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FLASH-BUTT WELDING OF HIGH-STRENGTH RAILS OF NOWADAYS PRODUCTION

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Over the recent five years, the high-strength rails of the new generation of type R65 of steel grade K76F of the production of the plant «MK Azovstal» as well as high-strength rails of type R65 of steel grade 76F of Russian production with their welding in continuous welded track are more and more often laid at the railroads of Ukraine. At the E.O. Paton Electric Welding Institute the comprehensive investigations of weldability of these rails were carried out using flash-butt method with the aim of development of industrial technologies. In welding of all the investigated batches of high-strength rails the required values of mechanical properties of welded joints were obtained at welding modes, characterizing by energy input 1.5–2 times lower than that in welding of rails of previous generations. The welding technology using pulsed flashing was developed providing a highly-concentrated heating and formation of quality joints of high-strength rails of different production, as well as the new generation of machines for flash-butt welding of high-strength rails under the stationary and field conditions was developed. 10 Ref., 11 Figures, 3 Tables.

Keywords: *flash-butt welding, flashing, rails, high-strength rails, pulsed flashing, continuous flashing, defects in rails, quality control, continuous welded track*

The laying of high-strength rails of the new generation with their welding in continuous track is more and more widely used at the railroads of Ukraine. Mostly high-strength rails R65 of steel grade K76F of production of «MK Azovstal», as well as high-strength rails R65 of steel grade 76F of Russian production are applied. At the PWI the comprehensive investigations of weldability of these rails were carried out using flash-butt method with the aim of development of industrial technologies for their welding. At the same time, the weldability of modern high-strength rails R350HT produced by well-known companies «Voestalpine Schienen GmbH» (Austria), and rails VS-350Ya 350LDT of «Nippon Steel» (Japan) was also investigated. Table 1 shows chemical composition and mechanical properties of the mentioned steels.

In the manufacture of all the investigated rails the advanced technologies of converter production with the continuous casting of steel and continuous rolling are used.

For the rails of steel K76F the differentiated hardening and for steel 76F the volumetric one are used. The hardness of layer of steel K76F hardened over the surface of rail head is *HV* 374–401 (Figure 1), the depth of the hardened layer is different and amounts from 7 to 15 mm. The hardness of the base material is

Table 1. Chemical composition of rails steel of different manufacturers and grades

Steel grade (country)	Chemical composition, wt.%					
	C	Mn	Si	V	Ti	Cr
K76F (Ukraine)	0.71–0.82	0.80–1.30	0.25–0.45	0.03–0.07	–	–
76F (Russia)	0.71–0.82	0.75–1.05	0.25–0.45	0.03–0.15	–	–
VS-350Ya 350LDT (Japan)	0.72–0.82	0.7–1.2	0.35–1	0.01	0.025	0.3–0.7
R350HT (Austria)	0.72–0.82	0.15–0.60	0.65–0.75	0.03	–	0.15

Table 1 (cont.)

Steel grade (country)	Chemical composition, wt.%			Mechanical properties		
	P	Al	S	Tensile strength σ_t, MPa	Yield strength $\sigma_{0.2}$, MPa	Hardness *HB*
K76F (Ukraine)	0.035	0.015	0.045	1196	800	341–388
76F (Russia)	0.025	0.02	0.03	1280	870	370–409
VS-350Ya 350LDT (Japan)	0.025	0.005	0.02	1240	860	362–400
R350HT (Austria)	0.025	0.004	0.03	1175	840	350–390

in the range of *HV* 250–300. The microstructure of all the rail steels mentioned in Table 1 is sorbite, the precipitates of free ferrite are almost absent (Figure 2). The characteristic feature of hypereutectoid rail steel VS-350Ya is the presence of primary austenitic grains, and precipitates of iron carbide along the boundaries. It should be noted that R350HT rails are characterized by a coarse primary austenitic grain, the grain number is estimated as 3–4. A somewhat smaller austenitic grain size is in rails K76F. The structure of steel for rails VS-350Ya and 76F is finer, the number of their austenitic grain is 5–6.

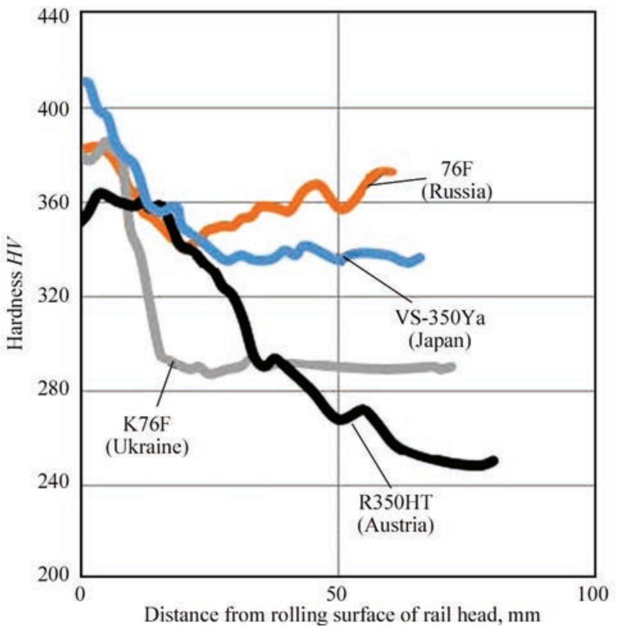


Figure 1. Distribution of hardness in the rail base metal in the vertical plane

The welding modes using continuous flashing (CF) are determined by the programs of changing the basic parameters given for rails R65 in works [1, 2]. As the basic parameter determining energy input, the duration of flashing was accepted, which for rail R65 amounts to 180 s. The welding of reference batches of rails of 10 pcs was carried out in stationary machine K1000 and also in mobile machine K922 (both machines are of the PWI design and manufactured at Kakhovka Plant of Electric Welding Equipment. After flash removal the welded specimens of rails of 1.22 m length were tested for static mechanical bending according to the standard procedure accepted in the world practice [3]. The metallographic examinations of welded joints were carried out in light microscope «Neophot 32», fractographic investigations and micro X-ray analysis of the fracture surface were performed in the JEOL Auger-microprobe JAMP 9500F. The batches of rails 76F were preliminary welded using CF welding technology [4]. Such a technology is successfully applied at the railroads of Ukraine, CIS countries and other countries where rail welding equipment, designed at the PWI, is used. At the same time, the required values of mechanical properties of welded joints of non-hardened rails are provided.

For welded joints of high-strength rails the minimum values of fracture loads and bending deflections, specified by the Technical Specifications, are given in Table 2. In the Table (mode 2) the test results on static bending of high-strength batch of rails, welded using CF, are given. As is seen from the data, the fracture load in the tests meets the standard requirements and the values of deflection are significantly lower. On the

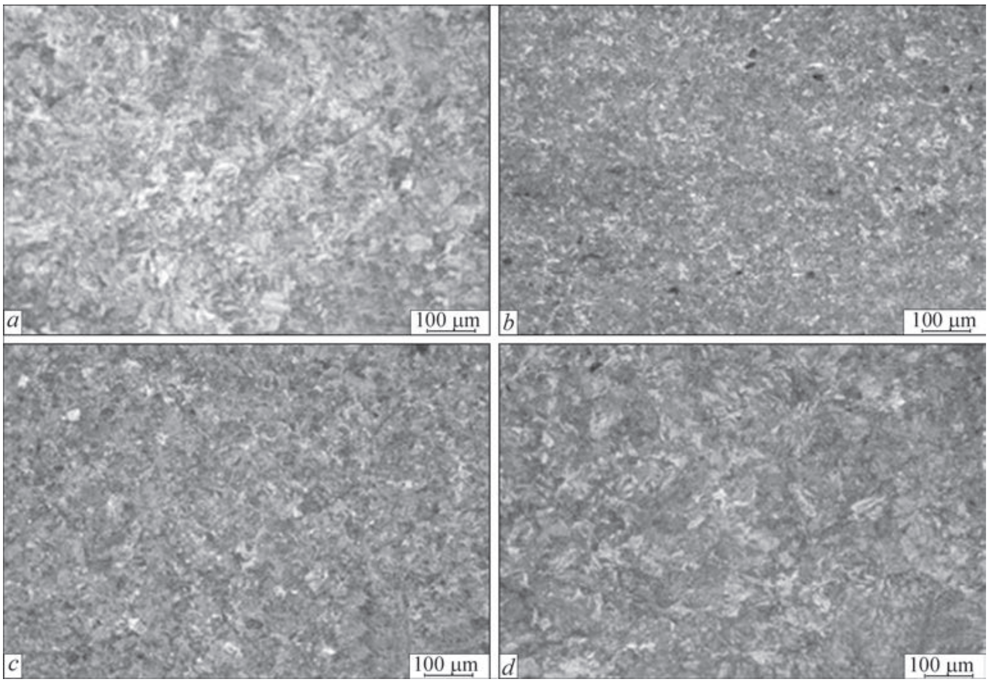


Figure 2. Microstructure of base metal of rail steel: *a* — K76F; *b* — 76F; *c* — VS-350Ya; *d* — R350HT

Table 2. Results of tests on static mechanical bending of different grades of batches of rails welded at different modes

Number of mode	Standard and steel grade	Welding time, s	Fracture load, kN	Bending deflection, mm	Note
	Ukraine	–	160	≥30	TU U 24.1-40075815-002:2016
	Russia		210	≥27	STO RZhD 1.08.002–2009
	Eurostandard		160	≥20	EN 14587-1:2007 E
1	K76F	180–200	$\frac{1750–2100}{2100}$	$\frac{17–32}{20}$	Continuous flashing
2	K76F	130–140	$\frac{1800–2000}{1900}$	$\frac{14–30}{19}$	Same
3	K76F	70–80	$\frac{2150–2400}{2250}$	$\frac{35–55}{40}$	Pulsed flashing
4	K76F	30–40	$\frac{1750–2000}{1950}$	$\frac{25–35}{28}$	Same
5	K76F	70–80	$\frac{2000–2300}{2150}$	$\frac{35–45}{38}$	»
5	76F	70–80	$\frac{2300–2600}{2450}$	$\frac{30–46}{38}$	»
5	VS-350Ya	70–80	$\frac{2620–2660}{2650}$	$\frac{32–40}{40}$	»
5	R350NT	70–80	$\frac{2770–3050}{3000}$	$\frac{58–66}{60}$	»

surface of welds fracture the defects were not detected. Along the joining line and the adjacent layers of metal a coarse structure of primary austenitic grains (Figure 3, *a*) is observed with grain number of 2–3. Along the grain boundaries of primary austenite the solid net of ferrite precipitates is clearly observed indicating the lower ductile properties of this area.

From the practice of flash-butt welding (FBW) it is well-known [5–7] that the reduction in welding energy input allows improving the structure of metal along the joining line and adjacent areas, in particular, reducing the grain sizes and precipitates of ferrite along their boundaries.

The batch of rails K76F was welded using CF with the low (t_w = 130–140 s) energy input (temperature field corresponding to mode 2 is shown in Figure 4, curve *3*). At the tests of welded specimens of this batch the decrease in values of ductility was observed (see Table 2). The reason for reduction of ductile properties in most cases is the formation of defects in the plane of the joints determined as dull spots (DS), the area of which is 10–50 mm^2 (Figure 5).

As the carried out investigations showed, in the DS microstructure on the background of the matrix pit fracture mainly (single cleavage facets are found),

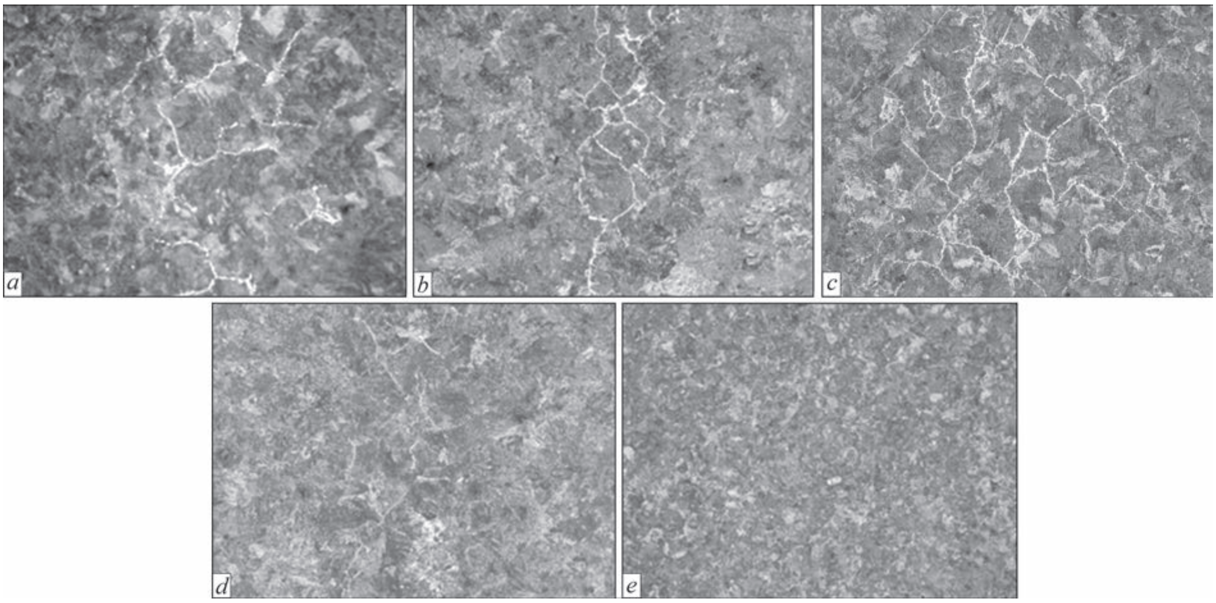


Figure 3. Microstructure (×100) of HAZ metal of welded joints: *a* — K76F (CF); *b* — K76F (PF); *c* — 76F (PF); *d* — VS-350Ya (PF); *e* — R350HT (PF)

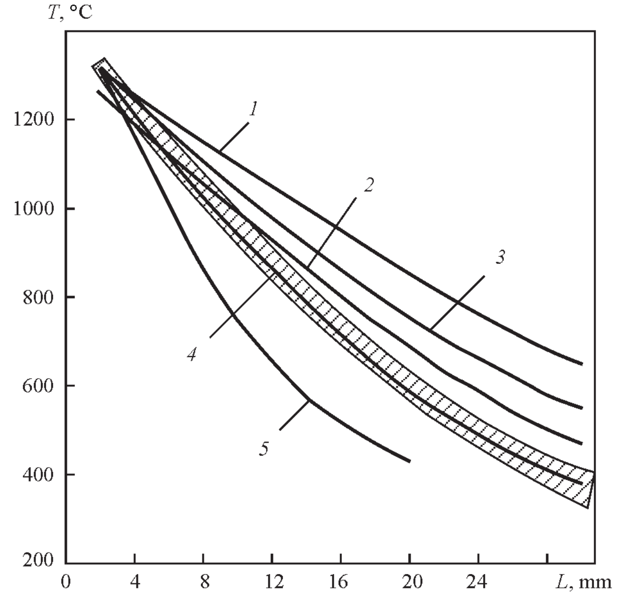


Figure 4. Distribution of temperature in HAZ before upsetting in welding rails R65 at different modes: *1–3* — CF with program decrease in voltage at t_w, s: *1* — 210–240; *2* — 180–200; *3* — 140–160; *4, 5* — PF at t_w, s: *4* — 70–80; *5* — 30–40

the numerous silicate inclusions of fused type of up to 10 μm size are present.

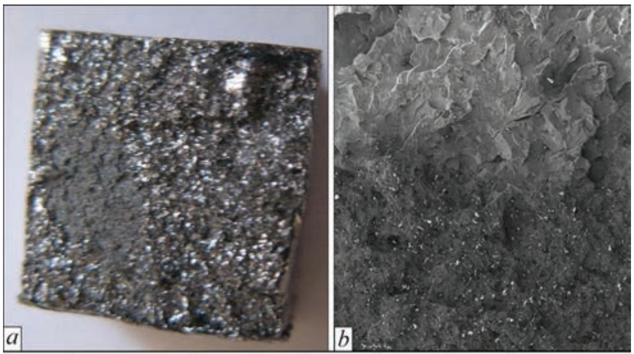
The defects of larger than 30 mm sizes reduce noticeably the results of investigations on bending, especially if they are located in the zone of tension. In the majority of standard documents in different countries regulating the quality evaluation, the presence of DS with total area of up to 30 mm^2 is not a rejection sign. If the spots of larger area are present in several specimens from a single reference batch, the decision is taken on the need in modifying the technology.

The aim of the carried out investigations was looking for the ways to prevent the formation of DS-type defects in welding at a reduced energy input. It was found that the formation of the mentioned defects is largely determined by flashing processes running at its final stage envisaged by the program (intensive flashing passing to upsetting). During this period at the edges of the flashed parts a melt is formed (Figure 6). In the melt the products of its oxidation by air from spark gap are always present. If the melt has a time to solidification before upsetting, then it fails to be completely removed due to deformation. The duration of solidification for melt at the edges of flashed parts is

$$t_m \rightarrow \frac{A\delta_1}{\lambda \dfrac{d\theta}{dx}} \geq \frac{\delta_{g\max}}{v_f}, \qquad (1)$$

$$\frac{d\theta}{dx} \rightarrow f(\theta, v_{flash}, A_2),$$

where $\delta_{g\max}$ is the maximum value of spark gap; v_f is the final flashing rate; Q is the melting point of materials to be welded; $\lambda(d\theta/dx)$ is the gradient of temperature field at flashing before upsetting; δ_1 is the gap size in the places, where flashing values are maximum at the surface; A, A_2 is the dimensionless parameter which depends on thermophysical constants of material to be welded (c_m, γ, Q_m, θ_l).



Number of area	C	O	F	Al	Si	Mn	Fe	Place of investigation
1	3.27	66.66	3.49	1.11	16.48	8.12	0.86	Silicate
2	1.63	61.08	2.73	2.15	16.70	14.73	0.99	Same
3	2.41	68.91	3.16	1.32	16.39	6.90	0.90	»
4	4.43	1.57	0	0.11	0	0.80	93.09	Matrix
5	5.51	0.86	1.88	0	0.18	0.81	90.76	Same
6	4.70	1.50	0	0	0.15	1.11	92.54	»

Figure 5. Macro- (*a*), microstructure (*b*) and results of chemical analysis of fracture surface of the joints of rails with DS

It follows from the expression (1) that the admitted duration of the melt solidification decreases with the increase in the gradient of temperature field, and the probability of defects formation is increased.

The decrease in $\delta_{g\max}$ value or increase in δ_1 helps to increase the duration of existence of the melt before solidification. The maximum δ_1 value is determined by thermophysical properties of the melt and forces of surface tension retaining the melt on the flashed surface. In the real conditions the thickness of the melt layer is unstable (Figure 6, CF), which is determined

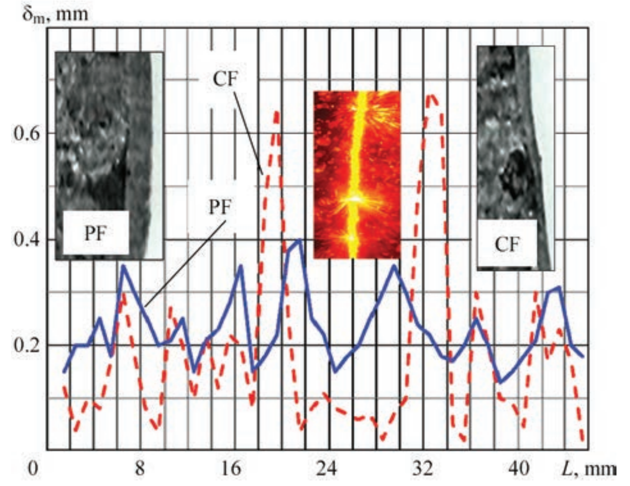


Figure 6. Distribution of melt on flashing surface of the head of rail K76F in welding with CF and PF

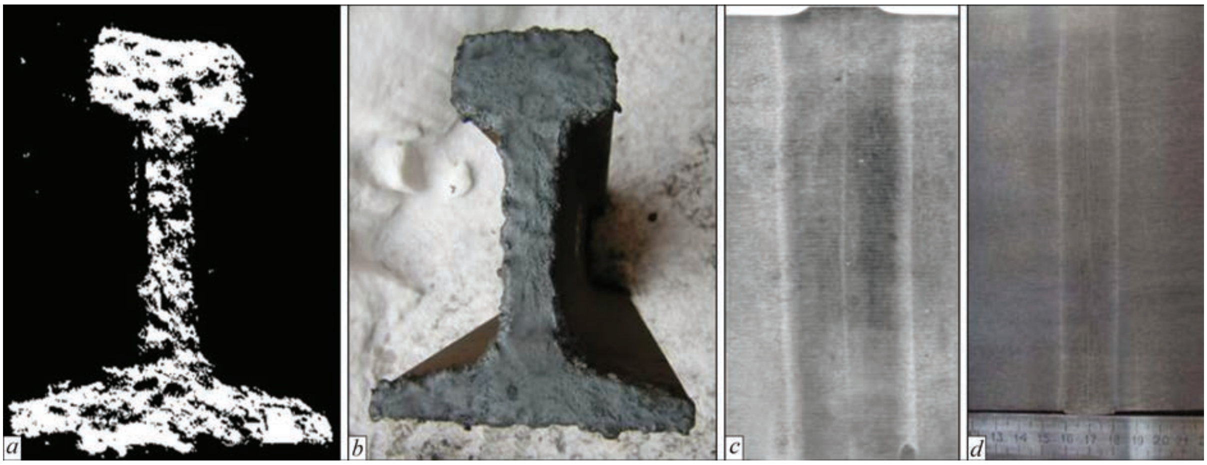


Figure 7. Flashing surface of rails R65 before upsetting during CF (*a*) and PF (*b*), and macrostructure of welded joints of rails at CF (*c*) and PF (*d*)

by explosive nature of flashing. The δ_g value is largely determined by the value of voltage during flashing.

The use of pulsed flashing [8] allows applying multifactor control of voltage, current and speed of movement of parts to suppress the explosive process of destroying the elementary contacts in flashing. It makes possible to maintain the high thermal efficiency of the process for the whole period of flashing and obtaining a highly-concentrated heating. Moreover, the flashing surface during PF is smoother (Figure 7 *a*, *b*), the depth of the craters, and respectively δ_g is 1.5–2 times decreased, and the thickness of the melt on the rail surface is stably maintained constant at a sufficiently high value (see Figure 6, PF).

Figure 8 shows record of the basic PF process parameters during welding rails. At PF, as well as CF, the basic process parameters are preset by the programs of changing the voltage, welding current, flashing rate and displacement. A typical program is shown in the Figure 8 (curve I). The initial period of the process takes place at CF mode with the subsequent PF. The welding current during transition to PF is almost 3 times increased, the rate of flashing remains at a constant level, and the energy input is determined by the duration of flashing process.

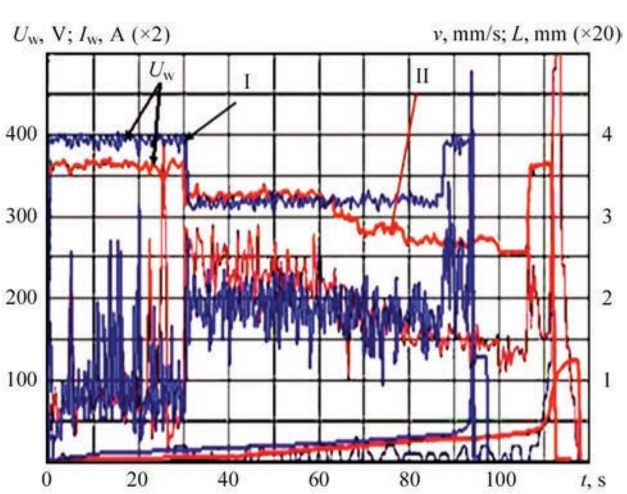


Figure 8. Record of the basic parameters of PF process

While using PF process it appears to be possible to produce high-quality joints 2–3 times reducing the energy input as compared to conventional welding modes accepted during CF and with resistance heating, at the same time there is no danger of DS arising. For example, in welding the rails of steel K76F using PF the quality joints were produced at welding duration of 30–40 s (see Figure 4, curve 5). The values of tests on bending meet the requirements of Technical Specifications (see Table 2, mode 4), and in the fractures of joints no defects were revealed. On the basis of the carried out investigations the optimum levels of energy input were identified for each of the mentioned rail steels, providing the highest values of strength and ductility.

Curve *4* in Figure 4 shows the optimum distribution of temperature in welding zone of rail of steel K76F, which provided the highest values of mechanical properties during tests of welded rails on static bending (see Table 2, mode 5). From the comparison of macrosection structure in Figure 7 it is seen that the total width of HAZ in welding using PF is twice smaller than that using conventional CF welding technology. The values of mechanical tests on static bending exceed the standard values specified by the Technical Specifications both on fracture load as well as on bending deflection.

In the industrial conditions the accurate reproduction of optimum heating modes at the rigidly preset programs of changing the basic parameters is rather problematic. Throughout the investigations carried out in the laboratory and industrial conditions, the main factors were established influencing the stability of reproduction of the preset heating modes and sustainable flashing. In particular, the influence of accuracy of rail edge preparation before welding and also voltage fluctuations in the electric mains of the power source on heating stability was found. Inaccurate cutting (more than ±1 mm) as well as voltage fluctuations in the mains result in unstable heating.

To eliminate these difficulties the improvement of technology was performed on both directions. The investigations were carried out to determine the influence of different factors on the accuracy of energy input, and their acceptable deviations in the process of production were established. At the same time, the development of automatic control systems of heating and flashing process was carried out, which allow correcting the heating program in a way to provide a constant energy input. The areas were determined (see Figure 4) characterizing heating at the maximum allowable changes in energy input, at which the required mechanical properties of welded joints are provided according to the standards.

Technologies for FBW of high-strength rails of steel K76F, 76F, VS-350Ya and R350HT. On the basis of the developed technologies, the programs for changing the main parameters were accepted, approved in welding the rails of steel K76F under the production conditions. The main values accepted for each type of rails and welding modes (see Figure 4) are based on the developed programs and are characterized by duration of heating process, gradient of the temperature field and, respectively, energy input, as well as necessary upsetting force. The value of voltage, average consumed power, shortening of parts in welding are supported by the systems of automatic control at a constant level. The limits of permissible deviations for given values of energy input differ greatly. For the rails of steel 76F more rigid limitations of energy input are established than for other batches of the investigated high-strength rails. It is caused by a high content of non-metallic inclusions in the rails of «Evraz» Metallurgical Works, RF. In microstructure of joints of all the investigated batches, welded at optimal modes (see Figure 3), the overall HAZ is 2 times smaller than it is accepted in CF welding. In the welding zone of rails of all the batches the increase in hardness with some decrease along the boundaries of the zone and in the center was observed (Figure 9). It is caused by change in the metal structure in the tempering zone at the boundaries of HAZ and decrease in carbon content in the plane of the joints. The width of these areas is negligible and does not influence the wear resistance of the surface of the rail rolling head.

In the areas with increased hardness the sorbite structure is observed. In general, the change in hardness is occurred in the ranges admissible for the mentioned rails, and while carrying out comprehensive metallographic examinations the martensitic structures in HAZ were not found.

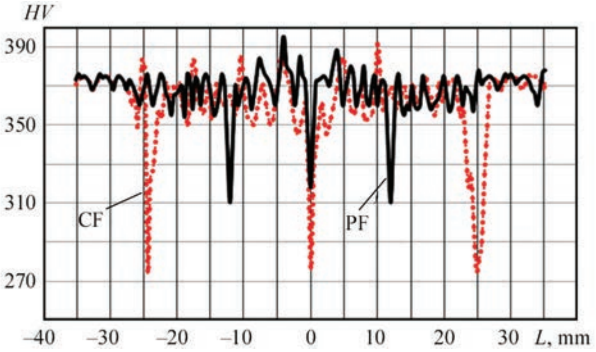


Figure 9. Distribution of hardness on rolling surface of R65 rail butt produced using CF and PF

The reference batches of the welded rails passed comprehensive tests. During checking using destructive and non-destructive testing methods in all the reference batches the defects were not revealed. The results of reference batches tests on static bending according to the international principles (see Table 2) meet the standards in Ukraine and the EU. It is necessary to consider that all the welded joints were not subjected to postweld heat treatment.

Self-adjustment system for automatic control of the FBW process of high-strength rails using pulsed flashing. The same as in CF, in PF the program of the main parameters of flashing process is preset determining its stability and preset energy input in welding, they include voltage and current in welding circuit, flashing rate, voltage value, force developed by the drive of welding machines and amount of deformation during upsetting. The programs are automatically corrected using feedbacks. The developed algorithms for control of the parameters envisage their correlation with the change of open-circuit voltage in the electrical mains, as well as short-circuit of welding circuit of the machine during welding process.

In typical recording of parameters in welding rails of type R65 of steel K76F under the industrial conditions at one of the rail welding enterprises of Ukraine curve I (see Figure 8) corresponds to welding at the optimal modes, curve II was registered when the mains voltage decreased by 50 V, that could significantly influence the quality of the joints, if the program would not be adjusted in welding process.

Due to the presence of feedbacks in the system, the program changed so that the energy input remained constant. The automatic correction of the preset program occurs also at the change of other parameters of the process, for example, increasing the short-circuit resistance of welding machine as a result of overheating or unsatisfactory state of the secondary circuit, as well as unsatisfactory cleaning of the surface of the rails to be welded. Naturally, the capabilities of the automatic system for control of the parameters are not unlimited and can not prevent grave violations of the accepted service conditions of the equipment. It allows extending the range of permissible deviations and providing a high reproducibility of the preset welding programs. At the same time, an additional possibility appears to control the quality of the joints according to the analysis of changes of all the mentioned parameters in welding process.

For each welded butt of the rails the computer system for control of welding machine issues a certificate, where both in text as well as in graphical form the change of basic parameters is registered, as well as their actual deviations from the preset optimum values. The control algorithms were developed, basing on which the system provides quality evaluation of welded butt in real time. The inspection results are provided immediately after welding on the display of the welding machine for information of the operator and at the same time are transmitted via e-mail to the diagnostic center, where a more thorough analysis is produced, taking into account the results of non-destructive testing and reference tests of specimens.

The results of operational control in the form of exchangeable report are introduced as a regulating document in the approved Technical Specifications for welding performance and are successfully applied at all rail-welding plants of Company «Ukrzaliznytsya». Together with the Diagnostic Center of «Ukrzaliznytsya» the unified system is created performing remote monitoring of rail joints quality not only in the stationary but also in the field conditions, where today the main volume of welding works is transferred.

PWI together with the Diagnostic Center processed a large volume of information (several tens of thousands of butts) on the quality of welding the joints of high-strength rails and related information on the state of welding equipment. On the basis of this information, the algorithms of evaluation of quality of welded joints during in-process control were specified. The proposals on maintenance of welding equipment and its preventive inspection were introduced.

Welding of rails with tension. During construction and repair of continuous tracks [9, 10], the problem of stabilization of temperature and stressed state of the track arises. In the majority of middle latitudes the temperature range is 90 °C. The level of stresses in rails varies in the temperature range from +50 to –40 °C. It is reduced due to the more rigid fixing of rails on the sleepers, which requires the complex of measures on tightening the base of the track, and the periodic unloading of stress in the rails is carried due to the change of rails-inserts of the appropriate length twice a year (in spring and autumn). The similar problem of unloading arises when it is necessary to repair track, when instead of a section, cut out with a defect, a new rail section is inserted which is welded to the section in two joints in points *A* and *B* (Figure 10).

In accordance with the standard documents in Ukraine and other countries for welding in the main tracks only FBW is allowed, providing the real uniform strength with the base metal, as well as according to the values of fatigue strength. In FBW the rails are shortened, and the allowance for flashing is preset by the program. Therefore, to obtain the required allowance for welding of two butts, the welded-in rail is bent in the horizontal or vertical plane to the value which provides the required allowance for welding. The drive of the machine should provide a high accuracy of shortening the rails at the final stage of upsetting.

This technology is used in repair of tracks at the railroads of Ukraine and other countries, that found reflection in the standard documents. In the course of performance of these operations a proposal appeared to carry out welding without bending of the welded-in rail and to obtain the necessary allowance for welding due to tension of both welded sections 2 and 3 (see Figure 10).

When using PF welding technology the allowance for welding is almost twice reduced as compared to the technologies accepted for welding rail in the track. This facilitates solving the task of using allowance during flashing as a parameter for control of tension of sections during welding of closing butts. The new parameters are added to the welding program, defining the movement during flashing, which determine the force and tightness value. As a result the general control algorithm was determined taking into account the conditions of works performance (temperature of laying of continuous track and environment in welding) and, respectively, the necessary parameters of tension. At the same time, the welder-operator introduces only the data on difference in temperature, at which welding is carried out. All the following operations, ending by flash removal, are performed automatically. After welding in the welded sections of rails on the repaired area the required temperature and stressed state are restored.

In the development of FBW technology of rails with tension a more radical technology for renovation of railway tracks was developed, providing their complete renovation. In laying the infinite continuous track the welding of sections of up to 1000 m is performed with tension, creating the permanent tensile stresses in them. Their value is calculated from the

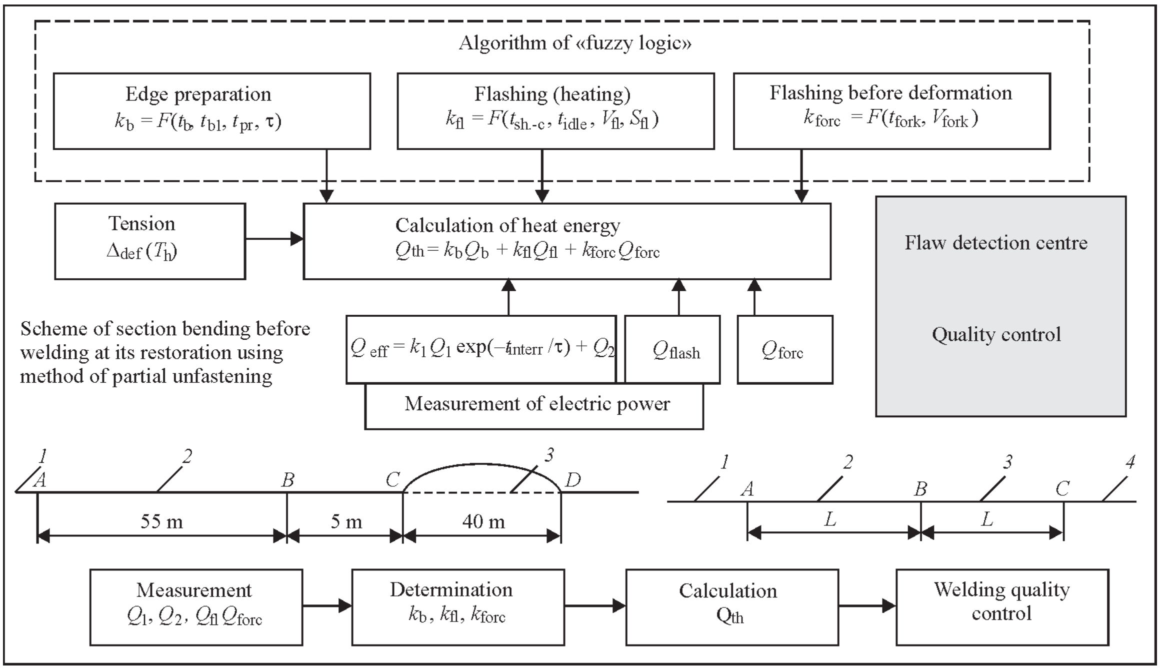


Figure 10. System of automatic multifactor control of welding process parameters in FBW of high-strength rails of steel K76F

condition that during changing the temperature in the range from –5 to 30 °C only tensile stresses will be maintained in the section, the value of which does not exceed 10–15 MPa (for middle latitudes). Such a technology using the welding equipment, designed at PWI (for the first time involving the PWI specialists), was applied by the American «Norfolk Southern Corporation». In the recent years at the railroads of this company the continuous tracks of length of several hundred kilometers (from station to station) are welded.

New generation of equipment for FBW of high-strength rails. To carry out the developed technology for welding high-strength rails, at the PWI a new generation of rail welding machines was developed, the technical characteristics of which are given in Table 3. The serial production of such PWI-developed equipment is performed by Kakhovka Plant of Electric Welding Equipment. The welding machines are used in the stationary and field conditions. Despite the differences in the design of mechanical components of the machines, they have common elements of automatic control of welding process, energy input, control systems and automatic control algorithms. All these new developments allow fully realizing the advantage of PF welding technology.

They use automatic systems for PF control based on application of high-speed hydraulic drives, adaptive electric systems for control of fast running electric processes. Their development and application allowed largely eliminating the unfavorable change of service conditions on the reproduction stability of preset welding modes. All the machines apply systems for automatic operation control of joints quality

Table 3. Technical characteristics of PWI-developed rail-welding machines

Parameter	Type of machine					
	K355A-1	K900A-1	K920-1	K921	K922-1	K922-2
Rated primary current (duty cycle = 50 %), A	395	395	540	540	540	540
Rated power (duty cycle = 50 %), kV·A	150	170	210	210	210	210
Transmission factor	60	60	54	54	54	54
Rated upsetting force, kN (kgf)	450 (45,000)	500 (50,000)	1000 (100,000)	1500 (150,000)	1200 (120,000)	1200 (120,000)
Rated clamping force, kN (kgf)	1250 (125,000)	1200 (120,000)	2500 (250,000)	3750 (375,000)	2900 (290,000)	2900 (290,000)
Rate of upsetting at idle operation, mm/s, not less than	20	25	35	35	40	50
Machine travel, mm	70	70	90	150	100	150
Mass of welding head, kg, not more than	2375	2500	2900	4200	3450	3500
Mass of delivery set, kg, not more than	4000	4100	4500	6000	5150	5100
Dimensions ($W \times H \times L$), mm	810×1059××1140	1030×1140××1550	1060×1195××1600	1190×1400××2430	1060×1300××1895	1060×1300××2050

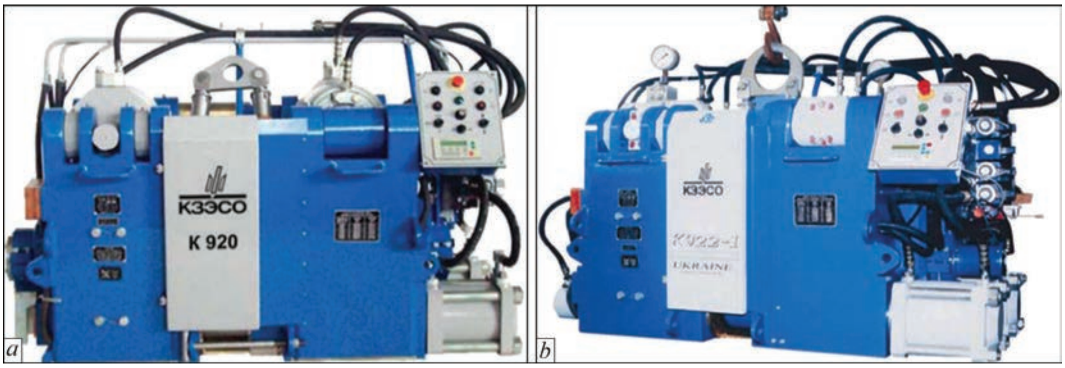


Figure 11. Mobile machines K920 (*a*) and K922-1 (*b*) for welding high-strength rails

on the basis of the recorded deviations from the preset values. The algorithms for quality evaluation in the function of these deviations and their introduction in a common electronic form to the general system in real time were determined.

The new machines (Figure 11) provide the upsetting force 2–2.5 times higher than the values of machines of the previous generation (K355, K900). It allows using PF modes for welding high-strength rails of different manufacturers. In addition, the opportunities for application of technologies of welding with tension were significantly expanded. The hydraulic drive of the machines allows developing force of up to 150 t and tightening the rail sections to distance of 300 mm to perform auxiliary operations during operation with long-length sections.

Conclusions

In welding of all the investigated batches of high-strength rails the required values of mechanical properties of welded joints were obtained at welding modes characterized by a low energy input which is 1.5–2 times lower than in welding of rails of previous generations.

The PF welding technology was developed providing a highly concentrated heating and formation of quality joints of high-strength rails of different production.

The system of multifactor control of flashing process parameters was developed and approbated in the industrial conditions, providing a stable reproduction of the preset energy input in welding of rails of different composition. The admissible limits of deviations from the preset value were determined.

The system of in-process quality control of welded rails was developed and tested under the industrial conditions.

The comprehensive tests of welded joints of different categories of high-strength rails were carried out. According to the basic values, the welded joints meet the requirements of different international standards.

The technology for welding of high-strength rails with tension was developed, providing the optimum level of internal stresses in continuous track during welding process.

A new generation of machines was developed for FBW of high-strength rails in the stationary and field conditions. The manufacture of such machines was mastered by Kakhovka Plant of Electric Welding Equipment (Ukraine).

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