Analysis of Structure-Phase States In-a-Bulk Hardened and a Head-Hardened Rails

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Abstract. A layer-by-layer analysis along the central axis and over the fillet of rails for low-temperature service, rails with enhanced wear resistance and contact fatigue resistance, and for senior-grade rails, bulk oil hardened and DT 350 rails head-hardened under different conditions has been carried out by modern material science methods. Quantitative variables have been established and a comparison of structure-phase states, defective substructure and internal stress fields has been made.

Keywords: rails, structure, phase composition, dislocation substructure, hardening

INTRODUCTION

Determination of optimum conditions of heat treatment is an urgent scientifically and practically significant problem which decision allows dedicated forming of mechanic properties of rail products. In the course of heat treatment, complicated structural phase changes take place in the cross-section of rails, and the defective substructure is formed and evolves. To reveal the physical nature and mechanisms of such changes, the determination of quantitative regularities of parameters of fine structure of rails [1] and their analysis assume ever greater importance. The purpose of the present paper is a comparative analysis of the structure, phase composition and dislocation substructure being formed in a rail head for rails of different categories subjected to bulk hardening and head hardening at various distances from the running surface.

MATERIAL AND METHODS

Samples of 25 m bulk hardened rails Russian State Standard P 51685-2000, as well as samples of 100 m rails of category "DT350" head-hardened directly after rolling produced by Joint Stock Company "EVRAZ Consolidated West Siberian Metallurgical Plant" were used as a material for study.

Structure-phase states and defective substructure of rails were studied by methods of optical and transmission electron microscopy (TEM) [2] of thin foils and X-ray phase analysis along two directions—on the central axis and over the fillet—in the layers located on the running surface and at the distance of 2 and 10 mm from the running surface (Fig. 1).

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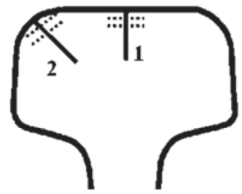

Figure 1. Rail sample preparation pattern for study by TEM methods. Directions on the central axis (*1*) and over the fillet (*2*) are shown with solid lines; dotted lines show the location of metal layers used for foils preparation

RESULTS AND DISCUSSION

To reveal the degree of uniformity of the rail structure, the respective parameters on the central axis and over the fillet were compared. A structural irregularity of rails was determined from the relationship:

$$\Delta X = X_1 - X_2,$$

where X_1 and X_2 are averages of the steel structure parameter on the central axis and over the fillet, respectively.

The analysis of the results given in Table 1, shows that more homogeneous structure (closer parameters on the central axis and over the fillet revealed when using X-ray diffraction methods for steel examination) is formed with bulk hardening of rails.

By TEM methods it is shown [3, 4] that irrespective of the mode of heat treatment, a polycrystalline structure is formed in the surface layer of samples about 10 mm thick represented by pearlite grains of lamellar morphology (eutectoid mixture of ferrite and cementite in which both phases are in the form of extended lamellas) (Fig. 2(a)), ferrite grains in which cementite particles of spherical, globular, and lamellar shapes are observed (in the text below referred to as ferrite-carbide mixture grains) (Fig. 2(c, d)), and grains of structurally free ferrite (ferrite grains not containing particles of carbide phase) (Fig. 2(e)). Irrespective of a heat treatment mode, lamellar pearlite grains are the basic structural component of rails.

Examination of the relative content of the given structural components and the dispersity of the pearlite structure (evaluated by an average value of interlamellar distance) shows that after bulk hardening the structure is more homogeneous (as compared to the structure of steel formed as a result of head hardening) in the near-surface layer of steel (a layer about 2 mm thick) and is less homogeneous in the layer at the distance of about 10 mm from the running surface (Table 2).

TABLE 1. The results of the comparative analysis of the rail structure parameter

Treatment Type	$\Delta V(Fe_3C)$, %	$\Delta a(\alpha\text{-Fe})$, Å	$\Delta(\Delta d/d)$	$\Delta D_{(CSR)}$, nm
Head hardening	2.5	0.0022	0.002	25.0
Bulk hardening	0.9	0.0006	0.00	5.1

Note: $\Delta V(Fe_3C)$ is a structural irregularity of rails by the cementite volume fraction; $\Delta a(\alpha\text{-Fe})$ is that by a lattice parameter α-Fe; $\Delta(\Delta d/d)$ is that by microstresses; $\Delta D_{(CSR)}$ is hat by dimensions of coherent-scattering regions.

TABLE 2. Inhomogeneity of relative content of the rail structural components

Treatment Type	Distance from the Surface, mm	$\Delta V(1)$	$\Delta V(2)$	$\Delta V(3)$	Δh, nm
Bulk hardening	2	0.08	0.08	0.00	11
	10	0.05	0.06	0.01	10
Head hardening	2	0.10	0.10	0.00	18
	10	0.04	0.04	0.00	3

Note: $\Delta V(1)$—mhomogeneity of relative content of pearlite grains; $\Delta V(2)$—inhomogeneity of relative content of ferrite-carbide mixture grains; $\Delta V(3)$—inhomogeneity of relative content of structurally free ferrite grains; Δh—inhomogeneity in an average value of interlamellar distance of pearlite grains.

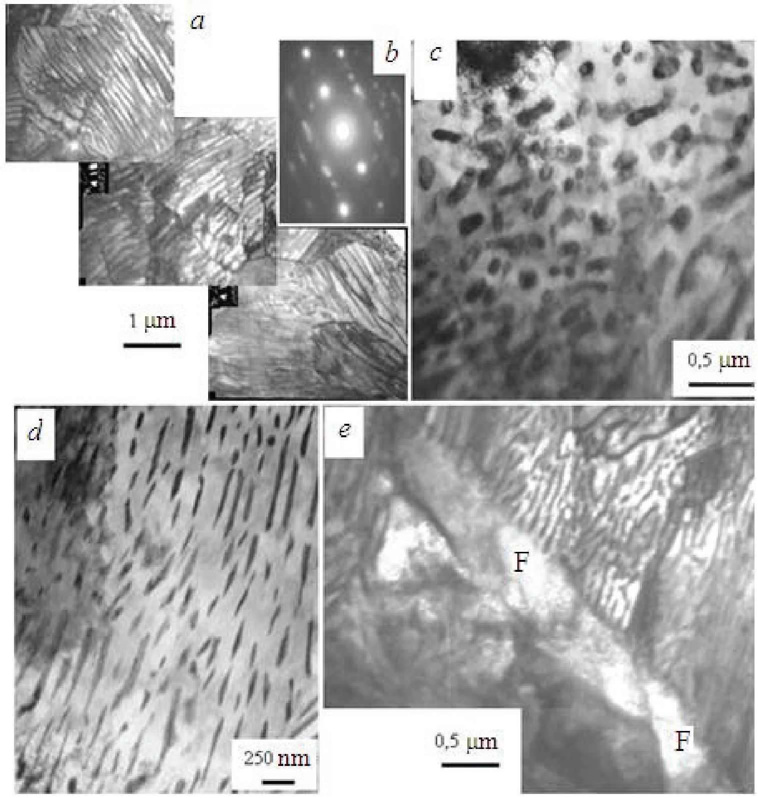

FIGURE 2. TEM images of the rail structure; (a), (c)–(e —bright-field images; (b)—microelectron diffraction pattern; in (e) *F*—a structurally free ferrite grain

Earlier it was noted [3, 4] that electron microscope images of structure of the rail steel samples examined practically always (it is not dependent on a category of rails and a hardening mode) contain bend extinction contours. Availability of bend extinction contours in the electron microscope images denotes lattice bending with torsion of the given region of the material, and, hence, the internal stress fields bending a thin foil [2].

Test evaluations of hardened steels [5] as well as evaluations of steels deformed in different ways and with different degree [6] showed that reasonable evaluations of internal stress fields might be made with the use of the following relation:

$$\sigma_\tau = Gt\frac{\partial\phi}{\partial l} \approx 10^{-2}G\frac{t}{h}, \tag{1}$$

where h is a crosswise size of the bend extinction contour; t is a foil thickness; G is a rigidity modulus of steel, and $\partial\phi/\partial l$ is a continuous misorientation gradient.

The research executed in the present work gives grounds to conclude that in rail steel stress concentrators are internal phase boundaries (ferrite and pearlite grain boundaries, pearlite grain boundaries and boundaries of pearlite colonies, and phase boundaries (interfaces between lamellas of cementite and ferrite in pearlite, and globular particle-matrix interfaces. Bend extinction contours are observed also in rather large (the tenths of a micrometer) cementite particles. The following fact attracts attention: globular particle-matrix interfaces are sources of internal stress fields only in steels subjected to bulk hardening. In head-hardened steels, bend extinction contours at globular particles were observed extremely rarely.

The research executed in the present work showed that, irrespective of a steel category and a hardening mode, bend extinction contours of the minimum crosswise size are formed at globular particles of carbide phase located in ferrite-carbide mixture grains. Wider bend contours are registered at phase boundaries. For example, an extinction contour formed at the boundaries of pearlite colonies has the width varying from 170 to 300 nm; at the ferrite and pearlite grain boundaries its width is from 150 to 200 nm; at the interface of a cementite globular particle and ferrite matrix this value is from 70 to 100 nm. Using the relation (1), it is easy to evaluate the amplitude of internal stress fields which lead to bending torsion of a steel lattice. Assuming foil thickness $t \approx 200$ nm, a rigidity modulus of steel $G \approx 80$ GPa, we will have as a result that internal phase boundaries generate stress fields of 0.5...0.9 GPa, and phase boundaries (particle-matrix) generate stress fields of 1.6...2.3 GPa. The yield strength of the steel examined is about 0.85 GPa, and the ultimate strength is 1.25 GPa. When comparing estimate results with strength properties of steel, one can come to the conclusion that the internal stress fields formed by internal phase boundaries do not exceed steel yield strength. The internal stress fields generated by phase boundaries (particle-matrix) can reach the value of the ultimate strength of steel and be the dangerous concentrators of internal stresses that can cause formation of microcracks in rails in service.

CONCLUSIONS

A comparative analysis of the structure, phase composition and defective substructure of steel along the rail central axis and over the fillet showed as follows:

– more homogeneous structure of the surface layer about 10 μm thick is formed with bulk hardening of rails;

– after bulk hardening, the structure more homogeneous in morphology (grains of pearlite, ferrite, and ferrite-carbide mixture) is formed (in comparison with the structure of the rail steel formed as a result of head hardening) in the near-surface layer (a layer in the thickness of ~2 mm) and less homogeneous in the layer located at the distance of ~10 mm from the running surface.

Steel hardening is accompanied by forming of the internal stress fields which magnitude depends on a stress concentrator type. It is shown that the most dangerous stress concentrators which can be a source of microcracks in rails in service are globular particle-matrix interfaces. Such potentially dangerous stress concentrators are formed mainly in steel subjected to bulk hardening.

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