https://doi.org/10.37434/tpwj2020.07.01

EVALUATION OF QUALITY OF WELDED JOINTS OF HIGH-STRENGTH RAILWAY RAILS OF MODERN PRODUCTION TAKING INTO ACCOUNT THE REQUIREMENTS OF UKRAINIAN AND EUROPEAN STANDARDS

S.I. Kuchuk-Yatsenko, E.V. Antipin, O.V. Didkovskyi, V.I. Shvets and **O.V. Kavunichenko**
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

In most heavy-duty railways of Ukraine, flash-butt welding is the dominant process for joining rails. Welding is performed in special shops and in field conditions during the construction of new main lines and repair of existing railways. Technologies and equipment are constantly being improved in connection with the use in the railways of Ukraine and other countries of the world, of new generations of high-strength rails with an increased wear resistance, in accordance with the requirements to high-speed main lines. In the last decade, the developed countries of the world are revising the basic standards governing the quality of rail steels and requirements to mechanical properties of rail welded joints, taking into account their use on heavy-duty and high-speed main lines. One of the specified tasks is the adaptation of the Ukrainian standard TU U 24.1-40075815-002: 2016 (for stationary and mobile welding machines), which determines the requirements to the quality of welded joints of high-strength rails, to the valid European standard EN 14587-1 2007 (for stationary welding machines) and EN 14587-2 2009 (for mobile welding machines). 9 Ref., 4 Tables, 12 Figures.

K e y w o r d s : flash-butt welding, railway rails, high-strength rail steels, pulsed flashing, heat-affected zone, temperature fields, rail defects, quality control, seamless track

In the majority of heavy-duty main railways of Ukraine, flash-butt welding is the dominant process for joining rails. Welding is performed in special shops and in the field conditions during construction of new main lines and repair of railway tracks in service. Here, stationary machines of K1000 type and mobile machines of K922-1 type are used, which were developed by PWI and manufactured by PJSC KZESO. The mentioned machines are also used in many countries of the world (RF, PRC, USA, Poland, Malaysia, Baltic countries, etc.). They were supplied by license agreements with PWI. The design of the main components of these machines and control systems is based on application of the technology of continuous flash (CF) butt and pulsed flash (PF) butt welding [1, 2].

Technologies and equipment are being continuously improved in connection with application in the railways of Ukraine and other countries of the world of new generations of high-strength rails with increased wear resistance, in keeping with the requirements to high-speed main lines. In the last decade, the developed countries of the world are revising the main standards regulating the quality of rail steels and requirements to mechanical properties of rail welded joints, taking into account their use in heavy-duty and high-speed main lines. PWI, together with the enterprises of JSC «Ukrzaliznytsa», takes part in this work. One of the posed tasks is adaptation of Ukrainian standard TU U 24.1-40075815-002:2016 (for stationary and mobile welding machines) that determines the requirements to the quality of welded joints of high-strength rails, to the valid European standard EN 14587-1 2007 (for stationary welding machines) and EN 14587–2009 (for mobile welding machines) [3].

At present high-strength rails of both domestic and foreign origin are used in the railways of Ukraine. Higher requirements are made to wear resistance, mechanical properties and structure of the welded joints. These requirements are described in the standards of different countries.

Table 1 gives the main requirements, which should be followed at evaluation of the quality of welded joints produced by flash-butt welding, in keeping with Ukrainian (TU U 24.1-40075815-002:2016) [4] and European (EN 14587-1 2007 and EN 14587-2009) standards.

All the investigations mentioned in the standard, are performed in full scope at certification of weld-

S.I. Kuchuk-Yatsenko — https://orcid.ord/0000-0002-1166-0253, E.V. Antipin — https://orcid.ord/0000-0003-3297-5382,
O.V. Didkovskyi — https://orcid.ord/0000-0001-5268-5599, V.I. Shvets — https://orcid.ord/0000-0003-4653-7453,
O.V. Kavunichenko — https://orcid.ord/0000-0002-5164-9796

Table 1 Comparison of the Ukrainian and European standards for welding the railway rails

Controlled parameter	EN 14587-1:2007	EN 14587-2:2009	ТУ У 24.1-40075815-002:2016
Mechanical testing			
Breaking load on the head, kN	1600	1600	1650
Breaking load on the foot, kN	Not tested	Not tested	1400
Deflection, mm	20	20	30
Macrostructure			
Minimum HAZ width, mm	25	20	Not controlled
Maximum HAZ width, mm	45	45	Same
Admissible difference between HAZ max and HAZ min, mm	10	20	»
Macrostructure			
Presence of martensite and bainite structure	Not allowed	Not allowed	Not controlled
Hardness distribution			
Unhardened rails (R260, R220, R260Mn, M76), *HV*30	min *P* = *HV*30–30 max *P* = *HV*30–60	min *P* = *HV*30–30 max *P* = *HV*30–60	min *P* = 10 % *HV*30
Heat-hardened rails (R350HT, K76F, E76F, K76T)), *HV*30	min *P* = *HV*30–325 max *P* = *HV*30–410	min *P* = *HV*30–30–325 max *P* = *HV*30–410	min *P* = 15 % *HV*30
Fatigue testing			
Cycle number, mln	5	5	Not controlled
Loading, kN	190	190	Same

*Data are given for rails of R65 and 60E1 (UIC60) type from steel grades R260, R220, R260Mn, M76, R350HT, K76F, E76F, K76T.

ing technology, welding equipment, as well as when training the welding machine operators.

Comparison of the standards shows that they differ not only by the characteristics that belong to mechanical testing of the welded joints, but also by analysis of the features of the HAZ microstructure and dimensions.

For comprehensive evaluation of the quality of welded joints of high-strength rails, as well as rails used in the railways of Ukraine, of M76, K76F type, produced by PJSC MW «Azovstal» (Mariupol, Ukraine) and rails from imported steels R260 and R350HT (British Standard French rail), PWI employees, together with specialists of JSC «Ukrzaliznytsa» and PJSC «KZESO» welded control batches of rails from different steel grades (in the quantity of 10 butt joints) in the mobile machine of K922-1 type with their further investigation, in keeping with the given standards (see Table 1).

Chemical composition and mechanical properties of control batches of rails, which were used for the investigations, are given in Table 2.

Practically all the rails in the railways of Ukraine are welded using the technology of pulsed flash-butt welding (PF) [5], which was developed at PWI. That is why, it was exactly the technology used for welding control batches of rails.

A typical program of the change of parameters in PF welding in shown in Figure 1.

Modes of welding different rails batches are different. It should be noted that in welding high-strength

Table 2 Chemical composition and mechanical properties of control batches of rails

Steel grade	Chemical composition, %				Hardness, *HB*	Strength limit, σ_t, MPa	Yield limit, σ_y, MPa	Operating life, gross t	Manufacturing plant
	C	Mn	Si	V					
M76	0.71–0.82	0.80–1.30	0.25–0.45	–	260–280	800–1100	500–700	0.45	PJSC MW «Azovstal» (Ukraine)
K76F	0.71–0.82	0.80–1.30	0.25–0.45	0.05	341–388	1300–1380	950–1050	0.5	
R260	0.62–0.82	0.70–1.20	0.15–0.58	0.03	250–270	942–980	498–540	0.9	Huta Katowice (Poland)
R350HT	0.72–0.82	0.15–0.60	0.65–0.75	0.03	350–370	1240–1300	840	0.9	British Standard French Rail (France)

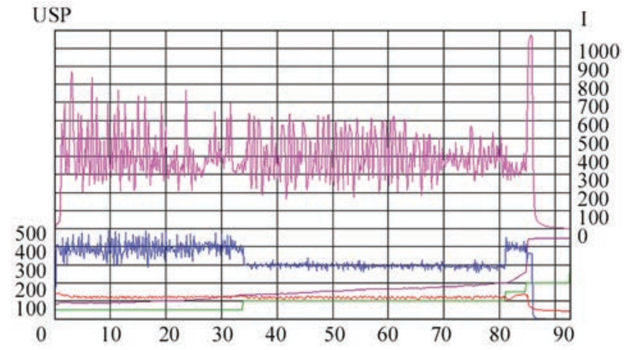

Fig re 1 Program of variation of the main parameters of pulsed flash-butt welding (PF)

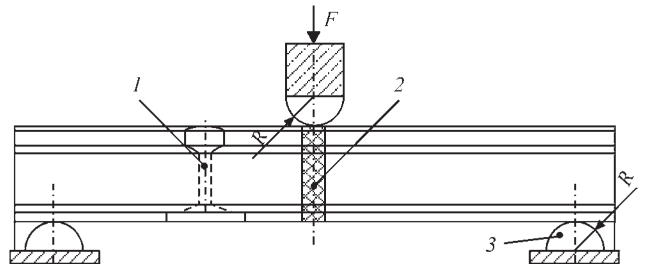

Fig re 2 Scheme of testing the welded butt joint for static mechanical bending (*F* — force; *1* — side view; *2* — weld; *3* — support)

rails of steel grades K76F and R350HT, the modes with limited heat input were used, in order to obtain the required mechanical properties. In welding M76 and R260 rails, having a lower hardness, modes with a larger welding heat input range can be used, with preservation of stable results in keeping with TU U 24.1-40075815-002:2016.

The main parameters that determine PF welding modes are given in Table 3.

Mechn ich testing Mechanical testing of welded joints of control batches of rails were conducted in TRM press with the measurement limit of 500 tf; testing was conducted with tension of the head and foot. Testing procedure is the same for the above standards. The difference of the European standard consists only in that testing is conducted only with foot tension. Test scheme is given in Figure 2.

The main welding quality characteristics, regulated by both the standards (see Table 1), which were obtained during welding of control batches of rails in the optimum welding modes, are given in Table 4.

Results of mechanical testing (see Table 4) showed that in order to obtain the necessary values of mechanical properties of welded joints of high-strength rails, it is necessary to limit and control the heat input in welding and to ensure heating with a higher temperature field gradient.

The values at bend testing in Ukrainian standard TU U 24.1-40075815-002:2016 are higher than the requirements of the European standard EN 14587-2:2009, both as to the deflection, and as to breaking load. Mechanical characteristics at testing the control batches are 1.5 to 2 times higher than the normative values of the European standard and satisfy the requirements of the Ukrainian standard. It should be noted that fine sulphide inclusions not exceeding the requirements admissible by the Ukrainian and European standards, were found in the fractures of some of the studied rails.

Comparison of the controlled characteristics (see Table 1) shows that alongside control of mechanical characteristics for static mechanical bending of welded joints of rails, there is a number of differences, envisaged by the European standard that concern the procedure of quality studies, in particular, met-

Tb le 3 Main parameters of the studied rail batches

Parameter	Rail type			
Steel grade	K76F	R260	R350HT	M76
Welding time, s	70–90	70–100	7–095	80–110
Welding current, A	370–390	350–370	360–390	340–370
Flashing allowance, mm	9–13	12–17	10–14	13–19
Upsetting value, mm	11–14	11–14	11–14	11–14

Tb le 4 Results of studying the quality of welded joints of control batches of rails

Steel grade	Bend testing		HAZ size, mm	Hardness distribution in the HAZ, *HV*	
	Breaking load, kN	Deflection, mm		min	max
K76F	2100–2400 2250	32–50 36	24–29	305	385
R350HT	2150–2400 2200	34–55 40	24–32	320	380
R260	2000–2350 2100	32–55 40	25–35	245	320
M76	1900–2350 2200	32–57 40	25–38	245	308

allographic, hardness measurements, as well as fatigue testing, not envisaged by the Ukrainian standard. Therefore, comprehensive studies of the control batches were conducted, taking into account the requirements of the two above-mentioned standards.

In PF welding of test batches in the optimum modes, the temperature fields were studied, at which sound joints were produced. Investigations were conducted using mathematical modeling of the process of rail heating by the method of flash-butt welding [6, 7], and modeling results are given in Figure 3.

Figure 3 gives the temperature fields in welding the control batches of rails in the optimum modes, and dot-dash lines show the temperature fields, corresponding to limit values of the HAZ width, admissible by European standard EN 14587-2:2009.

All the control batches of high-strength rails of R350HT, K76F steel grade (see Figure 3), differ by a narrower HAZ, and are within the limits, admissible by the European standard. In order to obtain the optimum metal structure in the HAZ, it is necessary to considerably limit the energy input. The temperature field in welding of high-strength rails differs by a higher gradient and smaller HAZ. More stable bending characteristics can be obtained at strict monitoring of the energy input.

High values of mechanical properties were achieved in welding in the optimum modes, which is due to formation in the HAZ metal of a finer structure of pearlite with ferrite precipitates on the grain boundaries, than in welding with a larger heat input. Performed investigations revealed that lowering of energy input in welding due to shortening of the flashing process duration and increase of welding current, allows improvement of the metal structure in the HAZ, while considerably reducing its width.

Investigations of the HAZ width. The standard of Ukraine TU U 24.1-40075815-002:2016 does not have any requirements to HAZ width. In keeping with the European standard, the HAZ width is determined visually by macrosections, as well as by lines of hardness distribution. In these areas, the temperature reaches that of high temperature tempering. Here, the welded joint macrostructure should meet the following EN 14587-2:2009 requirements:

1. The visible HAZ zone of the welded macrosection should have a symmetrical shape within the tolerance around the weld line and it should be within 20–45 mm for mobile machines. The admissible deviation between the HAZ minimum and maximum dimensions should not exceed 20 mm. This requirement should be applied equally to vertical axial sections along the entire rail depth and to the edges of the rail foot.

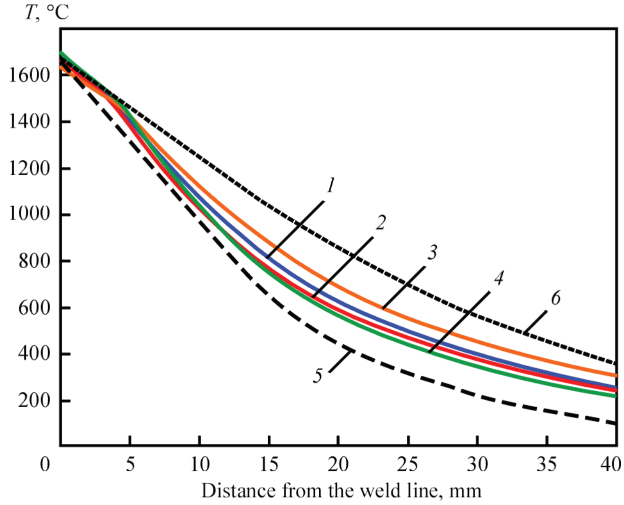

Figure 3 Temperature fields in welding the test batch of rails in the optimum modes: *1* — R260; *2* — R350HT; *3* — M76; *4* — K76F; *5* — min; *6* — max

2. There should be no indications of the joint absence, inclusions, cracks or shrinkage deformation.

3. Two flat spots are allowed on the weld line, which meet the following requirements:

- maximum vertical size of 10 mm and maximum thickness of 0.7 mm in the case, if the flat spots look like the densification of the weld line, and do not have a lens like shape;
- maximum vertical size of 4 mm and maximum thickness of 0.7 mm in the case, if the flat spot is lens-shaped;
- there should be no embrittlement as a result of welding, cooling or heat treatment.

Figure 4 shows the macrosections of welded joints of control batches.

HAZ width (Figures 3, 4) in welding high-strength and high-alloyed rails changes within 26–32 mm that is by 4–6 mm smaller than in welding rails of M76 type with lower strength and smaller content of such alloying elements as C, Mn.

It should be noted that welding of all control batches of rails was performed without post-weld heat treatment, which is used at contact welding of rails in foreign practice to improve the values of mechanical properties of the welded joints.

As one can see from the results, in order to obtain high mechanical properties, it is necessary to reduce the heating zone width to a greater extent for high-strength rails, than for rails with a lower hardness. The required HAZ can be determined by the temperature field obtained after welding in the optimum mode. It is also possible to determine the maximum admissible deviations of the HAZ from the optimum one, as in keeping with the European standard the deviation field is quite broad.

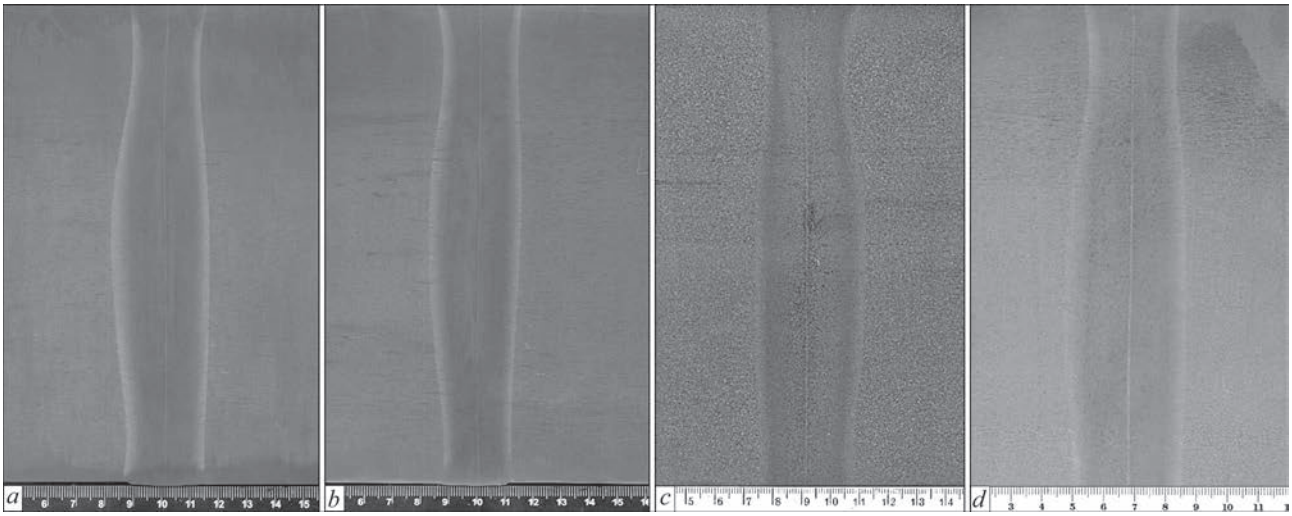

Figure 4 Macrosections of rails of different steel grades in pulsed flash-butt welding in the optimum modes *a* — R350HT (HAZ — 28 mm); *b* — K76F (HAZ — 27 mm); *c* — R260 (HAZ — 31 mm); *d* — M76F (HAZ — 37 mm)

One can see from the macrosections that HAZ width of the studied rail batches corresponds to the temperature fields obtained at modeling the process of flash-butt welding in the optimum modes. It should be also noted that in all the rail batches the deviation of the HAZ width across the entire cross-section is insignificant and does not exceed 10 mm that satisfies the requirements of the European standard (maximum admissible deviation of the HAZ width over the rail cross-section is 20 mm for mobile machines).

Hardness studies. Hardness studies were performed in batches of welded rails, which are shown in Figure 5. Investigations were conducted by the procedure which is specified by the European standard.

Hardness measurements were performed over the entire near-weld zone of each of the two welded samples, directly from their joint line, using the method of Vickers hardness testing, in keeping with EN ISO 6507-1 and with subsequent parameters:

- *HV* 30;

measurements should be taken 3–5 mm below the working rolling surface of the rail. Distance between the measurements should be 2 mm;

- width measurement is taken at not less than 20 mm distance from the weld through the HAZ into the base metal of the welded rails.

Here, in keeping with the European standard, different deviations of hardness distribution are allowed for different steel grades.

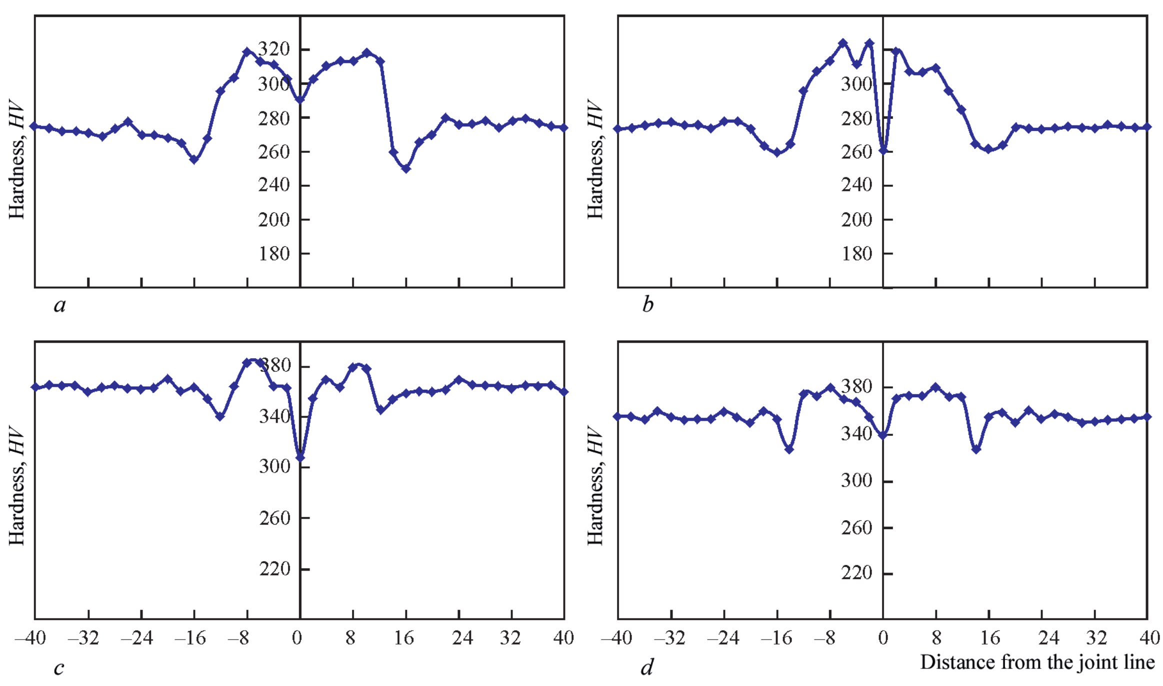

Figure 5 Hardness distribution in welded rail batches: R260 (*a*); M76 (*b*); K76F (*c*); R350HT (*d*)

Rails of steels grades R220, R260 and R260Mn. For R220, R260, and R260Mn rails the obtained values of minimum and maximum strength should meet the following requirements:

a) minimum strength *P* should not be smaller than *HV*30 — 30;

b) maximum strength *P* should not exceed *HV*30 — 60, where *P* is the average strength of the initial rail, measured in hardened rail traverse.

In particular, the hardness value that goes beyond the limits of the above minimum and maximum values should be allowed, if such a hardness value is within the limits of two adjacent values that correspond to the requirements.

Rails of R350HT steel grade. For R350HT rails the values of minimum and maximum strength, obtained within 10 mm on each side from the weld line, should meet the following requirements:

● minimum hardness should not exceed *HV*30 — 325;

● maximum hardness should not exceed *HV*30 — 410.

In particular, the hardness value that exceeds the above minimum and maximum values should be allowed only in the case, when it is on the weld line.

Hardness decreases in the weld center, where a structure of sorbite-pearlite and areas of the ferrite phase form. In the weld central part, where the sorbite structure prevails, the hardness value is maximal. Hardness lowering is observed also along the HAZ boundaries, where presence of high-temperature tempering structure, which forms at temperatures of 580–620 °C, is observed. Temperature rise in the areas, adjacent to the weld center, depends on the temperature field gradient and temperature of the HAZ region.

Heat input determines the cooling rate of the butt joint – the lower the heat input, the higher the cooling rate. In its turn, the cooling rate determines the temperature of austenite decomposition. Lowering of decomposition temperature is the cause for reduction of interplate distance in sorbite and, consequently, hardness increase.

Heat-hardened rails of K76F and R350HT steel grades feature a high hardness, unlike M76 and R260 rails. That is why these rails require different energy input in welding. In welding of high-strength rails, it is necessary to avoid large hardness dips in the HAZ, and in welding rails with a low hardness, the large increase of hardness in the near-weld zone should be avoided. Maximum hardness deviations in the HAZ metal are regulated by the European standard.

As one can see (Figure 5), investigation results correspond to the requirements of the European standard.

Metallographic investigations. In the Ukrainian standard, metallographic examination of welded joints is not envisaged. Microstructural studies of rail steels R260 and R350HT, as well as of the microstructure of welded joints of control batches of rails (Figure 6), were conducted, in accordance with the European standard. The welded joints should have no indications of martensite or bainite at 100fold magnification of the visible zone due to heating impact. Microstudies are conducted on samples 15 mm high and 25 mm wide. Here, the sample should be cut out of the rail head 3 mm below the rolling surface. The sample should include 2 mm on one side of the weld, the joint line and 23 mm on the other side of the weld.

Base metal of R260 and R350HT rails has the structure of sorbite-pearlite. The microstructure of rails of R350HT grade, compared with that of rails of R260 grade, is characterized by a smaller size of sorbite colonies, and a small number of pearlite colonies. The grain size of the metal of R260 grade rails corresponds to numbers 2–3, and that of rails of R350HT grade — to numbers 4–5 by ASTM scale. The above enumerated structural factors determine the strength properties of heat-hardened rails.

In welded joints of R260 (Figure 7) and R350HT (Figure 8) rails in the areas of the joint line and coarse grain, the microstructure is that of sorbite-pearlite. Precipitation of hypoeutectoid ferrite is observed along the joint line, on the boundaries of primary austenite grains.

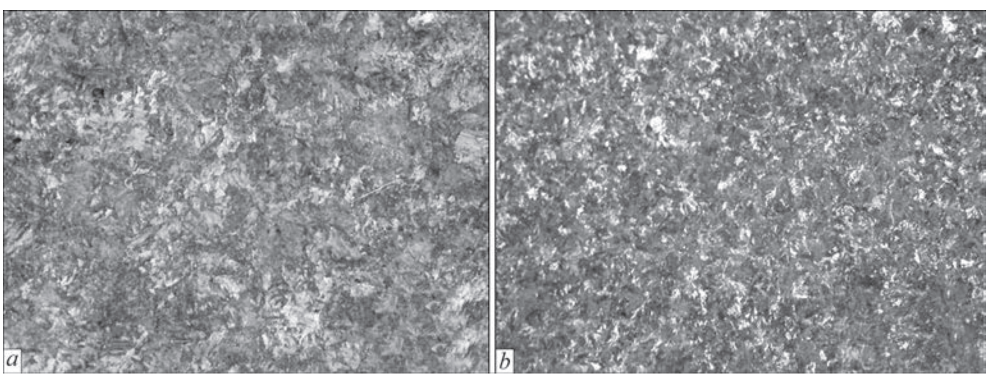

Figure 6. Microstructure (×100) of rail steel of the following grades: *a* — R260; *b* — R350HT

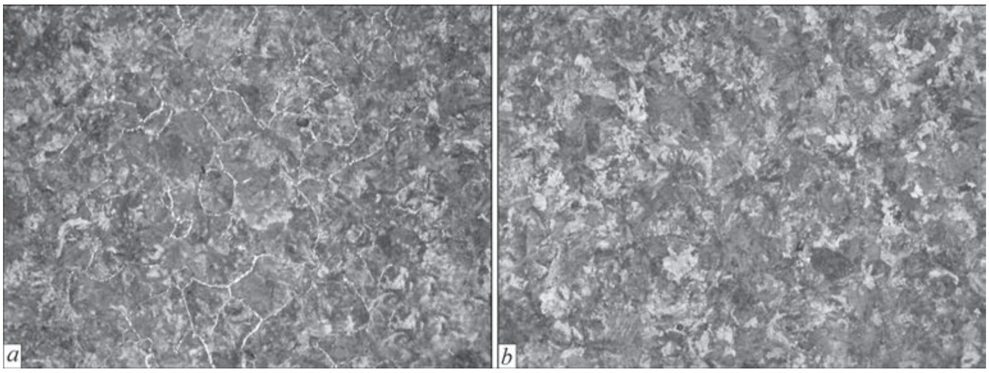

Figure 7 Microstructure (×100) of a welded joint of R260 rails in the head zone: *a* — joint line; *b* — coarse grain region

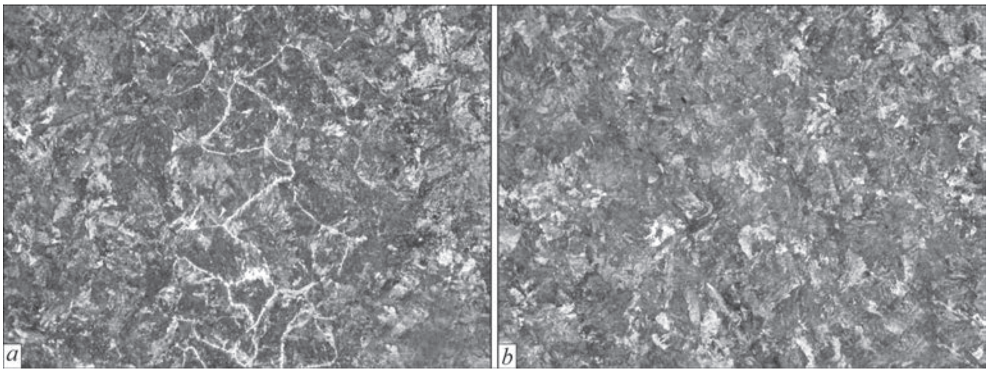

Figure 8 Microstructure (×100) of a welded joint of R350HT rails in the head zone; *a* — joint line; *b* — coarse grain region

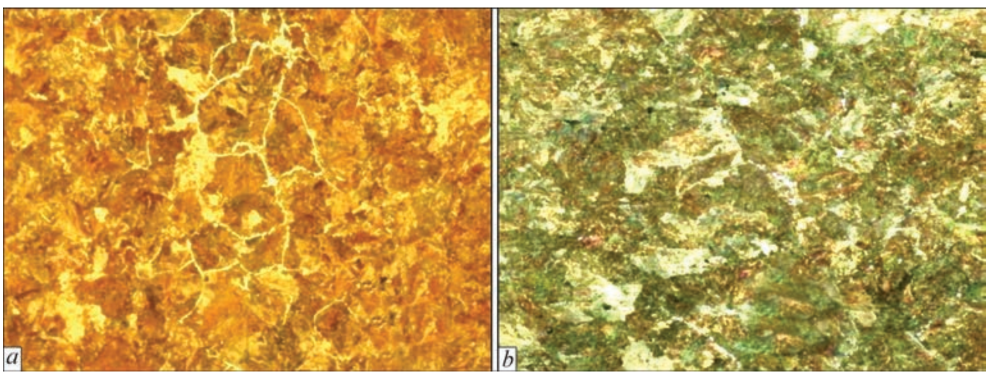

Figure 9 Microstructure (×100) of a weld of rail of the following grade: *a* — M76 and *b* — K76F along the joint line

Ferrite precipitation in a much smaller amount is observed in the coarse grain areas, adjacent to the joint line. Characteristically, in rails of R260 grade the fraction of ferrite is greater, both along the joint line, and in the coarse grain regions.

Base metal of rails of K76F and M76 grade has sorbite-pearlite structure. The microstructure of the joint line of rails from steels of M76 and K76F grade was also studied in pulsed flash-butt welding (Figure 9). The welded joints of K76F rails have more visible ferrite than those of R350HT and R260 rails.

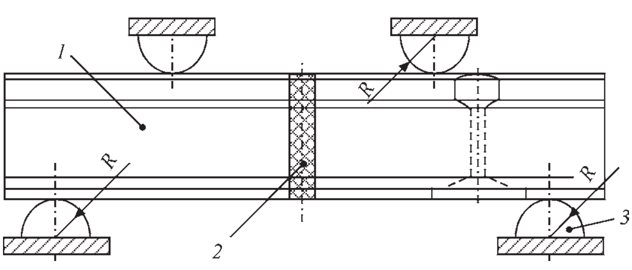

Figure 10 Fatigue strength testing of a welded joint: *1* — side view; *2* — weld; *3* — support

As a result of comparison, it can be noted that no traces of bainite or martensite structures were revealed in welded joints of the studied rail batches, produced in the optimum modes. Moreover, the welded samples of rails of the control batches were tested by UT means and by dye-penetrant method, in keeping with the European standard procedures. No defects were found in the welded joints.

Fatigue strength testing. Also in accordance with the requirements of the European standard, all the butt joints were subjected to fatigue strength testing (Figure 10). Fatigue testing of samples of rails of R260 and R350HT steel grades were conducted, in keeping with EN 14587-2:2009E normative document in ZDM-200Pu testing machine, certified by the appropriate state services. Test welded butt joints of rails from control batches 1.2 m long were tested by pure bending by cyclic loading with maximum cycle stresses of 190 MPa, and loading cycle asymmetry of 0.1. Test base was 5.0 mln. cycles, and loading frequency was 5 Hz. Samples withstood 5 mln cycles without fracture.

It was found that in the case of application of PF technology the mechanical, and strength properties and the structure of the joints, required in keeping with the European and Ukrainian standards, are ensured.

Analysis of results of studying the mechanical properties and structure of welded joints shows the high stability of properties at mechanical testing and evaluation of structural changes in the welded joints. The HAZ width is in the lower value range. This is due to the fact, according to the Ukrainian standard, the deflection should be not less than 30 mm, compared to the deflection of 20 mm, specified by the European standard. In order to obtain higher ductility properties according to the standard of Ukraine, the modes of welding with controlled energy input were developed. It allows producing a finer structure in the weld central part at admissible hardness deviation. Therefore, the HAZ width in the control batches of welded samples of rails is equal to 27–31 mm, that is within the tolerance field of this parameter, but in the region close to the minimum admissible one (20 mm), hardness remaining within the limits admissible by the European standard.

Optimum values of the characteristics, satisfying the requirements of the considered standards, were determined on the base of the conducted experimental studies of the mechanical properties and structure of metal of the control batches of rails.

No inclusions of martensite and bainite type were found in the structure of the HAZ metal of all the rail batches. A mathematical model of temperature field calculation at flash-butt welding of railway rails was used to predict the probable appearance of such structures, at the possible determined welding modes [6, 7].

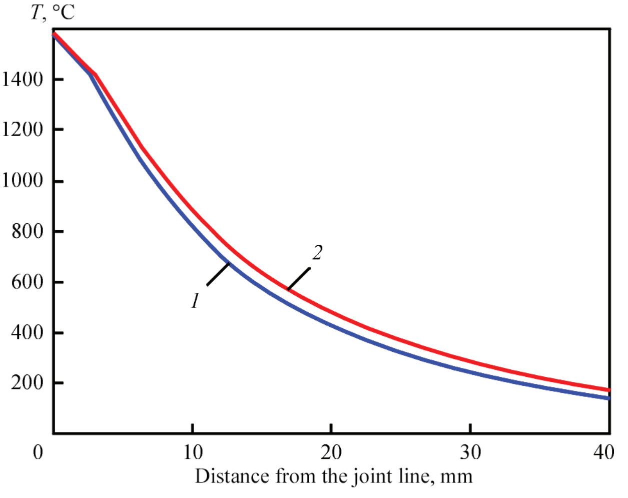

Figure 11. Welding of rails of R350HT (*1*) and R260 steel grades with lower energy input

As is known, HAZ width and its admissible deviations in keeping with the European standard are given in Table 1. Taking into account the performed calculations, mathematical modeling should be used to determine the minimal admissible width of the HAZ for the studied rail steels. It was also established that heating and total heat input should be reduced within reasonable limits, as it is accompanied by increase of the cooling rate, metal grain refinement in the HAZ, as here the probability of formation of defects of oxide spot type in the joint plane becomes higher [8]. In addition, there arises the need for appearance of hardening structures, such as martensite and bainite, in the HAZ metal.

The developed mathematical model, as well as the conducted experiments, was used to establish that appearance of bainitic and martensitic structures in the HAZ metal in welding high-alloyed and high-strength rails of E260 and R350HT type can be expected at formation of temperature fields with HAZ width of approximately 17–20 mm, given in Figure 11. Lowering of heating and reduction of the HAZ size affects the structure of rails of R260 type to a greater extend,

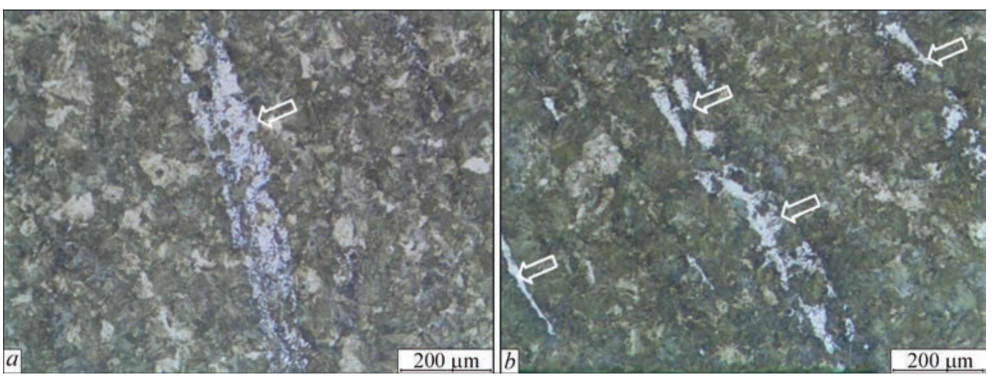

Figure 12. Martensite structures in the near-weld zone of welded joints of R350HT (*a*) and R260 (*b*) rails in welding with lower energy input

and proneness of this steel to appearance of hardening structures, such as martensite and bainite, is high due to their high alloying with Mn.

HAZ width in this case is equal to 17–20 mm. It is experimentally confirmed that at such a heating, martensite structures are present in the welded joint of R260 rails at HAZ width reduction below 20 mm, as shown in Figure 12. Martensite-austenite structures are located both along the rolling lines, and in an arbitrary volume of metal [9]. In welding rails of R350HT and K76F grades appearance of martensite structures was observed at lowering of heating and producing HAZ smaller than 18 mm that is below the value allowed by the European standard.

The highest values of mechanical and strength properties, as well as absence of hardening structures, were achieved in welding high-strength rails with formation of the next region of the temperature fields, which are presented in Figure 3.

At determination of welding modes of high-strength and high-alloyed rail steels of the mentioned types, formation of temperature fields (Figure 11), corresponding to minimum admissible width of the HAZ, specified by the European standard, should be avoided. This requires application of control systems, which allow monitoring the energy input in welding.

Conclusions

Control batches of rails of M76 and K76F grades, made in Ukraine, as well as rails of R260 and R350HT grade, made in Europe, which were welded in the optimum modes in keeping with the standard of Ukraine TU U 27.1-40081293:2016 fully meet the requirements of European standard EN 14587-2 2009.

It was established that development of the technology of welding high-strength rails should take into account the HAZ width as a controlled parameter that significantly affects the welded joint quality.

The effect of the possible deviations from the main welding parameters, which are regulated by the valid Ukrainian standard, on formation of the temperature fields and joint quality in different pulsed flash-butt welding modes was determined experimentally, as well as using the developed procedure of mathematical modeling of the process of metal heating in flash-butt welding.

It was established that in order to obtain high mechanical values in welding high-strength rails of K76F, R260 and R350HT steel grades, it is necessary to apply technologies, which ensure highly concentrated heating with limited energy input. Such heating is provided by pulsed flash-butt welding technology. Here, formation of HAZ of smaller than 20 mm width, which is specified by the European standard as the minimum admissible one, should be avoided.

The optimum programs for controlling the main welding parameters that ensure the required values of strength and structure of high-alloyed and high-strength rails of the studied batches, were determined within the considered standards. All the mentioned rail batches were welded using the main welding parameters that correspond to the Ukrainian standard, allowing for their correction within the admissible limits.

It is recommended to introduce into the Ukrainian standard the definition and control of the HAZ width after welding, taking into account the properties of rail steel, used in Ukraine.

1. Kuchuk-Yatsenko, S.I. (1992) *Continuous flash-butt welding*. Kiev, Naukova Dumka [in Russian].
2. Kuchuk-Yatsenko, S.I., Didkovsky, A.V., Shvets, V.I. (2008) Technology and equipment for flash-butt welding of high-strength rails. *The Paton Welding J*., **11**, 111–120.
3. *TU U 27.1-40081293-002:2016*: New welded rails for railways: Dnipropetrovske NKTB, NDKTI PJSC Ukrzaliznytsya [in Ukrainian].
4. (2009) *Eurostandard EN_14587-1, –2*.
5. Kuchuk-Yatsenko, S.I., Didkovsky, O.V., Bogorsky, M.V. et al. (2002) *Flash-butt welding method*. Pat. 46820, Ukraine, Int. Cl. 6B23K11/04, C2; Pat. 2222415, RF (2003); Pat. 6.294.752, USA (20.06.01); Pat. ZL001016772/5 (2004), PRC.
6. Weingrill, L., Enzinger, N. (2017) Temperature fields evolution during flash-butt welding of railway rails. *Mat. Sci. Forum*, **9**[illegible], 2088–2093.
7. Kuchuk-Yatsenko, S.I., Milenin, A.S., Velikoivanenko, E.A. et al. (2018) Mathematical modeling of the process of metal heating in continuous flash-butt welding. *The Paton Welding J*., [illegible], 2–8.
8. Kuchuk-Yatsenko, S.I., Shvets, V.I., Didkovsky, A.V. et al. (2013) Defects of joints of high-strength rails produced using flash-butt welding. *Ibid*., **9**, 2–8.
9. Zabilsky, V.V., Nikonova, R.M. (2005) Ductile-brittle transition in steels at near-solidus temperatures. Mechanism of embrittlement of grain boundaries. *Fizika Metallov i Metallovedenie*, 99(**3**), 19 [in Russian].

Received 24.06.2020