

Nonmetallic Inclusions in Rails Made of Electro-Steel Alloyed with Chromium

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Abstract—Based on metallographic (with an “OLYMPUS GX-51” microscope) and spectral (using spectrometer “ARL iSpark” method “Spark-DAT”) analyses, the relative concentration and size of most non-metallic inclusions for rail elements (head, web) from electro-steel of E79KhF and E90KhAF grades were determined. It was found that the highest relative concentration of manganese sulfides (MnS) is 30.8–43.4 ppm. At the same time, 60–100% of these inclusion types have a small size (less than 4 μm), and cannot be detected using standard metallographic analysis with 100-fold magnification. The revealed high relative-concentration of sulfide inclusions directly correlates with the established positive sulfur liquation in considered rail elements, which reaches up to 40%. Despite the high MnS concentration, their influence on the rail quality can be considered not dangerous, considering their high ductility during hot deformation and the prevalence of these inclusion types with a small size (less than 4 μm). Among silicate-type inclusions, SiO₂ inclusions (3.4 – 14.9 ppm) have a significant concentration. All detected inclusions of this type have a size not exceeding 4 μm. It was found that the concentration of complex inclusions containing alumina (Al₂O₃–CaO–MgO, Al₂O₃–CaO–MgO–CaS, Al₂O₃–CaO, Al₂O₃–MgO) is insignificant: in total, it does not exceed 3.1 ppm and 1.6 ppm for individual types. The concentration of corundum (Al₂O₃) is also insignificant and does not exceed 0.3 ppm. In this case, small-sized alumina inclusions (less than 6 μm) prevail. Due to the low contamination (considering the relative concentration and size of inclusions) with non-plastic silicate and alumina non-metallic inclusions, their influence on the rail quality was not significant. It is confirmed by the absence of defects detected during ultrasonic testing.

Keywords: railway rails, rail steel, chromium alloying, nonmetallic inclusions, sulfides, silicates, plasticity, hot deformation, liquation

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INTRODUCTION

Contamination with nonmetallic inclusions is a key characteristic of railway rail quality and determines their operational characteristics to a significant extent. In this case, not only the amount of nonmetallic inclusions, but also their type, shape, size, and distribution in rails play an important role.

In spite of many significant research works devoted to the study of nonmetallic inclusions in railway rail [1–7], as well as their effect on mechanical and operational characteristics of rails [8–14], their scope is limited. This is caused by significant process features of the rail production abroad and significant changes in the production technology of rails and rail steel in Russia in the past 5–10 years. Many of these changes include: transitioning to large-scale rail production from steels of new brands alloyed with chromium; using new types of reducing agents and alloys; refining

ladle conditions of rail steel; using environmental exposure technologies on steel during continuous casting; and transitioning to long-rail production (up to 100 m) on universal structural mills put into service. Furthermore, instead of using the previously-used E76F and E90AF steel brands [15, 16], E76KhF and E90KhAF are more commonly manufactured in which the following are now currently practiced: a complete aluminum refusal as a reducing agent occurs; the time rail steel blowing with inert gas during ladle refining was significantly increased (up to two times) [17, 18]; electromagnetic mixing and “soft reduction” during caster reconstruction occurs; and a new structural mill with a continuous group of universal mill stands was put into operation on JSC “EVRAZ—Joint West Siberian Metallurgical Plant” (JSC “EVRAZ WSMP”)—currently the leading national manufacturer of railway rails.

Table 1. Distribution of nonmetallic inclusions by elements of suitable rails of the current production

Type of inclusion	Distribution of inclusions along the rail elements		
	head		web
	side shots	central shots	
Rail from E76KhF steel			
Non-deforming silicates	1b; 2b	1a; 1b	1a; 1b; 4a
Sulfides	2b; 3b	—	—
Spot oxides	1a	—	—
Plastic silicates	—	3b; 1a	2a
Aluminum nitrides	—	1b	1b; 2b
Rail from E90KhAF steel			
Non-deforming silicates	1b; 2a	1b	1b; 2b; 3b
Sulfides	—	2b; 3b	—
Stitched oxides	—	—	—
Plastic silicates	1a	—	1b

Thus, the composition and distribution study of nonmetallic inclusions in railway rails is presently a relevant problem.

The chemical composition of the specimens was determined by spectral analysis using the ARL iSpark spectrometer.

STUDY PROCEDURES

The specimens from the head and web of suitable (passed ultrasound testing) rails under current production of E76KhF and E90KhAF steel casts were used as the studied samples.

Nonmetallic inclusions were studied using an OLYMPUS GX-51 optical microscope through standard semiquantitative analysis according to GOST 1778–70 and using an ARL iSpark spectrometer through the Spark-DAT method. The Spark-DAT procedure (Spark Data Analysis and Treatment) determines the type, concentration, and size distribution of nonmetallic inclusions. This procedure is based on the signal intensity expansion of the photoelectron multiplier into low-intense peaks, which correspond to the main metal, as well as high-intense peaks, which are related to nonmetallic inclusions [19–21]. The “Standard Inclusion Analysis” method was employed within the mentioned procedure, in which the number of inclusions is determined as the number of individual element peaks or as a coincidence of various element peaks. To determine the concentration of some specific inclusion types (such as aluminates, sulfides, and silicates), the “Extended Inclusion Analysis” method was used as a preset model. A total of four measurements was carried out for each specimen.

RESULTS AND DISCUSSION

According to the semiquantitative analysis results (Table 1), nondeforming silicates are the predominant type of nonmetallic inclusions in suitable rails (Fig. 1a). In this case, contamination with the mentioned type of inclusions in rail heads is significantly less than that in the web.

Sulfides predominate in the rail head (Fig. 1b). There are also inclusions in the form of plastic silicates, aluminum oxides and nitrides, in which contamination is significantly less in the rails made from E90KhAF steel in the rail head.

Analysis of nonmetallic inclusions through the Spark-DAT method showed that MnS possess the highest concentration in the rail head and web (30.8–43.4 ppm). In this case, in contrast to semiquantitative analysis data, concentrations of the mentioned inclusion types did not have any significant differences in the head and web (Fig. 2a), which is caused by the predomination of small (less than 4 μm) inclusions that are not detected during standard metallographic analysis at 100 $\times$ zoom. According to the analysis in the rail head made from E76KhF steel, all the inclusions possess a small (less than 4 μm) size; the small inclusion fraction is 59.9% in the rail head made from E90KhAF steel (Fig. 2d), while this value is 56.2 and 72.1% in the rail neck made from E76KhF and E90KhAF steel, respectively (Figs. 2b and 2c).

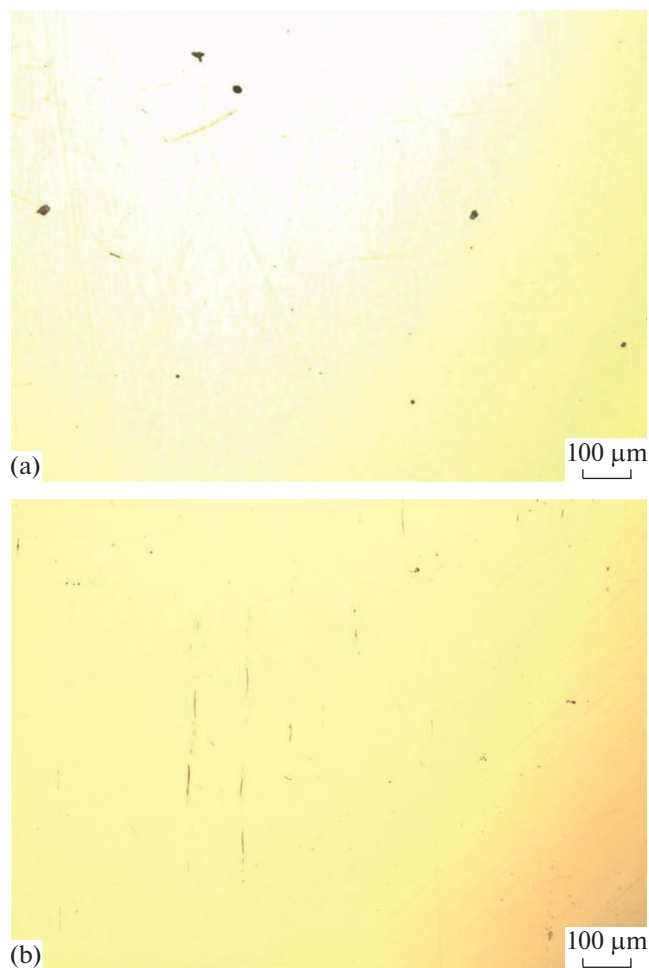


Fig. 1. Typical non-metallic inclusions in rails made of steels E76KhF and E90KhAF: (a) non-deformed silicates in the rail web (score 3b); (b) sulfides in the rail head (score 3b).

Investigation of rail chemical composition (Table 2) showed the positive sulfur and carbon liquation in the head and web of both rails; sulfur liquation corresponded to up to 30% in the head and up to 40% in the neck, while carbon liquation reached up to 3.0 and 2.7%, respectively. The presence of positive sulfur liquation directly correlates with a relatively high sulfide concentration in the rail elements. No significant liquation of other chemical elements was detected. In addition, the chemical composition of both analyzed rails fully meets the requirements of GOST R 51685–2013.

MnS correspond to plastic nonmetallic inclusions, which are expanded into stitches during hot rolling; therefore, their relatively high concentration should be considered safe for the rail quality, in particular the possible predomination of small inclusions.

Only silica SiO_2 possesses a sufficiently high concentration among silicate-type inclusions (3.4–14.9 ppm); in this case, the detected inclusions of this type are

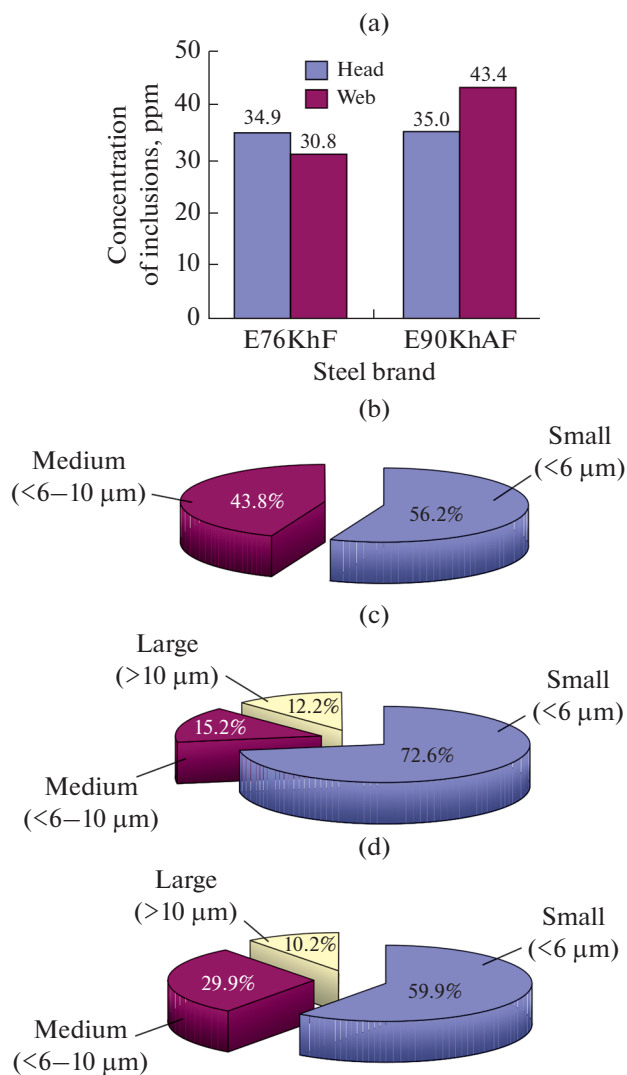


Fig. 2. MnS distribution along the profile of chromium steel rails: (a) relative concentration of inclusions; (b, d) size distribution of inclusions in the rail web made of E76KhF (b) and E90KhAF (d) steel; (c) size distribution of inclusions in the rail head made of E90KhAF steel.

small and less than 4 μm. The mixed-inclusion concentration with alumina (Al_2O_3 –CaO–MgO, Al_2O_3 –CaO–MgO–CaS, Al_2O_3 –CaO, Al_2O_3 –MgO) is marginal and less than 3.1 ppm and 1.6 ppm in total for individual types (Fig. 3a, 4a). In this case, the inclusions from the Al_2O_3 –CaO–MgO (1.3–1.6 ppm) and Al_2O_3 –CaO–MgO–CaS systems (0.9–1.2 ppm) possess the largest concentration. The corundum (Al_2O_3) concentration is also marginal and less than 0.3 ppm (Figs. 3a and 4a). With regard to the size distribution of alumina inclusions, it should be noted that small (less than 4 μm) size is predominant for most of them (Figs. 3b and 4b). A significant nonmetallic-inclusion fraction of relatively large (more than 10 μm) sizes was

Table 2. Rail chemical composition by the profile elements

Content, wt %	Sampling location for E76KhF				Sampling location for E90KhAF			
	head	web	ladle sample	GOST R 51685–2013 requirements	head	web	ladle sample	GOST R 51685–2013 requirements
C	0.809	0.811	0.790	0.710–0.820	0.886	0.872	0.860	0.830–0.950
Mn	0.936	0.936	0.940	0.750–1.250	0.739	0.749	0.780	0.750–1.250
Si	0.568	0.563	0.570	0.250–0.600	0.533	0.534	0.540	0.250–0.600
P	0.015	0.014	0.015	Max–0.020	0.009	0.010	0.011	Max–0.020
S	0.013	0.011	0.010	Max–0.020	0.012	0.014	0.010	Max–0.020
Ni	0.100	0.099	0.100	Max–0.200	0.090	0.081	0.080	Max–0.150
Cr	0.411	0.409	0.410	0.200–0.800	0.295	0.292	0.290	0.200–0.600
Cu	0.118	0.119	0.120	Max–0.200	0.116	0.116	0.120	Max–0.200
N	0.010	0.009	0.010	—	0.012	0.012	0.011	0.010–0.020
V	0.041	0.040	0.040	0.030–0.150	0.086	0.090	0.080	0.080–0.150
Ti	0.003	0.002	0.002	Max–0.010	0.003	0.004	0.003	Max–0.010
Al	0.003	0.002	0.003	Max–0.004	0.003	0.003	0.004	Max–0.004
Nb	0.002	0.001	0.002	—	0.001	0.001	0.001	—
Sn	0.007	0.006	0.007	—	0.005	0.006	0.006	—
Sb	0.0016	0.0015	0.002	—	0.0012	0.0013	0.002	—

detected only for the inclusions of $\text{Al}_2\text{O}_3\text{--CaO--MgO}$ and $\text{Al}_2\text{O}_3\text{--CaO--MgO--CaS}$ types in the rail made from E76KhF steel (Fig. 3b).

Overall, a low (assuming relative concentration and size of inclusions) contamination of the analyzed rails with non-plastic silicate and alumina nonmetal inclu-

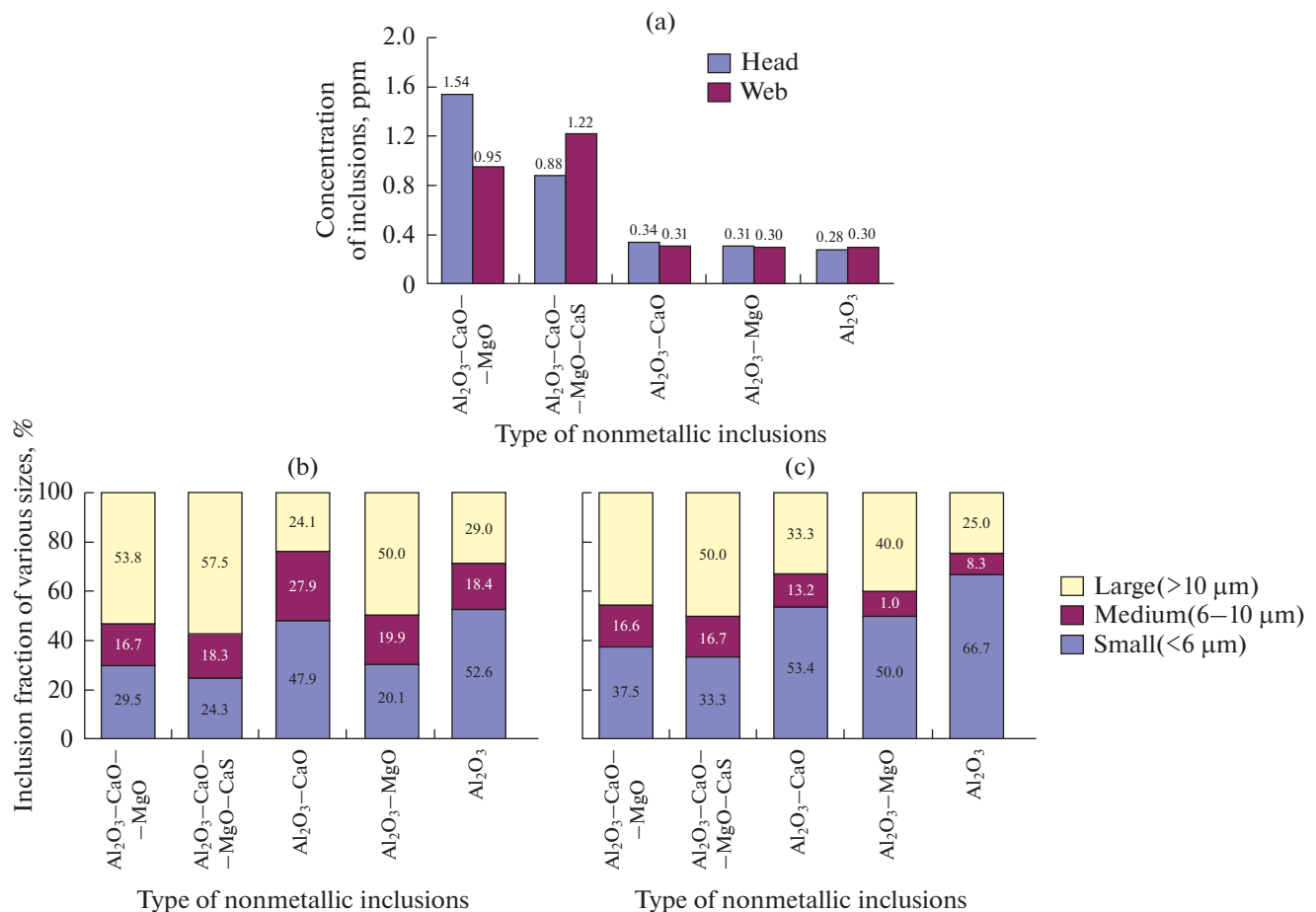


Fig. 3. Alumina inclusion distribution along the rail profile made of E76KhF steel: (a) relative concentration of inclusions; (b, c) dimensions of inclusions in the head and web of the rail.

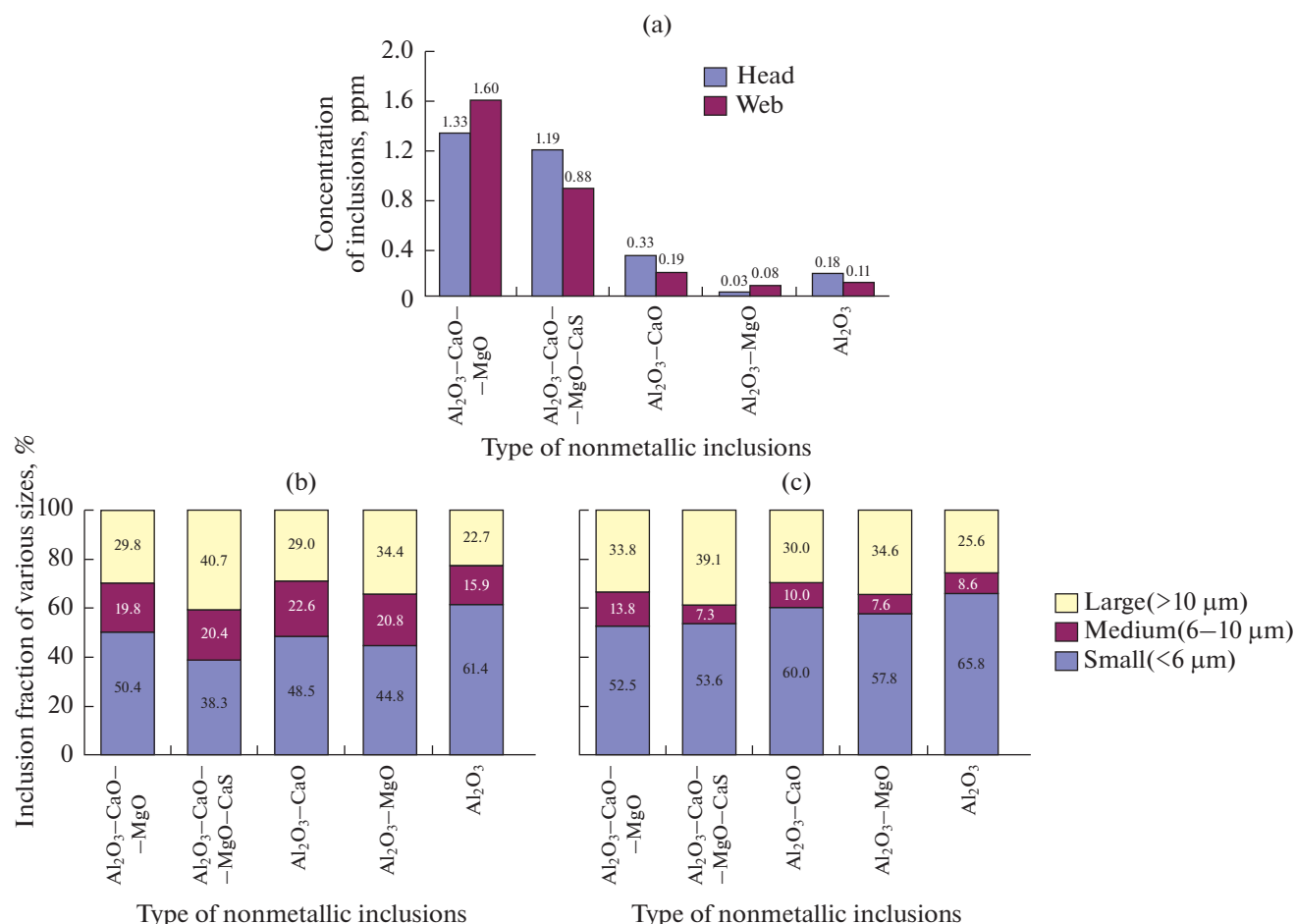


Fig. 4. Alumina inclusion distribution along the rail profile made of E90KhAF steel: (a) relative concentration of inclusions; (b, c) dimensions of inclusions in the head and web of the rail.

sions should be noted. The mentioned inclusions do not significantly affect the rail quality, which is confirmed by the absence of defects detected upon ultrasound testing.

CONCLUSIONS

In summary, the following statement can be made from the study of nonmetallic inclusions in the rails from E76KhF and E90KhAF electro-steel brands in current production: MnS are the most common nonmetallic inclusions. The relative concentration of these inclusions is 30.8–43.4 ppm; in this case, 60–100% of inclusions possess a small (less than 4 μm) size. The revealed high concentration of sulfide inclusions directly correlates with the determined positive sulfur liquation in the considered rail elements. MnS are related to plastic nonmetallic inclusions; therefore, their relatively high concentration should be considered safe for the rail quality, in particular, considering small-inclusion predomination.

Nondeformable silicates SiO_2 (3.4–14.9 ppm) and mixed alumina inclusions of the $\text{Al}_2\text{O}_3\text{--CaO--MgO}$ and $\text{Al}_2\text{O}_3\text{--CaO--MgO--CaS}$ systems (up to 1.6 and 1.2 ppm, respectively) possess relatively high concentration among non-plastic inclusions. The total concentration of mixed alumina inclusions is less than 3.1 ppm, while that of corundum (Al_2O_3) is 0.3 ppm. In this case, 100% of silicate inclusions and a large alumina-inclusion fraction possess a relatively small (less than 4 μm) size. The detected low concentration along with a small size of non-plastic silicate and alumina nonmetallic inclusions have resulted in no effect on the rail quality as confirmed by defect absence upon ultrasound testing.

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