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STUDIES OF STRUCTURAL FEATURES OF JOINTS OF RAILS OF R260MN GRADE IN FLASH-BUTT WELDING

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ABSTRACT

The properties and features of the microstructure of joints of the rail steel of R260MN grade with an elevated content of manganese produced by flash-butt welding with pulsating flashing were investigated. The formation of martensitic-austenitic structures due to non-uniform distribution of austenitic stabilizing manganese is shown. A number and sizes of isolated martensitic-austenitic structures is insignificant and does not critically affect the joint test results. The control of the segregation inhomogeneity of manganese is achieved by improving the metallurgical process.

KEYWORDS: flash-butt welding, rails of R260MN grade, hardness distribution, martensitic-austenitic structures, segregation inhomogeneity

INTRODUCTION

An increase in speed and load capacity of trains requires improvement of service characterisitcs of the rails. The possibilities of heat treatment of pearlite rail steels are limited. One of the ways to solve this problem is to improve the chemical composition of rail steel by changing the ratio of basic elements (carbon, manganese, silicon) and additional alloying. In pearlite rail steel of M76 grade, the content of carbon is estimated in the amount of 0.69–0.82 %, manganese — 0.75–1.05 % and silicon — 0.18–0.4% (Table 1). Carbon, manganese and silicon increase the resistance of overcooled austenite. The pearlite transformation occurs in the area of lower temperatures with the formation of lamellar structures with a high dispersion and, accordingly, strength. Vanadium, titanium and niobium microalloying provides a dispersion hardening of pearlite with a simultaneous decrease in the interlamellar distance and refinement of the microstructure [1, 2]. In the rail steels of grades E76F, K76F, M76F and E76T, K76T, the service characteristics are noticeably increased. The known are pearlite rail steels of grades M76KhSF and E76KhSF, where as alloying elements vanadium and chromium were used. Alloying with chromium improves the hardness of rails that increases their wear resistance.

In the course of works on the improvement of rail steels, the possibilities of increasing carbon content over eutectoid (> 0.82 %) was considered. The content of carbon in such rails of grade AREAL 136HE-370 produced by the Japanese corporation Nippon Steel & Sumitomo metal group amounts to 0.99–1.0 %. In [3], we showed that in flash-butt welding (FBW) of rails of hypereutectoid composition, a redistribution of carbon in the microstructure of joints occurs. The decay of hypoeutectoid carbide phase is accompanied by the formation of carbon inclusions. The latter causes a decrease in carbon content in the matrix and the formation of the structure of the joint similar to that of pearlite rails of the hypoeutectoid composition. It should be noted that in the area of coarse grain in the joint, the hardness as compared to the base metal is slightly reduced and amounts to *HV* 3900 MPa. The reason for this is the lack of hypoeutectoid carbide phase on the boundaries of primary austenitic grains.

One of the directions of improving the wear resistance of pearlite surface hardened rails was an increase in the content of manganese, which increases by calcination. These include rails of R260MN grade, the upper limit of the content of manganese is 1.34 wt.% (Table 1).

At the PWI, the technology of flash-butt welding of high-strength rails R260 and R350NT with pulsating flashing was developed and successfully used that provides stable mechanical properties at the level of the base metal. According to the thermokinetic curves, the decay of austenite in the thermodeformational conditions of FBW of the mentioned rail steels, the formation of martensite in the joints does not occur [4]. The microstructure of the joints is pearlite, which differs in different areas of HAZ with a degree of dispersion. The properties of joints meet the requirements of European standards [5, 6].

Using previous developments after optimization of the mode, welding of the batch of rails of R260MN(60E1) grade produced by the metallurgical company ArcelorMittal was carried out. The tests of welded joints on fatigue, static bending and hardness distribution carried out at the Rails Expertise Centre SNCS (France) recognized that the parameters and test results meet the requirements of the European

Table 1. Chemical composition of rail steels (wt.%)

	C	Mn	Si	P	S	Cr	Al	Ni	Ti	V
M76	0.71–0.82	0.75–1.05	0.25–0.45	≤0.035	≤0.04	–	–	–	–	–
AREAL 136 HE-X (NipponSteel, Japan)	0.99–1.00	0.69–0.71	0.50–0.52	≤0.030	–	0.21–0.22	≤0.005	–	–	0.04
R260	0.60–0.82	0.65–1.25	0.13–0.60	<0.03	<0.03	<0.15	<0.004	<0.1	<0.025	<0.03
R260MN standards of manufacturer ArcelorMittal, Spain	0.66	1.34	0.27	0.018	0.008	0.03	0.001	0.22	0.22	0.04
Rail R260MN(60E1) which was investigated	0.75	1.45	0.28	0.017	–	0.35	–	0.03	–	–

standard [7]. At the same time, a small number of structural components were found in the microstructure of joints of some batches of rails, whose hardness is ~ 776–900 *HV* 0.1, which does not meet the requirements of the European standard.

The aim of this work was to find the features of the microstructural state of HAZ of joints of rails of R260MN(60E1) grade.

PROCEDURE AND EQUIPMENT

The joints of rails of R260MN(60E1) grade with the content of manganese of 1.45 wt.% (Table 1) were considered. The joints were produced in the K1000 machine for flash-butt welding with pulsating flashing. After optimization of the mode, the recommended parameters should be within the following ranges: welding time — 70–90 s, welding current — 360–390 A, tolerance for flashing — 10–14 mm, value of the upsetting — 11–14 mm.

The macrostructure of the joints was detected in accordance with the requirements of GOST R51685–2013 on a full-profile template, cut out in the transverse direction. The etching of polished specimens was carried out with an aqueous out polished of chlorine iron.

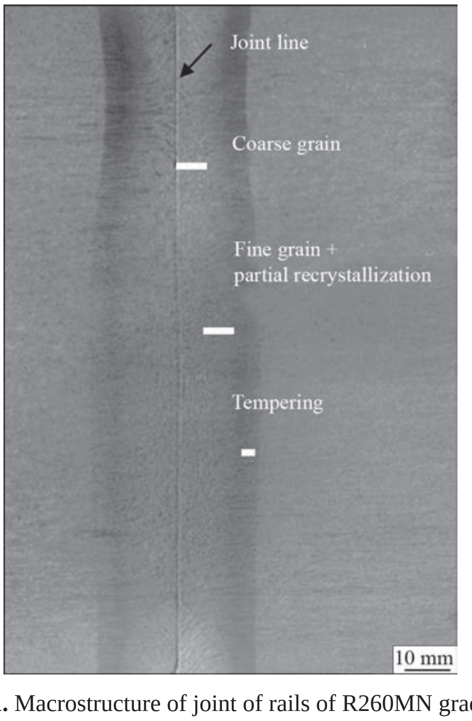


Figure 1. Macrostructure of joint of rails of R260MN grade

Metallographic examinations were performed in the optical NEOPHOT 32 microscope equipped with a digital camera. Microstructure was revealed by etching of preliminary polished specimens in a 4 % alcohol HNO_3 solution. To analyse the microstructure and determine the chemical composition of the structural components, the Auger-microprobe JAMP 9500F of JEOL Company (Japan) and X-ray energy dispersion spectrometer JNCA Penta FET x3 of Oxford Instrument Company were used. The energy of the primary electron beam was 10 keV at a current of 0.5 nA for SEM and EPMA methods. Before examinations, the surface of the specimens was subjected to cleaning directly in the analysis chamber of the device by etching with argon ions Ar+ with the energy of 1 keV during 10 min. The rate of etching over the reference SiO_2 specimen was 4 nm/min. The vacuum in the analysis chamber was within $5\cdot10^{-8}$–$1\cdot10^{-5}$ Pa.

The Vickers hardness was measured in the hardness meter NOVOTEST TC-GPB with a load of 292.4 N (30 kg). The distribution of hardness in the joint was investigated at a distance of 5 mm from the rolling surface of the rail.

RESEARCH RESULTS AND DISCUSSION

Metallographic examinations of joint macrostructure showed (Figure 1) that the HAZ is symmetric relative to the weld line. Its width was 30–40 mm and is within the limits admitted by the European standard [7] – 20–45 mm. The macrostructure of the HAZ is typical for similar joints of pearlite rail steels and consists of a weld zone, to which the area of coarse grain is adjacent. Further, the areas of small grain, partial recrystallization and tempering are located. Defects in the structure are absent.

According to the distribution curve (Figure 2), the hardness in the joint grows in the area of coarse grain and reduces in the tempering area. The level of deviation from the hardness of the base metal meets the requirements of the European standard: the maximum hardness should not exceed the hardness of the base metal by 60 *HV* 30, the minimum one should not be lower than the hardness of the base metal by 30 *HV* 30 [7]. Examinations of the joint microstructure showed that the base metal is hardening sorbite with some hypoeutectoid ferrite on the boundaries of primary austenitic grains (Figure 3). The contamination with nonmetallic inclusions is insignificant and corresponds to the grain size number 3–4 according to GOST 1778–70. Nonmetallic inclusions are represented by sulfides of a globular shape or which are elongated along the rolling direction with embeddiments of oxides and carbonitrides. Single globular inclusions of oxides are observed.

In the HAZ, microstructure represents mainly a lamellar pearlite of varying degree of dispersion (Figure 4). The size of the interlamellar distance in pearlite affects the values of hardness: reduction in the interlamellar distance leads to an increase in hardness. The exception is the tempering area. The microstructure of the tempering area is granular sorbite formed as a result of coagulation of carbide plates. Along the joint line in the band with a width of ~ 200 μm, primary austenitic grains are edged by the precipitations of hypoeutectoid ferrite. The size of primary austenitic grains corresponds to the size number 3–4 on the ASTM scale.

A characteristic feature of the joint microstructure is the formation of light areas in the HAZ, which are well distinguished against the background of pearlite.

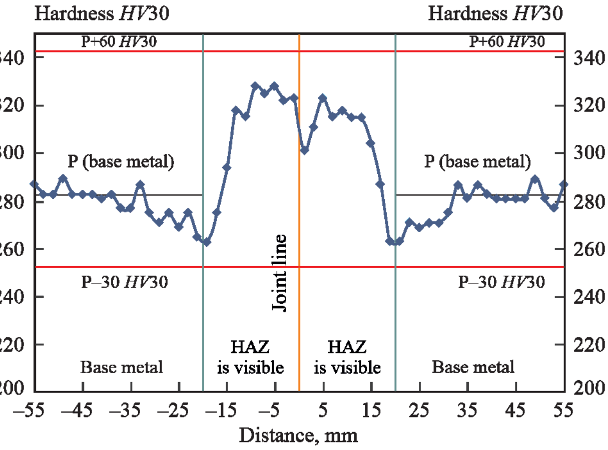


Figure 2. Distribution of hardness in the joint of rails of R260MN grade

Their size varies from tens to hundreds of microns. These structural components are observed along the rolling bands (Figure 5, *b*) and in the form of volumetric formations of arbitrary shape (Figure 5, *c*) at a distance of 1–5 mm from the joint line. Examinations in the electron microscope revealed similar structural components also on the boundaries of primary austenitic grains (Figure 5, *d*). The presence of acicular and lens-like inclusions within these structures with a hardness of 901–928 *HV* 0.1 and 762–776 *HV* 0.1 respectively gave reason to claim that these structural components represent residual austenite with decay products, in particular, acicular martensite, so-called martensitic-austenitic structure.

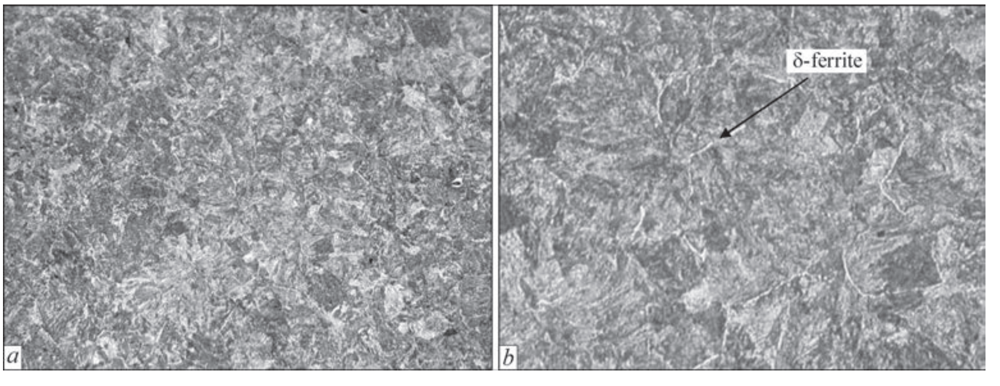


Figure 3. Microstructure of base metal of the rail of R260MN(60E1) grade: *a* — ×100; *b* — ×1000

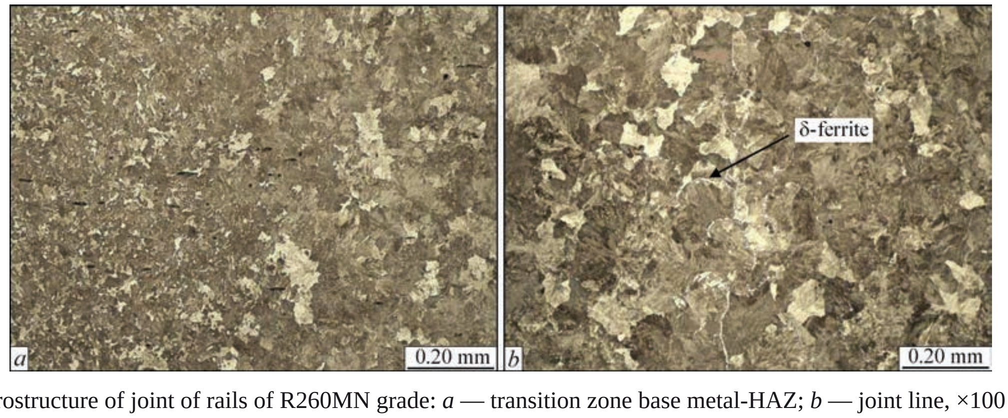


Figure 4. Microstructure of joint of rails of R260MN grade: *a* — transition zone base metal-HAZ; *b* — joint line, ×100

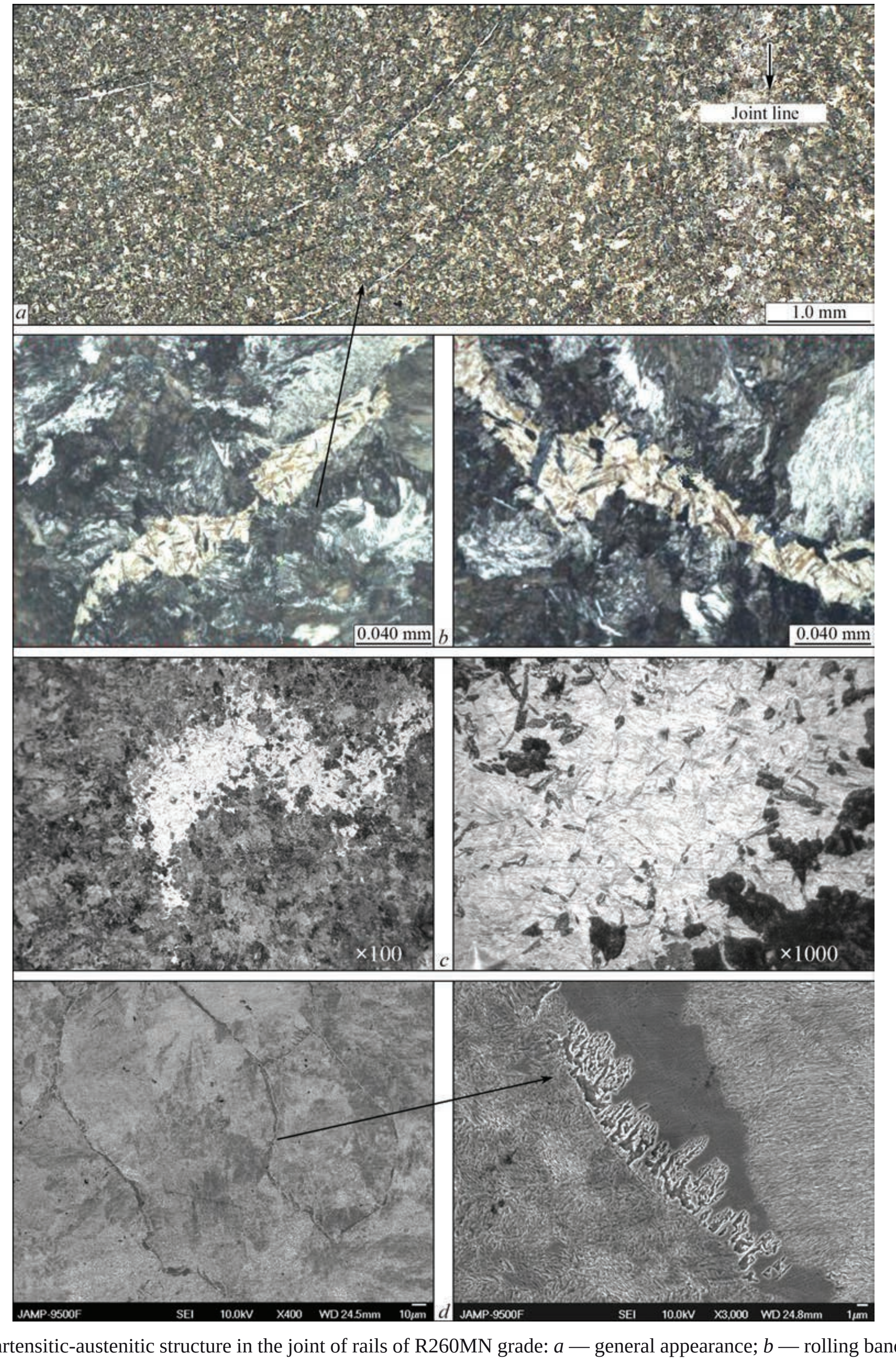


Figure 5. Martensitic-austenitic structure in the joint of rails of R260MN grade: *a* — general appearance; *b* — rolling bands; *c* — volumetric formations; *d* — boundaries of primary austenitic grains

While studying microstructure in the scanning electron microscope, the area presented in Figure 6, *a*, was considered. It was found that lens-like inclusions in residual austenite are bainite (Figure 7). Bainite is formed both in the volume of residual austenite (Figure 7, *a*) as well as on its boundary with the matrix (Figure 7, *b*). The features of bainite morphology and carbon distribution between ferrite, carbides and adjacent residual austenite are presented in Figure 7, *b*. Analysis of the structure parameters showed that the interlamellar distance in the pearlite of the matrix varies within 0.102–0.123 μm (Figure 6, *c*). This is commeasurable with the parameters of the structure of ordinary rail joints — 0.8–0.12 μm [8]. It should be noted that in the microstructure, there are areas with a higher degree of pearlite dispersion, in

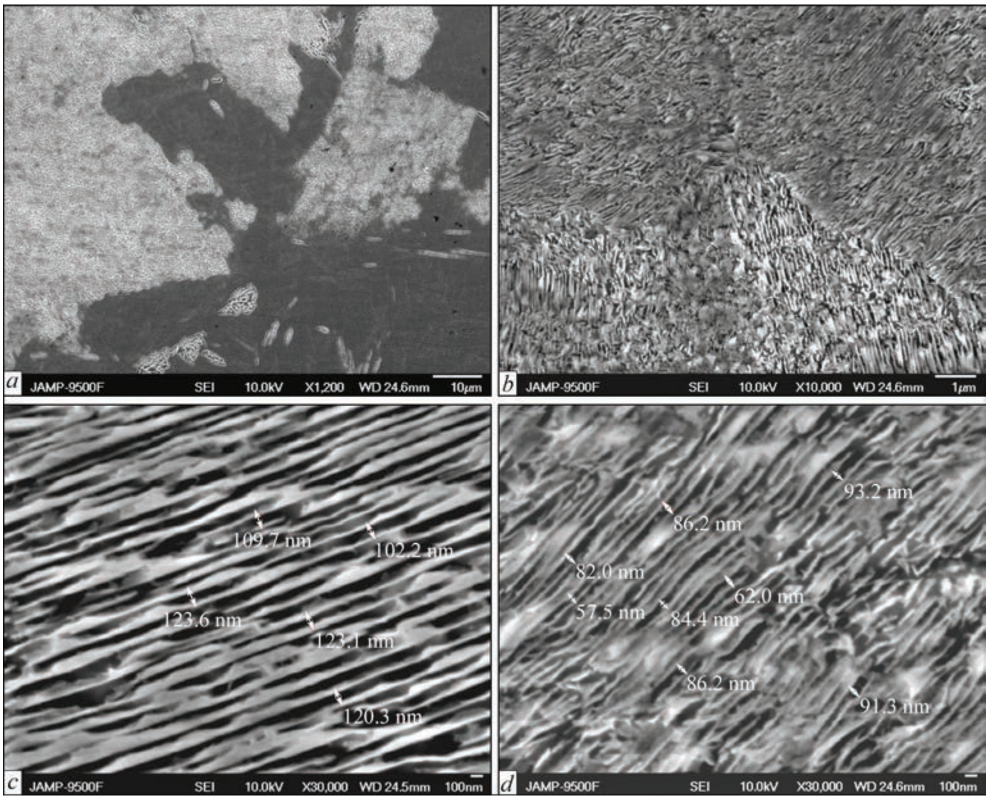
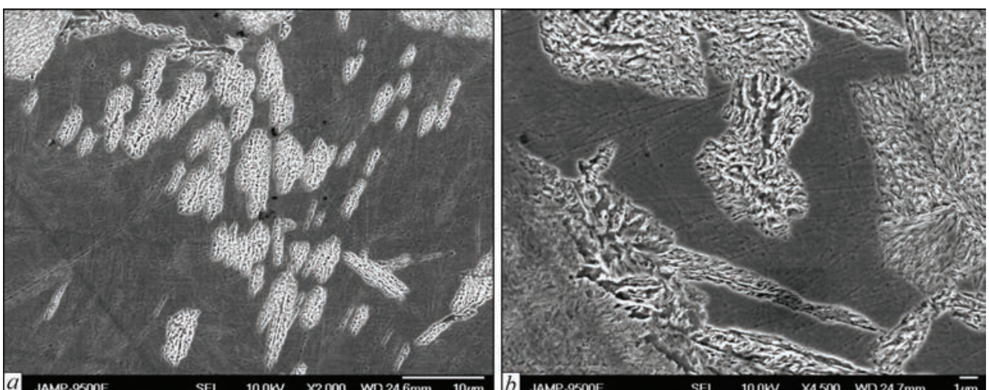


Figure 6. Pearlite in the microstructure of joints of rails of R260MN grade: *a* — area of analysis; *b* — matrix; *c*, *d* — results of measuring interlamellar distance



	C	Si	Mn	Fe	
1	12.79	0.58	1.90	84.73	Carbide
2	16.87	0.50	3.08	79.55	Carbide
3	4.98	0.66	2.13	92.23	Ferrite
4	8.45	0.50	2.94	88.11	Austenite

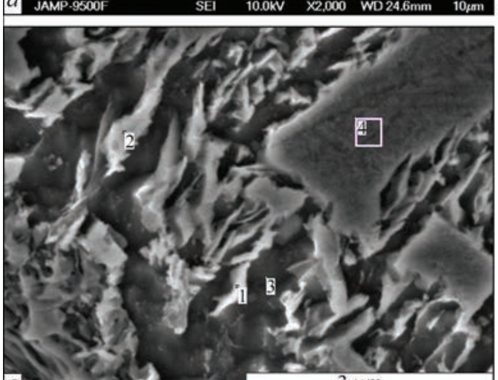
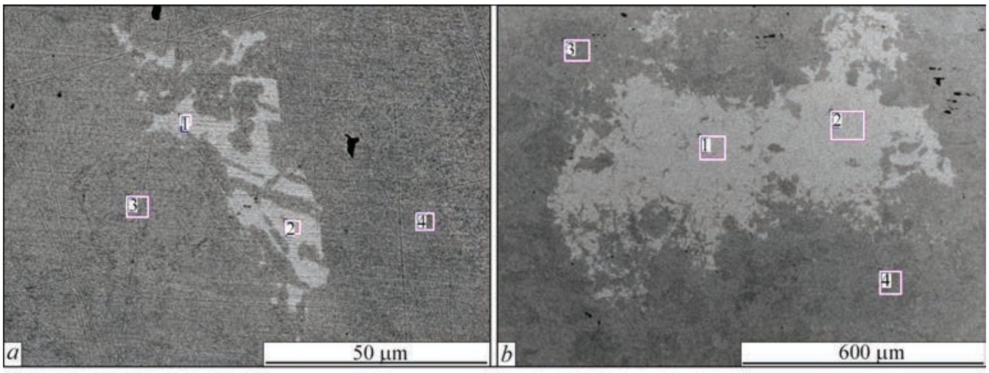


Figure 7. Bainite in the microstructure of joints of rails of R260MN grade: *a* — in the volume of residual austenite; *b* — on the boundary of residual austenite and matrix; *c* — results of X-ray microanalysis of structural components (at.%)



	C	O	Si	Mn	Fe
1	4.98	0.15	0.36	2.63	91.89
2	3.41	0.74	0.55	2.34	92.96
3	4.73	1.06	1.08	1.62	91.50
4	5.74	1.46	0.48	0.76	91.56

	C	O	Si	Mn	Fe
1	5.56	0.69	0.75	2.25	90.75
2	6.51	1.00	0.43	2.22	89.85
3	5.50	0.84	0.43	1.39	91.84
4	6.04	0.34	0.55	1.42	91.65

Figure 8. Results of X-ray microanalysis of chemical inhomogeneity in the region with martensitic-austenitic structures (at.%)

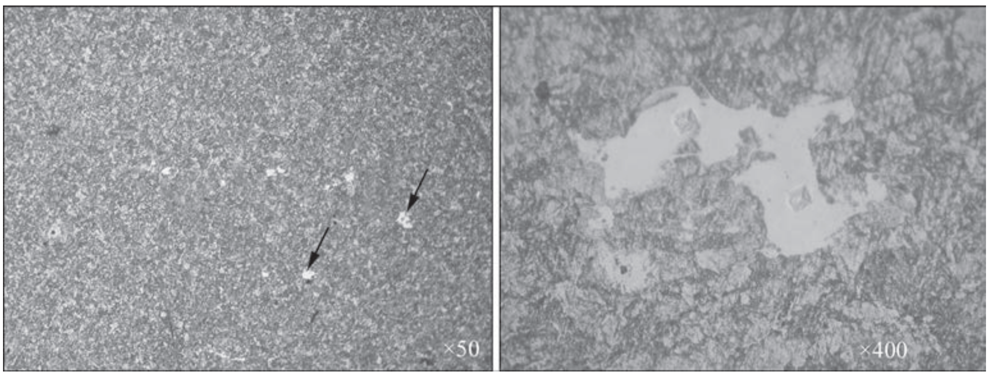


Figure 9. Microstructure of base metal after heat treatment on the mode: T = 850 °C, exposure is 4 min, cooling in the air

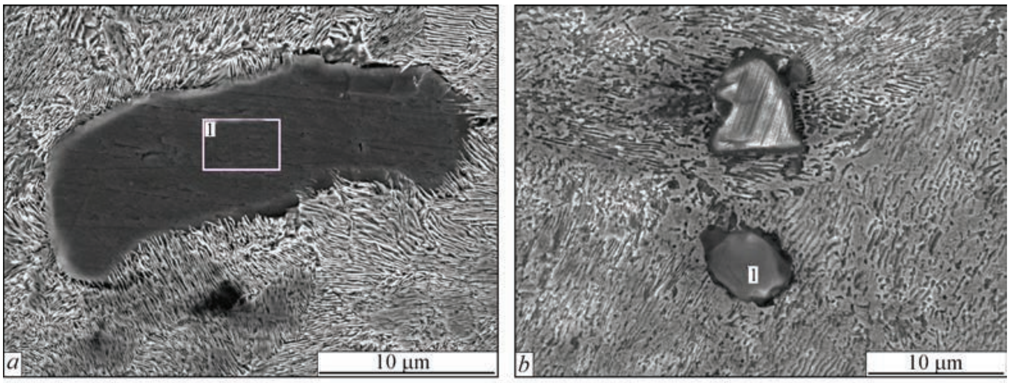
particular, on the boundary with residual austenite — 0.057–0.093 μm (Figure 6, *d*).

It is known that under other equal conditions, the nature of the decay of austenite during cooling is affected by the chemical composition [9]. The lack of systematic formation of residual austenite areas gives grounds to suggest about the chemical inhomogeneity of the joint metal. In the comparative analysis of the chemical composition of the matrix and residual austenite, an increased content of manganese in the latter was noted: 2.63–2.34 and 1.62–0.76 at.% (Figure 8, *a*) and 2.25–2.22 and 1.42–1.49 at.% (Figure 8, *b*), respectively. This is agreed with the fact that manganese is an austenite stabilizing element. The inhomogeneity of the distribution occurs due to the tendency of manganese to dendritic and zonal segregation during crystallization of steel castings [10]. The initial inhomogeneity is to some extent preserved after rolling and heat treatment, although it is converted. In the metal it is observed near the separate volumes enriched with manganese of the rolling band.

The effect of heat treatment on the possible transformation of martensitic-austenitic structures was studied. The following modes of the specimen heat treatment were used: T = 850 °C, t = 4 min; T = 920 °C, t = 4 min; cooling in the air. The comparative analysis of microstructures showed that normalization does not eliminate martensitic-austenitic structures. Moreover, martensitic-austenitic structures were manifested in the base metal (Figure 9). Obviously, the mentioned modes do not affect the inhomogeneity of manganese distribution. The elimination of inhomogeneity requires a homogenization tempering, which is hardly probable in the conditions of rail production.

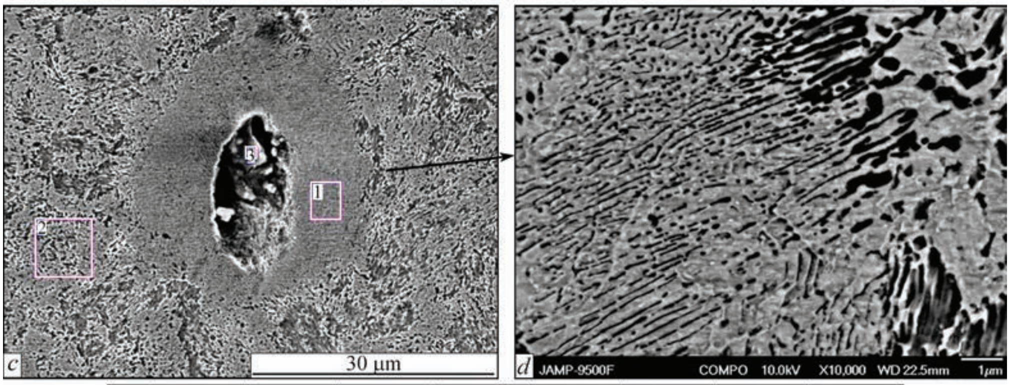
It is known [11] that the degree of inhomogeneity depends mainly on the rate of cooling of castings in the production of steel. Probably, to eliminate the nonuniform distribution of manganese, it is necessary to control and improve the metallurgical process.

It is interesting to note about the inhomogeneity of the joint microstructure caused by nonmetallic inclusions. Thus, if manganese sulfides and oxides do not affect the structure formation (Figure 10, *a*, *b*), then, around complex nonmetallic inclusions, whose composition includes chromium oxicarbides, an area with a low carbon content is observed (Figure 10, *c*). The linear size of the area corresponds to the size of nonmetallic inclusions and amounts to ~100 μm. Re-



C	Si	S	Mn	Fe
1.01	0.05	46.40	44.87	2. 68

	C	O	Mg	Al	Ti	Mn	Fe
1	6.0	62.07	3.08	23.99	0.41	7.96	1.48



	C	N	O	S	Si	Cr	Mn	Fe
1	7.04	0.12	4.77	0	0.43	0.36	1.26	86.02
2	12.19	0.51	5.05	0.12	0.42	0.18	1.26	80.28
3	18.73	1.77	37.15	30.28	0	7.32	2.74	2.03

Figure 10. Nonmetallic inclusions in the steel of R260MN grade and the results of X-ray microanalysis of chemical composition of structures (at.%): *a* — manganese sulfide; *b* — complex oxides; *c* — complex nonmetallic inclusions with chromium content; *d* — transition zone

duction in carbon content shifts the transformation of austenite into a region of higher temperatures. This finds its reflection in the microstructure (Figure 10, *d*).

CONCLUSIONS

1. Formation of joints of the rails of R260MN grade with an elevated content of manganese in FBW as compared to the rails of R260 grade is satisfactory and similar to that one observed in typical pearlite rails.

2. In the joints of the rails of R260MN grade, there may be the formation of martensitic-austenitic structures along the rolling bands, on the boundaries of the primary austenitic grains, and also in the form of volumetric formations of an arbitrary shape at a distance of 1–5 mm from the joint line. The appearance of martensitic-austenitic structures is caused by the inhomogeneity of the distribution of an austenitic stabilizing manganese in the metal of the rails, which is prone to dendritic and zonal segregation during crystallization of steel castings. The presence of martensitic-austenitic structural components does not meet the requirements of the European standard for microstructure.

3. Normalization does not eliminate the inhomogeneity of manganese distribution in the joints of the rails of R260MN grade. Preventing the inhomogeneity of manganese distribution and the formation of martensitic-austenitic structural components in the microstructure requires the control and improvement of the metallurgical process in steel production.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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