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THE MICROSTRUCTURE OF DIFFERENTIALLY HEAT STRENGTHENED RAILROAD RAILS MANUFACTURED BY THE EVRAZ ZSMK COMPANY

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The article analyzes the microstructure of differentially heat strengthened railroad rails produced by the EVRAZ ZSMK Company and determines the types and compositions of nonmetallic inclusions. The segregation processes of the main chemical elements of the rail steels (C, Si, Mn, Cr, S, and P) and the variation of hardness over the cross section of rail profiles were investigated. Typical nonmetallic inclusions are nondeformable silicates concentrated primarily in the rail webs and plastic sulfides concentrated in the rail heads. Some of the rails exhibited chemical heterogeneity with clusters of nonmetallic inclusions in the profile necks.

Keywords: railroad rails, differentiated heat treatment, microstructure, nonmetallic inclusions, mechanical properties, chemical heterogeneity, hardness.

INTRODUCTION

In Russia, railroads are important infrastructure for cargo turnover, with approximately 85 – 90% of the goods transported by rail. In this regard, the quality and operational stability of railroad rails, which determine railroad throughput, have a significant influence on the efficiency of various sectors of the industry in Russia.

Until 2013, railroad rails in Russia were produced on linear-type rolling mills originally designed in the 1930s. By the beginning of the XXI century, Russian rails were significantly inferior in a number of key rail parameters compared to world leading manufacturers such as Nippon Steel Corporation (Japan), Thyssen Krupp Stahl (Germany), Voestalpine Schienen Gmbh (Austria), and Tata Steel (France) because of the use of the outdated technology of volume rail hardening in oil [1], while international manufacturers use differentiated hardening in various media (polymers, compressed air) (Table 1). The discrepancy in the quality of rails produced in Russia resulted in the purchase of significant amounts of rails from other countries [2, 3]; in the period from 2010 to 2013, the imported rails was 18 – 39% of the total rail purchases.

A radical reconstruction of the Russian rail production occurred in 2013. Modern universal rail and structural steel mills were brought online at EVRAZ ZSMK (EVRAZ United West-Siberian Iron and Steel Works) and Mechel, where their main products were differentially heat strengthened, long railroad rails (up to 100 m long) [4 – 6]. Heat treatment of rails at these enterprises was via rolling heating [7, 8]. Alternatively, EVRAZ ZSMK uses compressed air as a quenching medium and Mechel uses polymer solutions.

The rails of these manufacturers quickly passed the certification procedure, and since 2014, they have fully met the needs of Russian Railways. As a result, rail products for Russian railroads have not been purchased from international manufacturers since 2014.

Although, railroad rails produced in Russia have similar quality, and are even superior to rails from global leading manufacturers according to a number of indicators, increas-

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TABLE 1. Types of Railroad Rail Hardening

Rail manufacturer	Heating for hardening	Hardening method
Voestalpine Schienen Gmbh (Austria)	Rolling heating	DH* in polymer solution
Tata Steel (France)	Separate volumetric heating with high-frequency current	DH with compressed air
Nippon Steel Corporation (Japan)	Rolling heating	DH with compressed air
EVRAZ ZSMK (Russia) until 2013		Volume hardening in oil
EVRAZ ZSMK (Russia) after 2013		DH with compressed air
Mechel (Russia) after 2013		DH in polymer solution

* Differentiated hardening.

ing their operational stability and reducing preterm and emergency failures are still issues. This situation is because of the increased traffic density on Russian railroads, especially in the eastern territories (Eastern Siberia, the Far East), where the operational durability of the rails is the lowest because of the climate (long winter period with temperatures below –20°C) and geographical landscape (a significant proportion of the area with a small radius curvature less than 650 m).

One of the most effective ways to increase the operational stability of railroad rails is to increase the microstructure quality, including reducing contamination by nonmetallic inclusions. However, there are few studies of the formation processes of the rail microstructure under their production conditions in the new Russian rail and structural steel mills that have limited experience. Notably, during the transition of the rail production to the new rolling mills, the technology of their rolling and heat treatment changed, and the production of the initial continuously cast ingots changed. In particular, the chemical composition of the rail steels underwent significant changes. Earlier 76F steel was used for the mass production of rails, and now, most rails are manufactured from 76HF steel (DT350 category rails are differentially heat strengthened using rolling heating). A significant amount of the rails are also produced from 90HAF hypereutectoid steel (DT370IK category rails are differentially heat strengthened using rolling heating for increased wear resistance and contact endurance).

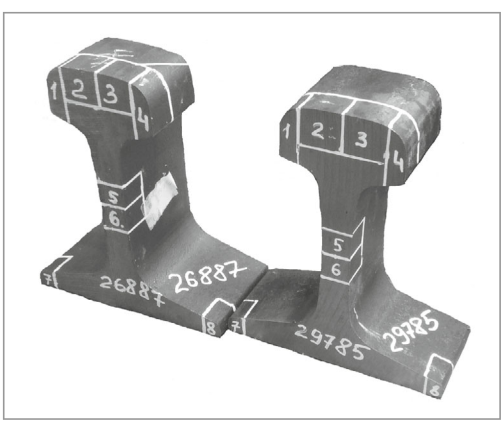

Fig. 1. Schemes of specimen sampling of rails of various melts for research.

This work aimed to study the microstructure of differentially heat strengthened railroad rails of various categories, including the distribution of characteristic nonmetallic inclusions along the rail profile.

METHODS OF STUDY

Samples of rails from the current EVRAZ ZSMK production of DT350 (E76HF steel) and DT370IK (E90HAF steel) categories selected from various elements of rail profiles were studied (Fig. 1). The chemical compositions of the investigated steels are presented in Table 2.

Nonmetallic inclusions were analyzed using the GOST 1778–70 standard on unetched sections at a magnification of 100× (metallographic light microscope, OLYMPUS GX-51)

TABLE 2. Chemical Composition of Steels for Railroad Rails Produced by EVRAZ ZSMK

Steel	Content of chemical elements, wt.%									
	C	Mn	Si	V	Cr	N	Cu	Ni	S	P
E76HF (DT350)	0.72 – 0.80	0.82 – 0.97	0.39 – 0.56	0.03 – 0.07	0.36 – 0.54	0.006 – 0.012	0.07 – 0.14	0.05 – 0.11	0.009 – 0.018	0.008 – 0.015
E90HAF (DT370IK)	0.84 – 0.93	0.76 – 0.95	0.42 – 0.53	0.08 – 0.11	0.24 – 0.39	0.010 – 0.015	0.06 – 0.12	0.03 – 0.12	0.007 – 0.016	0.006 – 0.014

Note. The category of rails is given in parentheses.

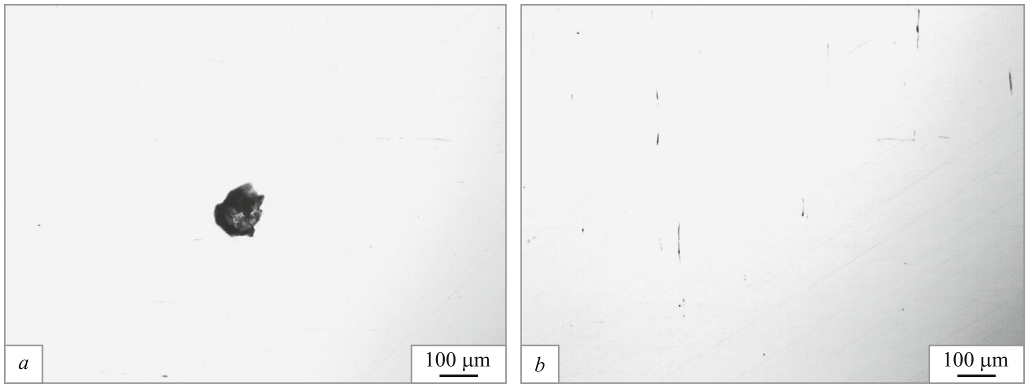

Fig. 2. Characteristic nonmetallic inclusions in railroad rails: *a*) nondeforming silicates in the rail web (score 4a); *b*) sulfides in the rail head (score 3b).

and according to the Spark-DAT method (Spark Data Analysis and Treatment) using an ARL iSpark spectrometer. The Spark-DAT technique separates the intensity of the photomultiplier signal into low intensity peaks attributed to the base metal and high intensity peaks of nonmetallic inclusions [9 – 11]. Using the Spark-DAT methodology, at Stage 1, the Standard Inclusion Analysis method was used, where the number of inclusions was determined as the number of peaks of an individual element or the number of coincidence peaks of various elements. To determine the concentration of specific types of inclusions, such as aluminates, sulfides, and silicates, the Advanced Inclusion Analysis method was used as a preset model. Four measurements were performed for each sample. Notably, the ARL iSpark spectrometer has a limitation in the size range of detected nonmetallic inclusions, when inclusions smaller than 1 – 2 μm and larger than 10 – 15 μm are not identified. Additionally, the Spark-DAT technique divides the detected inclusions into conditional groups depending on their size. In this study, the inclusions were divided into three groups, fine (2 – 6 μm), medium (6 – 10 μm), and coarse (larger than 10 μm). Studies of the microstructure of heat treated rails were performed on thin sections after etching using the standard technique according to GOST 5639–82.

In addition, segregation of the main chemical elements of rail steels (C, Si, Mg, Cr, S, and P) over the section of rail profiles was studied using x-ray fluorescence spectral analysis according to GOST 28033–89 (Shimadzu XRF-1800 spectrometer) and photoelectric spectral analysis according to GOST 18895–97 (Spectrometer DFS-71). The segregation degree L (%) was determined using Eq. (1),

$$L = (C_{ch} - C_{ladle})/C_{ladle} \times 100\%, \quad (1)$$

where C_{ch} is the concentration of the chemical element in the rail sample at the measurement site, %, and C_{ladle} is the concentration of a chemical element in a ladle sample for melting steel used to produce the rail, %.

The hardness of samples taken from various elements of rail profiles was measured using a hardness testing machine, TK-2M.

RESULTS

The analysis of nonmetallic inclusions, using a semiquantitative technique according to GOST 1778–70, revealed that the predominant type of inclusions, regardless of the rail category, were nondeforming silicates (detected in all samples) (Table 3). At the same time, the highest concentrations and size of such inclusion were noted in the rail web where their maximum score was 4a according to GOST 1778–70 (Fig. 2*a*). In the rail head, an increased (compared to other elements of the rail profile) concentration of sulfides was revealed, with the maximum inclusion score of 3b ac-

TABLE 3. Distribution of Nonmetallic Inclusions along the Railroad Rail Profile

Type of nonmetallic inclusions	Distribution of inclusions (maximum score) by rail elements:		
	Head	Web	Flange
DT350 category rails made of steel E76HF			
Nondeforming silicates	2b/1b	4a	3b
Sulfides	3b/–	–	–
One-dimensional oxides	1a/–	1a	–
Plastic silicates	–/3b	2a	–
Aluminum nitrides	–/1b	2b	3b
DT370IK category rails made of steel E90HAF			
Nondeforming silicates	1b/1b	3b	2b
Sulfides	–/3b	–	2b
Stitched oxides	2a/–	–	–
Plastic silicates	1a/2b	1b	–

Note. The numerator shows the results of the study of lateral samples and the denominator presents the study results of the central samples.

TABLE 4. Relative Concentration and Size of the Nonmetallic Inclusions in Railroad Rail Elements

Inclusion	C_{incl}, ppm			
	E76HF steel rails		E90HAF steel rails	
	Head	Web	Head	Web
SiO_2	7.73 (100/0/0)	9.27 (100/0/0)	3.35 (100/0/0)	14.92 (100/0/0)
MnS	34.86 (100/0/0)	30.78 (56.2/43.8/0)	35.04 (59.9/29.9/10.2)	43.35 (72.6/15.2/12.2)
Al_2O_3	0.28 (52.6/18.4/29.0)	0.30 (66.7/8.3/25.0)	0.18 (61.4/15.9/22.7)	0.11 (65.8/8.6/25.6)
Al_2O – CaO – MgO	1.54 (29.5/16.7/53.8)	0.95 (37.5/16.6/45.9)	1.33 (50.4/19.8/29.8)	1.60 (52.5/13.8/33.8)
Al_2O_3 – CaO – MgO – CaS	0.88 (24.3/18.3/57.5)	1.22 (33.3/16.7/50.0)	1.19 (38.8/20.4/40.7)	0.88 (53.6/7.3/39.1)
Al_2O_3 – CaO	0.34 (47.9/27.9/24.1)	0.31 (53.4/13.2/33.3)	0.33 (48.5/22.6/29.0)	0.19 (60.0/10.0/29.9)
Al_2O_3 – MgO	0.31 (30.1/19.9/50.0)	0.30 (50.0/10.0/40.0)	0.03 (44.8/20.8/34.4)	0.08 (57.8/7.6/34.6)

Notations: C_{incl} is the relative concentration of inclusions.

Note. The content of inclusions (%) with size < 2 – 6 μm/6 – 10 μm/> 10 μm, respectively, are presented in parentheses.

cording to GOST 1778–70 (Fig. 2*b*). Notably, the contamination of DT307IK category rails with nonmetallic inclusions was less than that of the DT350 category rails.

Based on the analysis of the nonmetallic inclusions performed using the Spark-DAT method, only SiO_2 inclusions have a sufficiently high concentration among the silicate-type inclusions (Table 4). Additionally, all identified inclusions of this type were relatively small (less than 2 μm). Manganese sulfides (MnS) have the highest concentration in the considered size range of nonmetallic inclusions. In contrast to the results of the semiquantitative analysis presented above, no significant difference in the concentration of MnS in the rail head and web were detected because of the predominance of fine inclusions that are not detected by metallographic analysis with a magnification by 100×. Studies have also shown that the concentration of inclusions of other types is extremely low. Specifically, the concentration of complex inclusions containing alumina (Al_2O_3 – CaO – MgO, Al_2O_3 – CaO – MgO – CaS, Al_2O_3 – CaO, Al_2O_3 – MgO) did not exceed 3.1 ppm in total.

The studies revealed a significant segregation of C, Mn, and S along the cross section of the rails and within their individual elements (Fig. 3). A segregation in carbon also determines a wide range of hardness within the individual elements of the rail profile (Table 5), and segregation in sulfur, reaching +100% (rel.), determines a significant concentration of sulfides.

Studies of the rail microstructure have established the standard for differentially thermally hardened rails. The head microstructure represents hardened sorbite (Fig. 4*a*), while the rail web and flange microstructures are pearlite (Fig. 4*b* and *c*). The grain size in the rail head corresponds to No. 9 and No. 10, while the grain size in the web and flange are No. 8 and No. 9, according to GOST 5639–82, which indicates the use of the optimal heating mode for billets for rolling. However, chemical inhomogeneity was also revealed in the web of numerous rails in this study (Fig. 5*a*), and nonmetallic inclusions were located inside its strips (Fig. 5*b*).

DISCUSSION

The results of this study of nonmetallic inclusions in railroad rails manufactured by EVRAZ ZSMK, performed using the semiquantitative analysis (Table 3) and the Spark-DAT method (Table 4), suggest that typical nonmetallic inclusions in rails, regardless of the category (steel grade), are nondeforming silicates represented mainly by SiO_2 inclusions and plastic MnS sulfides. Inclusions of these types of relatively large sizes (detected using the semiquantitative analysis technique at 100×) are distributed unevenly along the rail profile, sulfides have the highest concentration in the head, and silicates have the highest concentration in the rail web.

Nondeforming silicates in the rail head can have a potentially negative impact on the operating durability of rails [12 – 15]. Considering their low concentration, this effect is not significant. Complex inclusions based on alumina, which are the most potentially hazardous in terms of the formation of contact fatigue defects during the operation of rails [16 – 19], have an extremely low concentration (Table 4); as a result, their effect is not significant.

The studies of the railroad rails microstructure using profile elements (Fig. 4) indicate the use of an optimal temperature and velocity parameters for differentiated hardening. The microstructure of all elements of the rail profile was fine grained, such that the grain score did not exceed No. 9 according to GOST 5639–82 in the head and No. 8 in the flange and web. The microstructure of the web and flange also corresponded to hot-rolled pearlitic steel and had sufficient ductility; the microstructure of the head (sorbite) corresponded to hardened steel with increased hardness.

The presence of defects in the form of bands of chemical inhomogeneity in the web of numerous rails are an issue (Fig. 5). Such a structure creates uneven mechanical proper-

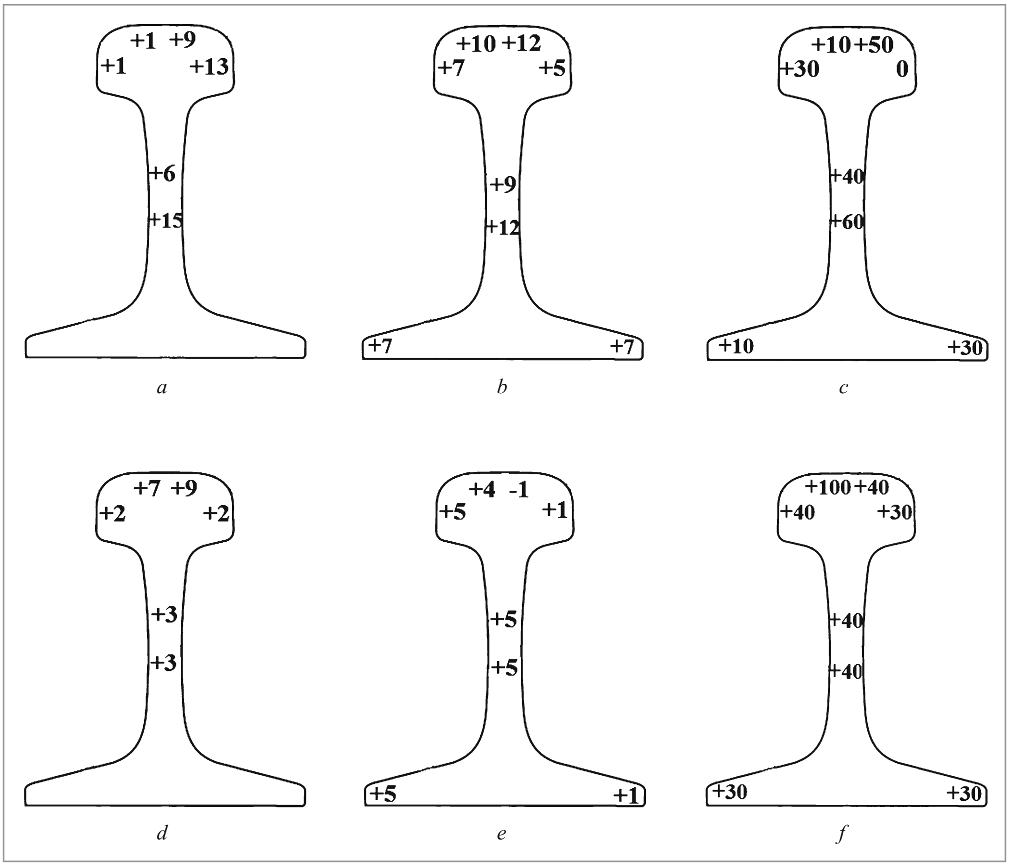

Fig. 3. The maximum degree of segregation in the sample (numbers in the figures are given as %) of (*a*, *d*) carbon, (*b*, *e*) manganese, and (*c*, *f*) sulfur over the cross section of (*a* – *c*) DT350 and (*d* – *f*) DT370IK rails. Calculated using Eq. (1).

ties and, as a result, reduces the operational characteristics of the rails. Notably, significant chemical inhomogeneity (segregation) was also revealed at the macro level, i.e., along the elements of the rail profiles (Fig. 4). According to generally accepted concepts, chemical heterogeneity is formed in continuously cast ingots that are the initial billets for the production of rails, in case of deviation from the optimal temperature and speed conditions for steel on a continuous casting machine. The modes of rolling and thermal processing of the rails do not have a significant effect on the development of chemical inhomogeneity. Similarly, the use of optimal rolling modes prevents the transition of segregation defects from the web to the head of the rail profile being formed [20]. Thus, for EVRAZ ZSMK, improving the quality of the rail microstructure will improve the rail steel.

CONCLUSIONS

Based on the studies of the microstructure of differentially thermally hardened railroad rails manufactured by EVRAZ ZSMK, the following conclusions can be drawn.

1. The distribution of nonmetallic inclusions along the rail profile is uneven. In the rail web, nondeforming silicates, mainly in the form of SiO_2, have the highest concentration, and plastic MnS have the highest concentration in the rail head.

TABLE 5. Hardness of the Railroad Rail Elements

Rail category	Steel	*HB*, kgf/mm^2		
		Head	Web	Flange
DT350	E76HF	286 – 331/341 – 452	207 – 255	255 – 293
DT370IK	E90HAF	341 – 415/352 – 415	248 – 293	248 – 293

Note. The numerator shows the hardness of the lateral samples of the head and the denominator shows the hardness of the central samples.

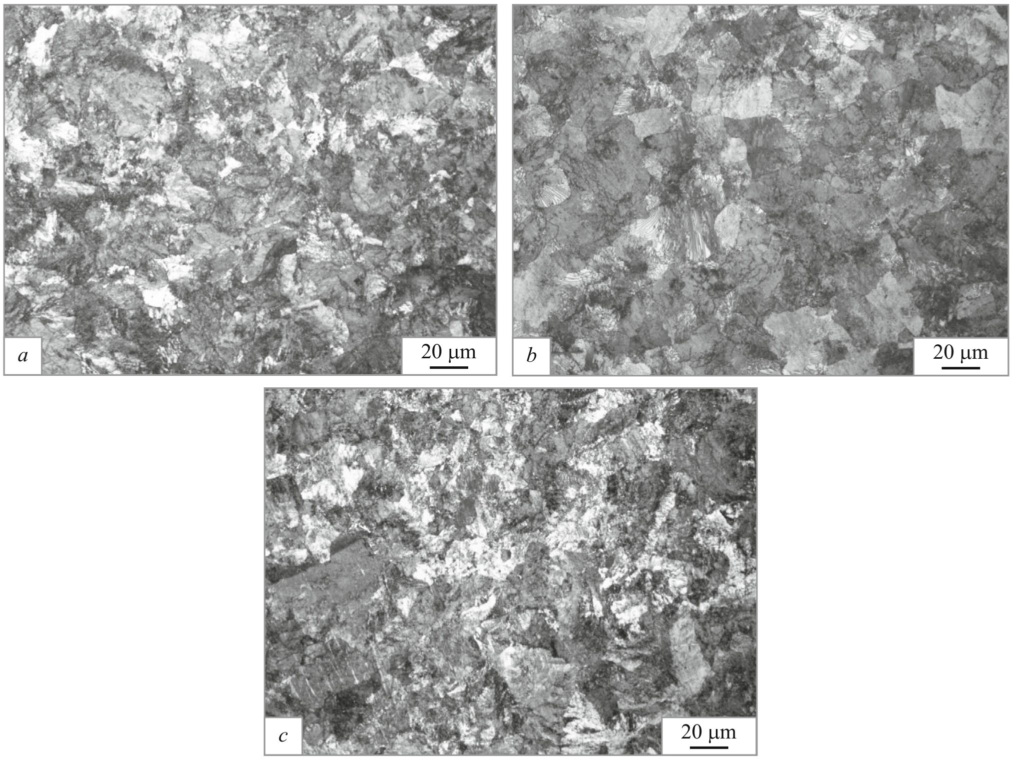

Fig. 4. Microstructure of the (*a*) rail head, (*b*) web, and (*c*) flange of DT370IK.

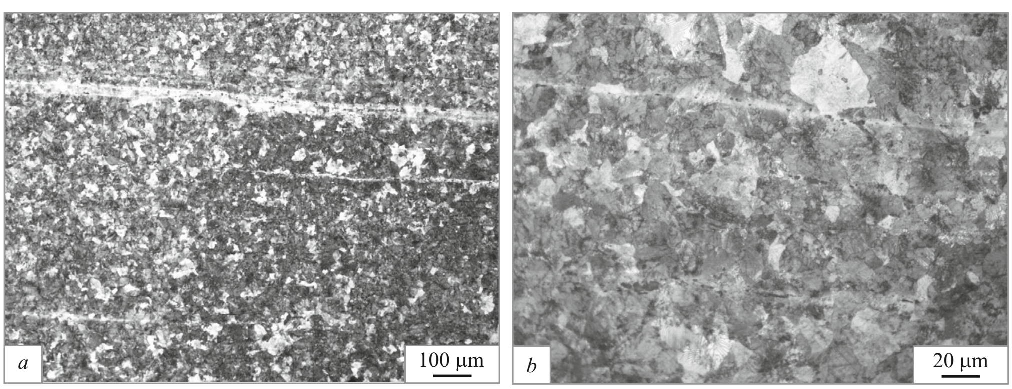

Fig. 5. Microstructure of the rail neck of DT350: *a*) chemical heterogeneity; *b*) nonmetallic inclusions in the bands of chemical inhomogeneity.

2. The rail microstructure is fine grained, which indicates the use of an optimal temperature and speed modes for differentiated thermal processing.

3. Chemical inhomogeneity with accumulation of nonmetallic inclusions was detected in the microstructure of the web of numerous rails. Chemical heterogeneity was also revealed at the macro level between individual elements of the rails and inside the rails.

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