DOI: http://dx.doi.org/10.15407/tpwj2018.11–12.03

TECHNOLOGIES AND EQUIPMENT FOR FLASH-BUTT WELDING OF RAILS: 60 YEARS OF CONTINUOUS INNOVATIONS

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The article summarizes the 60-year experience of the E.O. Paton Electric Welding Institute in innovative solutions in the field of development of technologies and equipment for flash-butt welding of rails. Many of them are pioneering, which is confirmed by a number of licensing agreements with leading countries of the world. Today, the stock of flash-butt welding machines and complexes, operating throughout the world, designed at the PWI and manufactured by the Kakhovka Plant of Electric Welding Equipment, amounts to more than 2,500 units, which is about 60 % of the global stock of machines. 13 Ref., 4 Tables, 22 Figures.

Keywords: *flash-butt welding, rails, eutectoid and hypereutectoid steels, technologies and equipment, continuous flashing, pulsating flashing, heating simulation, long-length rail sections, welding with tension, quality monitoring*

In the postwar period, in order to restore tens of thousands of kilometers of railway tracks which were destroyed or worn out during the war, it was urgently necessary to perform a large amount of works on rail welding. Some existing rail welding workshops in different regions of the country, equipped with imported machines for resistance welding of rails, could not cope with this task, since they did not have a sufficient power base and the required power to supply the resistance welding machines of 400–500 kV·A. Moreover, the main task was not solved: welding of rails on the track during construction of seamless tracks. The use of other well-known technologies of rail welding: electric arc and thermit ones did not provide the required level of mechanical properties of welded joints in seamless tracks. In addition, they were significantly inferior to resistance welding by the efficiency and cost of works. In the early 1960s, the task was put forward by the government to the team of the PWI to create technology and equipment for welding rails directly on the track when laying the seamless tracks. For this purpose, it was necessary to solve the priority tasks:

- to find the possibility of a significant reduction in the power of welding machine and, accordingly, the necessary source of power supply;
- to significantly reduce the mass of welding equipment, which would allow maneuvering of welding machine in welding rails laid on the track;
- to fully automate the process of welding and eliminate the influence of the accuracy of preparation of rail ends before welding on the quality of joints;
- to develop welding technology, which provides equal strength of welded joints with the base metal and high resistance to cyclic loads.

The development of the technology for resistance welding of rails was based on the method of metal heating using continuous flashing (CF). The CF process is applied in industry for flash-butt welding of parts with a wall thickness of up to 10–12 mm [1]. It is characterized by stable energy input and high quality of joints in welding of thin-walled parts. In welding parts with larger thickness of cross-section elements, including rails, CF is not used in the world practice, because it does not provide the required heating of ends of the materials to be joined. In addition, for exciting of CF a significant power is required.

The PWI has developed methods and devices for significant reducing the power required to excite CF [2], as well as for intensifying heating during flashing due to the increase in its thermal efficiency. The main of them is the search for processes of stable flashing at low specific powers due to simultaneous control of instantaneous values of voltage and speed during flashing using feedbacks by the value of welding current.

It was established [3] that one of the main conditions for stable reproduction of a stable flashing process is the reduction of short circuit resistance of the welding circuit in flash butt-welding machines ($Z_{sh.-c}$). Due to the original design of welding circuit, where as its current-conducting elements, the power units of flash-butt welding machines are used, it was possible to significantly reduce $Z_{sh.-c}$. As a result of using these innovations, the power consumed during welding and, accordingly, the power of supply sources was

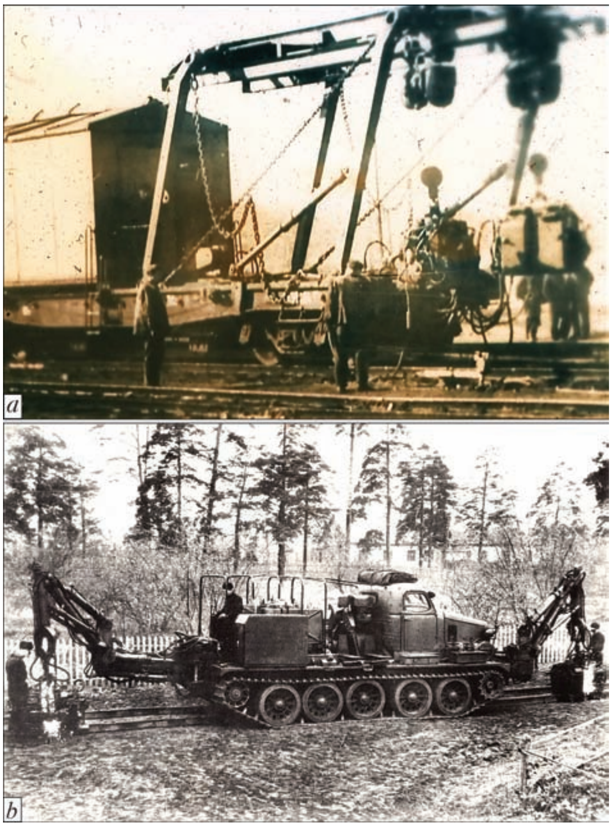

Figure 1. Mobile rail welding complexes with the machine K355: *a* — PRSM; *b* — RSA

significantly (2.5–3.0 times) reduced. The welding process was fully automated, providing high and stable quality of welded joints. Based on this technology, the first mobile machines for rail welding on the track were developed. As a result of these works, the fundamentally new technologies of welding using CF with the programmed control of basic parameters were developed [4]. Already in the early 1960s at the PWI the mobile and rail welding machines of the type K155 were designed and manufactured. The machines were distinguished by a small mass (2 tons instead of 15–20 tons) and lower power (150 kW instead of 350–500 kW) as compared to the best stationary machines for flash-butt welding of rails. The control system of the machines was based on the developments of the PWI [5]. The first model of the industrial rail welding machine (K355) was manufactured at the PWI and tested on the railways of Ukraine. On the base of this machine, the world's first mobile complexes for flash-butt welding of rails on the track were created. According to the documentation developed at the PWI, the industrial production of machines K355 since 1960s was mastered by the Kakhovka Plant of Electric Welding Equipment (KZESO). By the end of the 1960s on the railways of the post-Soviet space, already about 100 machines K355 were in operation, the implementation of which was carried out by the PWI specialists. Taking into account the experience of the production operation of the first batches of welding machines, their design was improved, different mobile rail welding complexes (Figure 1) were created, which included, except of welding machines, self-propelled installations with lifting mechanisms on the base of mobile platforms (see Figure 1, *a*), as well as on the base of all-terrain vehicles (see Figure 1, *b*). In mobile complexes, standard power plants of 200–250 kW power were used. To increase efficiency, in mobile rail welding complexes of the type PRSM — track rail welding self-propelled machine (see Figure 1, *a*) used in the railways of the former Soviet republics, two welding machines were installed, each of which is oriented to a single rail section. Such a scheme of works was accepted during reconstruction of tracks with a complete replacement of rail sections. For repair works, the complexes with one machine were used. The complexes based on all-terrain vehicles proved to be very efficient (see Figure 1, *b*). In this case, there is no need in power plants for the power supply of welding machines. Both welding machines, operating simultaneously, receive power supply from one generator connected to the diesel of an all-terrain vehicle. Since the early 1970s, mobile rail welding machines produced by the KZESO began to be exported to different countries of the world. The first batches of machines were delivered to France (Matiza), Austria (Placer), USA (Holland). At the same time, different mobile complexes on the automobile and railway travel were used, developed on the base of the machine K355, taking into account different forms of works organization during reconstruction and repair of railways. During implementation and operation of tens and hundreds of machines in different countries, the PWI continued its works on the development of the technology of welding rails using CF, taking into account the different types of sizes and chemical composition of rail steels and optimized welding modes and typical programs for control of welding process. One of such typical programs is shown in Figure 2. At the same time, algorithms for assessing the quality of the joints by deviations of the recorded values from those, preset by the programs, were determined. The common recommendations for assessing the quality of rail joints in real-time mode were developed immediately after performing welding according to the results of in-process control. The in-process control became an integral part of the technologies of flash-butt welding of rails. Such control was particularly relevant during works at remote areas of railway tracks. The in-process control during welding of rails on railroads was introduced by normative documents from the 1980s as an obligatory operation during welding of rails. Basing on it from the beginning of the 1990s the computerized control systems for the control of basic welding parameters were developed, with which the new generation of rail welding machines of the type K900 was equipped (Figure 3). In the CIS countries, such machines replaced the machines K355. From the beginning of the 1990s the machines K900 began to be exported to Europe, the USA and China.

Technologies and equipment for flash-butt welding of high-strength rails of eutectoid and hypereutectoid structure. The increase in the freight and speed traffic on the railways in the last decade caused the necessity in increasing mechanical properties of the rail, their wear resistance and service life. The majority of high-strength rails of modern production have a guaranteed service life of 1.5–2.0 times higher than in the rails of previous generations. This is achieved due to the application of new technologies for production of rail steel using a converter process in combination with continuous rolling and vacuum control. At the same time, a volumetric or differentiated thermal hardening of rail rolled metal is used. The production of rails of eutectoid and hypereutectoid class was mastered, which allowed a significant increase in the hardness and wear resistance of the rail steel. The chemical composition and mechanical properties of such rails are given in Table 1. In flash-butt welding of such rails by the technologies, used for joining rails with carbon content at the level of hypereutectoid steels, the required parameters of mechanical properties were not provided.

One of the causes for lowering the mechanical properties is the metal softening in the welding zone as a result of the formation of a coarse-grained structure in the central part of the weld, reducing the joint strength.. Decreasing the energy input by shortening the duration of flashing process has a positive effect on the improvement of the structure, but leads to occurring defects in the zone of a joint [6], which significantly reduces the strength and ductility of welded joints. The relationship was established between the occurrence of defects in the plane of a joint with the formation of a spark gap, in particular, during flashing, in the sections with the maximum value of a spark gap $\Delta_{g\,max}$ and the thickness of the melt on the flashing surface δ_l, as well as the temperature gradient in the near-contact layer of the part ends [7]. The formation of defects occurs if a melt has a time to crystallize before the beginning of ends deformation. For producing qualitative joints it is necessary to fulfill the condition: the duration of melt crystallization t_m on the ends of the flashed parts:

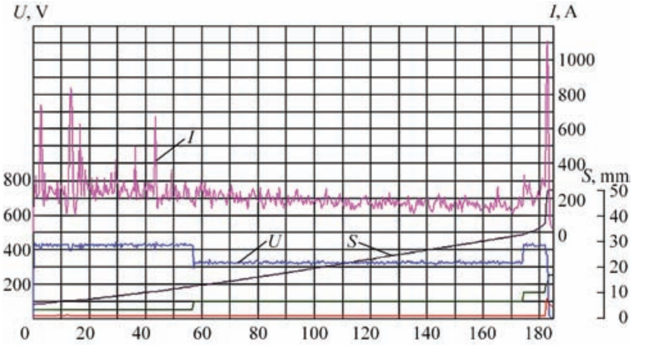

Figure 2. Typical program for changing basic parameters during welding rails using continuous flashing

$$t_m \geq \frac{\Delta_{g\,max}}{v_f},$$

where t_m is the duration of crystallization of the liquid layer of the melt of thickness $\delta_{l;}$ $\Delta_{g\,max}$ is the maximum value of the spark gap; v_f is the final flashing rate before upsetting.

$$t_m \to f\left(\delta_l, \theta_l, A\lambda \frac{d\theta}{dx}\right),$$

where θ is the average melt temperature; A is the dimensionless parameter, determined by the thermophysical steel properties; $\lambda \frac{d\theta}{dx}$, is the gradient of temperature field in the near-contact layer.

With an increase in the temperature field gradient, the time of crystallization decreases and the probability of defects formation increases. In order to provide the required crystallization conditions, it is necessary to increase the final rate of flashing before upsetting v_f, or to reduce the value of $\Delta_{g\,max}$. The increase in the flashing rate v_f is provided by the program of changing the voltage at CF, but the possibilities of this measure are largely exhausted, since a further increase in the v_f is associated with the need in increasing the voltage U_2 and is accompanied by an increase in the craters depth. At the same time the value δ_l is decreased. In the course of investigations carried out at

Figure 3. Mobile rail welding machine K900

Table 1. Chemical composition and mechanical properties of high-strength rails of modern production

Steel grade	Chemical composition. %					
	C	Mn	Si	V	Ti	Cr
M76	0.71–0.82	0.80–1.30	0.25–0.45	–	–	–
K76F	0.71–0.82	0.80–1.30	0.25–0.45	0.03–0.07	–	–
E76F; K76F	0.71–0.82	0.75–1.05	0.25–0.45	0.03–0.15	–	–
R260	0.62–0.82	0.70–1.20	0.15–0.58	0.03	–	≤ 0.15
R350NT	0.72–0.82	0.70–1.20	0.15–0.58	0.03	–	≤ 0.15
R350NT	0.72–0.82	0.15–0.60	0.65–0.75	0.03	–	0.15
VS-350Ya; 350LTD	0.72–0.82	0.7–1.2	0.35–1.0	0.01	0.025	0.3–0.7
AREAL 136 10 SP	0.81–0.82	1.0–1.15	0.50–0.54	0.005	0.002	1.3–1.22
AREAL 136 HE370	0.99–1.00	0.69–0.71	0.50–0.52	0.002	0.001	0.21–0.22

Table 1 (cont.)

Steel grade	Hardness HV	Tensile strength σ_t, MPa	Yield strength σ_y, MPa	Relative elongation δ, %	Relative reduction in area ψ %	Plant-manufacturer
M76	260–280	800–1100	500–700	≥ 6	≥ 20	Ukraine
K76F	341–388	1300–1380	950–1050	10–15	25–35	
E76F; K76F	370–410	1180	800	8	25	Russia
R260	260–300	942–980	498–540	10–15	15–25	Poland
R350NT	350–380	1240–1300	–	9–12	–	France
R350NT	650–380	1240–1300	–	9–12	–	Austria
VS-350Ya; 350LTD	362–400	>1240	–	>9	–	Japan
AREAL 136 10 SP	388–420	1350–1400	840–950	12–15	–	
AREAL 136 HE370	380–430	1320–1350	850–950	12–15	22–25	

the PWI, it was found that adjusting the spark gap by changing the instantaneous feed rate in combination with a voltage change, allows suppressing the explosive-like process of its flashing (at which the relief of the flashing surface is formed), increasing its thermal efficiency and intensity of heating. At the same time, the value of $\Delta_{g\ max}$ decreases. The process was called pulsating flashing (PF) [8]. Its application allows changing the intensity of heating during melting in wide ranges, at the same time with the high gradients of temperature field, the heating to a high temperature of the near-contact metal layer is provided, the spark gap decreases, and favorable conditions for the formation of joints at a decreased energy input are created. Figure 4 shows the dependences characterizing the change in thermal efficiency in the process of PF, as well as in CF of R65 rails for comparison. The calculation of basic parameters, characterizing heating, was performed using mathematical modeling of heating at CF. The calculation is based on the model of heating a single contact at the change in density of current, passing through the contact, heating temperature of the ends of parts and degree of overheating. As is seen from the abovementioned diagram, the efficiency at CF is quite high in the initial period of flashing — 0.7 and it decreases as the temperature of the ends of parts grows to 0.45 [9]. Reducing the voltage in the welding process allows increasing it to 0.5. This is the maximum possible value achieved at CF. From the analysis of dependence, it can be seen, that at CF there is a significant reserve for increasing the intensity of heating due to an increase in thermal efficiency, especially in the second period provided for by the program (see Figure 4). Applying PF, there is a possibility of increasing the mean current I_w passing through the specimens by increasing the area of simultaneously existing contacts, not exceeding the average speed of parts shortening, by adjusting the instantaneous values of feeding rates and voltage U_2. Figure 5 shows the records of current values at PF and CF. In both cases, the same programs for changing the voltage U_2 of the average feeding rate v_{feed} were established. By adjusting the instantaneous feed rates, the mean value of current and voltage is maintained at a preset level, and the value of the mean current increases significantly (by 35 % in the first flashing period and by 30 % in the second one) during flash-

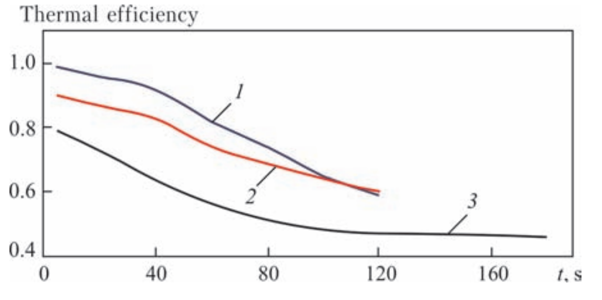

Figure 4. Dependence of thermal efficiency on flashing duration at PF (*1*, *2*) and CF (*3*): *1* — 120 s, *I* — 450 A; *2* — 120 s, *I* — 370 A; *3* — 180 s, *I* —170 A

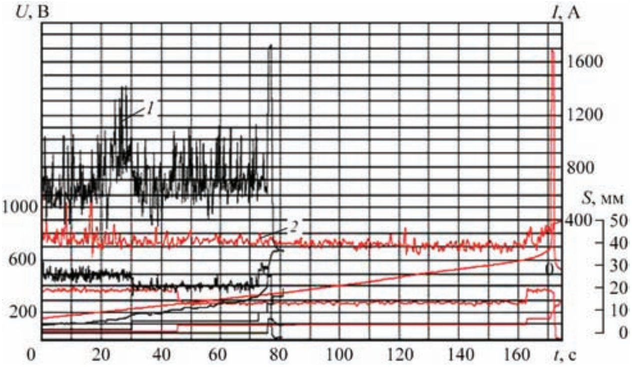

Figure 5. Record of basic welding parameters at PF (*1*) and CF (*2*)

ing. During PF the heating process quickly reaches a quasistationary state and heating is stabilized at this level. The distribution of temperature in the HAZ metal changes significantly. The temperature of the near-contact metal layers despite the reduction in energy input, increases and the width of the HAZ decreases (Figure 6). In this case, the ratio of the energy, generated in single contacts and lost at their fracture, is changed. The suppression of the explosive-like phase of heating the contact, when the metal is brought to boiling, reduces the fraction of lost energy and leads to increase in the efficiency at all the stages of contact heating.

Figure 7 shows the temperature fields obtained by calculation and experimental way at different values of welding current (I_w) in the process of PF of rails R65 made of steel M76 and K76F. The program for changing the basic parameters of U_2, v_{feed} is accepted as the same, and the duration of flashing corresponds to the established quasistationary temperature state for each heating mode. The current value at PF was accepted to be higher relative to that accepted at CF. As can be seen from the comparison of curves, the transition to pulsating flashing leads to the increase in the mean value of welding current (I_w) and reduction in the duration of the process. With increasing current,

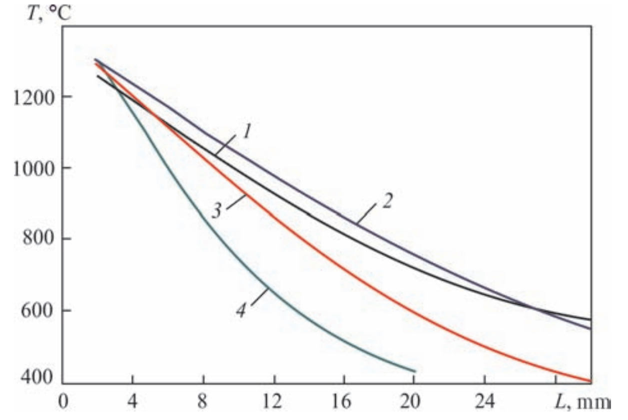

Figure 6. Temperature distribution in the HAZ before upsetting during welding of R65 rails at different modes: *1* — with preheating (t_w = 200–250 s); *2* — CF with programmed voltage drop (t_w = 180–220 s); *3* — PF (t_w = 110–120s); *4* — PF (t_w = 60–70 s)

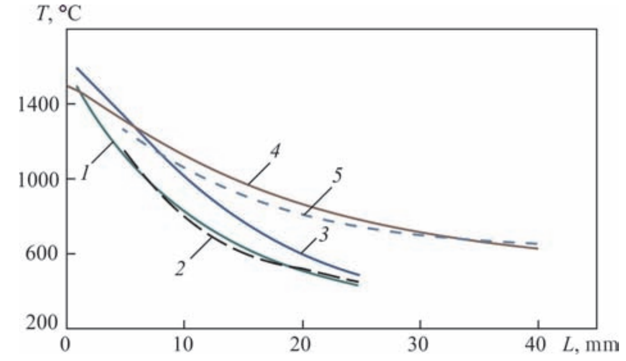

Figure 7. Temperature distribution in the HAZ before upsetting during welding R65 rails with different values of current and flashing duration: *1* — PF at T = 60 s, I = 370 A (calculated); *2* — PF at T = 60 s, I = 370 A (experimental); *3* — PF at T = 60 s, I = = 450 A (calculated); *4* — CF at T = 180 s, I = 170 A (calculated); *5* — CF at T = 180 s, I = 170 A (experimental)

the gradient of the temperature field increases, and the temperature of the near-contact layers adjacent to the flashing surface increases. The flashing surface is smoother as compared to that of CF (Figure 8). Even at 3 times shortened duration of heating as compared to CF, the temperature of near-contact layers undergoing intensive deformation remains higher than that at CF (see Figure 7). This creates necessary conditions for the formation of quality joints at high gradients of the temperature field.

To test the possibilities of producing quality joints during welding of rails with a minimum energy input, a batch of high-strength rails M76, manufactured by the NKMZ, as well as rails of Azovstal, was welded. For comparison, the batches of rails M76 and KF were also welded at the modes accepted for CF. The accepted modes for welding of these batches using PF provided a lower energy input, characterized by temperature fields (see Figure 6). For comparison, the temperature fields are also given, corresponding to the accepted modes of heating using CF. The total width of the zone of structural transformations was smaller than at the optimal mode of welding accepted at CF, and the duration of flashing process was reduced by 2–3 times. All the batches of M76 and KF, weld-

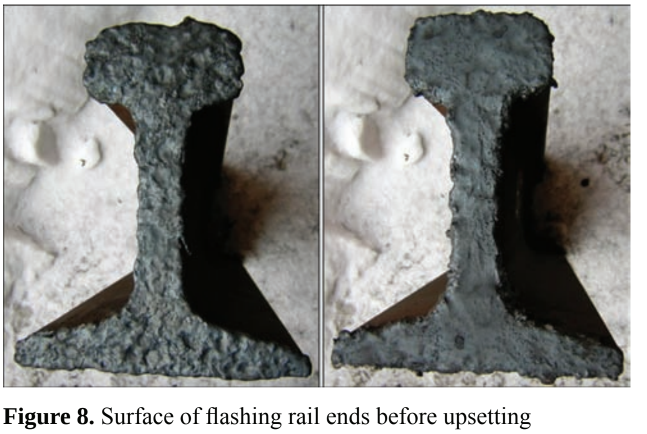

Figure 8. Surface of flashing rail ends before upsetting

Table 2. Results of tests of M76 and K76F steel rails on static bending in welding using CF and PF with different energy input*

Values of mechanical tests	1	2	3	4
E76F «Evraz» (Russia)				
Fracture load, t	1700–2200 2000	1750–1900 1850	2200–2400 2250	1950–2100 1900
Deflection, mm	10–30 20	12–26 18	32–40 35	20–28 24
K76F (Azovstal Iron & Steel Works (Ukraine))				
Fracture load, t	1600–2000 1800	1750–1950 1850	2100–2400 2250	1850–2050 1900
Deflection, mm	18–30 25	21–30 22	34–50 42	25–32 28

*CF — 1; PF — 2–4; distribution of temperatures 1–4 see Figure 6.

ed with different energy input, were tested for static bending in accordance with the accepted method, and the structure of welded joints was also examined. The test results are shown in Table 2. During tests of batches of rails of steel grade M76 and K76F, welded at CF, the test results were distinguished by unstable and low values. Reduction in the flashing duration from 200 to 160 s allowed improving the structure and increasing the values of ductility during tests of single specimens, but a number of specimens with defects in the welding plane significantly increased. The values of mechanical tests of batches, welded at PF met the regulatory requirements, but differed depending on energy input. The highest and stable values were observed in the batch welded at PF with a heating duration of 60 s for the rails M76 and 80 s for K76F. The main result of these investigations was the conclusion that at PF it is possible to vary the energy input during welding of high-strength rails in a wide range without fear of tdefects occurrence in the joint plane. In fractures of the test batches of rails, during tests with fracture of rails in the joint plane, no defects such as oxide films were detected, even at a minimum welding duration. The absence of defects in welding with high gradients of temperature fields proves the fact, that at PF more favorable conditions for the formation of joints are created.

Table 3. Results of tests on static bending in welding using CF (period II)

Steel grade	Fracture loading, t	Deflection, mm
M76	1900–2200 2150	34–65 48
K76F	2100–2400 2250	34–50 42
E76F	2300–2600 2400	32–42 35
R260	2250–2500 2400	37–50 48
R350NT	2000–2200 2100	34–50 40
R350NT	2870–3100 3000	58–66 62
VS-350Ya	2300–2700 2500	30–50 40
AREAL 136 10 SP	2200–2400 2300	35–45 40
AREAL 136 HE370	2200–2550 2300	34–45 38

The carried out investigations established that at PF the maximum value of Δ_{curv} decreases by 1.5–2.0 times, and the thickness of the melt δ_1 is more stable and its minimum values are higher than at CF. It is also necessary to take into account the fact that even at minimum energy input, the temperature of the near-contact layers with thickness of up to 3 mm is close to 1300 °C, which provides their high degree of deformation during welding, contributing to the removal of oxide structures. The microstructure in different areas of the HAZ differed depending on the value of energy input. Metallographic examinations of the microstructure of welded joints of rail batches allowed identifying common features of their formation. The total width of the heat-affected zone is more than 2 times decreased with a decrease in energy input as compared to that accepted at CF (Figure 9, *a*). In the welding zone, an increase in hardness with its local decrease in the weld center and along the zone boundaries is observed. This is predetermined by a change in the metal structure in the tempering zone at its HAZ boundaries and a decrease in the carbon content in the joint plane (Figure 9, *b*). The width of these sections is negligible and does not affect the wear resistance of the surface of a rail contact head. In the areas with increased hardness, on separate areas the structure of sorbite-like pearlite is transformed into a bainitic structure; such structures are formed on welding modes of less than 40 s. At the maximum duration of flashing the weld center in the joint plane, the formation of free ferrite inclusions along the grain boundaries is observed (Figure 10, *b*). The absence of

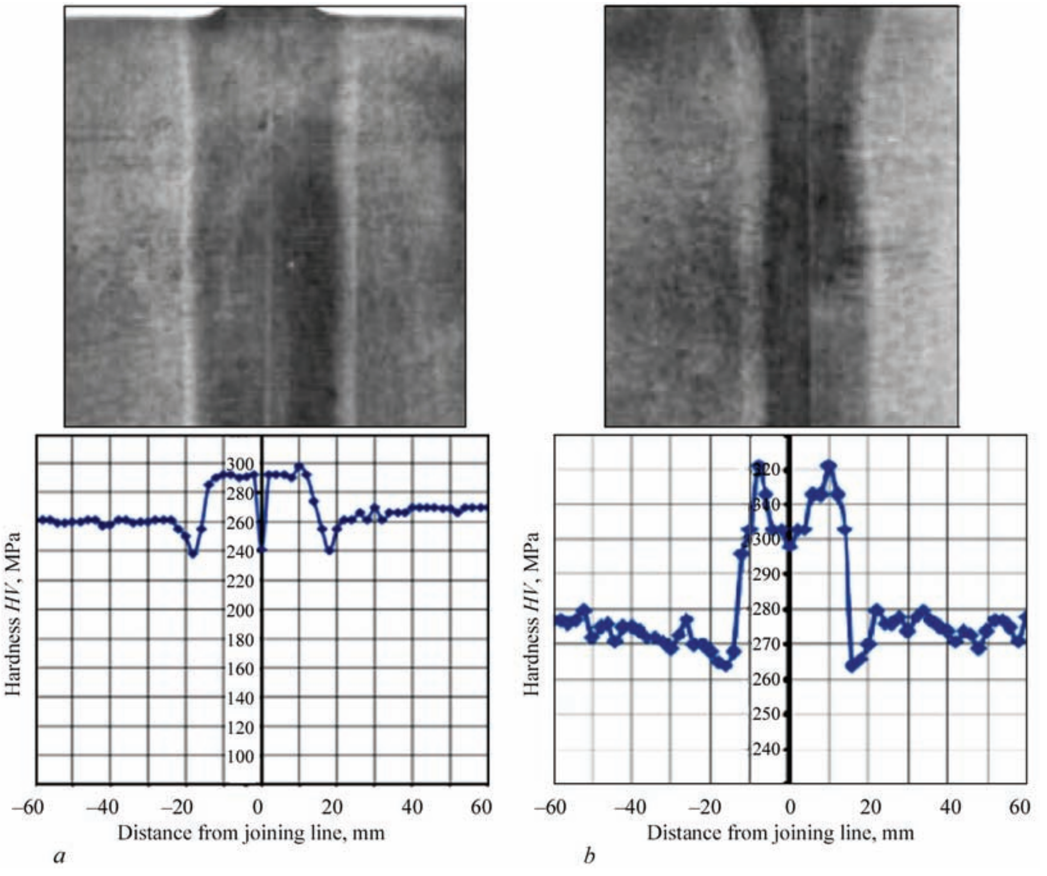

Figure 9. Macrosections during flashing of welded joints of rails M76, using CF (*a*) and PF (*b*)

defects in welding with high gradients of temperature fields indicates the fact that at PF, the choice of the optimal value of energy input can be determined based on the conditions for obtaining an optimal structure in the HAZ.

In the last decade, in the railways of many countries of the world, including Ukraine, the use of high-strength rails of eutectoid and hypereutectoid composition began. The flash-butt welding of rails is performed applying stationary and mobile machines of PWI design, which are exported to many countries of the world. The PWI team took part in the developments of technologies for welding rails of different production, including high-strength ones. The considerable experience was gained in welding of rails of different manufacturers.

For welding of high-strength rails with eutectoid and hypereutectoid carbon content, the programs of welding using PF are used shown in Figure 11. The programs for changing the basic parameters are taken as basic and are certified. The control of energy input is carried out by changing the flashing duration and the welding current value. Since the programs are focused on using the design of the PWI in the machines, their adaptation to the capabilities of welding equipment (resistance to $Z_{sh.-c}$ and power of the welding circuit, quick-response of the drive) was minimized. The basic elements, which determine the mechanical properties of metal in all the batches of rails, are iron, carbon, manganese and silicon. As the alloying elements vanadium, titanium, niobium, nitrogen and chromium were used. The mentioned elements strengthen the metal, including carbides and carbonitrides. The basic microstructure for all the investigated batches of rails is the quenching sorbite, which differs only by the degree of dispersion in different rails. The steels R260 and R350NT are distinguished by an increased content of manganese, which improves their calcination ability. When changing the energy input in sufficiently wide ranges (t_w = 40–80 s), the formation of defects in the welding plane was not observed, but a significant effect of change in energy input on the structural transformations in the HAZ was revealed. In welding of steels R350NT of the investigated batches of rails on the boundary of the heat-affected zone and in the central part of the joint zone, a decrease in hardness is observed. This is predetermined by the heating of the HAZ metal to a high tempering temperature and a decrease in the carbon content in the central part of the weld as a result of heating the metal to the melting temperature. With a decrease in the energy input, the reduction in hardness is manifested to a lesser extent, and the width of the softening regions decreases. This effect is manifested in all the investigated rails, hav-

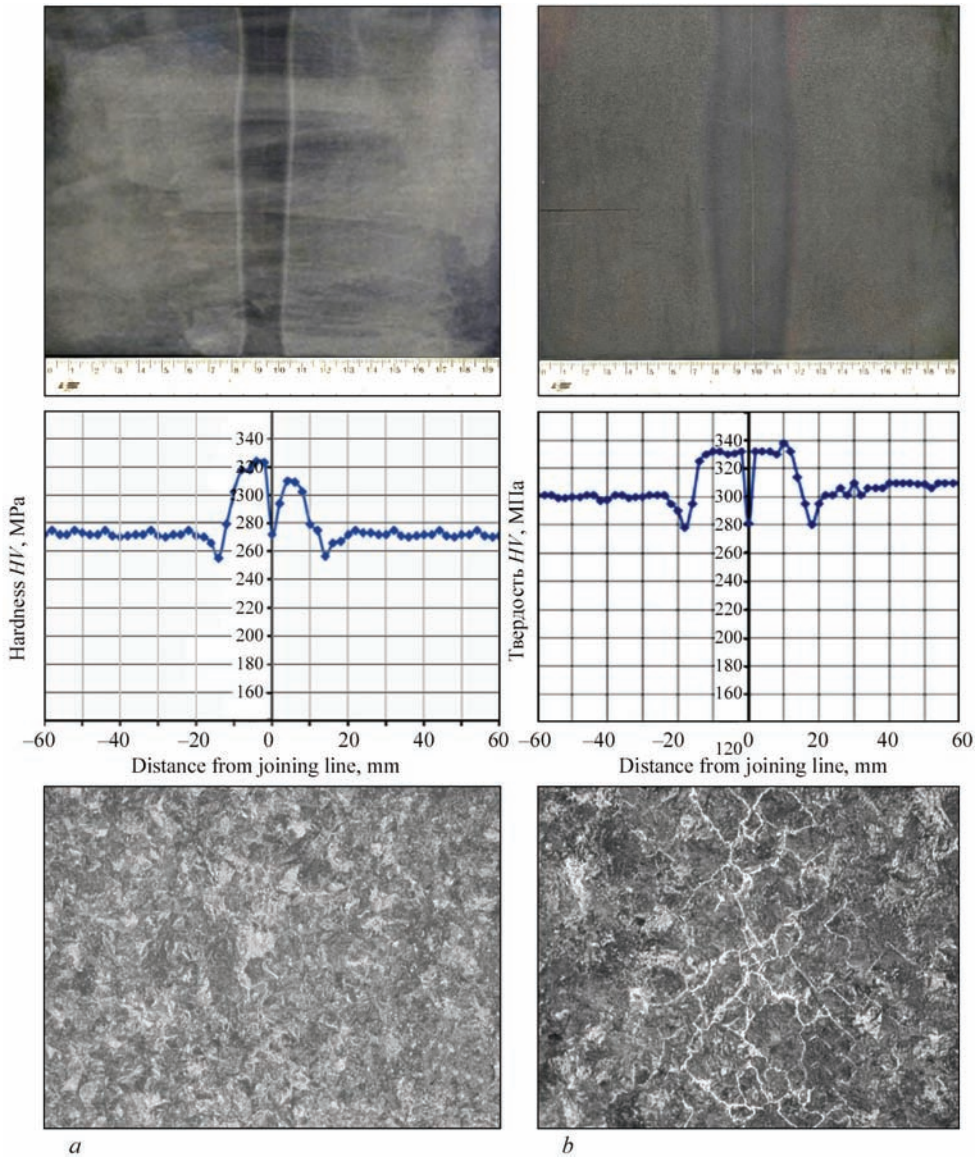

Figure 10. Macro-, microstructure (×100) of hardness distribution (*HV*) of welded joints of R260 rails with different heat input: *a* — T_w = 65–75 s; *b* — 90–100 s

ing a hardness of 380–400 MPa. Completely different is the influence of reduction in energy input on the HAZ structure of steels R260. The hardness at a decrease in the energy input increases sharply over the entire width of the HAZ, and at its boundary and in the center the softening is manifested, but to a lesser extent. This is explained by the fact that steel R260

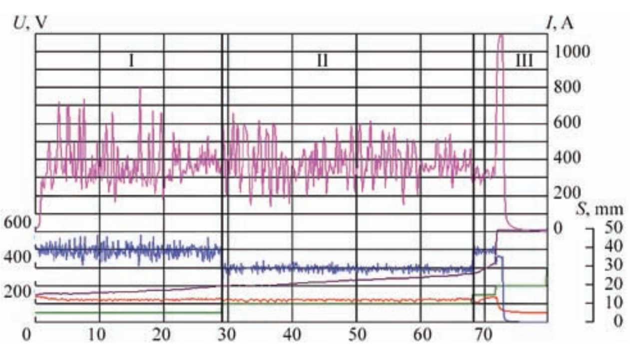

Figure 11. Basic program for changing basic parameters in welding using PF of different rails (I, II, III — periods of program)

with eutectoid carbon content is strengthened (during manufacture) to a lesser extent, not reaching the maximum possible value for obtaining higher values of plasticity. During welding, a repeated quenching with increased strength and hardness occurs. According to the technical conditions regulating the requirements to welded joints, it is necessary that during welding the steels of the specified class, the values of hardness deviations in the HAZ should not be higher than +60 *HV* and below –30 *HV* of the base metal hardness. This complicates the determination of optimal welding conditions, especially for the rails R260. The distribution of hardness in the HAZ during welding the rails R260 at different energy input is shown in Figure 10. To obtain the required hardness, it is necessary to dose the energy input during welding more accurately (see Figure 10, *a*). The distribution of hardness in the welds of steel R260 at changing the energy

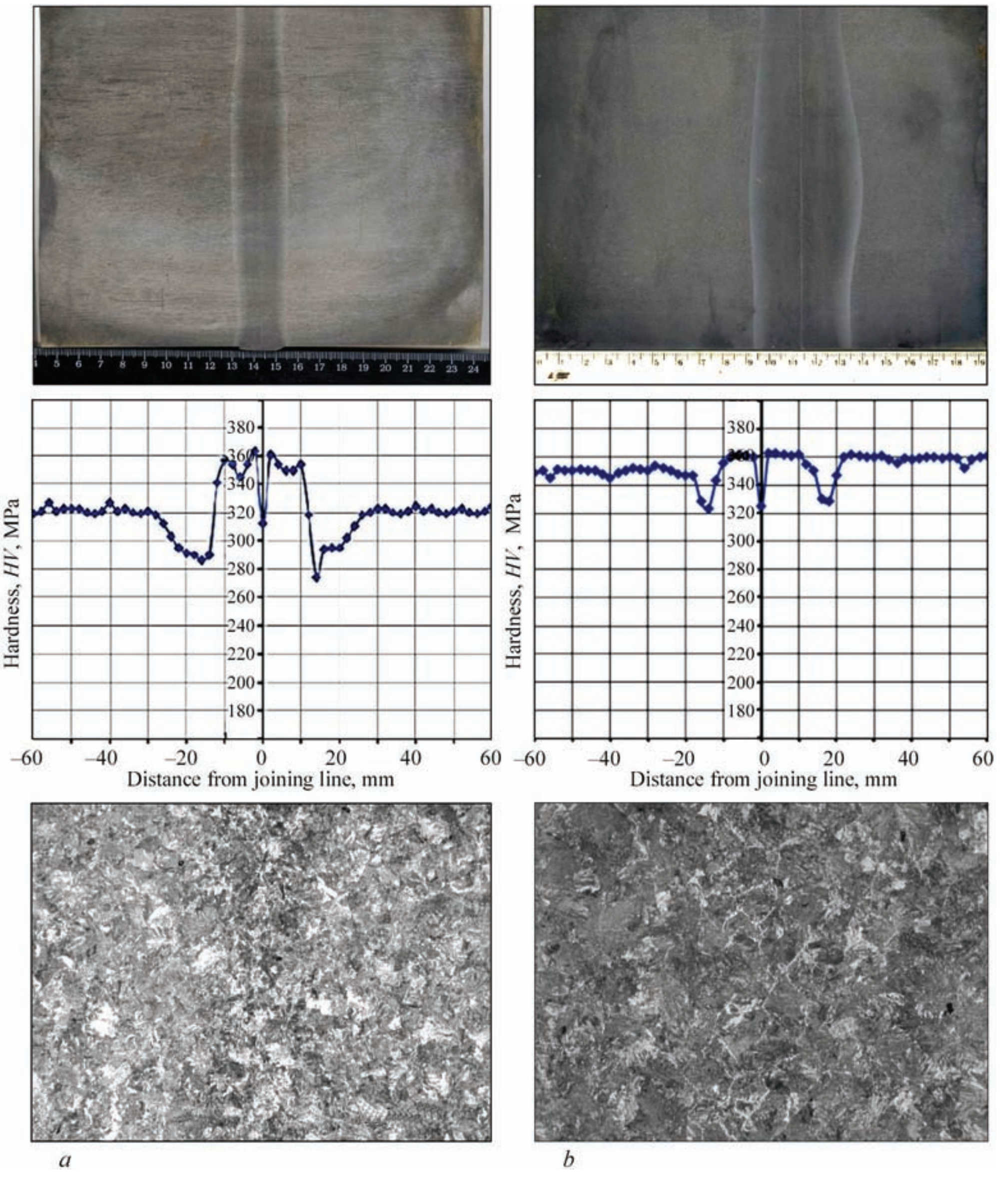

Figure 12. Macro-, microstructure (×100) and hardness distribution (*HV*) in the welded joint of rails of grade R350NT with different heat input: *a* — T_w = 65–75 s; *b* — 90–100 s

input differs from the optimum value specified by the program. In the specimens of steel R260, the width of the HAZ is determined by the distance between the boundaries of the high tempering areas. The structure of these areas represents a tempering sorbite, in the weld center the structure of primary austenite has a grain size number 3–4, along the boundaries of these grains, the areas of free ferrite are detected. With an increase in the energy input, their thickness increases, which is accompanied by a decrease in hardness at the weld center and mechanical properties during testing. A change in the energy input duration within relatively small limits (10 s) leads to noticeable changes in hardness in the HAZ (see Figure 10). In the specimens of the steel R350NT (Figure 12), the width of the HAZ is greater. At its boundaries and in the center, a decrease in hardness is observed, which is predetermined by the softening at the boundaries and the formation of the pearlite-sorbite structure in the center with precipitations of free ferrite along the grain boundaries of the primary austenite. Unlike the steel R260, with the change in energy input, the hardness in the HAZ increases slightly and remains at the level of the base metal. In the center, the degree of hardness reduction is determined by the amount of free ferrite. In the considered specimens, the ferrite is not formed in the form of a solid network around the grains of primary austenite, which guarantees a high level of value during bending tests.

The steels ARIEL13610SP and ARIEL136HE370 are distinguished by their high mechanical properties and wear resistance [10].

In the base metal of these steels (Figure 13), at the boundary of the primary austenitic grains of the pre-eutectoid ferrite, the precipitations of the carbide phase are present. At the size of the colonies of sorbite

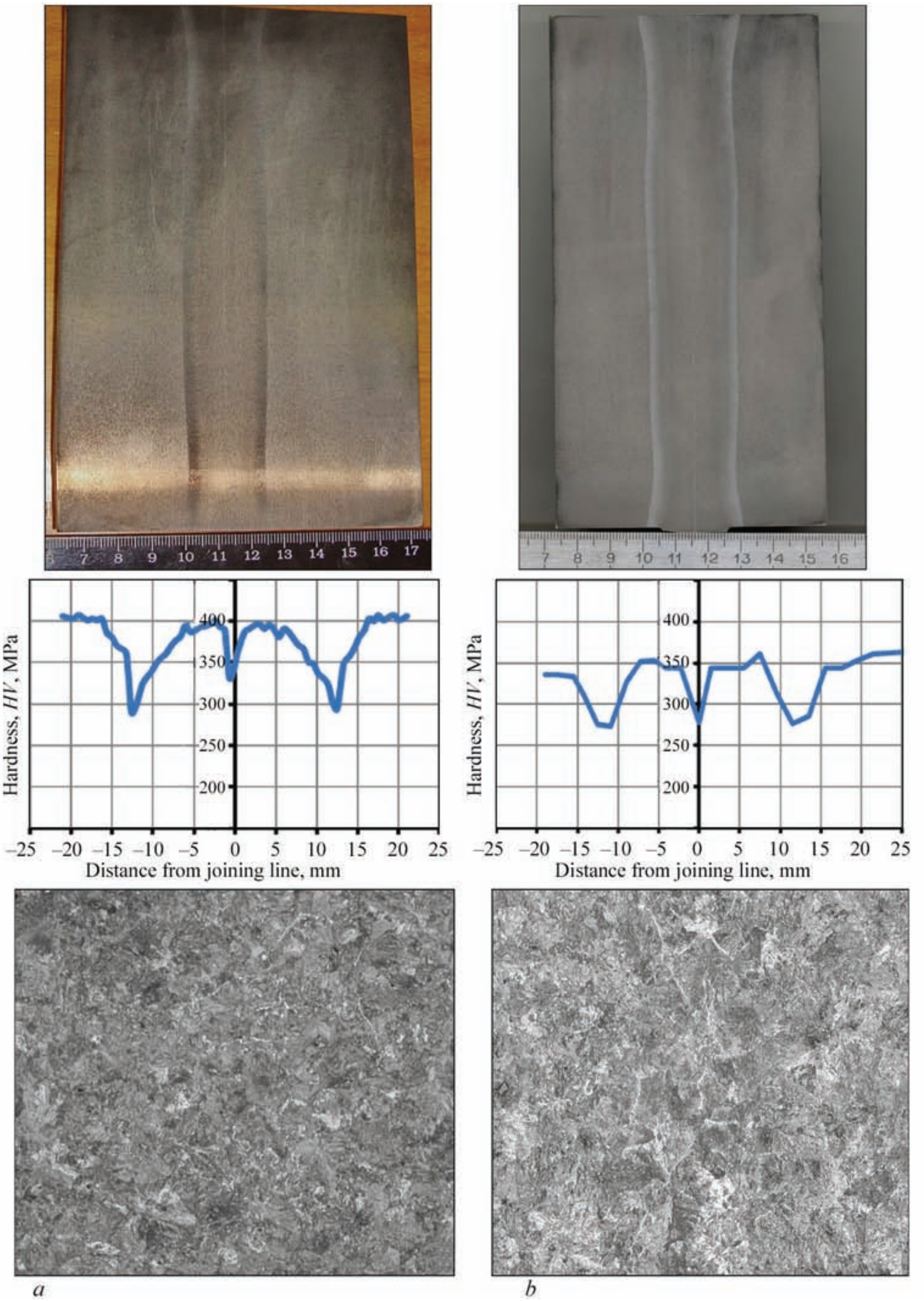

Figure 13. Macro-, microstructure (×100) of the joint zone and hardness distribution (*HV*) in the welded joint of rails of grade AREAL 136 10 SP (*a*) and AREAL 136 HE370 (*b*)

of 10–15 mm, the thickness of precipitations of the carbide phase amounts to tenths fractions of a micron. The presence of this phase increases the wear resistance [11]. In welded joints of these steels, produced at optimal conditions, the carbide phase is absent, and along the joining line, as in the other given examples of high-strength steels, the hardness decreases as compared to the level of the base metal. The degree of reduction is determined by the amount of energy input. During welding of such steels at the accepted mode, the width of the heating zone is larger than in the steel R350NT and amounts to (about 30 mm), which allows withstanding the required tolerances for deviations of hardness values in welded joints.

The welding of rails of the mentioned steels was carried out in the mobile machines K922 of the PWI design, which are used in the railways of Ukraine and other countries. The technology of welding using PF was based on the program of energy input (see Figure 6). Its basic parameters are the following: the value of open-circuit voltage U_2, upsetting forces were taken the same for the rails of all the batches. The energy input was regulated by changing the flashing duration and the value of welding current I_w in the pe-

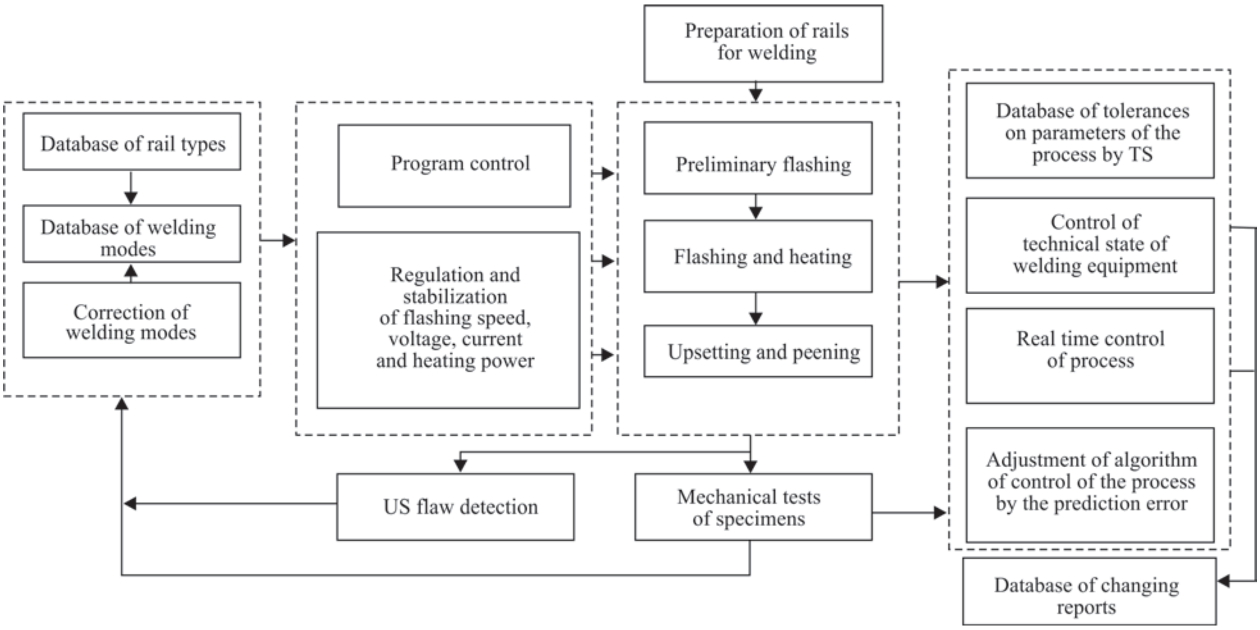

Figure 14. System of automatic multifactor control of parameters of welding process in welding of high-strength rails K76F

riod II, specified by the program. The optimal modes for welding each rail batch were established and the reference batches in the amount of 10 butt joints were welded, which were subjected to tests in accordance with the requirements of the EU and Ukrainian standard. The test results are given in Table 3. All the welded joints of reference batches satisfy the requirements of the mentioned standards not only by the results of mechanical tests, but also during testing the quality of joints using nondestructive methods of testing. The rails of the type R260 and R350 were tested for fatigue and withstood 5 mln cycles without fracture. It should be noted that all the welded joints of reference batches were not subjected to heat treatment after welding. In the process of investigations and gained experience of the production use of the developed technologies, it was established that during welding at the modes characterized by a low energy input, a more strict limitation of the admissible deviations of the preset welding parameters is necessary, especially those affecting the energy input. Therefore, the implementation of PF welding technology in production conditions became possible after the development of the new systems and algorithms for automatic control of the welding process at the PWI. Instead of using rigid programs for changing the basic parameters accepted during welding of standard rails, a self-adjusting system for control of parameters was developed (Figure 14). The system allows maintaining the optimum mode of stable flashing and heating in real industrial conditions, largely regardless the changes in operating conditions (voltage mains fluctuations, changes in ambient temperature as compared to the calculated one, being 20 °C).

A distinctive feature of the developed technologies is the presence of feedback by the basic parameters in the control systems, automatically correcting their value preset by the program during deviation from the preset values. In the process of flashing, short-term corrections of the preset values are carried out in order to stabilize their preset mean values. The algorithms for control of this process were developed for each of the parameters, for example, the value of welding current and energy are regulated by the feed speed so, that their mean values maintained at a preset level. At the same time, the level of the voltage is taken into account, supplied to the parts to be welded, resistance of the welding circuit and the force, generated by the hydraulic drive of the machine (during welding with tension). The similar multifactor algorithms for regulation are also used by the other flashing parameters. In some cases, the accumulation of short-term changes of the values preset by the program, can lead to correction of the program itself, for example, to increase in flashing duration in each of its periods. If these changes do not exceed the admissible ones, then they are acceptable. The algorithms for assessing the effect of changes on the quality of joints were determined. They allow expanding the range of admissible deviations and provide a high reproducibility of the preset welding programs.

The capabilities of the automatic system for control of welding parameters are not infinite and cannot prevent rough violations of the operating conditions of welding equipment.

The registration of programs for changing basic parameters during welding of a butt joint provides an effective use of the developed algorithms for evaluation of the joint quality according to the value of deviations in a real time of works. For each welded butt joint, the computer system for control of the welding machine issues a certificate, where the change in the basic parameters, as well as their actual deviation from the optimal values is shown in textual and graphical form. The algorithms of control were developed, on the basis of which the system provides a quality evaluation of a welded butt joint in real time and includes it to the certificate. The test results are issued simultaneously after the end of welding on the machine display for information to the operator and simultaneously to the diagnostic center, where a more thorough analysis is carried out taking into account the results of destructive testing of butt joints and ultrasonic inspection. The specialists of the PWI together with the PrJSC «Ukrzaliznytsia» performed a large amount of works (several tens of thousands of welded butt joints). On the basis of this information, the algorithms for assessing the quality of joints during in-process control and the normative documents regulating the quality assessment [11] were specified.

The multifactor system for control of welding machines (see Figure 14) is used in stationary and mobile machines of the PWI design. In the design version for mobile machines, it is combined with a drive, providing welding of rails with tension, where additional feedbacks are used, providing the fulfillment of programs for moving welded rails combined with their tension.

These operations are controlled by a common computer, which simultaneously performs welding programs, in-process control and rail tension by the mobile machines.

Welding of long-length rails with tension. During repair of seamless railroad tracks after cutting out of defective or worn-out sections of rails, as well as during reconstruction of tracks, it is necessary to weld long-length rail sections attached to the crossties between them. For this purpose, instead of a cut-out section of rails between the ends of the joined sections, a rail-insert is installed, which is welded-on to the ends of the rail sections [12]. During welding of the second closing butt, in accordance with the standards, it is necessary to restore the temperature-stress state on the section where welding was performed. This is achieved by adjusting the length of the rail-insert due to its elongation or shortening by the value $L_t = f(\Delta T)$, where $\Delta T = \theta_{fix} - \theta_w$ (θ_{fix} is temperature of the fixing welded plates, θ_w is the temperature at the moment of welding rails). For railways of Ukraine, the temperature of fixing the rails is $\theta_{fix} = 30$ °C. Most of such works are carried out at the ambient temperatures $\theta_{fix\ w}$ ($\theta_{fix\ w} < \theta_{fix}$), respectively, it is at the same time necessary to shorten the length of the insert-rail. In order to obtain the required increment of L_t and also to provide allowances for welding, the insert and a part of the rail track of the released section are bent. After welding the section is returned to its initial position. This operation is very labor-intensive. It is performed using a set of mechanisms (lifting, tension) and a large number of auxiliary workers. The railway traffic in the period of repair is stopped, which is associated with great material losses. The PWI specialists together with the USA companies, engaged in reconstruction and repair of railways, developed the technology and equipment which allowed combining welding with restoration of temperature-stress state of the track. It is based on the idea of creating such a level of tensile stresses in the process of welding in the joined rail sections, at which, at a preset temperature range (–40–+50 °C), the possibility of the formation of compression stresses is excluded. The carried out calculations showed that to solve this problem, it is necessary, that the level of tensile stresses does not reach the limit values, exceeding 16 % of the yield strength of rail steel, which is acceptable. To perform the tension, it is proposed to use a hydraulic drive for flash-butt welding machines of the PWI design, performing flashing and upsetting. The process of flash-butt welding was proposed to be carried out using programs involving two stages. At the first stage, the high-speed movement of the end of the welded insert is provided to the size of the preset gap Δ_g. The duration of this stage does not exceed a few seconds. After contact of the ends of the rails and the exciting of flashing, the program of welding rails accepted for the rails of this type with their simultaneous tension is performed. During welding, the rails are shortened and their tension is continuing. After the end of welding, the required shortening is provided $L_t = L_{w\ t} + \Delta_g$, where L_w is the shortening of the rail during welding ($l_w = l_{flash} + l_{upsett}$)$\Delta_g$ is the gap between the ends of rails, preset before welding. The regulation of the tension value is carried out by setting the gap Δ_g. In the considered variant, the rails adjoining the welded joint are not stretched and the whole tension L_t is carried out due to the elongation of a rail-insert. In many cases, the forces required for tension of a rail-insert of the standard length of 24 m cannot be provided. In this case, the required value of tension is provided due to additional jointing of rail ends from the crossties adjacent to the weld to the value $L_{cr.\text{-}t}$, T. The total force L_t is formed due to the choice of the value $L_{cr.\text{-}t}$ and Δ_g, i.e. $L_t = L_{cr.\text{-}t} + \Delta_g + L_w$.

In welding of rails with tension, the technology of welding rails with PF is used. The programs for control of welding process are stored the same as during welding of separate rails without tension using common systems for automatic control of flashing parameters and introduction of additional feedbacks of parameters controlling energy input. The change of stress forces during welding affects the operation of the hydraulic drive of welding machines. Except of the data determining the parameters of welding modes, the development of additional systems of automatic control, stabilizing the energy input, was required.

In welding with a tension, the data on the temperature of rails, at which their welding is performed, are entered into the computerized control system: θ_w, the total length of sections areas released from the fasteners ($L_{cr.-t}$), the length of the rail-insert, as well as the size of the gap between rail section and the insert Δ_g. In addition, the value of the fixing temperature on the welded area θ_{fix} is separately entered.

In welding with tension after the end of welding, the weld metal is heated to the temperature of 1100–1200 °C and is maintained in a compressed state by the drive of the welding machine. At the same time, the control systems, mounted into the machine, control the duration of cooling the weld to the temperature of 100–200 °C. Simultaneously, the flash, formed during welding, is cut out automatically. After performing these operations, the rails are unclamped and the welding machine is removed from the butt. The duration of rail welding does not exceed 2 min, and the auxiliary operations largely depend on the chosen scheme of works organization during welding. Performing the tension according to the variant, when preparation of a rail-insert of a preset length is used without jointing the adjacent areas of the sections, the maximum efficiency of rail welding complexes is provided, and using the variant, requiring the jointing of a certain section of the track, the duration of auxiliary operations increases and depends on the length of the section, released from the cross-ties.

Figure 15 shows the dependence of the force (*1*) and the value of the travel of the movable clamp of the welding machine (*2*), necessary for the implementation of the rails tension, corresponding to $\Delta T = 30$ °C at different length of their section, released from the cross-ties. If the tension is carried out only with the help of the rail-insert of 24 m length, a tension force of 100 t and the travel of the movable clamp of about 150 mm are required. At the condition that the ends of rails are released from fastenings at different length, the force is significantly reduced. An increase in the travel of the movable clamping machine has a much smaller effect on the weight of the rail welding machine than the effect of the upsetting force. Therefore, the rational relationship of these parameters of the machines determines their capabilities during

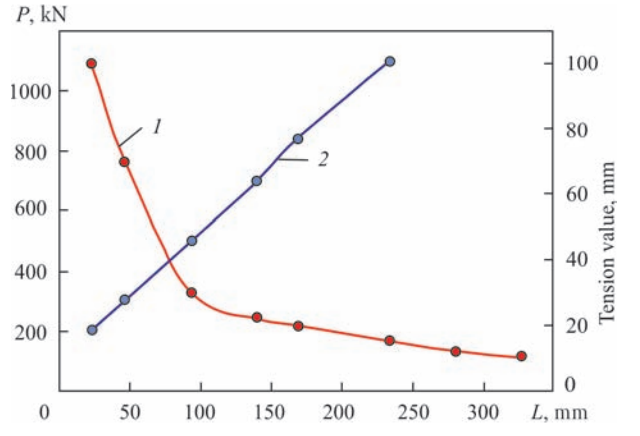

Figure 15. Dependence of tension forces (*1*) and tension value (*2*) of travel of moving clamp of the machine on the length of the jointing section of the rail fastening on the cross-ties at $\Delta T = 30$ °C

operation in different conditions. The rail welding machines of previous generations of the type K355, K900, available at the railways, cannot be used for welding with tension, primarily due to the insufficient upsetting force and the limited travel of the movable clamps. In addition, during development of new generations of mobile rail welding machines for welding with tension, a significant change in their basic units, systems of hydroelectric control, design of the drive for welding circuit and flash remover were required.

In recent years, the PWI developed several generations of machines for flash-butt welding with tension. Unlike the machines of previous generations, a number of new solutions was applied in them, namely:

- machines have upsetting forces and, accordingly, clamping forces which are 2–3 times higher. The upsetting forces and clamps are increased with an increase in the movement travel of the movable clamping;
- machines have a multifactor system for the control of basic parameters of the welding process, providing a stable reproduction of preset welding programs regardless of the change in the tension forces;
- welding circuit of the machines despite the increase in the sizes of the force drive for feed the mechanical part, provides the required minimum level of $Z_{sh.-c}$;
- cutting of flash during welding is carried out by the mechanism of flash remover, built-in to the body, which is controlled in the clamped state up to the full cooling of the butt joint. This eliminates the probability of rupture of a heated butt joint during unclamping of the machine.

The developed new generation of rail welding machines allows welding long-length rail sections, combined with their tension. The technical characteristics of the machines are given in Table 4. The machines are distinguished by an increased upsetting force, exceeding the values of previous generations of machines by 2–3 times. In addition, the movement drive

Table 4. Technical characteristics of stationary and mobile rail welding machines developed by the E.O. Paton Electric Welding Institute and manufactured by the PJSC «KZESO»

Technical parameters	Types of machines of the OJSC «KZESO»									
	K900	K920	K921	K922-1	K930	K950	K945	K960-1	K1045	K1000
Rated voltage of mains, V	380	380	380	380	380	380	380	380	380	380
Highest secondary current, not lower than, kA	60	67	67	67	67	67	67	67	60	84
Rated power, (DC 50 %), kV·A	150	211	236	210	210	210	210	210	150	300
Upsetting force, kN	450	1000	1500	1200	1200	1200	1200	2000	600	900
Clamping force, kN	1350	2500	2900	2900	2900	2900	2900	4650	1500	2000
Travel of moving column of the machine, mm	70	100	150	100	200	250	400	280	100	100
Weight of the machine, kg	2700	3000	4100	3450	3600	3650	3700	5670	3500	8800

has a 2–4 times increased travel of the movable part of the machine, taking into account the different values of tension during welding.

The machines provide different PF processes to a full extent, adapted to the specifics of flashing drive loads while performing a pulsating process of moving welded parts in combination with their tension. The drive is characterized by a high quick-response, providing a change in the value of spark gap with an accuracy of tenths of millimeters. With an increase in the upsetting and clamping force, the weight of the machines increases, which defines the design of the auxiliary equipment used in flash-butt welding of rails. The power part of mobile complexes is determined by the power of diesel generators. It remains the same as for previous generations of machines of 250–300 kV·A. With an increase in the weight of welding machines, more powerful lifting devices of the complexes are required, which reduces their mobility. During the use of the machines K900 of previous generations, a large number of such complexes were manufactured in different countries. Therefore, the demand for flash-butt welding machines with tension appeared, having a lower weight and adapted to the existing mobile rail welding complexes of previous production.

The advantages of flash-butt welding with tension are fully realized in the machines K921 (Figure 16) designed by the PWI. The upsetting force of 150 t, developed by the drive of the machine, allows carrying out welding with tension during reconstruction of railway tracks with their transfer to the high-speed mode of operation. During welding, the section regions, adjacent to a welded butt for not more than 15–20 m, are released. The machines K921 are used in the USA, where more than 10 thou of high-speed racks are welded using such machines. The machines K922 (Figure 17), designed at the PWI in accordance with license agreements, which are adapted to the already operated complexes in many countries of the world, are used in different mobile complexes equipped with flash-butt welding machines K922 of the KZESO production. About 20 of such machines operate at the railways of Ukraine. A successful combination of upsetting force (up to 120 t) and the travel of the moving clamp (150 m) provides minimization of the length of the section, released from the cross-ties, and allows using these machines in different conditions. At the same time, the machines K920, K930 with upsetting force of 100 t are being developed and they are adapted to the mobile rail welding complexes of the machines (K900) of previous generation, available in many countries of the world.

In accordance with the license agreement with the Holland Company, the PWI developed the machines K930 and K945 (Figure 18), which have an increased travel of the mobile clamping of up to 450 m with an upsetting force of 120 tons. This allows welding long length rail sections during reconstruction of railway

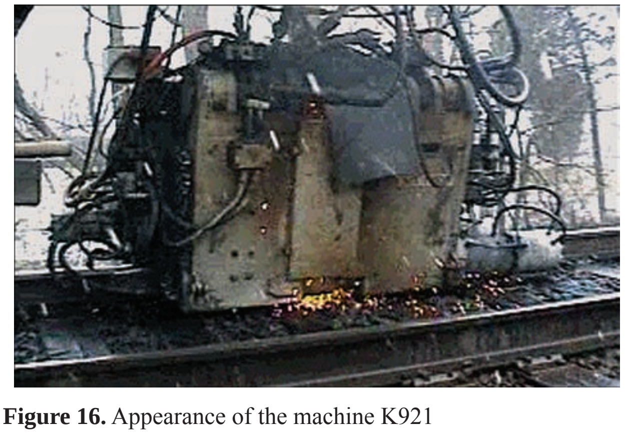

Figure 16. Appearance of the machine K921

Figure 17. Appearance of the machine K922

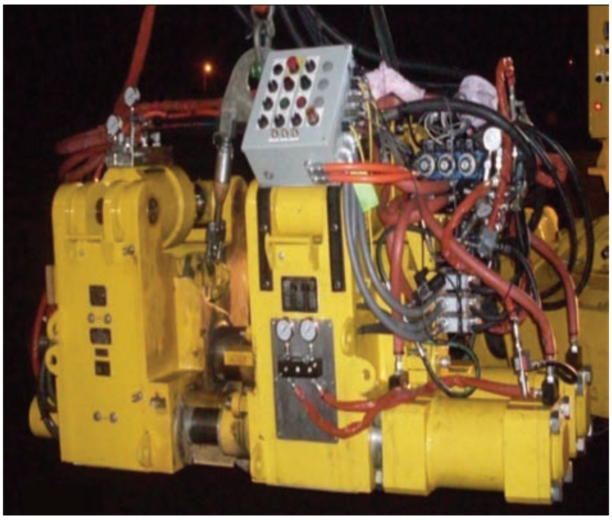

Figure 18. Appearance of the machine K945

Figure 19. Mobile rail welding complex KSM 007 with welding head K922-1 based on a Volvo machine

tracks. Accordingly, the mobile complexes for operation with such machines were developed. The minimization of weight and expanded capabilities of upsetting drive allowed creating highly-manouevrable complexes using the machines K945 (Figures 19–22). Ten such complexes have been operating since 2014 at the railways of the Great Britain. They use the machines K945, developed at the PWI and manufactured at the KZESO.

Conclusion

The many-year developments of the PWI technologies and equipment for flash-butt welding of rails made a significant contribution to the development of railway roads in the countries of the former CIS and the world. According to the data of the plant KZESO, at present more than 2,500 machines is operating, developed by the PWI, manufactured and supplied by the plant in accordance with license agreements and contracts to different countries of the world. Only in the last 5 years, such rail welding machines were exported to the USA, Canada, China, France, Iran, Malaysia, Austria, Morocco, Poland and other countries, which accounts for 60 % of the world stock of

Figure 20. Mobile rail welding complex KRS-1 with welding head K922-1

Figure 21. Mobile rail welding complex (USA)

Figure 22. Mobile rail welding complex (UK)

flash-butt rail welding machines and 90 % of mobile rail welding machines [13]. Their use contributed to the acceleration of construction and reconstruction of railways, including high-speed railroads. Only at the railways of China more than 100 machines K922 are used, which contributed to the acceleration of the construction of high-speed railroads there. At the USA railways, the machines K900, K920, K930, K922, K921 are used.

The PWI continues to develop the technologies and equipment for flash-butt welding of high-strength rails, the demands for which are continuously sent to the Institute. This is predetermined by the increase in the traffic volume of railroads and the need in increasing the life of rails in operation. The metallurgical industry begins to master the production of high-strength rails with a guaranteed service life, which exceeds the average level of achieved wear resistance by 2–3 times. The existing experience shows, that the rails of such quality are difficult to weld. The new technologies of their welding and automatic system for the control of welding process are needed.

Along with the developments of new technologies, the PWI continues to develop new equipment for welding of rails on the track and in stationary conditions.

In accordance with a licensing agreement with the Progress Rail, USA, an experimental model of the machine K960 with an upsetting force of 200 tons was designed and manufactured, which is being tested, as well as the machine K963 for welding rails with rail frogs. The machine K960 is characterized by unique capabilities for the further development of technologies of welding with tension, and the new machine K963 allows for the first time to weld-in the rails with the ends of railway frogs on the track.

The further improvement of the system of remote quality monitoring of rail joints in real time is very promising. The use of modern means of information technology opens up broad opportunities for the further development of an effective type of quality control of welded rail joints. The development of new technologies, systems for automated control of the process of flash-butt welding of rails continues.

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Received 18.10.2018