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NATURE DETECTION OF INTERNAL DEFECTS IN RAILROAD RAILS PRODUCED BY EVRAZ ZSMK COMPANY USING ULTRASONIC CONTROL IN MILL FLOW

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The article discusses the nature of defects in railroad rails manufactured by the EVRAZ ZSMK company, using the metallographic and x-ray phase analyses. In addition, a regression analysis of the influence of the rail steel production parameters on the probability of rail rejection is performed. The mechanisms behind the formation of internal defects are reviewed. It is demonstrated that the most characteristic internal defects of rails, causing their rejection during the ultrasonic control, are stratifications with the accumulation of non-plastic and low-melting non-metallic inclusions. The parameters of melting and extra-furnace processing of rail steel affect the probability of specified defects formation in rails.

Keywords: railroad rails; internal defects; ultrasonic control; non-metallic inclusions; stratifications; cracks; rail steel

INTRODUCTION

The last decade witnessed significant progress in the Russian metallurgy in manufacturing rail products, including those associated with the radical modernization of rail production. Despite this, several significant technological problems remain regarding the quality of railroad rails. The high level of rail rejection during the ultrasonic testing in the flow of rail-and-structural steel mills due to some unacceptable internal defects is one of the most significant problems. This rejection, reaching 4 – 5% of the total volume of rail production, leads to a significant increase in their cost and reduces the productivity of rail-and-structural steel mills, improving the quality of rails relevant nowadays.

Notably, the technology of rail steel and rails production has significantly changed in recent years, making the results from the past studies on rail quality inefficient. Therefore, over the past 10 years, EVRAZ ZSMK has recurrently implemented technical solutions with a significant impact on the structure of rails, including changing the technology of rail steel deoxidation (refusal to use aluminum as a deoxidizer) [1, 2], transition into the mass production of rails from the steel alloyed with chromium and steel with a carbon content increased to hypereutectoid values [3, 4], changing the scheme of extra-furnace thermal processing of steel by introducing sequential processing on two ladle-furnace units [5, 6], implementing electromagnetic stirring and "soft reduction" during the continuous casting of steel [7, 8], transition into rail rolling using a continuous group of universal stands instead of rolling in two-roll stands [9, 10], and transition into the differentiated hardening of rails with compressed air instead of bulk hardening in oil [11 – 13].

Based on the above data, the necessary theoretical basis for the development of technical solutions aimed at improving the quality of rails involves obtaining scientific information about the nature of characteristic defects of rails in current production.

This work aimed at studying the nature of the characteristic internal defects of railroad rails, which cause their rejection during the quality control in the flow of rail-and-structural steel mills.

METHODS OF STUDY

The samples of the railroad rails of categories DT350 (E76HF steel) and DT370IK (E90HAF steel) of the current

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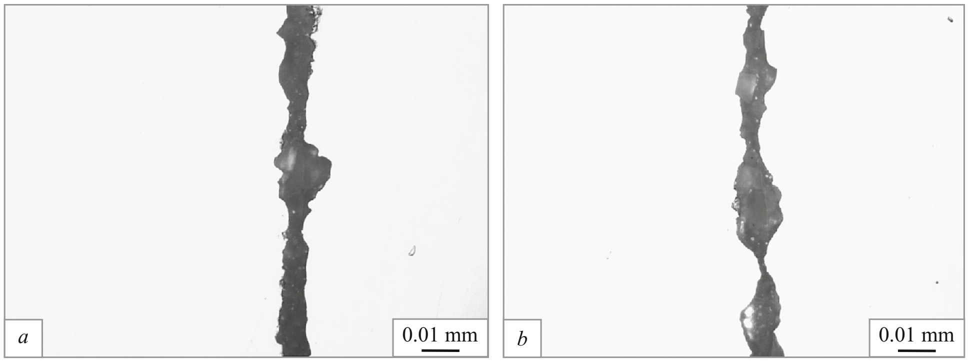

Fig. 1. The fragments of stratification in the web of railroad rails.

production of EVRAZ ZSMK, which were rejected based on the results of ultrasonic quality control of the structure in the flow of the rail-and-structural steel mill, were analyzed.

The nature of the defects causing the rejection was determined using metallographic analysis (OLYMPUS GX-51 light microscope) and x-ray phase analysis (Shimadzu XRD-6000 x-ray diffractometer). Additionally, a regression analysis of the influence of rail steel production parameters on the probability of rail rejection was performed to determine the causes of defect formation. The method of the passive experiment was used, i.e., the analysis of the reports of 500 melts of the E76HF rail steel of the current production of the electric-furnace melting shop of the EVRAZ ZSMK company. Simultaneously, the reproducibility of the results was ensured by analyzing two samples of melts, i.e., those with an increased and a reduced level of rejection.

RESULTS AND DISCUSSION

Based on the results of the metallographic studies of rail samples rejected during ultrasonic testing, the characteristic internal defects were revealed to be located in the rail web and can be categorized into two types.

Type 1 defect represents relatively large stratifications (up to 5 mm or more in length), characterized by significant accumulations of non-metallic inclusions in their location (Fig. 1). Such internal defects are the most common (85% cases) reason for rail rejection.

The x-ray phase analysis (Fig. 2) determined that at the location of such defects, there are accumulations of non-plastic non-metallic inclusions of sillimanite Al_2SiO_5 (33% Al; 18% Si; and 49% O), silicon oxide SiO_2 (47% Si and 53% O),

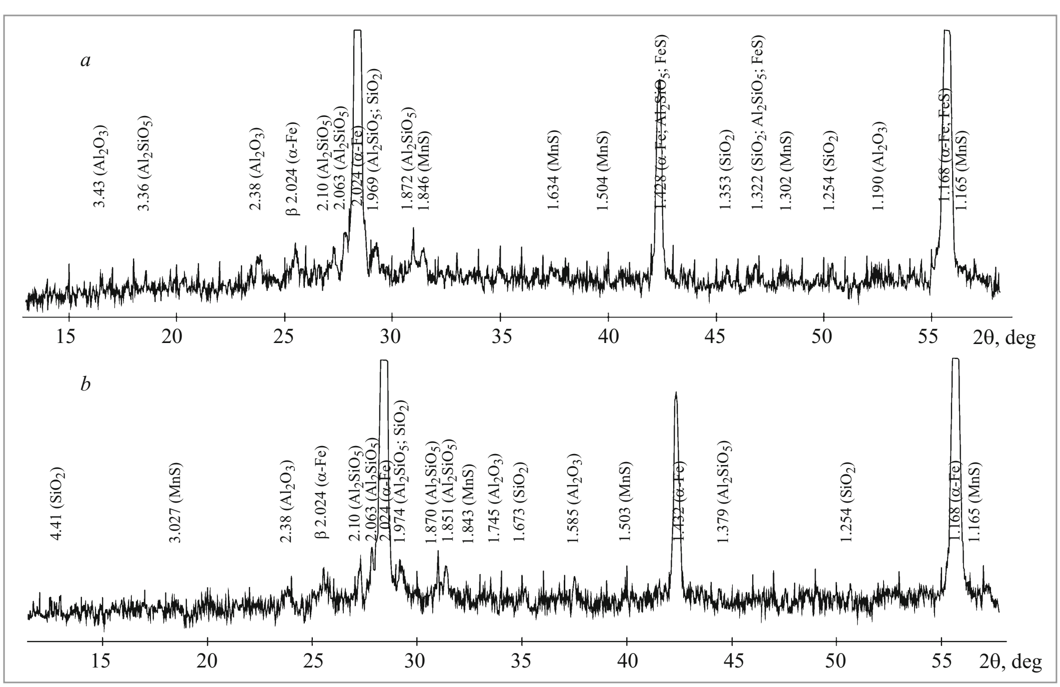

Fig. 2. Sections of diffraction patterns from the area of stratification localization in the rail web at the beginning (*a*) and end (*b*) of the defect.

TABLE 1. The Dimensions of Non-Metallic Inclusions in Railroad Rails

Non-metallic inclusions	Maximum inclusion score		
	Head	Web	Flange
Non-deforming silicates	2a/2b	4a/4a	3a/3b
Sulfides	3a/3b	1a/–	–/–
One-dimensional oxides	1b/1a	2a/1a	–/–
Plastic silicates	3a/3b	1b/2a	1a/–
Aluminum nitrides	2a/1b	1b/2b	3a/3b

Note. The numerator presents the maximum score of inclusions for the rejected rails, and the denominator indicates the same for the proper rails (GOST 1778–70).

TABLE 2. Statistical Characteristics of the Functions and Parameters of Optimization for the Rejection Analysis of Railroad Rails for Internal Defects

Parameter	Scope of application	Mean value	Mean square deviation
Ultrasonic testing rejection, %	0 – 38.5	27.3	5.6
Sulfur content at EAF outlet, %	0.019 – 0.078	0.031	0.005
Duration of argon blowing at LFU, min	7.2 – 268	76.7	16.8
Basicity of LFU slag	1.2 – 5.1	2.6	0.38
Hydrogen content in steel after vacuum pumping, ppm	0.6 – 1.5	0.96	0.16
Copper content in finished steel, %	0.06 – 0.16	0.094	0.014
Tin content in finished steel, %	0.003 – 0.014	0.005	0.001

Note. Melt samples with an increased level of rejection are presented.

corundum Al_2O_3 (53% Al and 47% O), and the low-melting inclusions of iron sulfide FeS. In addition, significant alabandite MnS inclusions (67 – 70% Mn and 33 – 30% S) were revealed.

The analysis of non-metallic inclusions from the location area of type-1 defects, based on the standard semi-quantitative method following GOST 1778–70 demonstrated that the composition and concentration of inclusions do not differ significantly from the proper rails of the current production (Table 1).

According to the data obtained, the internal defects of type 2 consist of relatively small cracks (up to 1 mm long) elongated in the direction of rolling (Fig. 3). In this case, contrary to the defects presented in Fig. 1, no accumulations of non-metallic inclusions are observed the localized region.

TABLE 3. Statistical Characteristics of the Functions and Optimization Parameters for Rejection Analysis of Railroad Rails for Internal Defects

Name	Scope of application	Mean value	Mean square deviation
Ultrasonic testing rejection, %	0 – 12.3	3.1	1.8
Sulfur content at EAF outlet, %	0.018 – 0.045	0.026	0.004
Duration of argon blowing at LFU, min	43 – 252	85.1	11.2
Basicity of LFU slag	1.8 – 4.9	2.6	0.27
Hydrogen content in steel after vacuum pumping, ppm	0.7 – 1.2	0.83	0.09
Copper content in finished steel, %	0.05 – 0.13	0.081	0.011
Tin content in finished steel, %	0.002 – 0.011	0.004	0.001

Note. Melt samples with a reduced level of rejection are provided.

Such defects are detected in approximately 15% of the rejected railroad rails.

Based on the statistical studies conducted on a sample of melts with an increased rail rejection (Table 2), a significant effect on the rejection of rails for the internal defects in the technological parameters of rail steel production was established, including the sulfur content at an electric arc furnace (EAF) outlet, slag basicity and duration of argon blowing during the extra-furnace processing of steel in a ladle-furnace unit (LFU), and the contents of hydrogen, copper, and tin in the finished steel. The increased content of these elements in steel increases the rejection of rails; increased slag basicity and duration of inert gas blowing during processing at an LFU reduces the probability of internal rail defects. Based on the statistical processing of data in the reports of 500 melts of the E76HF rail steel of the current production using the standard method of multiple regression analysis, an equation was obtained to determine the proportion of the rejection of rails B_{inc} (%) during the ultrasonic testing on a sample of melts with an increased level of rejection:

$$B_{inc} = 20.5 + 30.23[S]_{out} - 0.03D_{blow} - 1.16Bas + 7.70[H] + 31.12[Cu] + 210.86[Sn], \quad (1)$$

where $[S]_{out}$ is the sulfur content in the steel at the EAF outlet (%), D_{blow} is the duration of blowing during processing at the LFU (%), Bas is the slag basicity during processing at the LFU (%), [H] is the hydrogen content in steel after vacuum pumping, (ppm) [Cu] is the copper content in the finished steel (%), and [Sn] is the tin content in the finished steel (%).

Studies conducted on a sample of melts with a reduced level of rail rejection (Table 3) confirmed the reproducibility

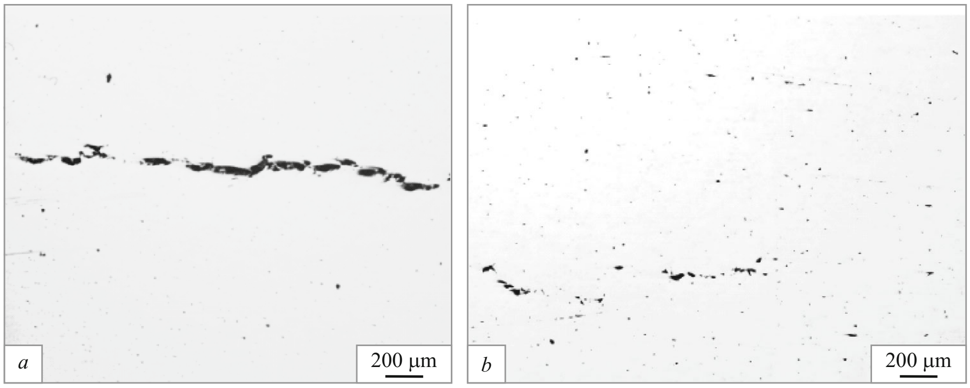

Fig. 3. The initial (*a*) and final (*b*) areas of an internal crack formed in the web of railroad rails.

of the results obtained, and the following equation was obtained:

$$B_{red} = 0.4 + 25.12[S]_{out} - 0.02D_{blow} - 0.84Bas + 4.1[H] + 23.2[Cu] + 155.61[Sn], \quad (2)$$

where B_{red} is the rejection of rails during the ultrasonic testing on a sample of melts with a reduced level of rejection, %.

Notably, the regression equations (1) and (2) establish the relationship between the production parameters of rail steel and the rejection of rails, regardless of the defect type (Figs. 1 and 3) because assigning a defect to a specific type according to the accepted conditional classification of an array of melts, required for statistical analysis, is not technically feasible.

Simultaneously, based on the physical meaning, the defects formed as stratifications with the accumulation of non-metallic inclusions (Fig. 1) are significantly affected by the sulfur content in the steel at the EAF outlet, slag basicity, and the duration of argon blowing during processing at LFU. Therefore, an increase in the sulfur content in steel increases the non-metallic sulfide inclusions in the rails. Conversely, an increase in the slag basicity and the duration of blowing during processing at LFU reduces the concentration of non-metallic inclusions via their assimilation by the slag.

The influence of the increased contents of copper, tin, and hydrogen in steel on the increased rejection of rails is associated with the formation probability of type-2 defects, namely internal cracks without the accumulation of non-metallic inclusions (Fig. 3).

According to generally accepted ideas, the mechanism of copper and tin influence, increasing the formation of undesirable defects in steel rolled stock, is associated with the tendency of these impurities to segregate in the intergranular spaces and at a low-melting temperature [14, 15]. An increase in the total concentration of the specified residual impurities in steel leads to a proportional increase in their content at the grain boundaries, determining the metal embrittlement at hot rolling temperatures and increasing the probability of defects. Notably, the results qualitatively and quantitatively coincide with those of numerous other studies conducted about rolled metal products for various purposes. Therefore, the upper limit of changes in the contents of copper and tin range in the sample under consideration (Tables 2 and 3) corresponds to the threshold concentrations, and after reaching them, according to Refs. [16 – 19], the steel quality significantly deteriorates.

It is well known that an increase in the hydrogen content increases the formation probability of internal defects in the form of flakes. Notably, in the considered sample, the upper limit of the hydrogen content in steel (1.5 ppm and 1.2 ppm in Tables 2 and 3, respectively) is lower than the concentrations recognized as "hazardous" by most researchers (over 2.0 – 2.5 ppm). In this case, the significant impact of other factors downshifting the limits of the permissible hydrogen content is relevant. Based on the application of the technology of differentiated hardening of rails, such factors should primarily include significant internal stresses [20].

In general, the results of the metallographic and statistical studies indicate the steelmaking origin of the characteristic internal rail defects, resulting in their rejection during the ultrasonic quality control of the structure. Although for the multiple regression Eqs. (1) and (2), the explained total relative degree of influence of the parameters of the metallurgical treatment is 75% and 69%, respectively, while the remaining 25% and 31% of the unexplained variation cannot be attributed to the influence of the rolling stage parameters based on the results of metallographic studies. In this case, the unexplained share of influence is associated with the steelmaking process parameters, which are not registered instrumentally during the rail steel production and the impossibility of separating defects by types in statistical analysis.

CONCLUSIONS

1. Based on a complex study combination conducted using the metallographic, x-ray phase, and statistical analyses, the nature and mechanisms of characteristic internal defects formation of railroad rails and the reasons for their rejection during the ultrasonic testing have been established.

2. Typical internal defects can be conditionally divided into two types, namely stratifications of relatively large sizes (up to 5 mm long or more) with the accumulation of non-plastic and low-melting non-metallic inclusions in the localized area and relatively small cracks (up to 1 mm long) without a significant accumulation of non-metallic inclusions. In this case, characteristic defects, regardless of their type, are located in the web of rails.

3. Typical internal rail defects arise from the steelmaking process. In this case, the probability of stratifications is essentially determined by the sulfur content in the steel at the outlet of the melting unit and its extra-furnace treatment parameters at the LFU; additionally, the probability of internal crack formation is determined by the content of hydrogen, copper, and tin in steel.

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