Gradients in rails at long-term operation

Anton Yuriev¹, Vasilii Kormyshev², Alexander Glezer³, Victor Gromov²*, Yurii Ivanov⁴ and Alexander Semin²

¹JSC ‘Evraz-West-Siberian Metallurgical Combine’, 654043, Kosmicheskoe shosse, 19, Novokuznetsk, Russia
²Siberian State Industrial University, 654007, 42 Kirov Street, Novokuznetsk, Russia
³Institute of Metal Science and Metal Physics named after G.V. Kurdyumov Central Research Institute I.P. Bardina, Moscow, Russia
⁴Institute of High Current Electronics SB RAS, 634055, 2/3 Akademicheskii Ave., Tomsk, Russia

*gromov@physics.sibsiu.ru

Abstract. Long-term operation of rails is accompanied by the formation of the gradient structural constituents consisting in the regular change in relative content of lamellar pearlite, fractured pearlite and structure of ferrite-carbide mixture in cross-section of rail head. As the distance to the surface of rails increases the relative content of metal volume with the structure of lamellar pearlite decreases and that with the structure of fractured pearlite and ferrite-carbide mixture increases. The ferrite-carbide mixture structure has a nanodimensional range of grains, subgrains and particles of the carbide phase forming it.

1. Introduction

The processes of formation and evolution of structural phase states and properties of rail surface layers in long-term operation is a complex system of interrelated scientific and technical problems. The improvement of differentiated quenching modes of long rails for the formation of high operational properties should be based on the knowledge of mechanisms of structural phase changes in cross-section of rails at their long operation. The revealing of these mechanisms is possible only in analyzing the regularities of evolution of fine structure parameters and estimating the contributions of structural constituents and defective substructure to the hardening of rails at long operation. The gradient materials are called to be those whose typical feature is the regularly changing characteristics of elemental and phase composition, defective substructure state [1] in the bulk and/or on the surface of a product. Gradient structural phase state may be formed in a material both as a result of self-organization of defective substructure, elemental and phase composition initiated by different thermo-power effects and be purposefully designed [1-4]. The majority of gradient structures used in technology are artificial. Gradient structures are divided into two large classes depending on their location in a material volume: bulk and surface. The number of types of surface gradient structures is considerably larger.

It is apparent that at severe deformation effect being realized at long operation the different processes (recrystallization, relaxation processes, phase transitions, decay and formation of phases, amorphization, etc) leading to the evolution of structural phase states and being accompanied by the formation of structural phase gradients [5-9] may take place. Therefore, the revealing of nature and regularities of
structure, phase composition and defective substructure in rail head at long operation is of topical character.

A behavior of rail steel at long operation, in its nature, is very close to that of metallic materials at severe (megaplastic, MPD) deformation [5-10].

The general mechanisms of structural formation and evolution at megaplastic deformation of perlite steel are the following: formation of nanometer grains of ferrite, deformation-induced decay of cementite plates under the action of shear stresses and subsequent formation of nanodimensional cementite of dislocations and boundaries of ferrite nanograins by migration of carbon atoms chiefly along dislocation nuclei.

The research is concerned with the search for regularities of formation of gradient structural phase states in rail steel of perlite class subjected to severe plastic deformation by extremely long operation on railway.

2. Material and Methods
The materials under study were the differentiatedly quenched 100-meter rails of DT350 category removed from railway on Experimental testing ground in Shcherbinka town after the passed tonnage of 1411 mln. tons brutto. In chemical composition, the metal of rail specimen meets the requirements of technical specifications TU 0921-276-01124323-2012 for rails of DT350 category that follows from the results shown in Table. 1.

Metal macrostructure was detected by the method of deep etching in 50% hot water solution of hydrochloric acid on incomplete transverse template (head, neck). The macrostructure estimate was done in accordance with RD 14-2P-5-2004 ‘Classification of macrostructure defects of rails rolled from continuously cast billets of electrosteel’. The metal microstructure was studied on metallographic sections cut from the upper part of head (fillet) after etching in 4% alcohol solution of nitric acid. The studies of steel structure were carried out using the methods of optical microscopy (device Olympus GX51), scanning electron microscopy (device MIRA 3 Tescan) and transmission electron diffraction microscopy (device EM-125) [11-14]. The subjects of research for transmission electron microscopy (foils 150-200 nm thick) were manufactured by the method of electrolytical thinning of plates located near the surface and at a distance of 2 mm and 10 mm from the surface, cut out by the methods of electric spark erosion of metal along fillet radius.

3. Results and discussion
It is stated that the rail structure in the layer located at a distance of 10 mm from the fillet surface is formed by pearlite grains of lamellar morphology (Figure 1, a). The regions of ‘degenerate pearlite’ (Figure 1, b) and grains of structurally-free ferrite (ferrite grains in volume of which cementite particles are absent) (Figure 1, c) are present in negligible quantity.

At a distance of 2.0 mm from the working surface of fillet the deformed pearlite containing the cementite plates fractured into separate parts displaced relative to each other is added to the above mentioned structural constituents of steel (Figure 2, a). In the surface layer of the fillet the structure called by us ‘ferrite-carbide mixture’ is formed in addition to the previously mentioned ones (Figure 2, b).

The characteristic feature of the structure is a nanodimensional range of grains, subgrains and particles of the carbide phase forming it. The size of grains and subgrains forming the type of structure varies in the limits of 40-70 nm (Figure 3, a). The size of carbide phase particles located along the boundaries of grains and subgrains varies in the limits of 8-20 nm (Figure 3, b).

The relative content of structural constituents of rail metal varies according to Figure 4.

It is clearly seen that long operation of rails is accompanied by the formation of gradient of structural constituents consisting in the regular decrease in the relative content of the material bulk with lamellar pearlite structure, as the fillet surface is approached and the increase in relative content of material bulk with structure of fractured pearlite and ferrite – carbide mixture.
It has been detected by the method of transmission electron microscopy that a dislocation substructure (Figure 5, a) is present in the ferrite constituent of pearlite colonies and grains of structurally free ferrite. Following the classification given in [15, 16] the dislocations form tangles and nets or are distributed chaotically. The results presented in Figure 5b, testify that the scalar dislocation density of rail increases as the fillet surface is approached. The scalar dislocation density increases the most intensively in the structure of lamellar pearlite, the less intensively - in the structure of degenerate and fractured pearlite.

The long operation of rails is accompanied by the formation of internal stress fields in steel. In studying the steel structure by the methods of transmission electron microscopy a presence of stress fields in the material shows itself in the appearance of bend extinction contours [14] on electron microscopic images indicating a curvature-torsion of crystal lattice of this foil’s part (Figure 6, a).

The bending of a crystal lattice in metals and alloys, including steels (curvature – torsion of crystal lattice) may be of several types [17]. Firstly, a truly elastic bending, being created by stress fields accumulated from the incompatibility of deformation, for example, grains of polycrystal, colonies of lamellar pearlite or plastic material with non-deformable particles. The sources of stress fields that arise mainly under inhomogeneous deformation of a material, in this case, are boundary junctions and grain boundaries of polycrystals, disperse-non-deformable particle/matrix interfaces, in some cases - cracks. Secondly, a plastic bending, if it is created by dislocation charges that the excessive dislocation density localized in some material bulk. Thirdly, an elasto-plastic bending, when both sources of stresses are present in a material.

The analysis technique of internal stress fields based on the behavior of bend extinction contours at inclination of a foil in a microscope column was developed and tested, for the first time, on different materials in papers [18, 19]. The estimation procedure of the internal stress field value is reduced to the determination of gradient of curvature-torsion of crystal lattice χ:

\[ \chi = \frac{\partial \varphi}{\partial \lambda} = \frac{0.017}{h} \]

where h - transverse dimensions of bend extinction contour.

The value of excessive dislocation density \( \rho_{\pm} \) is connected with the gradient of curvature-torsion of crystal lattice \( \chi \) through Burgers vector of dislocations \( b \):

\[ \rho_{\pm} = \frac{1}{b} \cdot \frac{\partial \varphi}{\partial \lambda} \]

Thus, having determined experimentally the transverse dimensions of bend extinction contour in this or that structural constituent of steel it is possible to estimate the value of excessive dislocation density.

When analyzing the results presented in Figure 6, b, it can be noted that the largest magnitudes of excessive dislocation density values are reached in the structure of lamellar pearlite, the smallest – in the structure of ferrite-carbide mixture. With the distance from fillet surface the value of excessive dislocation density decreases that is indicative of the decrease in the amplitude of internal stress fields of rail metal.

It is established that a localization scale of internal stress fields of rail material, in a regular way, depends on a distance from the fillet surface. It is found that in the steel layer located at a depth of \( \approx 10 \) mm the internal stress fields are localized in the bulk of pearlite colony; the sources of stress fields are the interfaces of colonies and grains of pearlite (Figure 6, a). In the layer located at a distance of \( \approx 2 \) mm from fillet surface the extinction contours are localized in the bulk of several plates of ferrite (Figure 7, a). In the layer forming the fillet surfacethe extinction contours are localized mainly in the bulk of separate plates of ferrite (Figure 7, b). It means that the deformation effect taking place at long operation of rails results in the localization volume gradient of internal stress fields of rail metal and therefore, the significant increase in a quantity of stress concentrators that, in turn, will contribute to the increase in the level of embrittlement and operation failure of rails.
4. Conclusion
It has been established that the rail structure after long operation in the layer located at a distance of 10 mm from the fillet surface is formed by pearlite grains of lamellar morphology. The regions of ‘degenerate pearlite’ and grains of structurally free ferrite (ferrite grains in whose volume the cementite particles are absent). It has been shown that a long operation of rails is accompanied by the formation of structural constituents’ gradient consisting in a regular change in the relative content of lamellar pearlite, fractured pearlite and structure of ferrite-carbide mixture in cross-section of rail head. As the fillet surface of rail is approached the relative content of metal bulk with the structure of lamellar pearlite decreases but that with the structure of fractured pearlite and ferrite-carbide mixture increases. A typical feature of the ferrite-carbide mixture structure is an anodimensional range of grains, subgrains and particles of the carbide phase forming it: the dimension of grains and subgrains forming the type of structure varies in the limits of 40-70 nm; the size of the carbide phase particles located along grain and subgrain boundaries varies in the limits of 8-20 nm. It has been revealed that a long operation of rails is accompanied by the formation of gradient of material defective substructure consisting in a regular increase in the value of scalar and excessive dislocation density. It has been determined that the scale of localization of rail internal stress fields depends in a regular way on the distance from the fillet surface changing from the bulk of pearlite colony, on the whole, at a depth of \(\approx 10\) mm to the bulk of separate ferrite plates in a fillet layer. It means that the deformation effect taking place in rail operation results in a substantial increase in a number of stress concentrators that, in its turn, contributes to embrittlement of the material.

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