite particles then, after the operation of rails the site of carbon location, along with the cementite particles, was the crystal structure defects of steel (the dislocations, boundaries of grains and subgrains).

Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield point, $\sigma_{0.2}$, N/mm$^2$</th>
<th>Ultimate strength, $\sigma_{\text{u}}$, N/mm$^2$</th>
<th>Elongation unit per length, $\delta$, %</th>
<th>Contraction ratio, $\psi$, %</th>
<th>Impact toughness KCU at temperature $+20^\circ$C, J/cm$^2$</th>
</tr>
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<tbody>
<tr>
<td>DT 350</td>
<td>820</td>
<td>1270</td>
<td>11.5</td>
<td>40</td>
<td>34</td>
</tr>
<tr>
<td>Requirements of Russian standard R 51685 – 2013 for DT 350 category rails not less</td>
<td>800</td>
<td>1180</td>
<td>9.0</td>
<td>25.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>
Fig. 2 Electron microscopy image of tread surface structure
a – light field; b – microelectron of pattern; c – dark field obtained in reflection [012] Fe3C; in (b) the arrow designate the reflection of obtaining of dark field (c); in (c) cementite particles.

Fig. 3 TEM image of pearlite colony structure being formed on dissolution of cementite plates by mechanism ‘at the site’ (the first stage of transformation process of cementite plates of pearlite colony). The arrows designate the fragments in cementite plates.

Fig. 4 TEM image of the second stage of transformation process of cementite plates of pearlite colony being realized by mechanism ‘at the site’.

Fig. 5 TEM image of the third stage of transformation process of cementite plates of pearlite colony being realized by mechanism of dissolution ‘at the site’. The arrows designate the nanodimensional particles of carbide phase in the structure of cementite plates.

Table 2

<table>
<thead>
<tr>
<th>Sites of carbon location</th>
<th>Estimate expressions</th>
<th>Literary source</th>
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<tbody>
<tr>
<td>α-iron base solid solution</td>
<td>$ΔC_α = ΔV_α \frac{α_α - α_α^0}{39±4} \times 10^7$</td>
<td>[32, 33, 34]</td>
</tr>
<tr>
<td>Particles of carbide phases</td>
<td>$ΔC(Fe_3C) = 0.07 \cdot ΔV_1$</td>
<td>[32, 14, 35]</td>
</tr>
<tr>
<td>Elements of defective structure</td>
<td>$ΔC_d = C_0 - ΔC_α - ΔC(Fe_3C)$</td>
<td>[32, 35]</td>
</tr>
</tbody>
</table>

*Here $ΔV_α$, $ΔV_1$ – volume fraction $α$-Fe and carbide phases, respectively; $α_α$ – present day parameter of $α$-phase lattice; $α_α^0 = 0.28668$ nm; $α_α = 0.28782$ nm; $C_0$ – average content of carbon in steel.
Table 3
Carbon distribution in rail steel structure after passed tonnage of 691.8 mln.t brutto

<table>
<thead>
<tr>
<th>Structural elements</th>
<th>Carbon concentration, weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface</td>
</tr>
<tr>
<td>Cementite particles</td>
<td>0.33</td>
</tr>
<tr>
<td>α-Fe crystal lattice</td>
<td>0.0284</td>
</tr>
<tr>
<td>Defects of crystal structure</td>
<td>0.3816</td>
</tr>
</tbody>
</table>

Conclusion

By methods of modern physical material science the studies of structure, phase composition, defect substructure and redistribution of carbon atoms being formed at different distances along the central axis and the fillet in the head of 100-m differentiated hardened rails after long service were carried out and the fracture mechanisms of lamellar pearlite were analyzed. The structure of rail steel is presented by pearlite grains of lamellar morphology, and the grains of ferrite – carbide mixture and structurally free ferrite.

It is shown that the long service life of rails is accompanied by the occurrence of two processes of structural transformation and the phase composition of lamellar pearlite colonies simultaneously: (1) the cutting of cementite plates and (2) the dissolution of cementite plates. The first process being realized by the mechanism of carbide particles cutting and pulling of their fragments apart is accompanied only by the change in their linear sizes and morphology. The second process of cementite plates fracture of pearlite colonies is realized by the escape of carbon atoms from cementite crystal lattice to dislocations in consequence of which the phase transformation of rail metal is possible. It is noted that carbon atoms being leaved the cementite crystalline lattice are located at the defects of steel crystalline lattice (dislocations, grain and subgrain boundaries).

References

Перенос атомов углерода на дислокации и последующее растворение частиц цементита пластин.
Трансформации карбидной фазы в поверхностных действиях двух взаимодополняющих механизмов независимо закаленных рельсах категорий ДТ

Аннотация. Используя методы просвечивающей электронной микроскопии, показано, что зерна пластинчатого перлита, зерна феррито-перлитной смеси и зерна свободного феррита являются основными морфологическими составляющими дифференцированно закаленных рельсов категории DT. Уровень механических свойств и качество стальных рельсов дифференциально закаленных рельсах категории ДТ

For citation

Образец для цитирования

ПРИ ДЛИТЕЛЬНОЙ ЭКСПЛУАТАЦИИ УГЛЕРОДА В СТРУКТУРЕ ПЕРЛИТА