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FEATURES OF MICROSTRUCTURE OF JOINTS OF HYPEREUTECTOID AREAL-136HE-X RAIL STEEL IN FLASH-BUTT WELDING

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ABSTRACT

The microstructure and properties of butt joints of rails from hypereutectoid Areal 136HE-X steel produced by the flash-butt welding technology were investigated. It was found that under thermal and deformation conditions of welding, carbon redistribution is accompanied by the formation of particles in the microstructure with carbon precipitation and a decrease in carbon content in the matrix. A number of particles grows in the direction of the butt and their highest concentration is observed in the near-contact layer. According to the distribution of hardness in the zone of a coarse grain, in contrast to the butt joints of hypoeutectoid rails, as compared to the base metal, the hardness is slightly reduced — *HV* 3900 MPa and *HV* 4000 MPa, respectively. This is caused by the absence of free carbides in the microstructure. The features of microstructure do not significantly affect the results of tests on static bending and meet the requirements of domestic and European standards.

KEYWORDS: flash-butt welding, hypereutectoid rail steels, carbon redistribution, hardness distribution, static bending

INTRODUCTION

The complex conditions of operation of rolling stock of railway transport require the improvement of strength characteristics of both the rails and their joints. This was the reason for the start of numerous developments, the aim of which was to produce rail steels resistant to an increased axial load on the track and cyclic loads caused by an increased speed of movement. The possibilities of heat treatment of hypoeutectoid rail steels are exhausted. As one of the ways to improve the quality of rails, the use of hypereutectoid steels with a carbon content of more than 0.8 % is considered. It is envisaged to increase wear resistance due to carbide structural components on the boundaries of primary austenitic grains.

During construction of railway tracks, the most common technological process of joining rails is flash-butt welding (FBW) [1]. FBW of rails is fully automated and used worldwide as a method that provides a high quality and efficiency of the process. An increase in carbon content in rail steel required the improvement of FBW technology. It is known about the works [2, 3] on the development of methods and optimization of conditions for FBW of hypereutectoid rails, which were conducted by Nippon Steel & Sumitomo Metal Corporation (Japan). The choice of conditions was carried out with taking into account the comparison of the distribution of hardness with the nature of abrasive wear of metal within a joint.

In Ukraine, FBW of rails is performed by using stationary and mobile machines of the PWI of the NASU. To weld rails with a hypereutectoid carbon content, certified programs of pulsating flashing are used, according to which the adjustment of heat input is carried out by changing the duration of flashing and values of welding current [4, 5].

Hypereutectoid steels contain carbon in an amount from 0.8 to 2.14 %. Their structure represents a hardening sorbite with the precipitations of carbides on the boundaries of primary austenitic grains, the presence of which in the structure increases hardness and wear resistance [6]. An increase in carbon content in rail steels is limited by the ability to form a dangerous carbide network.

In equilibrium conditions, carbon in steel can be in a solid solution based on α- and γ-iron, in the composition of carbides, in the clusters of dislocations, on interphase and intraphase boundaries. Due to a high diffusion mobility at high temperatures, in the process of thermal and thermomechanical treatment, redistribution of carbon is possible. The problem of thermodynamics and the mechanism of decay of cementite and accelerated carbon transfer to defects of the structure during plastic deformation is considered in the monograph [7]. Redistribution of carbon between the structural components of steel, as well as the exit of the structure to defects in the conditions of high temperatures and plastic deformation is considered in the work [8]. The study of the evolution of the structure showed that in martensitic steel, an increase in carbon on defects in the structure at its reduction in α-iron at the same time. In steel with a bainite structure, the amount of carbon increases in α-iron, at the same time

Table 1. Chemical composition of rail Areal 136 HE-X steel (wt.%)

Element	C	Mn	Si	V	Ti	Cr	P	Al	S
According to the certificate	0.99–1.00	0.69–0.71	0.50–0.52	–	–	0.21–0.22	–	0.005	0.02
According to the results of spectral analysis	0.97	0.69	0.49	0.01	0.008	0.21	0.012	≤0.01	0.008

it decreases in γ-iron and in the particles of cementite, which are located in the volume of bainite plates, in addition, a transfer of carbon to crystalline structure defects occurs. It is known [9], that operation of railway rails is accompanied by a significant redistribution of carbon in a thin surface layer. If in the initial state the main carbon content is concentrated in the composition of cementite Fe_3C, then after a long-term operation of rails, the content of carbon is determined at dislocations, grain and subgrain boundaries.

Under thermodeformation conditions of FBW, the prerequisites for redistribution of carbon exist. The aim of the work was to determine the features of the microstructure of joints of hypereutectoid rail steels with an increased carbon content in FBW.

PROCEDURE AND EQUIPMENT

Welding of hypereutectoid rails of grade AREAL 136HE-X manufactured by Nippon Steel Corporation (Japan) was carried out in the K1000 machine for flash-butt welding using pulsating flashing. After optimization of conditions, the recommended parameters should be within the following values: welding time — 70–90 s, welding current — 360–390 A, tolerance for flashing — 10–14 mm, upsetting value — 11–14 mm. The grade composition and results of the spectral analysis of the delivered batch of rails are given in Table 1.

The macrostructure of the joints was revealed in accordance with the requirements of GOST R51685-2013 on a full-profile template, cut out in the transverse direction. Etching of polished specimens was carried out with an aqueous solution of ferric chloride. The microstructure was revealed by etching of preliminary polished specimens in a 4 % alcohol solution of HNO_3. Metallographic examinations were performed in the NEOPHOT 32 optical microscope equipped with a digital camera. To analyze the microstructure and determine the chemical composition of structural components, Auger-microprobe JAMP 9500F of JEOL Company (Japan) with the installed X-ray energy dispersive JNCA Penta FET x3 spectrometer of «Oxford Instrument» Company was used. The energy of the primary electron beam was 10 keV at a current of 0.5 nA for the REM and PCMA methods and a current of 10 nA for the method of Auger-electron spectroscopy. Auger-spectra were recorded with the energy resolution $\Delta E/E = 0.6$ %. Prior to the studies, the surface of the specimens was subjected to cleaning directly in the analysis chamber of the device by etching with argon ions Ar + with an energy of 1 keV during 10 min. The etching rate over the reference specimen-witness SiO_2 was 4 nm/min. The vacuum in the analysis chamber was in the range of $5\cdot10^{-8}$–$1\cdot10^{-5}$ PA.

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

RESULTS OF RESEARCH AND DISCUSSION

Metallographic examinations showed that macrostructure of the joint is similar to that of hypoeutectoid rails and consists of a weld zone, to which the zone of a coarse grain is adjacent, followed then by the zones of a fine grain, partial recrystallization and tempering (Figure 1). The width of the heat-affected zone (HAZ)

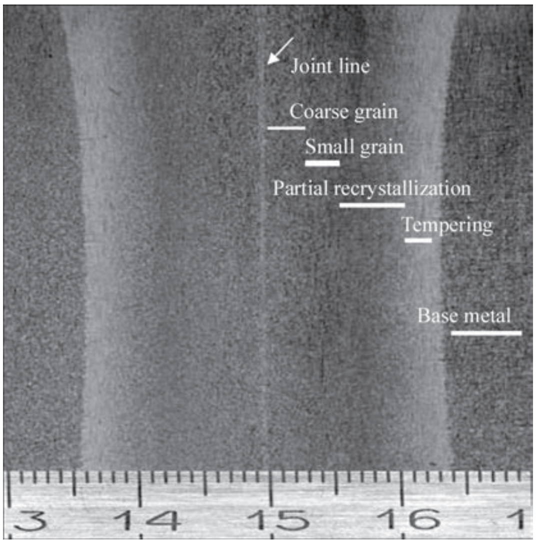


Figure 1. Microstructure of rail joint of steel of grade AREAL 136 HE-X (×25)

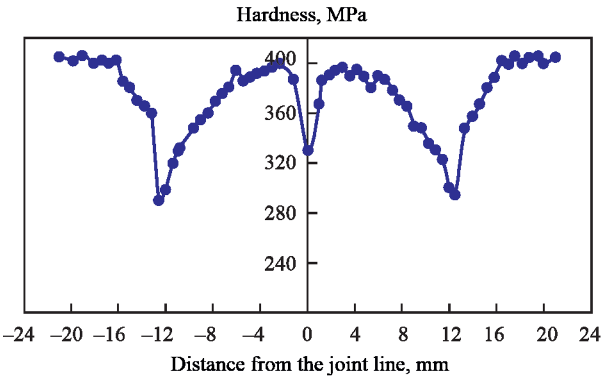


Figure 2. Distribution of Vickers hardness in the joint of the hypereutectoid rail steel of grade AREAL-136HE-X. Load is 30 kg

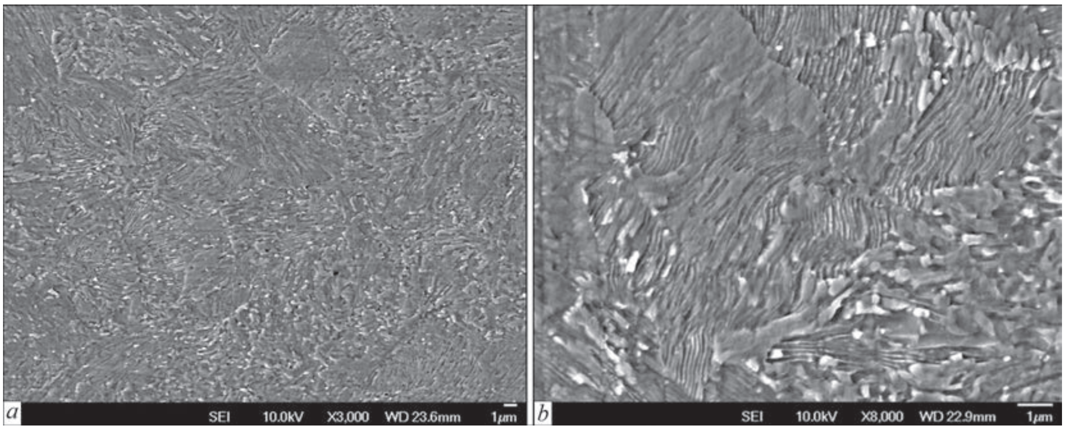


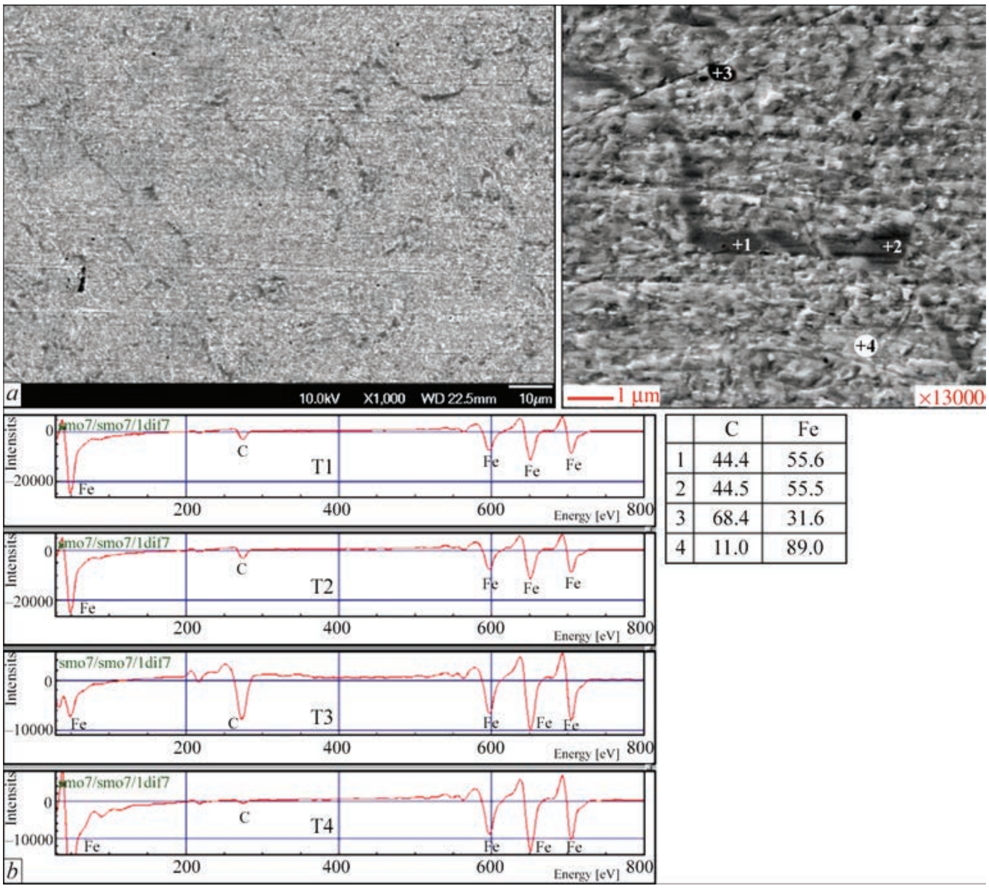
Figure 3. Microstructure of hypereutectoid steel of grade AREAL 136 HE-X: *a* — ×3000; *b* — ×8000

of the studied joint was 30 mm. Analysis of the hardness distribution showed (Figure 2) that in the zone of a coarse grain, unlike in the joints of hypoeutectoid rails, the hardness is slightly reduced as compared to the base metal — *HV* 3900 MPa and *HV* 4000 MPa, respectively.

The study of the microstructure showed that the base metal represents a hardening sorbite (Figure 3). The size of sorbite colonies is estimated at 10 μm. The interplate distance in sorbite is estimated at 0.14 μm. It should be noted that cementite plates in sorbite are deformed and refined.

During the analysis of the microstructure it was found that in the base metal along the grain boundaries, a structural component with a carbon content of 44.5 at.% is observed, the rest is iron. Its thickness is tenth fractions of a micron (Figure 4). The formation of a solid carbide network is not observed. The particles chaotically distributed in the matrix are observed, in the composition of which 68.4 at.% of carbon is recorded.

Taking into account the possible error while using the Auger-spectral method of analysis, it can be assumed that at the grain boundaries, a hypoeutectoid carbide phase is observed and in the structure of steel,



	C	Fe
1	44.4	55.6
2	44.5	55.5
3	68.4	31.6
4	11.0	89.0

Figure 4. Precipitations of carbide phase at the boundaries of grains of the hypereutectoid rail steel of grade AREAL 136 HE-X: *a* — microstructure; *b* — Auger-spectra and results of Auger-spectral analysis (at.%)

Table 2. Composition of nonmetallic inclusions in the Areal 136 HE-X steel (at.%)

Number	C	O	Mg	Al	Si	Ca	Mn	Fe
1	0.44	63.30	2.16	25.82	3.46	3.30	0.68	0.84
2	1.09	61.36	3.05	24.98	3.64	2.66	1.35	1.86
3	1.14	61.31	1.65	27.57	1.55	0.97	0.98	4.83
4	1.57	60.75	2.64	23.57	4.09	2.97	1.07	3.34
5	1.54	62.41	0.82	27.45	2.32	1.55	0.17	3.74
6	1.35	57.03	0.67	25.00	2.12	2.00	0.73	11.08

particles with carbon precipitations are present. It should be noted that the ratio of carbon and iron in the carbide phase does not correspond to the stoichiometric one in cementite: 75 at.% iron — 25 at.% carbon.

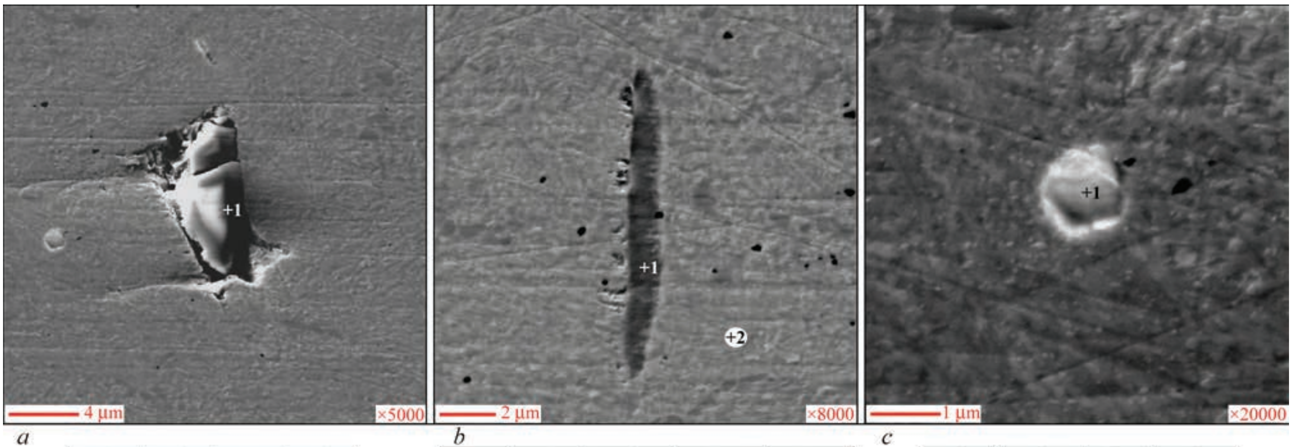
Contamination with nonmetallic inclusions is insignificant. Primarily, deoxidation products are observed unsystematically located in the matrix: aluminium oxides with impurities of calcium, silicon and magnesium (Table 2, Figure 5, *a*). Sulfides of up to 10 μm length (Figure 5, *b*) are observed, elongated along the direction of the rolled metal and dispersed aluminium carboxides with the size of less than 1 μm, not previously mentioned in the structure of rail steels (Figure 5, *c*).

The study of the metal in the HAZ showed that the microstructure represents a lamellar pearlite of varying degree of dispersion (Figure 6, *a*). The exception is the tempering zone, where coagulation of sorbite cementite occurs, resulting in a decrease in hardness in this region (Figure 6, *b*). At the recrystallization area along the boundaries of the primary austenitic grains, precipitations of a hypoeutecoid ferrite with a thickness of less than 1 μm are found (Figure 6, *c*). The presence of a hypoeutectoid ferrite is obviously a consequence of a decrease in carbon content in austenite formed during welding, which is lower than an eutectoid one.

Along the joint line as a result of depletion of the near-contact layer with carbon during flashing of the rail ends in welding, a band with a hypoeutectoid ferrite is formed at the boundaries of the primary austenitic grains (Figure 7). The band width is about 300 μm. According to the ASTM scale, the grain size of the primary austenite corresponds to a grain size number of 2–3. The interplate distance in sorbite is estimated at about 0.17 μm, which is much larger unlike that in the area of a coarse grain, which is 0.10 μm (Figure 6, *d*). The size of the interplate distance is the main factor that determines the level of hardness of steel. Accordingly, a significant decrease in hardness is observed along the joint line.

Despite the existing preconditions, carbides at the boundaries of primary austenitic grains were not detected in the joint, a number and sizes of chaotically distributed globular particles increased, that are similar to particles with precipitations of carbon in the base metal (Figure 8, *a*). According to the results of Auger-spectral analysis, the studied particles contained 84.2–92.8 at.% C, the rest was the iron (Figure 8, *b*). Their number increases in the direction of the butt joint, the highest concentration is observed in the near-contact layer.

The interplate distance in sorbite determines the hardness of steel — its reduction leads to an increase in hardness. In the base metal and in the area of a coarse grain, the interplate distance is 0.14 and 0.10 μm, respectively. However, the hardness in the area of a coarse grain is lower than that of the base metal — 3900 and 4000 MPa, respectively. Apparently, this is associated



a

C	O	Fe	Al
0.6	72.0	1.1	26.3

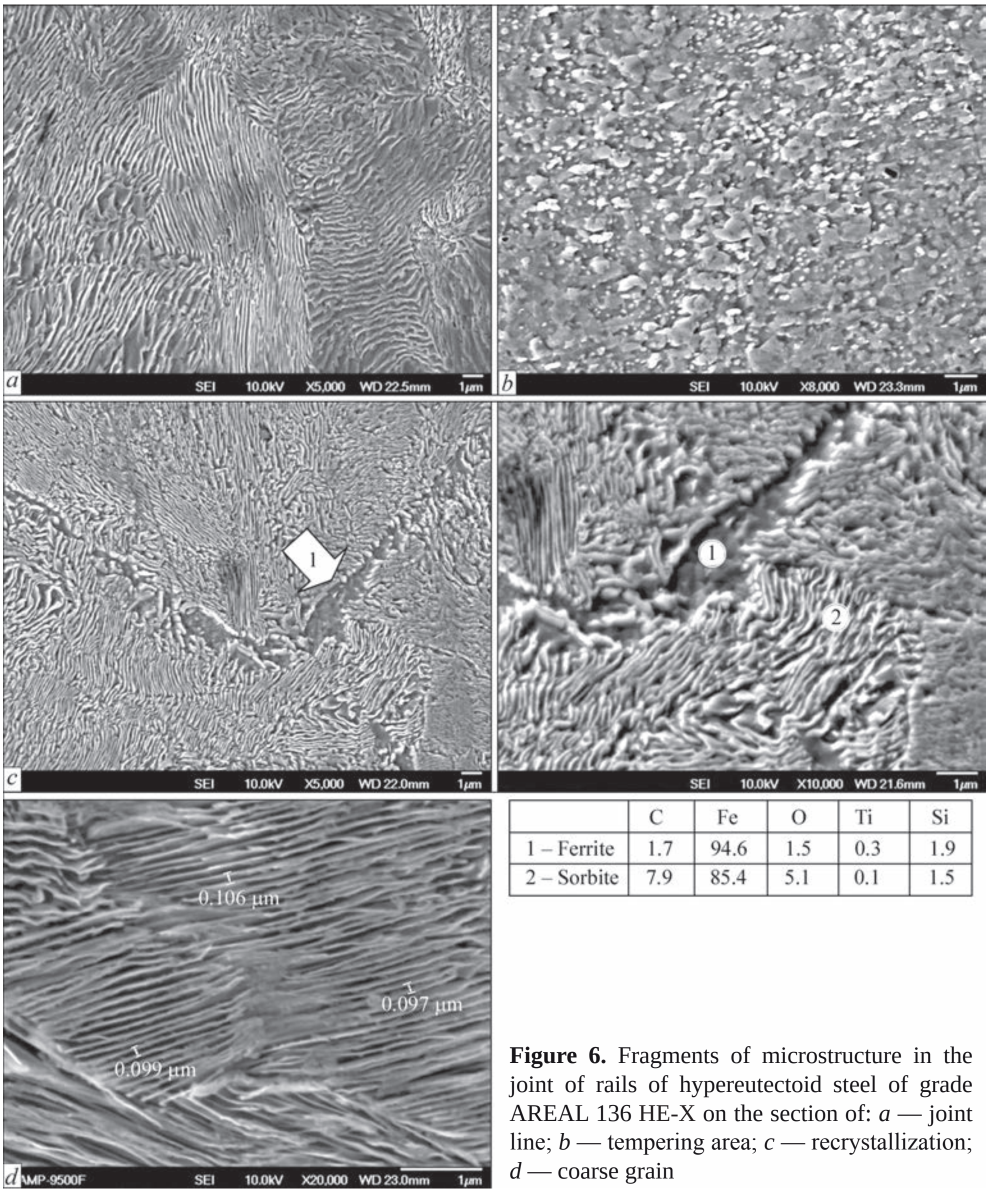
b

	C	S	Fe	Mn
1	1.0	43.6	15.9	19.3
2	13.8	0	86.2	0

c

C	O	Fe	Al
33.4	46.6	0.7	19.3

Figure 5. Nonmetallic inclusions of hypereutectoid steel of grade AREAL 136 HE-X and results of the Auger-spectral analysis (at.%) of: *a* — aluminium oxide; *b* — sulfide; *c* — aluminium carboxide



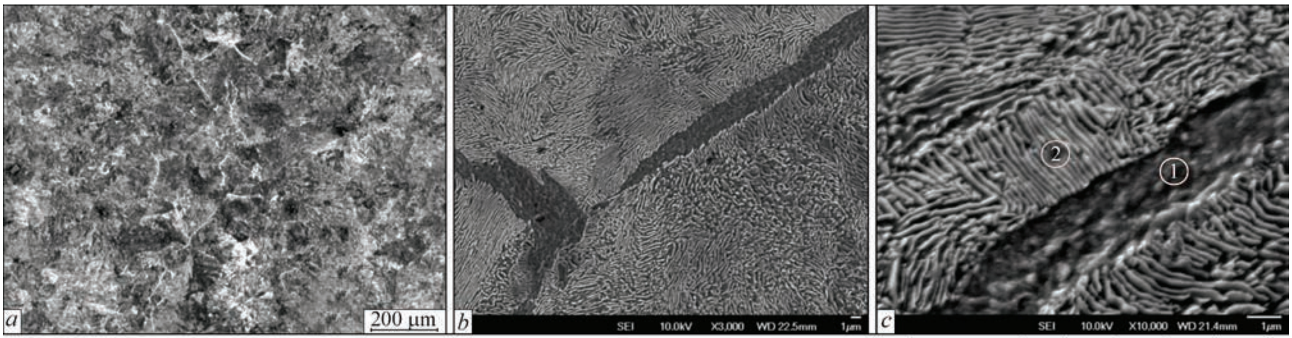
	C	Fe	O	Ti	Si
1 – Ferrite	1.7	94.6	1.5	0.3	1.9
2 – Sorbite	7.9	85.4	5.1	0.1	1.5

Figure 6. Fragments of microstructure in the joint of rails of hypereutectoid steel of grade AREAL 136 HE-X on the section of: *a* — joint line; *b* — tempering area; *c* — recrystallization; *d* — coarse grain

with the presence in the base metal of the carbide phase at the boundaries of the primary austenitic grains and its absence in the structure of the joint.

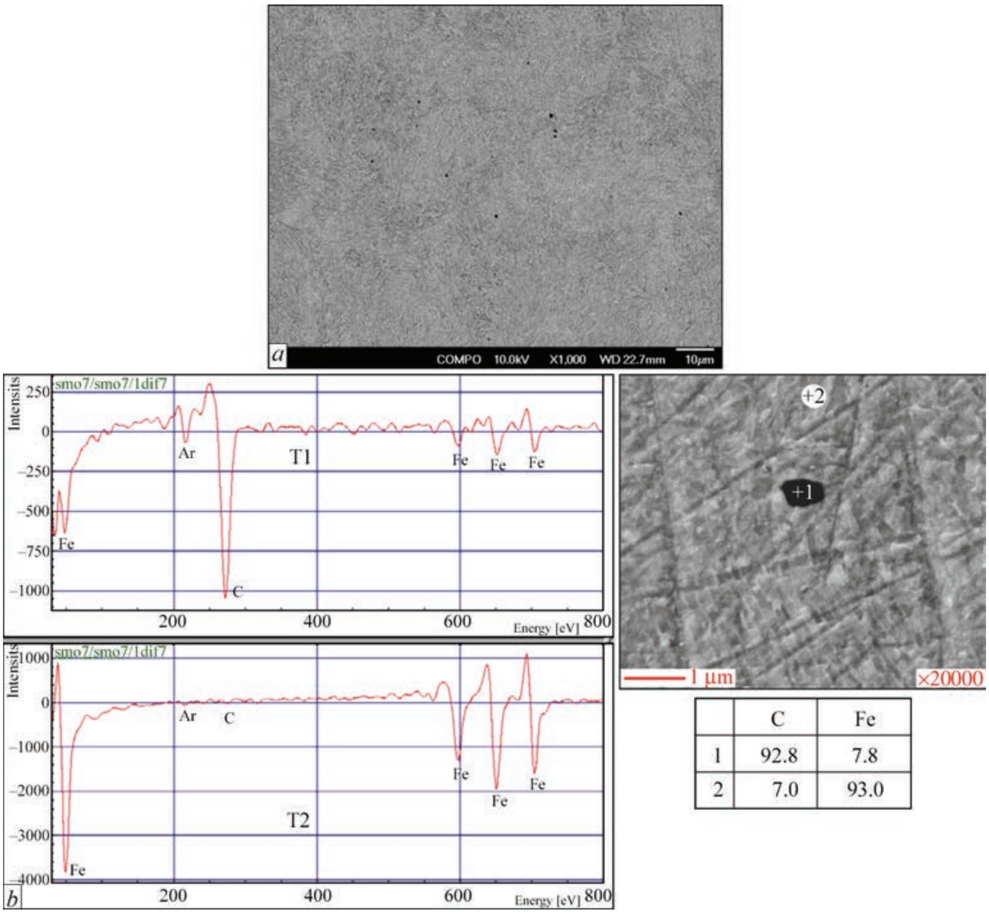
Fractographic examinations showed that on the fracture surface of the joint, carbon is present primarily around nonmetallic inclusions (Figure 9, *a*, *b*). The presence of formations of the C–N–O system should be noted adjacent to carbon and containing 54.91–61.36 at.% of carbon; 14.65 at.% of nitrogen; 8.39 at.% of oxygen (Figure 9, *c*).

It is believed that carbon in the structure of carbon steels and cast irons is present in the composition of chemical compounds (carbides), solid iron solution, as well as in the form of the main allotropic modifica-



Point	C	O	Fe	Ti	Si
1 –Ferrite	1.0	3.3	94.4	0.5	1.0
2 – Sorbite	6.1	2.2	90.6	0.7	0.5

Figure 7. Joint line of rails of hypereutectoid steel of grade AREAL 136 HE-X: *a*, *b* — microstructure (×100, ×3000); *c* — results of Auger-spectral analysis (at.%)



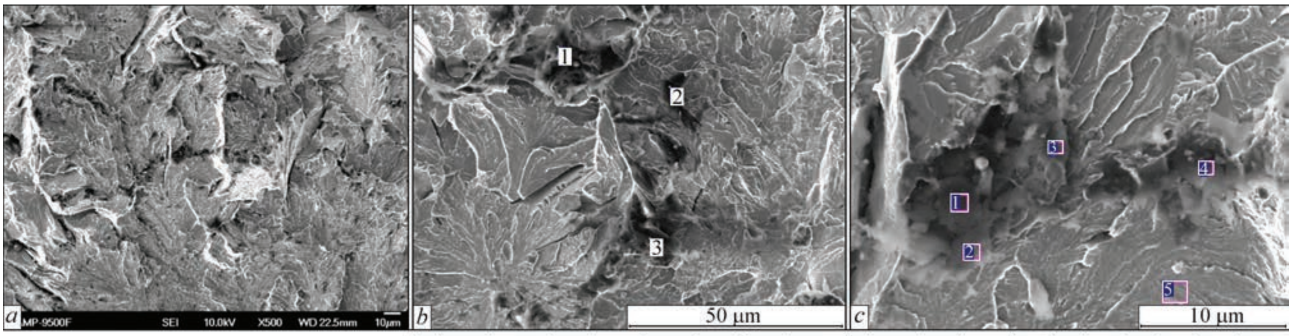
	C	Fe
1	92.8	7.8
2	7.0	93.0

Figure 8. Inclusions of carbon in the joint of rails of hypereutectoid steel of grade AREAL 136 HE-X: *a* — location in the microstructure; *b* — Auger-spectra and results of Auger-spectral analysis (at.%)

tion — graphite. However, in the studies of a number of authors based on experimental data, it was shown that in the alloys of the Fe–C system, carbon can be present in the states that do not meet the abovementioned variants [10]. In particular, in welded joints fullerenes were revealed — a molecular form of carbon [11]. The obtained results of fractographic examinations give reasons to suggest the existence of carbon modifications different from graphite in the structure of rail joints.

Carbon inclusions can be considered as a violation of metal continuity. Taking into account their small amount, sizes and a globular shape, a significant decrease in strength characteristics is not envisaged.

The tests on static bending during tension of the foot with a load of 1740–2400 kN were carried out.



	C	O	Na	Si	S	Cl	Ca	Fe
1	82.86	6.62	0.79	0.39	0.16	0.28	0.24	8.67
2	81.20	12.97	0.23	0.21	0.07			5.32
3	64.02	7.44	0.51	0.35				27.68

	C	N	O	Na	Mg	Al	Si	S	Mn	Fe
1	59.66	19.32	15.42	0.50		0.45	0.52	1.97	0.04	2.12
2	54.91	14.65	8.92	0.56			0.43	1.21	0.08	19.75
3	55.72	15.48	8.39	0.28	0.11		0.40	1.39	0.50	17.75
4	61.36	15.85	13.22	0.62	0.19	0.64	0.66	0.90	0.27	5.76
5	11.78		2.82				1.53		0.88	82.99

Figure 9. Inclusions of carbon on the fracture surface of the joint of hypereutectoid rail steel AREAL 136 HE-X: *a* — microstructure of the fracture surface; *b* — inclusions of carbon and results of X-ray microanalysis (at.%); *c* — inclusions of the C–N–O system and results of X-ray microanalysis (at.%)

The bending deflection was 26–43 mm. The results of tests, as well as the size of the HAZ meet the requirements of domestic [12] and European [13] standards.

CONCLUSIONS

1. The microstructure of the joint of the hypereutectoid rail steel of grade AREAL-136HE-X, produced by flash-butt welding, represents a lamellar pearlite of a different degree of dispersion. The exception is the tempering area where coagulation of sorbite cementite occurs. Along the joint line as a result of depletion of the near-contact layer in flashing of rail ends during welding, at the boundaries of primary austenitic grains, a band with a hypoeutectoid ferrite is formed. Hypoeutectoid ferrite in a small amount is also observed in the area of recrystallization. Carbides at the boundaries of primary austenitic grains were not detected in the joint. At the same time, in the microstructure globular particles with a high carbon content are observed.

2. The results of examinations of the microstructure evidence that in the thermodeformation conditions of FBW, redistribution of carbon occurs, the result of which is its transfer to defects of the structure. In this time, carbon content in the matrix decreases and recrystallization in the HAZ metal occurs similarly to hypoeutectoid rail steels.

3. Investigation of hardness distribution showed that in the area of a coarse grain, unlike the joints of hypoeutectoid rails, the hardness is reduced as compared to the base metal — *HV* 3900 MPa and *HV* 4000 MPa, respectively. This is caused by the absence of the area of a coarse grain, carbide phase at the boundaries of primary austenitic grains for the microstructure unlike the base metal.

4. The results of tests of the hypereutectoid rail steel of grade AREAL-136HE-X on static bending meet the requirements of domestic and European standards. The use of FBW to produce high-quality joints of the rails of a hypereutectoid composition is recognized as challenging.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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