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WELDABILITY OF ELECTROSLAG REMELTED HIGH-CARBON STEEL AT FLASH-BUTT WELDING

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The paper presents the results of examination of the structure and properties of samples of rail metal produced by laboratory melting (in slightly deformed and cast state), which were obtained by electroslag remelting after flash-butt welding of rails. Examination showed that the microstructure of weld metal and heat-affected zone in both the cases features a homogeneous dense structure. Fracture of the samples took place mainly in the heat-affected zone. Strength of welded joints from metal in the cast state is lower, than that of slightly deformed one, which is apparently caused by coarse grains, the size of which can be reduced using heat treatment. Electroslag remelted rail steel in the cast and slightly deformed state has a level of mechanical properties in the range of requirements made to nonthermostrengthened rails K76 in GOST R 51045 and DSTU 4344 that reveals the prospects for application of electroslag remelting for manufacture of rails, including rail tongues, applied in as-cast state. 25 Ref., 3 Tables, 7 Figures.

Keywords: *flash-butt welding, rail steel, electroslag remelting, slightly deformed and cast metal, welded joint, metallographic studies, mechanical properties*

A current tendency in development of the railways is increasing the speed of the traffic, organizing which for passenger trains required making changes in technical equipment of the track and technologies of rail production and joining [1]. In the railways of Ukraine laying of new generation high-strength rails K76F (DSTU 4344:2004), 76F (GOST R 51045–97), and, not so long ago, R35HT (EN 13674-1:2011 + A1:2017) has been performed recently for the especially loaded sections of the railway track [2]. All these rails were produced in converters with subsequent ladle treatment and, furtheron, continuous casting and rolling of steel. In view of the absence of modern beam rail mill at PJSC MK «Azovstahl» (Mariupol, «Metinvest») local rails do not quite meet the current requirements (small length and low resistance, which is practically two times lower than that of foreign samples) [3, 4]. Imported rails on average can stand passage of approximately 800–1000 million gross tons of cargo in the track before replacement, compared to 450–500 million gross tons for the domestic rails [5].

In order to reduce rail damage at their interaction with the rolling stock wheels, high hardness, wear resistance, contact fatigue strength of the head metal and at the same time, ductility, toughness, alternating load resistance of the rail web and foot should be ensured [6].

With this purpose, rail steels are subjected to ladle and vacuum treatment. However, despite the deep refining of steel, the nonmetallic inclusions (NMI) of unfavourable morphology often are the cause for rail failure [7–9]. So, VNIIZhT [10, 11] investigations revealed that fracture toughness is influenced, primarily, by inclusion shape and size, their nature and distribution in steel.

PJSC MK «Azovstal» researchers showed that the most hazardous are sharp-angled inclusions of titanium nitrides and similar ones, as well as coarse inclusions of aluminium oxide and their clusters, which are the products of deoxidation and microalloying of rail steel, that led to a change of rail production technology [12, 13].

Electroslag remelting process is an effective method to remove NMI and change their morphology to a more favorable one [14, 15]. At present an extensive package of studies of NMI in ESR metal has been performed, which showed that at remelting under fluoride-oxide slags the quantity of NMI in the ingot metal is much lower, than that in the initial electrode, due to metal refining from sulphur and inclusion assimilation by slag [16–18].

It is known that modern rails are produced from continuously cast billets by subsequent rolling. The casting speed in CCMB depends on the billet section and may reach several meters per minute. A high speed of casting the continuously cast billet leads to formation of a deep liquid well, where feeding to replenish shrinkage is limited. This leads to segregation and porosity defects. However, it is not possible to significantly reduce the casting speed, as the menisk

Table 1. Comparison of rail welding processes [23]

Welding process	Welding time, min	Equipment		Operator skills	Weld quality
		Initial investment	Mobility		
FBW	2–4	Large	Low	Not required	Excellent
Gas pressure welding	5–7	Large	Medium	Required	Excellent
Thermit	30	Not large	High	Not required	Good
Electric arc	60	Not large	High	Required	Good

cools down and the billet surface quality deteriorates. Contrarily, at electroslag remelting (ESR) a very dense metal structure can be produced, but the ESR process efficiency is much lower and the process cost in this case is much higher, than that of continuous casting. Proceeding from world experience of ESR application, it can be anticipated that increase of rail cost at their production by ESR method using consumable electrodes, will not exceed \$ 100–300 per ton.

Works on producing sound rail metal by ESR were started at the E.O. Paton Electric Welding Institute of NASU together with PJSC MK «Azovstahl» as far back as in 1980s. Test batch of rails from ESR steel has passed full-scale testing in VNIIZhT experimental ring of 400 m radius along a curve, which is installed on wooden sleepers. Testing showed that fatigue life of rails from ESR steel is 3.4–4.7 times higher than that of the compared ones [19]. However, two times increase of the rail cost became the main obstacle to ESR application at that time. In order to assess the advantages of ESR metal for various critical applications, we conducted experimental melts [20, 21] and a package of studies of template metal quality in the cast state, after slight deformation and in butt welded joints.

The objective of the work is evaluation of applicability of ESR rail metal (in slightly deformed state and cast state) for a rail track joined by flash-butt welding, based on a complex of studies of the structure and properties of samples of a laboratory melt.

Rail welding. Kinds of processes. Rail joining into sections and then into the track is performed by welding, in order to reduce the number of butt joints and reach the maximum smooth running. Moreover, the impact of the wheel when rolling over the rail butt joint, leads to premature wear of their ends. The authors of work [22] showed that in the railroads with the predominant passenger train traffic (SNCF, HSPC, NS, DB, EJR) the number of defects in welded joints is equal from 5 up to 30 % of their total quantity, and in the railways for freight traffic (SPOORNET, HH1, HH2) and mixed traffic (BRANVERKET) a greater number of defects is observed exactly in welded joints (from 15 up to 60 %). Therefore, special attention should be given to weld quality.

Four main welding technologies, ensuring the safety and reliability of rail welded joints, are applied in the world for joining rails of high-speed and heavy-duty trunk railways. These are flash-butt (FBW), gas-pressure, thermit and electric arc welding [23] (Table 1).

Each of the considered processes of rail welding features its «pros» and «cons». In Ukraine, FBW is mainly used for welding rail steels, which is also widely applied abroad, as it meets the most stringent modern requirements to continuous rail tracks.

Procedure of producing electroslag metal samples, their flash-butt welding and metallographic studies. The metal for the experimental program was produced by the traditional electroslag process under laboratory conditions in a 3 t furnace with ingot drawing at drawing speeds of 20 and 40 mm/min. K76F rail (up to 0.82 % carbon content) from commercially produced steel (DSTU 4344:2004) was used as a consumable electrode. ANF-28M slag of the following composition, wt.%: 47 CaF_2; 3 Al_2O_3; 21 CaO; 11 MgO; 18 SiO_2 was applied. ESR ingots of 180 mm diameter were produced, from which templates were cut out in the cast state for welding. Part of metal of ESR rail steel ingots was rolled into a strip with blank heating up to 1050 °C temperature. Degree of deformation was 4:1, as the capacity of the laboratory mill used for rolling, was limited.

For comparative evaluation of the quality of welded joints of electroslag casting rail steel on samples (plates) with cross-sectional area of 1020 mm^2 from cast and slightly deformed metal, FBW was conducted by continuous flashing technology. The welding mode was selected in keeping with the parameters specified in TU U 24.1-40075815-002:2016 for R65 rails [24, 25]. Flashing duration, which is equal to 180 s for R65 rails, was taken as the main parameter, determining the energy input.

Metallographic studies were conducted in Neophot-32 microscope, fitted with QuickPhoto digital photography attachment. Obtained images were processed by «Atlas» program at 25–500 times magnification in the light field. To reveal the microstructure, the sections were etched in 5 % nitric acid solution.

Mechanical testing of cast and deformed metal of ESR rail steel, as well as their welded joints, was conducted by a standard procedure, in keeping with the requirements of GOST 1497–84 and GOST 6996–66,

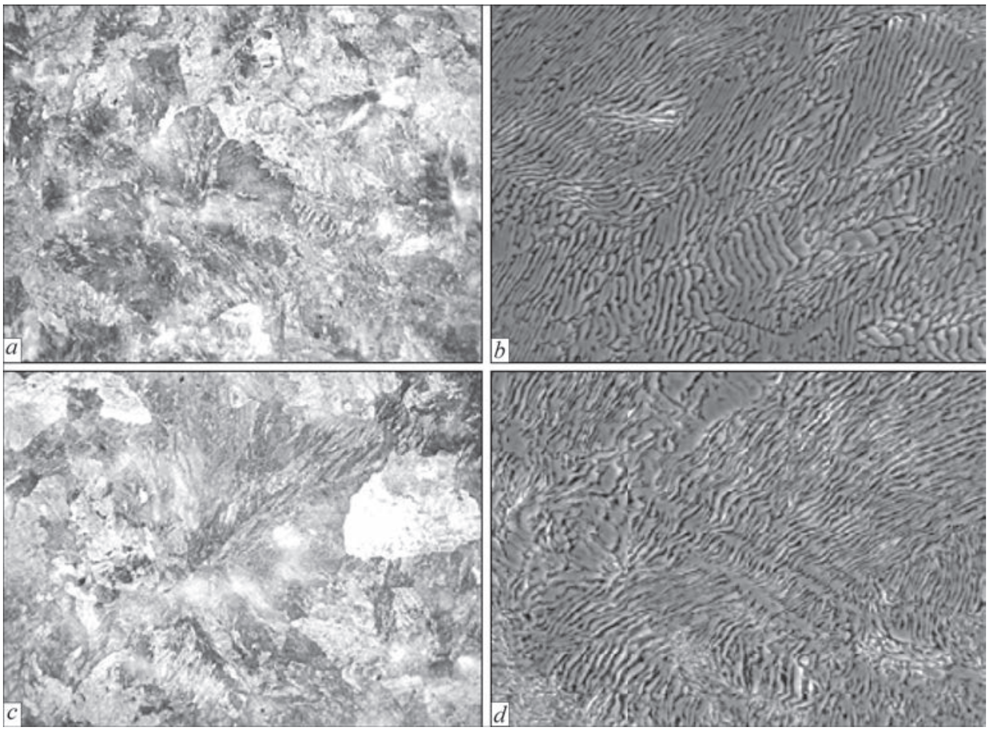


Figure 1. Microstructure (×100): optical (*a, b*) and SEM (*b, d*) of samples of metal of model ESR ingots formed with different drawing speed: *a, b* — 20 mm/min; *c, d* — 40 mm/min

for static (short-time) tension on samples of Mi3 and Mi18 type in MTS 318.25 machine (USA) with processing in TestWorks4 (MTS) software, providing a sufficient accuracy of the results (± 0.5 %)

Investigations of the structure and properties of cast and deformed metal of ESR ingot. Metal of ESR rail steel ingots has a homogeneous dense structure. No defects were found. The size of pearlite grains in ESR ingot at the drawing rate of 20 mm/min is equal to 100–120 μm, that of subgrains is 20–30 μm, whereas the size of pearlite grains in the ingot, produced at the drawing speed of 40 mm/min, is up to 80–100 μm, that of subgrains is 10–15 μm. Thus, even a small lowering of metal feed rate at gradual formation of the ingot has a positive influence on its structure. Density is also increased due to improvement of feeding to replenish shrinkage that promotes avoiding the central ingot heterogeneity.

Metal of both the ESR ingots has a typical homogeneous pearlite microstructure with thin cementite lamels (Figure 1). Measurements of interlamellar distance in pearlite showed close results for metal of both the ingots (0.74 and 0.56 μm for ingots with drawing speed of 20 and 40 mm/min, respectively). Pearlite dispersity in the ingot metal after ESR is smaller than that usually observed in rail steel samples after deformation and heat treatment (about 0.2 μm). It should, however, be taken into account that this is cast metal without deformation or heat treatment.

Results of spectral chemical analysis of metal before and after electroslag remelting are given in Table 2. Analysis of element content shows correspondence to K76F steel grade composition, according to DSTU 4344:2004. Lowering of silicon and sulphur content is observed.

Welding of templates from cast and slightly deformed (further on — deformed) ESR rail steel was performed in K1000 stationary machine, developed by PWI, in the same modes. Butt welded joints of plates 350–400 mm long after flash removal were cut into samples for comprehensive metallographic studies and mechanical testing, in order to assess the produced joint quality.

Cast metal templates for welding were assembled so that FBW joints formed in the longitudinal section of model ESR ingots with two variants of crystal growth direction: in the direction of growth (butt welded joint connects the central parts of the longi-

Table 2. Chemical composition of rail steel K76F before and after ESR

Grade	Standard	Element content, wt.%						
		C	Mn	Si	V	Al	P	S
K76F	DSTU 4344:2004	0.71–0.82	0.8–1.3	0.25–0.45	0.03–0.07	0.025	0.035	0.04
	After ESR	0.76	0.93	0.11	0.05	0.020	0.035	0.020

Figure 2. Welded butt joints of deformed ESR metal

tudinal templates) and with rotation through 180° so that the butt joint connected the worst zones of ESR ingot, namely the head and bottom parts. Deformed metal was welded along the rolling direction. Figure 2 shows the general view of the welded joint. Flash of 13–25 mm width, and 12–13 mm height formed on the surface of welded butt joints. The width of welded joint HAZ is up to 30 mm to each side.

Metal structure in all the ESR rail steel butt joints is ferrite-pearlite, with zones characteristic for welded joints (Figure 3). Microstructure of welds from cast and deformed metal is homogeneous and consists of equiaxed grains of approximately the same size.

Cementite precipitation is observed along the grain boundaries in weld metal (Figure 3, *a, d*), which is more pronounced for the cast metal welds. It is natural, as the characteristic pattern is found also in the structure of ESR metal — base metal of the welded joint (Figure 3, *c*). In the HAZ, the structure of both the cast and deformed metal is practically identical due to recrystallization under the impact of the temperature cycle of welding. In the HAZ region, cementite fringes are located not around the grain contour, but as fragments, as a result of grain refinement.

The grain size of cast ESR metal was evaluated in all the welded joint zones (using Tescan computer program). It is found that in the butt joints of cast templates the average grain size is equal to 87 μm, 60 μm in the HAZ, 85 μm in the weld, and in butt joints of deformed metal it is 54, 61 and 87 μm, respectively.

Results of mechanical testing of the cast and deformed ESR metal before welding and of FBW joints are given in Table 3.

Ultimate strength values for cast ESR metal after heat treatment are lower by 10 %, as are its ductile properties that is due to the stressed state of metal in the cast state, which can be relaxed by heat treatment. At the same time, in both the cases, these values are in the range of requirements made of nonthermostrengthened K76 rails, in keeping with GOST R 51045–97.

Evaluation of mechanical properties of metal in FBW joints of ESR rail steel showed no anisotropy of the ingot metal (head-bottom) (see Table 3). Sample

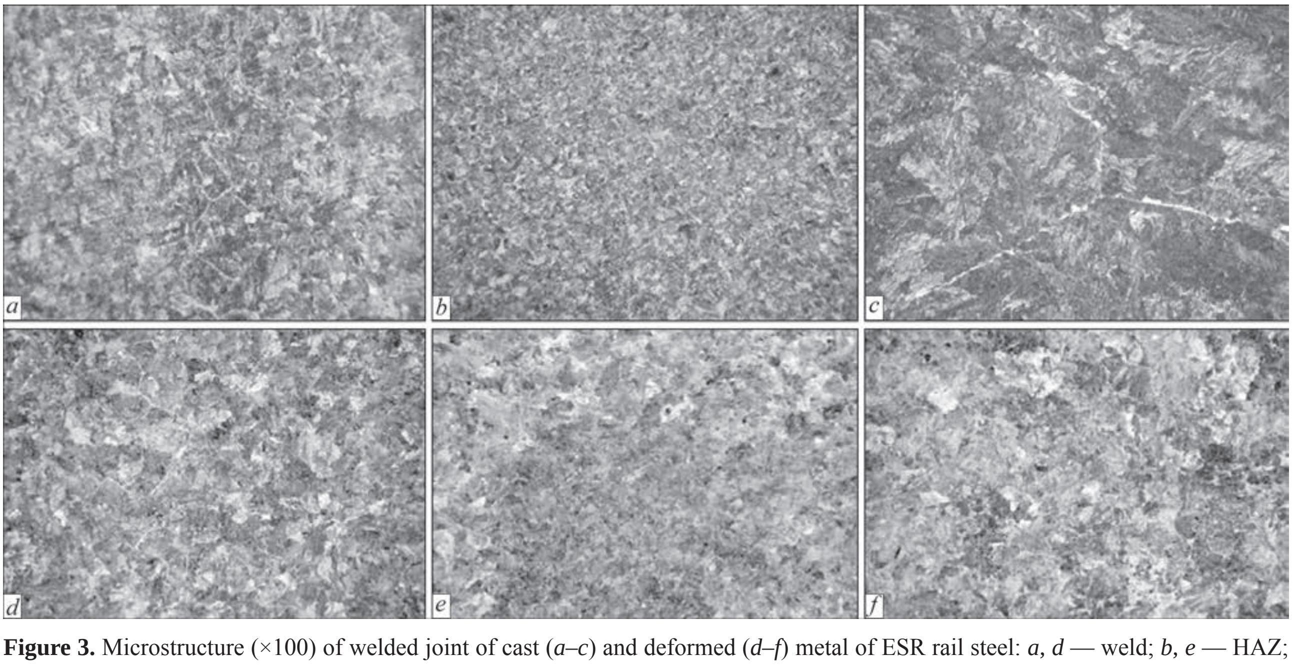


Figure 3. Microstructure (×100) of welded joint of cast (*a–c*) and deformed (*d–f*) metal of ESR rail steel: *a, d* — weld; *b, e* — HAZ; *c, f* — BM

Table 3. Mechanical properties of cast and deformed metal of ESR rail steel before welding and of FBW joints

Metal state		σ_t, MPa	δ, %
Before welding	Cast	871–887	2–3
	Deformed	954–959	4–5
After FBW	Cast	647–795	2–3
	Deformed	989–995	4–5
GOST R 51045–97		780 (for nonthermo-strengthened)	3

fracture occurred in the HAZ, and in some of the samples — in the base metal, that in our opinion is related to the hereditarily coarse grains in the cast ESR metal. The strength level of butt joints of cast ESR metal is, on average, 27 % lower than that of the wrought one, and its ductility is also lower. At the same time, a significant refining of the structure, observed in HAZ metal, confirms the need for application of heat treatment to improve the properties of cast ESR metal.

Fracture of butt joints of FWB templates of ESR metal after deformation occurred in the HAZ metal at 45–55 mm distance from the fusion line (see Figure 2). Strength and ductility index of the welded joint are somewhat higher than those for the initial deformed ESR metal (Table 3), that may be due to different size of samples and measurement accuracy.

Fractographic analysis of fracture surfaces showed the mixed nature of fracture in the cleavage and displacement modes for all the studied variants. Fracture initiated by the cracking mechanism, and ended by quick development of complete fracture, that is indicated by presence of ductile component in the complete fracture section (Figure 4, *a*, *b*). The main part of the fracture surface is represented by the brittle component that is characteristic for the high-strength rail steels, the dimensions of cleavage being larger in cast steel samples that corresponds to larger size of the grains.

ImagePro computer program was used to evaluate the fraction of the ductile component on fracture surfaces of cast and deformed metal welded joints (Figure 5). Content of the ductile component in cast ESR metal is up to 18 %, in cast metal welded joint it is 16 %, and in the deformed metal it is 24 and 23 %, respectively. Higher content of the ductile component in the deformed metal is due to grain refinement.

At surface examination, the ductile component looks different by its darker gray colour and mat surface, but by its chemical composition it does not differ from the brittle component (Figures 6, 7).

Inclusions of manganese sulphide and aluminium oxide were found on the ductile component surface, and predominantly manganese sulphide inclusions were observed in the brittle component.

Metallographic studies of the cast and deformed ESR metal showed that heating before rolling and slight deformation of metal (degree of deformation of 4:1) provided 1.5 times refinement of the size of metal grains. This difference is leveled out in the HAZ and weld metal of butt joints. However, the large grain size in rail steel of the electroslag ingot (in the cast

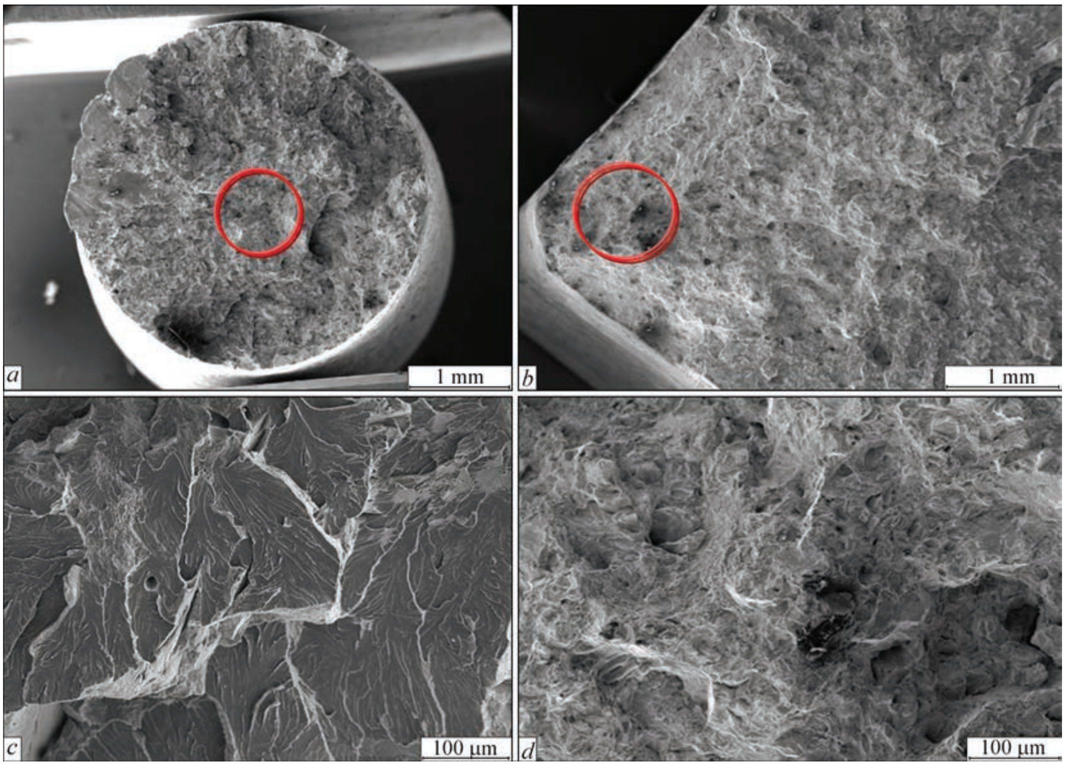


Figure 4. Macro- (*a*, *b*) and microfractograms (*c*, *d*) of welded joint fracture surfaces after mechanical tests of the cast (*a*, *c*) and deformed (*b*, *d*) ESR metal

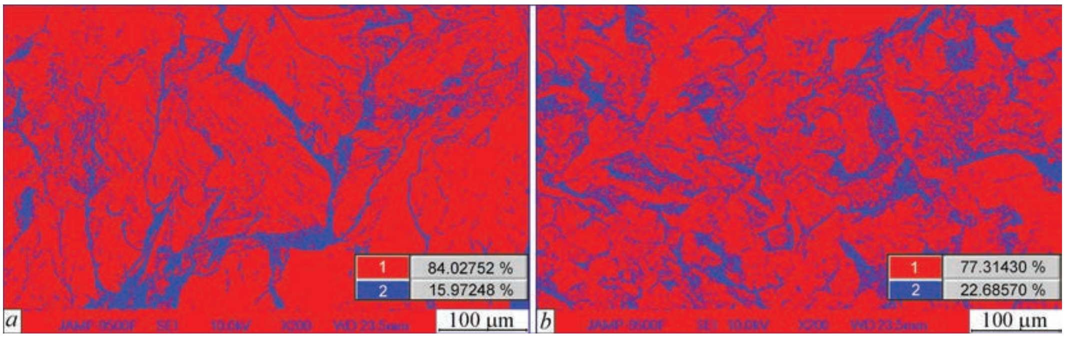
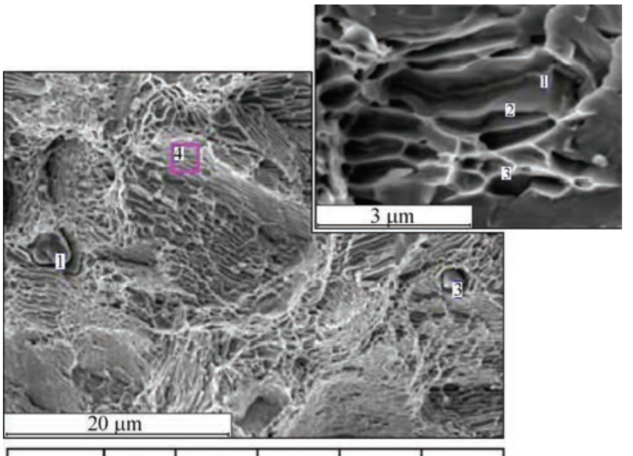


Figure 5. Ductile component of fracture surface of welded joint of cast (*a*) and deformed (*b*) metal of ESR rail steel: *1* — brittle component; *2* — ductile component



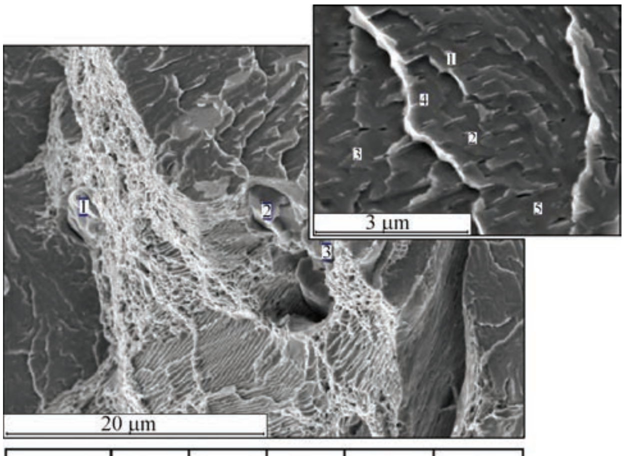
Spectrum	C	O	Al	S	Mn
1	2.23	0.63	0.03	34.37	58.75
2	2.17	0.35	0.06	27.20	55.13
3	1.88	42.73	27.99	0.58	0.84
4	2.05	0.83	0	0	1.34

Figure 6. Microfractoram of ductile component of fracture surface of ESR rail steel metal

state) impairs the welded joint properties that can be changed by application of heat treatment. Development of heat treatment modes will be the subject of a separate study.

In conclusion it should be noted that ESR rail steel in the cast and deformed state has a dense and homogeneous structure with a set of properties within the range of requirements, made of non-thermostrengthened K76 rails by GOST R 51045 and DSTU 4344, that opens up the prospects for manufacture of rails, including rail tongues, applied in the as-cast state.

ESR rail steel in the cast and slightly deformed state can be welded by flash-butt welding. Testing of metal of flash-butt welded joints of rail steel, produced in the laboratory, showed that the microstructure of the metal of the weld and HAZ in both the cases features a homogeneous dense structure. Sample fracture occurred predominantly in the HAZ. Strength



Spectrum	C	O	Al	S	Mn
1	2.06	0.17	0	24.39	51.01
2	2.20	0.96	0	35.69	55.90
3	0.21	3.58	3.07	14.24	70.85

Figure 7. Microfractogram of brittle component of fracture surface of ESR rail steel metal

of welded joints of as-cast metal is lower than that of slightly deformed one that is, apparently, due to the coarse grains, the size of which can be refined by application of heat treatment.

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