DEFECTS OF JOINTS OF HIGH-STRENGTH RAILS PRODUCED USING FLASH-BUTT WELDING

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The investigations of defects of structure of rail joints, made by flash-butt welding, were carried out. The defects were detected at the fracture surface of joints during static bending tests and also after fracture under the operation conditions. The analysis of microstructure and chemical heterogeneity of the fracture surface was performed using Auger-microprobe JAMP 9500F of the JEOL company (Japan). The defects formed as a result of deviation from the standard welding conditions include lacks of penetration and inclusions of iron-manganese silicates which considerably decrease the values at mechanical tests of welded joints. Their presence in the welded joints is not admissible. Clusters of inclusions of aluminium silicates, the so-called dead spots, and oxide films of the more complicated composition are formed in the joint on the basis of non-uniformly distributed non-metallic inclusions of rail metal. The dead spots of small area do not influence the values at mechanical tests of welded joints. Their total area on the fracture should not exceed 15 mm^2. On the basis of carried out investigations the criteria of quality evaluation of the high-strength steel joints, made by flash-butt welding using modern control systems, were determined. 9 Ref., 2 Tables, 11 Figures.

Keywords: *flash-butt welding, rail steels, static bending, fracture surface, defects of welded joints, lack of penetration, iron-manganese silicates, aluminium silicates*

In the last five years the large-scale laying of high-strength rails in the main Ukrainian and Russian rail roads is performed. The rails are mainly joined by flash-butt welding (FBW) using equipment and technology developed by the E.O. Paton Electric Welding Institute [1]. The quality control of welded rails is performed directly after welding using in-process and non-destructive ultrasonic testing. Moreover, in accordance with the standard requirements, at the beginning of each working shift the static bending tests of the reference specimens are carried out.

At the E.O. Paton Electric Welding Institute the large volume of data on all the kinds of tests of joints of high-strength rails in combination with investigation of fractures and data of mechanical tests was accumulated. It was found that at the same area of defects revealed in the joints of high-strength rails of converter melting, the values of mechanical tests are decreased to a greater extent than those in the rails of open-hearth production.

The aim of this paper is the study of defects in joints of high-strength rails of converter melting, made using FSW.

The specimens for investigations were selected at the rail welding enterprises on the basis of results of in-process and non-destructive ultrasonic testing. The defects of structure were detected on the surface of fractures after bending tests of welded butts. The tests were carried out according to the procedure accepted at the rail roads of Ukraine and Russia [2].

The metallographic investigations of microstructure of rail joints were carried out in the

Table 1. Chemical composition of rail steels of different production, wt.% (GOST R 51685–2000)

Steel grade	C	Mn	Si	P	S	V	Ti	Cr	Al	Cu
M76	0.71–0.82	0.75–1.05	0.25–0.45	<0.035	<0.040	–	–	–	0.02	–
E76F K76F				<0.025	<0.030	0.03–0.15	–	–	0.02	≤ 0.15
E76T K76T				<0.030	<0.035	–	0.007–0.025	–	0.02	
KF	0.78–0.81	0.89–0.91	0.30–0.39	0.013–0.02	0.003–0.01	0.057–0.061	–	0.03–0.04	–	0.02–0.04

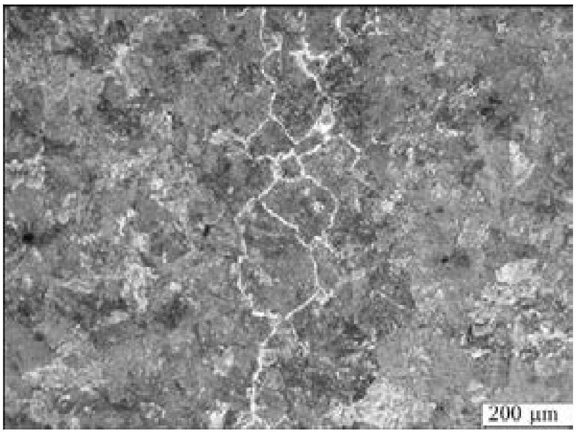


Figure 1. Microstructure of weld center of rail welded joint

light microscope «Neophot 32» and fractographic examinations with X-ray spectral microanalysis of the fracture surface were performed using Auger-microprobe JAMP 9500F of the JEOL company (Japan). The chemical composition of rail steels is given in Table 1.

The typical microstructure of rail weld metal produced at the optimal conditions, represents a sorbitic perlite (Figure 1). Along the joint line the band of about 200 μm width with precipitations of hypoeutectoid ferrite along the boundaries of the primary austenite grains is observed, the size of which is equal to the point 2–3 according to ASTM. Depending on the gradient of the temperature field in welding the amount of hypoeutectoid ferrite can change. At the optimal rigid conditions, characterized by the high gradient of temperature field, the thickness of ferrite fringe is minimum, and it can be interrupted. Such joints are characterized by the highest plastic properties.

The fracture of rail joints welded at the optimal conditions has a crystalline structure. The surface of fracture consists mainly of cleavage facets with a stream-like pattern and tongues, tear crests are also present (Figure 2).

At the fracture surface the refractory inclusions of titanium carbonitrides, calcium aluminates, manganese oxysulfides can be found (Figure 3). The size of these non-metallic inclusions is not more than dozens of micrometers. The presence of such inclusions gives a reliex shape to fracture. Their presence is not critical for strength characteristics of a joint.

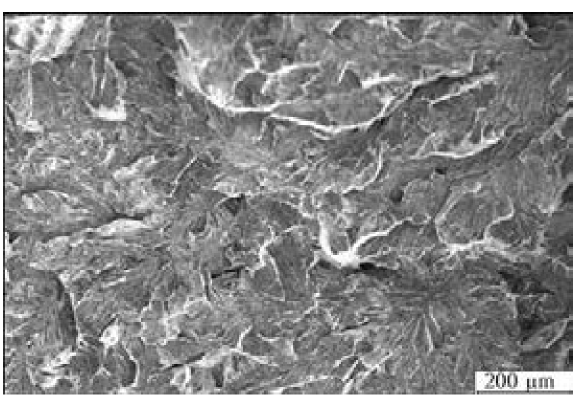


Figure 2. Fracture surface of rail welded joint

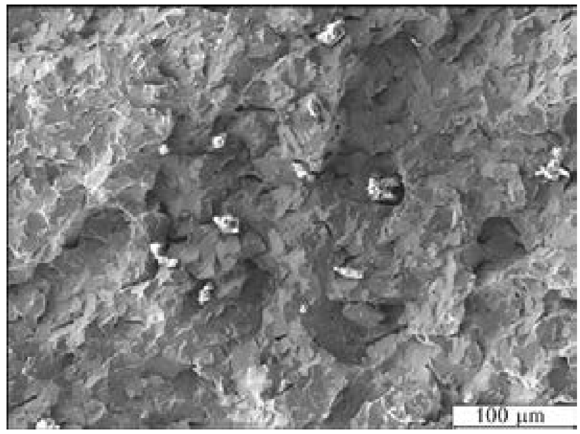


Figure 3. Refractory of non-metallic inclusions on fracture surface of rail welded joint

The defects which sufficiently influence the strength properties of the joints arise as violation of homogeneity of crystalline structure of a fracture.

One of such defects is lack of penetration. In FBW the lack of penetration is formed under the conditions when the metal of rail edge is in solid or solid-liquid state before upsetting. At the fracture it has an appearance of a plane bright area (Figure 4). It was established that microstructure of surface of the analyzed lack of penetration represents plane areas of rail metal matrix (Figure 5, spectrum No.1), divided by a structural

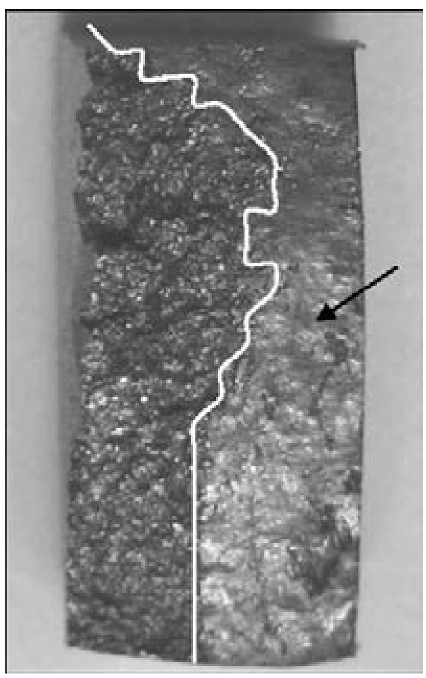
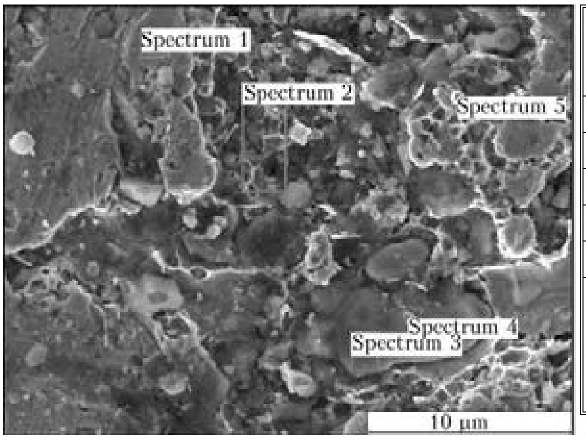


Figure 4. Lack of penetration on fracture surface of rail welded joint



Number of spectrum	Element content, at.%							Note
	C*	O	Na	Si	Ca	Mn	Fe**	
1	5.90	3.23	0.18	0.00	0.00	0.00	90.68	Matrix
2	28.77	22.60	1.61	3.20	1.24	0.74	41.83	Inclusions
3	3.00	53.06	0.08	0.16	0.08	4.19	39.44	Same
4	5.96	68.24	0.09	18.32	0.00	0.51	6.89	»
5	7.01	53.36	0.37	0.61	0.08	0.35	38.22	»

* — distribution of carbon in steel in during welding requires separate study which is beyond the scope of this article. ** — value of iron concentration depends on correlation of sizes of analyzed object and diameter of electron probe.

Figure 5. Microstrucutre of fracture surface and chemical heterogeneity on the area of lack of penetration in rail welded joint

component, composed of oxides and silicates (Figure 5, spectra Nos. 2–5). Obviously, this structure component is formed of non-metallic inclusions of base metal and oxidation products of rail metal fused along the boundaries.

The presence of defects of this type even of small area (1–2 mm^2) detected using modern means of ultrasonic testing, is not admissible in welded joints as far as they reduce the values at static and impact tests and provoke fatigue fractures of welded butts.

Another type of defects represents spots with a non-developed relief in the range of which the bright and dead spots are combined (Figure 6). The analysis of microstructure of fracture surface showed that bright spots represent a layer of iron-manganese silicates (Figure 7, *a*). Dead spots, adjacent to a monolithic layer, are the area of clustering the particles of iron-manganese silicates (Figure 7, *b*). The fracture occurs as a result of delamination along the film at the area of monolithic layer and along the pit mechanism in the places of inclusions clustering.

The iron-manganese silicates are formed in the process of welding at the oxidation of fused metal. It is supposed [3] that formation of oxide structures in the plane of a joint is determined by the presence of oxygen in the spark gap during the period of fusion, preceding the upsetting. It is shown in work [4] that the main factor influencing the formation of defects in the plane of a joint is the state of melt at the fused ends of parts during the period, preceding the upsetting. If the melt is preserved, then it is squeezed out during deformation from the butt together with oxides, forming at its surface, independently of oxygen content in the spark gap. The duration of existence of melt layer on edges depends on its thickness, gradient of temperature field in the near-contact area of edges and speed of parts fusion [5].

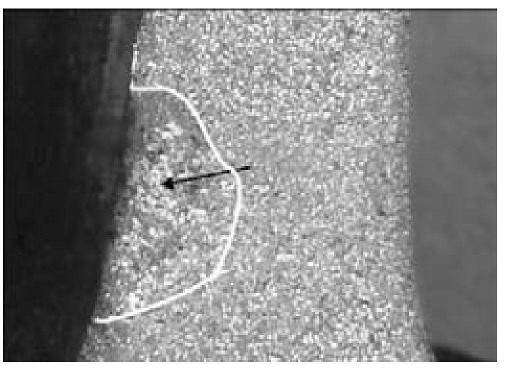
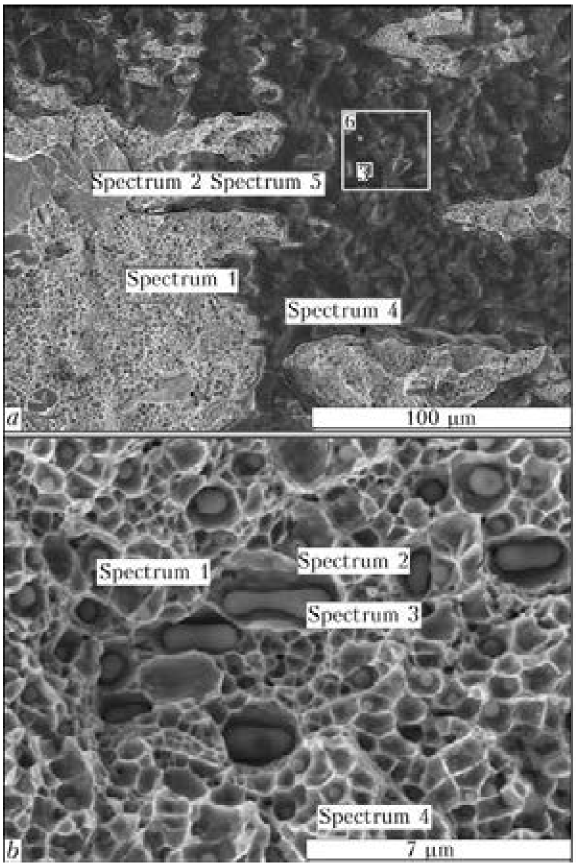


Figure 6. Iron-manganese silicates on the fracture surface of rail welded joint

The described defects are observed in the joints of rails welded with deviations from the preset values of welding parameters. They are reliably detected using modern methods of ultrasonic testing even at a small area (1–2 mm^2). Their presence in welded joints is not admissible as far as they decrease the values of mechanical properties at static and impact tests and provoke fatigue fractures of welded butts.

The particular place relates to the defects which are defined in the standard documents as «dead» (DS) or «grey» spots. At the surface of fracture they are observed as the areas of dark color with a non-developed relief (Figure 8). These are the defects which are most often observed during tests of welded joints of different metals produced using FBW.

The comparative analysis of chemical composition from the defect area showed that DS are enriched with aluminium, manganese, silicon as compared to the surrounding surface of crystalline structure (Figure 9, *a*). During the more detailed investigations it was established that DS represents the clusters of particles of manganese aluminium silicates, arranged in the metallic matrix (Figure 9, *b*). The particles have a fused



Number of spectrum	Element content, at.%					Note
	C	O	Si	Mn	Fe	
1	8.96	5.59	0.95	0.76	83.74	Clustering of silicate particles
2	5.42	3.16	0.00	0.10	91.31	Cleavage facet
3	2.24	56.41	12.63	8.87	19.85	Monolithic layer of silicates
4	0.74	58.67	12.69	7.46	20.44	Same
5	2.43	52.69	4.70	7.40	32.78	»
6	2.40	55.97	9.64	8.59	23.40	»

Number of spectrum	Element content, at.%					Note
	C	O	Si	Mn	Fe	
1	5.99	54.25	14.49	15.53	9.74	Silicate particles
2	7.22	48.70	15.58	10.01	18.49	Same
3	3.20	59.61	14.73	18.37	4.09	»
4	10.03	4.53	0.52	0.00	84.92	Matrix (without inclusions)

Figure 7. Microstructure and results of analysis of chemical composition heterogeneity on the area of fracture with iron-manganese silicates in the form of film (*a*) and inclusions (*b*)

shape and are characterized by a weak adhesion to iron.

It should be noted that at the fracture both the particles of aluminium silicates and also the spots of location of these particles, removed during fracture, are observed. The haze defect of fracture is predetermined by a pit relief of the surface after fracture along the inclusions.

The characteristic feature of inclusions of aluminium silicates is a negligible amount of iron in their composition (0.86–0.99 at.%). It evidences of the fact that their formation is not connected with the flashing of edges. They are formed in the layer adjacent to the fused metal on the base of inclusions of base metal (see Table 2). The saturation with manganese occurs during its transition from the matrix into the forming fusible silicate, which is possible due to the high diffusion mobility and surface activity of manganese in iron. The location of aluminium silicates in the layer adjacent to the fused metal impedes their squeezing out into the flash during upsetting.

It is known that fusible aluminium silicates are formed during underoxidation of silicon in presence of aluminium [6]. As the source of silicon the silicocalcium can be, used as deoxidizer during manufacture of rails, that is indirectly confirmed by presence of calcium in the composition of aluminium silicates. The aluminium gets to the steel from ferroalloys and, possibly, the ladle slag [7].

In the course of investigation of a large number of defects of the DS type in the rail joints of different manufacture it was established that they are considerably differed from the defects,

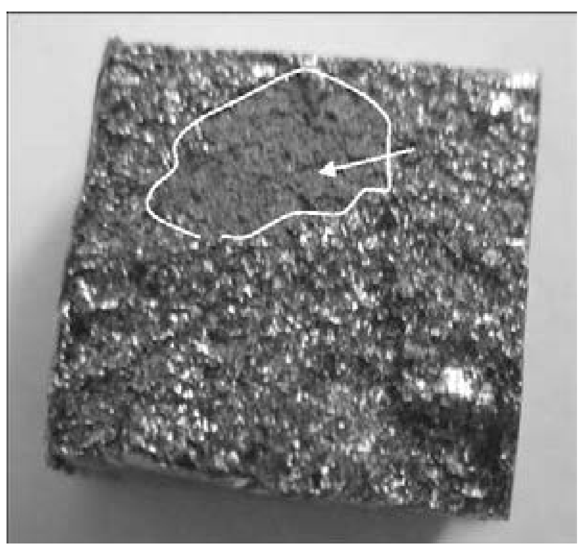
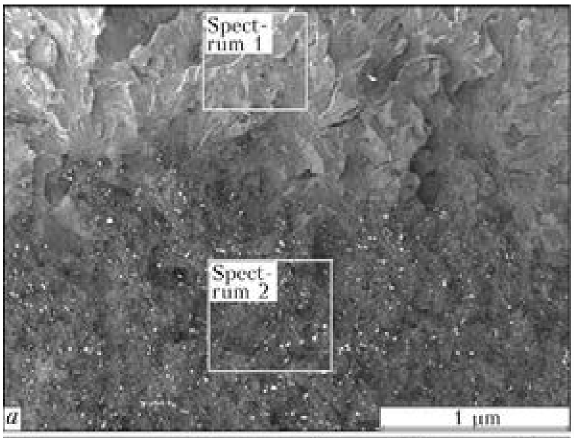
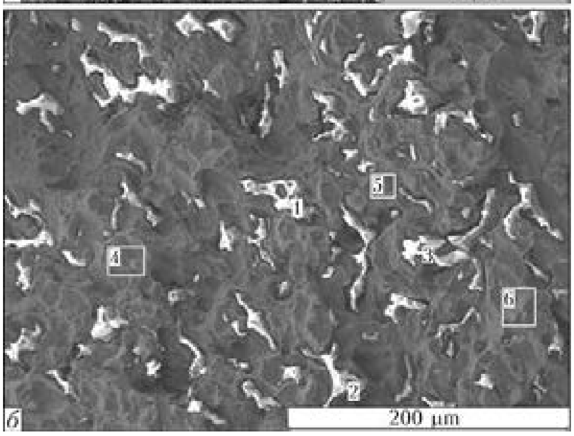


Figure 8. Dead spots in the fracture surface of rail welded joint



Number of spectrum	Element content, at.%						Note
	C	O	Al	Si	Mn	Fe	
1	8.34	2.74	0	0.25	0.13	88.55	Cleavage facet
2	7.01	16.52	0.45	4.08	5.86	66.08	Spot



Number of spectrum	Element content, at.%						Note
	C	O	Al	Si	Mn	Fe	
1	3.27	66.66	1.11	16.48	11.61	0.86	Inclusions
2	3.36	61.08	3.15	16.70	14.73	0.99	Same
3	2.41	68.91	1.32	16.39	6.90	0.90	»
4	4.43	1.57	0.11	0.00	0.80	93.09	Matrix
5	5.51	0.86	0	0.18	0.81	90.76	Same
6	4.70	1.50	0	0.15	1.11	92.54	»

Figure 9. Microstructure and results of analysis of chemical composition of fracture surface of rail joints on the area of a dead spot from area (*a*) and locally (*b*)

examined above, not only by the composition of their structure components but also by their thickness not exceeding 20 μm. Small thickness impedes their detection during ultrasonic testing, from the one hand, and on the other hand the presence of such defects in welds of rails does not have a considerable influence on the values at full-scale tests on static and impact bending. The limited number of DS in the joints of rails is admissible. Their total area is restricted to 15 mm^2 [2] by existing standards which is sufficiently grounded by experimental data.

In the last time, on the fractures of rails, fractured not only along the joint but also along the base metal, defective areas was found in the head area of the shape close to oval of dark color and non-developed relief (Figure 10).

It was established that fracture on the area of oval spot occurs according to the pit mechanism (Figure 11). Within the limits of area the groups of inclusions of 20 mm size were found representing the complex oxides composed of aluminium, silicon, magnesium, calcium (Figure 11, *a*). The inclusions, which are similar by their chemical composition, but finer in size, are pre-

Table 2. Results of X-ray spectral microanalysis of chemical composition of non-metallic inclusions in the rail steel, at.%

Steel grade	Fe	Mn	Si	S	V	Ti
M76	39.8–80.9	0.86–10.3	0.51–1.3	0.3–5.3	N/D	N/D
K76F	33.5–58.5	0.01–0.5	0.9–6.1	2.4–30.1	0.006	0.1–1.2
E76F	68.9–95.8	0.7–1.6	0.56–5.9	0.08–0.5	0.06–0.12	–

Table 2 (cont.)

Steel grade	P	Al	Ca	Cu	O	Mg
M76	0.02	N/D	0.03–5.3	0.01–0.11	6.3–55.2	N/D
K76F	0.02	0.001–5.3	0.1–5.3	0.01–0.15	11.9–30.5	0.2–0.5
E76F	0.01	0.29–0.31	0.55–5.2	0.15–0.18	1.86–21.8	0.4–0.7

sent in the pits (Figure 11, *b*). In the pits the inclusion of iron oxides can also be found, the size of which amounts to tenth fractions of micrometer (Figure 11, *c*).

The formation of oval spot is obviously occurs on the basis of DS as a result of interaction of aluminium silicates with ferrous oxide, for example, in the case of underoxidation of steel. Here more fusible oxide systems are formed, which are characterized by a high fluidity [8]. Under the thermodeformational conditions of rolling and welding these fusible oxides are penetrated along the structure boundaries and form the oval spots.

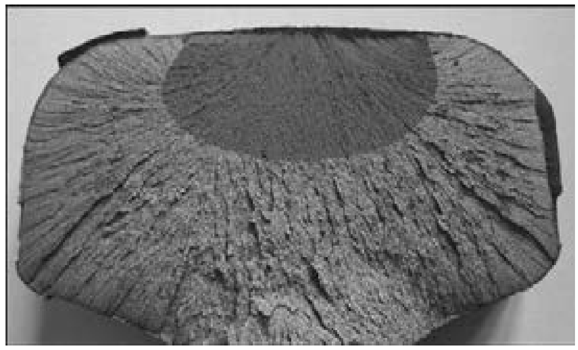
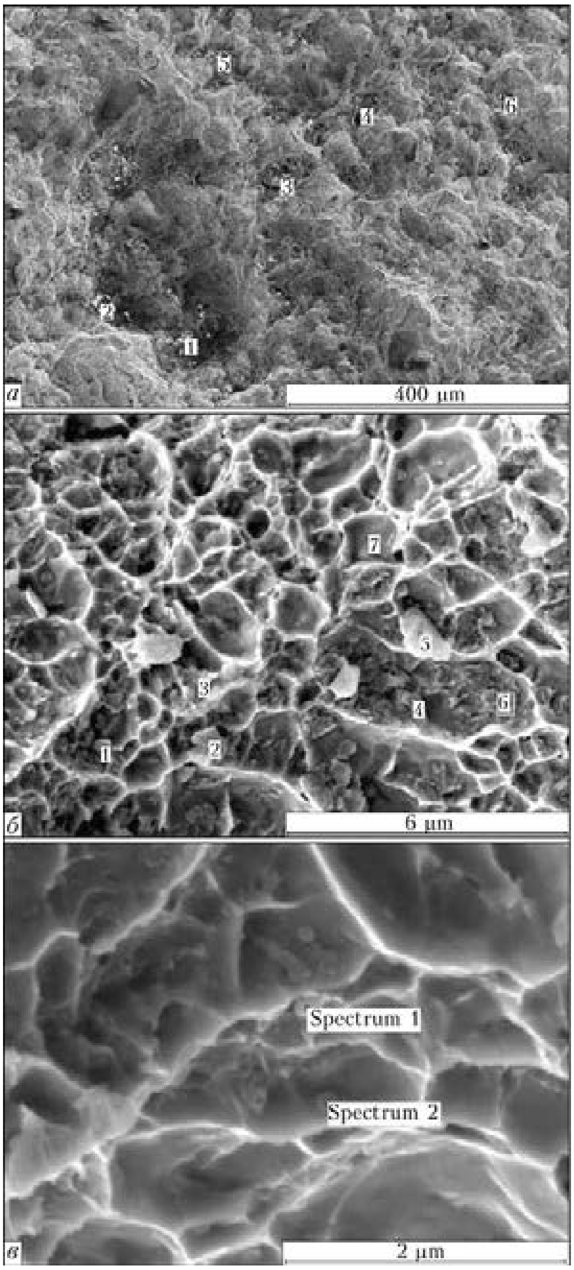


Figure 10. Oval spots on fracture of rails

The absence of metallic joint on the larger area results in considerable reduction in strength.



Number of spectrum	Element content, at.%							
	C	O	Mg	Al	Si	S	Ca	Fe
1	34.38	7.29	–	0.68	3.60	–	4.58	45.64
2	46.57	29.02	–	1.47	4.41	1.53	–	2.40
3	24.00	23.21	–	1.49	3.27	–	0.74	47.29
4	49.32	33.95	0.23	1.87	6.48	0.30	0.79	6.03
5	55,94	27.26	0.45	2.35	6.54	–	1.18	5.57
6	26.55	53.09	0.36	1.25	2.61	2.41	10.22	1.86

Number of spectrum	Element content, at.%							
	C	O	Al	Si	S	Ca	Cr	Fe
1	16.48	3.78	0	1.02	–	–	0.08	78.62
2	28.58	19.54	0	1.03	1.46	2.14	–	46.66
3	16.05	9.34	0.67	1.48	–	–	–	72.46
4	18.36	24.75	3.20	5.00	–	–	–	48.69
5	18.83	52.32	5.01	15.22	–	–	–	4.75
6	17.46	4.58	0.31	0.57	–	–	–	77.07
7	3.52	0.17	0	0.40	–	–	–	95.92

Number of spectrum	Element content, at.%			
	C	O	Si	Fe
1	13.61	22.79	0.81	62.79
2	16.87	10.99	0.52	71.63

Figure 11. Microstructure and results of analysis of chemical composition of non-metallic inclusions on the area of oval spot of fracture of rail welded joint: *a* — clusters of particles of aluminium, silicon, calcium, magnesium oxides; *b* — particles of oxides located in the pits; *c* — iron oxides

In welding of high-strength rails of modern production, as the results of large amount of test batches of welded rails show, the probability of DS formation increases as compared to the similar data obtained in welding of rails of open-hearth production. It is obviously connected with getting of aluminium into the steel as associated element, for example, during adding of vanadium, titanium, niobium or other technological operations. To eliminate the defects like these it is necessary to carry out works on improvement of processes of steel melting and pouring.

The increased tendency to DS formation in high-strength rails of current production presents difficulties during determination of optimal welding technologies. To obtain the values of plastic properties of joints required by the standards it is necessary to find the possibilities of producing additional reserve of metal ductility in HAZ to compensate the negative influence on this value of DS in case of their formation. The developers of technologies for welding of high-strength rails try to solve this problem by precision control of welding energy input and application of self-adjustable systems of flashing process control [9].

Basing on the carried out investigations the criteria for evaluation of joints of high-strength rails were determined which were laid into the basis of development of in-process and non-destructive testing of quality of welded rails produced by FBW using the modern systems for control of welding process and non-destructive testing.

Conclusions

As a result of carried out work on investigation of defects of welded joints of rails produced using FSW, it was established that most defects are located in the joint plane. According to their structure and influence on mechanical properties the defects can be divided into three groups.

The first group is represented by lacks of penetration. The second group of defects represents iron-manganese silicates not squeezed out during upsetting. The third group is the clusters of inclusions of manganese aluminium silicates, so-called dead spots.

The defects of the first and the second groups decrease considerably the values during mechanical tests. The defects of the third group at the total area of up to 15 mm^2 have no considerable influence on the values of mechanical properties of rails. The defects of the first, second and the third group of more than 15 mm^2 area are easily detected using modern of non-destructive ultrasonic testing.

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