DOI: https://doi.org/10.37434/tpwj2023.08.01

MODERN TECHNOLOGIES OF WELDING RAILWAY RAILS (REVIEW)

I.V. Ziakhor[1], **Ye.V. Antipin**[1], **O.V. Didkovskyi**[1], **O.V. Kavunichenko**[1], **A.M. Levchuk**[1], **Yu.A. Shylo**[1], **Yan Truska**[2]

[1]E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
[2]SaZ s.r.o. Company Koupelní 3908/6, 69501 Hodonín, Czech Republic

ABSTRACT

The known methods of welding railway rails in terms of their efficiency, productivity and ability to provide the quality of welded rails in accordance with the requirements of standards in force were analyzed. When evaluating the efficiency of different methods of welding, the technological features of formation of welded joints, values of mechanical properties, macro- and microstructure of the joints, the probability of defects formation, efficiency and possibility of automation of the welding process were taken into account. It is shown that such welding methods as thermit, automatic electric arc, gas-pressure and electric resistance found practical application. The varieties of the latter are flash-butt welding (FBW) using continuous flashing, FBW with resistance preheating and FBW with pulsed flashing. FBW technology with pulsed flashing allows providing optimal thermal cycles when welding steels with different chemical composition and properties and ensures compliance of welded joints with the requirements of standards in force. Scientific, technological and design developments of E.O. Paton Electric Welding Institute (PWI) were implemented in a series of stationary and mobile rail welding machines, which are equipped with mobile rail welding complexes, successfully introduced in many countries of the world.

KEYWORDS: thermit, electric arc, gas-pressure, flash butt welding of rails

INTRODUCTION

Current state and service conditions of Ukrainian railways, necessity of their integration in the international system of transport corridors, necessity of increase of movement speeds, ensuring correspondence to international standards for smoothness and safety of traffic — all this requires permanent development and improvement of the whole railway complex. First of all it refers to track facilities that are one of the most important elements of the railways. Condition of upper structure of a track determines the speed and safety of train movement, allowable loads on axles of carriages and locomotives [1]. Analysis of productivity of freight and passenger traffic on European railway shows that increase of their efficiency is mainly achieved due to technical progress [2, 3].

One of the scientific and technical problems requiring continuous solution is improvement of the technology and equipment for welding of a continuous seamless track [4] from railway steels of modern manufacture [5–7]. Seamless track is the most progressive structure of upper track construction. Its main advantage lies in almost complete elimination of rail bolted connections which are the reason of additional dynamic impact of the wheels on the rails.

Joining of rails in manufacture of extended rail sections (200–800 m) in fixed plants, as well as in the field, when laying the rails on the track, is carried out by welding [3, 4]. Service characteristics of railway rails and their welded butt joints are an important component of the life of railway networks, and they are regulated by current domestic and international standards [8–11]. Leading world manufacturers of railway rails constantly improve rail steels aimed to increase the hardness, brittle fracture resistance, and wear resistance, in particular in the rail head [12–17].

Methods of fusion [18–26] and pressure welding [3, 4, 27–35] are used for welding of rails in construction and repair of railway tracks. Methods of fusion welding have been used since 1920th, in particular, in repair and subsequently at construction of railway tracks. The methods used in practice are thermit [18–20], and electric arc (manual with stick electrodes, semi-automatic gas-shielded and flux-cored wire [21, 22], automatic electric arc bath welding, using a consumable nozzle [23–26]). Among the methods of pressure welding the efficient ones are gas-pressure [27–28], induction [29, 30], linear friction [31–34], and electric resistance welding [3, 4, 35–39]. The varieties of the latter are flash-butt welding (FBW) using continuous flashing, FBW with resistance preheating and FBW with pulsed flashing.

The works on development and investigation of the technology of electroslag welding of rails [40, 41] were conducted, but information on wide practical application of this method could not be found in available publications.

The aim of the review is analysis of well-known methods of welding of railway rails from the point of view of their efficiency, productivity and ability to provide the characteristics of welded rails quality in accordance with the requirements of standards in force.

Evaluation of the efficiency of different methods of welding the railway rails was based on technological peculiarities of formation of welded joints, values of mechanical properties, macro- and microstructure of the joints, probability of defect formation, suitability for testing (prediction) of butt joint quality, productivity and possibility of welding process automation.

Since thermit, electric arc, gas-pressure and flash-butt welding have found practical application in construction and repair of railway tracks, this review will be dedicated to analysis of exactly these methods.

THERMIT (ALUMOTHERMIC) WELDING

Thermit welding (TW) is the method in which heating and melting of rail ends is carried out by the heat of chemical reaction of a powder-like thermit mixture. It consists of oxidized iron and metallic aluminum as reacting components and of alloying components. The composition of the thermit mixture is specified in such a way that the composition of weld metal is close to that of the rail steel.

Reliable fixing of rails [18] is provided for the purpose of elimination of possible weld defects. A thermit mixture is poured into a crucible installed above the mould and the reaction is started using a pyrotechnic reagent. The time of the reaction is 15–30 s, the temperature during TW reaches 2000 °C or higher and molten steel and alumina slag are formed. They remain molten and are separated in the crucible due to a difference in the specific weight. Molten steel produced in such a way is poured between the rail ends. The process from release to solidification takes approximately 4 min. The total time of performance of one rail joint is approximately 30 min. The equipment for TW includes a torch for preheating, a crucible, a set of moulds and a flash-remover with a hydraulic drive.

As can be seen from the photo of TW weld macrostructure (Figure 1), the width of cast zone is up to 75 mm and the HAZ width is approximately 20 mm on both sides of the weld [19]. The values of hardness of the metal of the weld and HAZ in TW of thermally-hardened rails are significantly lower in comparison with the characteristics of base metal. To reduce the hardness gradient (Figure 2) in TW of high-strength rails, heat treatment is sometimes used, i.e. reheating of the weld to austenite region and accelerated cooling with compressed air.

Weld metal structure is characterized by grain size number 1 typical for overheated steel. Formation of defective structures with large grain size promotes a loss of steel ductility [20]. Presence in the weld of nonmetallic inclusions of manganese sulphide type can significantly influence formation of defects, which considerably decrease the ductility and strength values of welded joints at cyclic loads.

In TW the rail length during welding does not change, therefore this method is successfully used under field conditions for the final stage of rail installation. Quality of welding mainly depends on compliance with the conditions of preparatory works and quality of thermit mixture. This is responsible for low suitability of TW to automated control and prediction of weld quality. The necessary level of joint metal hardness depends on the rail grade, and it can be controlled by the quantity of alloying elements [20]. Despite the comparatively low productivity and impossibility of process automation, the TW technology due to high mobility and versatility has been used for more than 100 years for joining rails for various applications (on tram and railway tracks), as well as for welding railway crosses [18, 19, 23, 37].

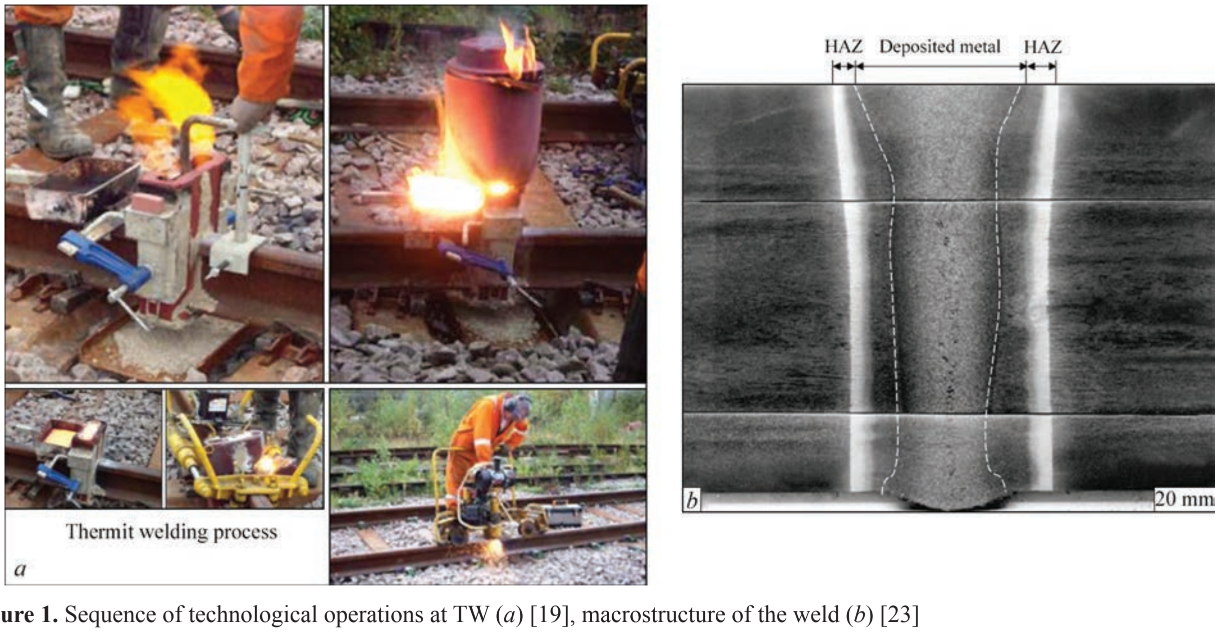

Figure 1. Sequence of technological operations at TW (*a*) [19], macrostructure of the weld (*b*) [23]

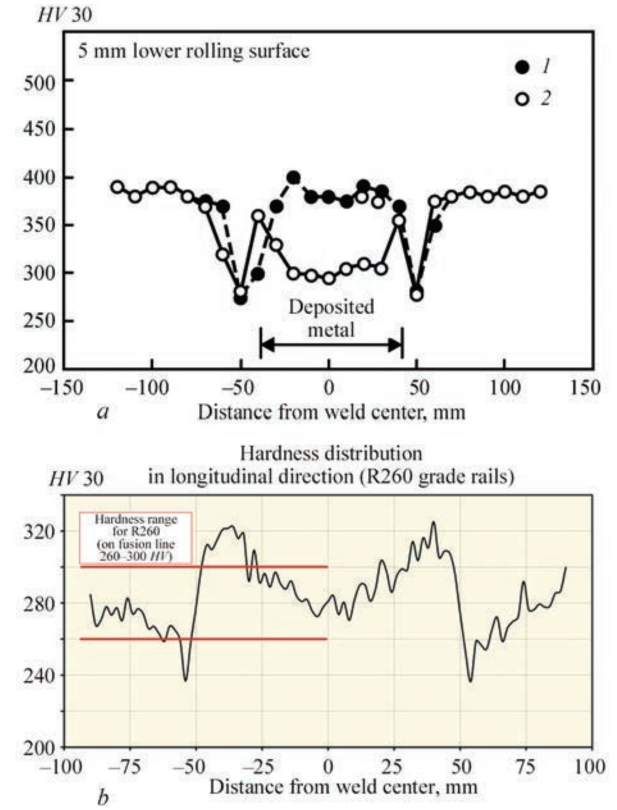

Figure 2. Hardness distribution in joining rails of R350HT (*a*) [23] and R260 (*b*) strength class [37]: *1* — after reheating and accelerated cooling; *2* — after welding

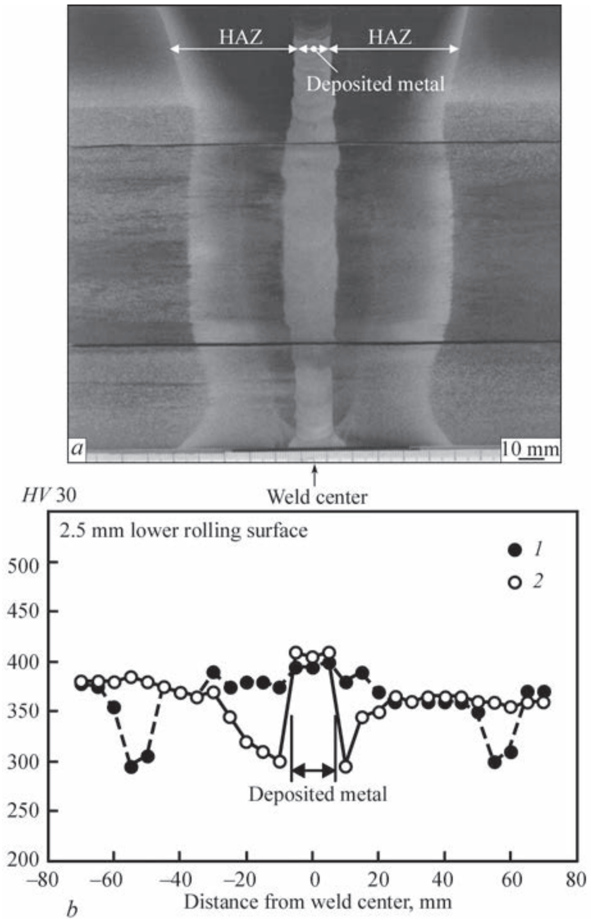

Figure 3. Macrostructure of weld (*a*), distribution of hardness in HAZ (*b*) of a joint of thermally-hardened rails [23]: *1* — after reheating and accelerated cooling; *2* — after welding

ELECTRIC ARC WELDING (EAW)

The simplest variation, namely manual bath EAW using coated electrodes, is mainly applied for joining of tram and crane rails [21]. However, this method does not provide a satisfactory quality of joining the railway rails, it depends on welder's qualification and is significantly inferior to other welding methods in terms of productivity. Semi-automatic bath EAW has higher productivity. It was used, in particular, in repair of underground railway tracks [21]. Crack formation in the welded joint zone was eliminated using preheating to 300–350 °C temperature. Work [22] describes the experience of application of hidden arc EAW using high-carbon electrodes for joining high-strength steel rails. The technological cycle of welding included preheating and postweld heat treatment. Higher productivity was achieved at automatic fusion welding using a combination of consumable electrode gas-shielded EAW technology (for the rail foot) and narrow-gap electroslag welding [22].

There is experience of successful application of EAW in construction of a high-speed railway line in Japan, where the quality of welded joints [23] was dramatically improved due to upgrading of the technology and welding consumables, as well as application of special heat treatment. Process of EAW of rails includes deposition of a root bead with full penetration, multipass welding of the foot, continuous welding from web to head and multipass welding of the rail head. Welding wire of 800–1100 MPa class was used for standard carbon steel rails. Weld metal has a bainitic structure, due to a low content of carbon in the wire. High-carbon welding wire was used to produce a pearlitic structure in weld metal [23] that improves wear resistance and resistance to wear-out of weld metal of high-strength rails. Welding productivity (one butt joint in 60–75 min) is at a low level even under the conditions of modern equipment application.

Figure 3 shows weld macrostructure and hardness distribution in the zone of the joint of thermally-hardened rails. Weld width is approximately 20 mm and total HAZ width is approximately 100 mm. Weld metal hardness is close to base material hardness of 390 *HV* 30, but zones of lower hardness are present from both sides of the weld. Reheating and accelerated cooling of welded butt joint, carried out for reduction of hardness gradient, promote a shifting of lower hardness zones for 60 mm distance from the weld center [23]. Work [24] shows that in EAW of rails the HAZ metal is the most dangerous area of the joint in terms of cold crack nucleation. Elimination of cold cracking in the joints is problematic without application of preheating to the temperature of at least 250 °C. Increase

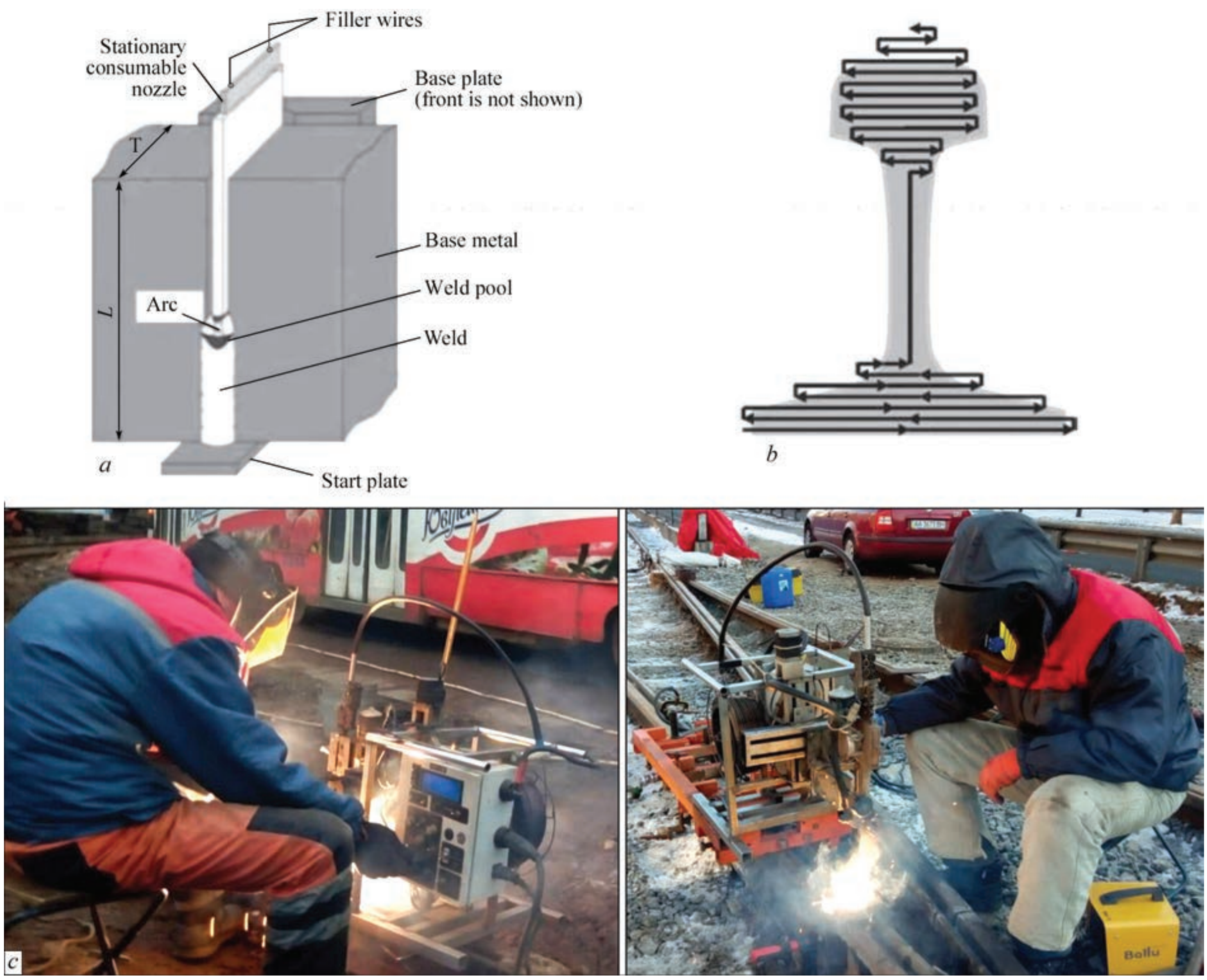

Figure 4. Scheme of the process (*a*), direction of nozzle movement (*b*) [25, 26], mobile equipment for EAW using a consumable nozzle (*c*)

of welding heat input promotes only deceleration of the processes of cold cracks development in the welded joints, but it does not prevent their nucleation.

Known EAW variations have low characteristics of efficiency in terms of guarantee of a defect-free weld, suitability for automated control (prediction) of welding quality, and process productivity.

PWI has developed a technology of automatic bath EAW using a consumable nozzle [25, 26]. Its peculiarity (Figure 4, *a*, *b*) is application of self-shielded flux-cored wire fed through a longitudinal channel in a flat nozzle being melted that allows welding performance at 12–16 mm gap and in some cases at 8–22 mm [25]. Owing to welding process mechanization, the developed EAW technology allows 2–3 times increase of work productivity and a considerable improvement of quality characteristics of welded joints, while preserving the high mobility and versatility of equipment (Figure 4, *c*). Special welding consumables and technology of automatic EAW provide satisfactory values of mechanical properties of the joints [25, 26]. Thus, weld metal hardness in welded joint of R65 rails is equal to *HB* 2600–3200 MPa, yield strength is 800–900 MPa [25], fracture load at static bend testing is 1500–1650 kN at deflection of 16–22 mm. This technology is suitable for welding of rail tracks of industrial enterprises, tram and crane tracks, as well as for performance of urgent repair operations on railways in the future.

GAS-PRESSURE WELDING (GPW)

GPW is a method of pressure welding, at which end faces of the rails are pressed together and a gas flame is used for heating [23, 27, 28]. GPW process (Figure 5) consists of the stages of heating, upsetting, forging and flash removal. The process of heating is carried out manually by a welding operator using an oxyacetylene mixture, so that the level of welding process automation is low. Since the tightness of contact of the ends being welded has a significant effect on the joint quality, the end faces are treated using special grinding devices which determines the corresponding requirements to the staff qualification and organization of preparation work.

During heating the end faces and adjacent areas of the weld are heated to 1200-1300ºC temperature. Pressure on the ends is usually constant, *P* = 20–30 MPa during the entire heating process. During GPW the rail ends are subjected to plastic deformation, the value of rail shortening is 20–40 mm. Convexity formed

Figure 5. Sequence of technological operations in GPW [19]: 1 — dressing of rail ends; 2 — setting up GPW unit; 3 — GPW process (heating stage); 4 — end of GPW process (upsetting); 5 — flash removal; 6 — welded part immediately after GPW

during forging is removed in the hot condition using flash-remover with a hydraulic drive. GPW provides sufficiently high productivity, namely time of welding of one butt joint is 6–7 min, depending on the rail profile. Equipment for GPW consists of a gas-heating device, a system for rail pressing together and a hydraulic flash-remover.

Width of the HAZ of a rail joint is about 100 mm (Figure 6), hardness value decreases approximately to 270–290 *HV* 30, therefore postweld heat treatment is used at GPW of thermally-hardened rails that significantly decreases the efficiency of operations. Typical defects, formed in GPW joints, are oxide films. In work [27] the GPW process using hydrogen as a heating gas was studied, in order to reduce oxide formation.

Regardless of the fact that the quality of welded joints in GPW depends on the level of operator training, quality of heating gas and preparation of rail end faces, suitability for control (prediction) of welded joint quality is higher in comparison with TW and EAW. Subject to qualified staff availability, correct organization of auxiliary and welding operations, GPW provides reliable welding of rails at relatively low investments. It is proved by successful experience of application of this technology in Japan [23]. This method did not become widely used in the EU countries and the USA.

FLASH-BUTT WELDING (FBW)

FBW can be carried out using continuous or pulsed flashing [36–39] and also flashing with resistance preheating [35, 43-47]. In FBW with continuous flashing (Figure 7, *a*) the rails are gradually brought closer at turned-on current source that leads to formation and melting of contact-bridges. This continuous process results in heating of rails to a set depth, and formation of a layer of liquid metal at the ends. After that the speed of drawing together is increased for a short time (intensive flashing stage) (Figure 8, *a*) and upsetting is carried out. The liquid metal with oxide films is pressed out from the joint outside and flash is formed at solidification, which is usually removed while hot.

FBW process with preheating includes the stages of resistance preheating (main preheating of rails), intensive flashing, upsetting and flash removal. In resistance preheating (Figure 7, *b*) the ends of rails are periodically pressed together with a small axial force and current is switched on, then they are separated and withdrawn which causes equalization of temperature fields in the rail cross-section. In resistance preheating the source of energy emission and preheating zone almost completely cover the metal located between the clamping jaws of the welding machine. After heating of rail edges to the necessary temperature, flashing and upsetting are carried out. Until the middle of the 60s of the XX century the rails were joined by FBW method with preheating under stationary conditions in bulky equipment of 20–30 t weight with available powerful (600–700 kVA) power sources.

A known current developer of technology and equipment for FBW with preheating is Schlatter Company (Switzerland) [35], which manufactures rail welding complexes, in particular stationary machines (Figure 8, *b*) for operation under plant conditions. Significant limitations for application of this technology are the necessity to use power sources of considerable capacity, relative complexity, large dimensions and high cost of the equipment, in particular of mobile rail welding complexes.

In 1960s PWI for the first time in the world developed the technological fundamentals and designed highly efficient mobile equipment for welding of railway rails under field conditions. They are based on FBW technology with continuous flashing with a programmed change of the main parameters of the welding process. Programmed change of parameters is carried out together with application of feedbacks which automatically correct the set values of parameters at welding conditions change. Successful realization of this technology is due to development of an original design of welding transformers with lower short-circuit resistance, in particular the idea was realized of application of elements of power hydraulic drive as current-carrying elements of the secondary circuit of the transformers.

The disadvantage of FBW technology with continuous flashing of rails are sufficiently large values of flashing allowance (around 40 mm) and total time of welding (180–240 s). FBW technology with pulsed flashing developed at PWI became a revolutionary improvement of the technology of FBW of rails [3, 4, 36, 38]. Multifactor regulation of flashing provides intensification of contact heating, reduction of metal consumption, and increase of thermal efficiency of the process. Due to highly concentrated heating, the total heat input, process duration and allowance for welding are reduced 1.5–2.0 times.

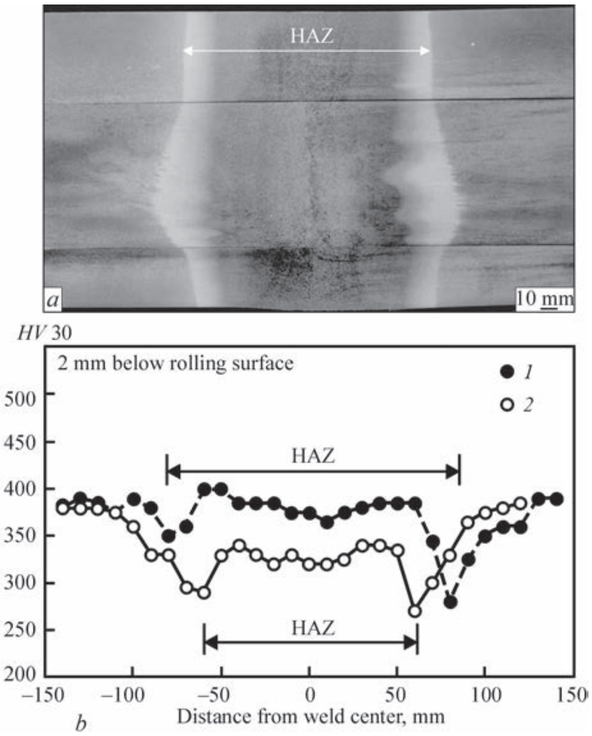

Figure 6. Macrostructure (*a*), hardness distribution in the HAZ (*b*) of the joint in GPW of thermally-hardened rails [23]: *1* — after reheating and accelerated cooling; *2* — after welding

For evaluation of the efficiency of different FBW technologies it is necessary to consider the current standards of Ukraine and EU concerning welded joints of railway rails. Table 1 provides comparison of the requirements of current standards with quality characteristics of welded joints of rails during FBW.

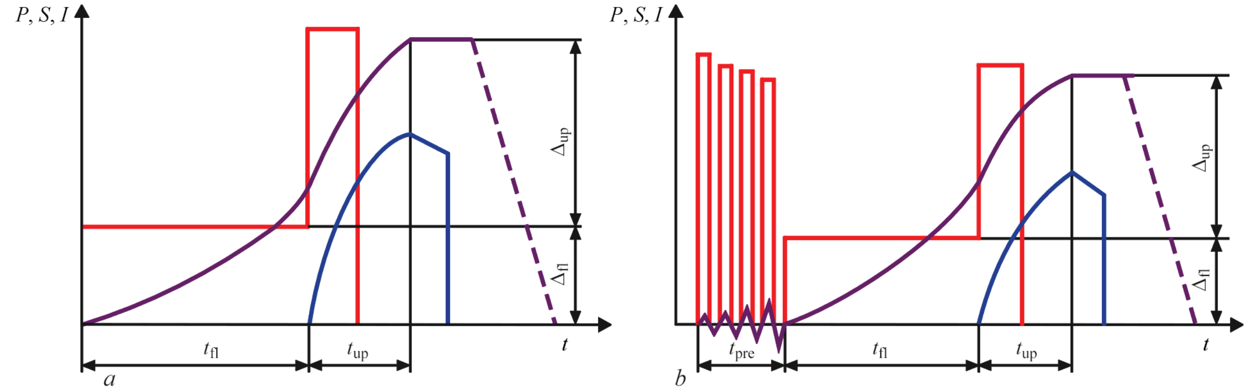

Figure 7. Typical cyclograms of FBW process with continuous flashing (*a*) and FBW with resistance preheating (*b*): t_{fl}, t_{up}; t_{pre} — duration of stages of flashing, upsetting, preheating; Δ_{fl} and Δ_{up} — allowance for flashing and upsetting; *P* — pressure; *S* — displacement; *I* — current

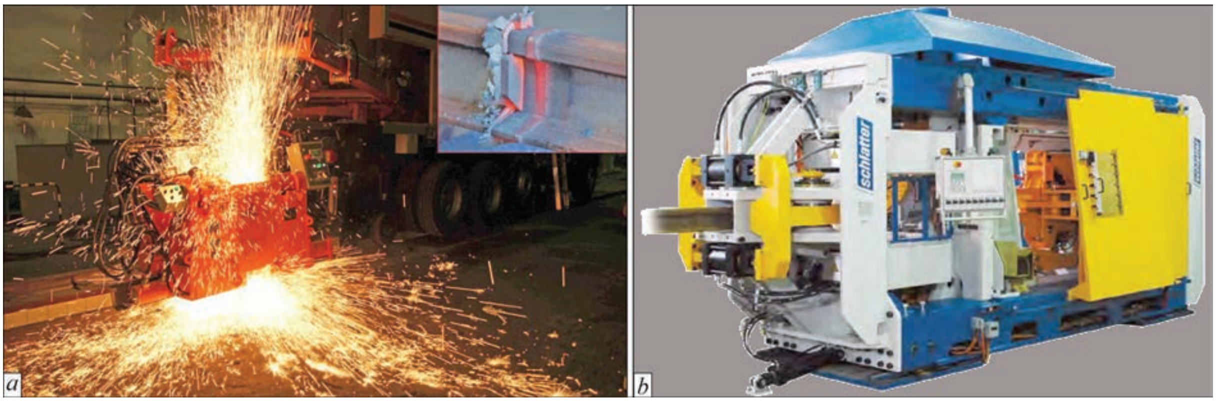

Figure 8. Mobile rail welding machine K922-1 during FBW with flashing (*a*), stationary rail welding machine Schlatter GAAS 80 (*b*) [35]

According to normative documents, namely domestic [8, 9] and European [10, 11] standards, the requirements to welded joints of railway rails can be conditionally divided into the following groups:

Table 1. Main requirements to quality characteristics of welded joints of rails at FBW

Parameter being controlled	EN 14587-1:2018	EN 14587-2:2009	TU U 24.1-40075815-002:2016
Mechanical properties at static bend testing			
Minimum fracture load at its application to rail head, kN	1600		1650
Sagging deflection, mm, not less than	20		30
Presence of defects at magnetic powder inspection			
Cracks	Unallowable		Unallowable
Presence of defects in the fracture of a joint after forced destruction of butt joints			
Lack of penetration	Unallowable		Unallowable
Flat spot (not lens)	Allowable $L < 10$ mm, $\delta < 0.7$ mm		Not more than 3 spots of the area of up to 15 mm^2
Flat spot (lens)	Allowable $L < 4$ mm, $\delta < 0.7$ mm		
Defects and HAZ parameters at macrostructure analysis			
Presence of lacks of penetrations, inclusions, cracks, shrinkage	Unallowable		
Minimum HAZ width H_{HAZmin}, mm	25	20	Not controlled
Maximum HAZ width H_{HAZmax}, mm	45	45	Not controlled
Allowable difference of HAZ width $H_{HAZ\,max} - H_{HAZmin}$, mm	10	20	Not controlled
Microstructure			
Presence of martensite and bainite at ×100	Unallowable	Unallowable	Not controlled
Hardness distribution			
Non-thermally hardened rails (R260, R220, R260Mn, M76, *HV* 30)	Min: $P - 30$ *HV* 30 Max: $P + 60$ *HV* 30		Min: $P - 10$ % *HV* 30
Thermally-hardened rails (R350NT, K76F), *HV* 30	Min: $P = 325$ *HV* 30 Max: $P = 410$ *HV* 30		Min: $P - 15$ % *HV* 30
Fatigue tests			
Number of cycles, mln	5	5	Not controlled
Load, kN	190	190	Not controlled
Note. *P* is the average value of hardness of the rail base metal.			

- values of mechanical properties — deflection and fracture loading in static transverse bending test of butt joints;
- presence of defects — types of unacceptable and maximum dimensions and number of acceptable defects;
- parameters of HAZ — its width and non-uniformity along the length and across the section of rails during analysis of welded joint macrostructure;
- distribution of hardness in the HAZ (minimum and maximum values);
- microstructure of metal in the joint zone and the HAZ — allowable pearlitic structure of different fineness (pearlite, sorbite, troostite), presence of areas with martensitic or bainitic structure is excluded;
- characteristics at fatigue testing of the joints.

Analysis of the data in Table 1 shows that there are considerable differences in the requirements of domestic and European standards, first of all, as regards the need to determine the strength values under cyclic loading of welded joints, and, secondly, quantitative evaluation of joint HAZ parameters. The information in the available foreign publications [43–47] indicates that the HAZ parameters (width, uniformity over rail section) and fatigue strength values are extremely important for prediction of wear resistance of welded joints and service life of the railway track (that is one of the defining criteria of evaluation of welding method efficiency).

That is why, it was a well-substantiated and timely decision of the Ministry of Infrastructure of Ukraine to approve the List of National Standards, correspondence to which gives a presumption of conformity to the requirements of Technical Regulations on Safety of Infrastructure of Railway Transport (Order dated 20.11.2019 No. 815). The mentioned List includes national standard DSTU EN 14587-2:2015 (EN 14587-2:2009, IDT), harmonized with the corresponding European regulatory document [11]. It means that in construction and repair of domestic railway tracks using rails of foreign manufacture the quality characteristics of the joints should be evaluated based on the requirements of the European standard.

Therefore, HAZ parameters, hardness distribution in the joint zone, microstructure (absence of hardening structures) are important criteria for evaluation of the efficiency of FBW technology. Available publications and many years of practical experience indicate that similar to any other method of welding of railway rails, a problem for FBW is formation of a hardness gradient in the HAZ (Figure 9): for thermally-hardened rails — zones of reduced hardness from both sides of the fusion line (Double Dip Hardness) [43–47], for non-thermally hardened rails — significant increase of hardness in overheating zone [4].

The main problem of FBW method with preheating is stabilization of the thermal field appearing during welding. Increase of cross-sectional area of the rails leads to a significant drop of the process energy efficiency and also a decrease of power coefficient. Practical experience indicates that appropriate development of the technology of FBW with preheating allows meeting the requirements to welded joint quality (Table 1). However, realization of this technology of welding is complicated under field conditions because of considerable dimensions of the mobile rail welding machines.

Technology of FBW with pulsed flashing allows regulating the thermal cycles in wide ranges in welding of steels of different composition and properties, and with optimization of the technological modes it provides specified by standards in force [10, 11] quality of rail joints made both by stationary and mobile rail welding machines [4, 39].

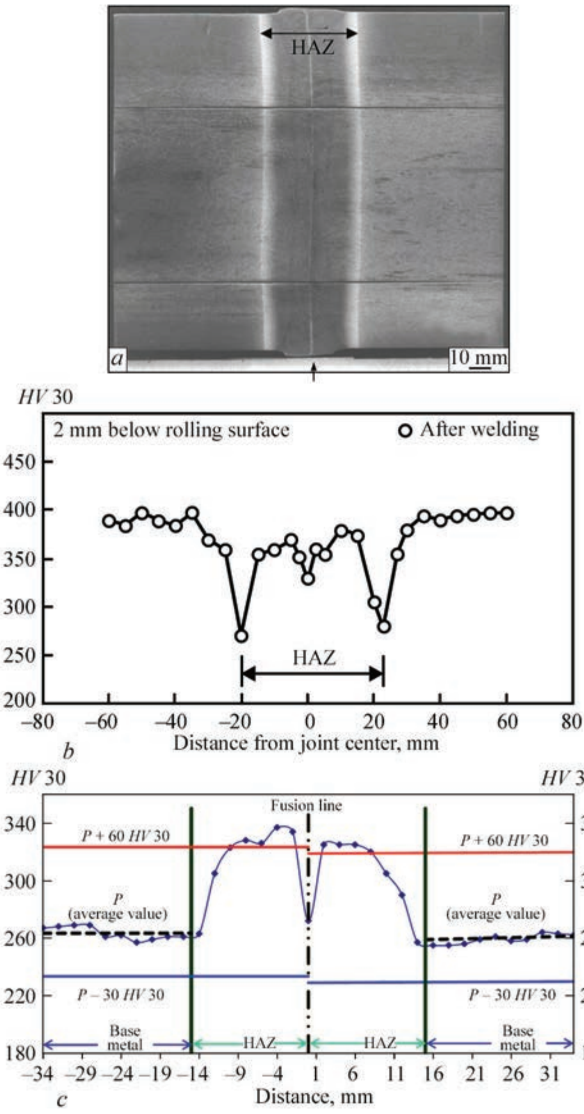

Figure 9. Macrostructure of welded joint of rails in FBW (*a*); distribution of hardness in the joint of rails of R350HT (*b*) and R260 grades (*c*)

Table 2. Comparison of the methods of railway rail welding [23]

Welding methods	Welding time, min	Equipment		Operator skills	Welding quality
		Initial investments	Mobility		
FBW	2–4	Considerable	Low	Not required	High
GPW	5–7	Considerable	Medium	Required	High
EAW	60	Low	High	Required	Satisfactory
TW	30	Low	High	Not required	Satisfactory

Table 3. Evaluative comparison of the methods of railway rail welding

Characteristic (value)	FBW	GPW	EAW	TW
Process metallurgy	Forging	Forging	Melting	Melting
Process automation	High	Medium	Medium	Low
HAZ width, mm	20–45	120–150	80–100	115–140
Suitability for control (prediction) of joint quality	High	Medium	Low	Low

COMPARISON OF DIFFERENT METHODS OF RAIL WELDING

Table 2 provides evaluative comparison of the considered rail welding methods by several characteristics from reference [23] and Table 3 gives evaluation by other considered criteria.

Practical experience shows that despite a comparatively low productivity and complexity of process automation, fusion welding methods (TW and EAW) due to low initial investments, high mobility and versatility, have been used for more than 100 years for joining of rails for different applications on tram and railway tracks, and crane tracks of industrial enterprises, and TW is successfully used for welding of crosses on railway tracks.

Gas-pressure welding provides reliable welding of rails under the condition of availability of qualified staff and proper organization of the auxiliary and welding operations, despite a low level of automation of the processes of rail end preparation, heating and joint quality control. It was demonstrated by successful experience of application of this technology in Japan.

Practical experience of application of FBW with resistance preheating, in particular from Schlatter Company, indicates a correspondence of quality characteristics of rail welded joints to the requirements of standards in force. The main limitation for application of this technology is a relative complexity, large dimensions and high cost of rail welding equipment.

From 1960s till 2010s the technology of FBW with continuous flashing was successfully used in rail joining under stationary and field conditions, in particular for all types of rails of open-hearth production. The disadvantages of FBW technology with continuous flashing of rails are relatively high values of flashing allowance, total time of welding and complexity of provision of thermal cycles specified by the normative documents that are necessary for sound joining of modern wear-resistant rails.

FBW technology with pulsed flashing allows regulating in wide limits the thermal cycles when joining railway rails of different profiles or grade from steels of diverse composition and provides joint quality specified by standards in force. Production of mobile and stationary rail welding machines equipped with computer systems for control

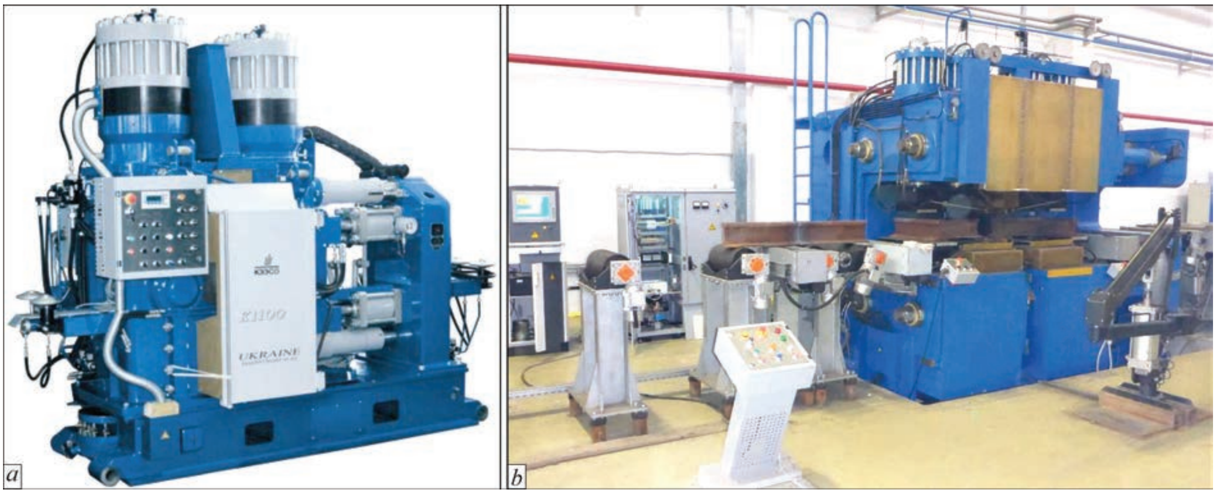

Figure 10. Stationary rail welding units K1100 (*a*), K924 (*b*) designed at PWI

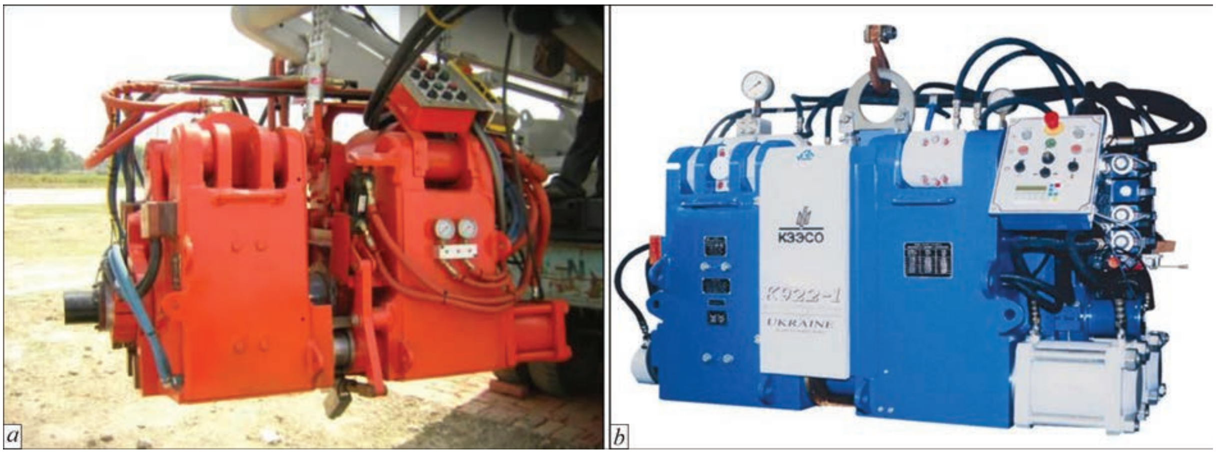

Figure 11. Mobile rail welding machines K920 (*a*), K922-1 (*b*)

of the process and the main welding parameters was mastered in the 2000s. The base of the systems is the principles of controlling the pulsed flashing process [48–50]. A system for automatic control is based on application of fast acting hydraulic drive, industrial computer with a monitor for data visualizing, controller, and sensors of displacement, voltage and pressure. Welding of each joint includes self-regulation of the parameters that provides optimization of the program of their change at all the stages of flashing and on the whole during welding. Computer control system registers all the welding parameters, determines their allowable deviations from set values and provides evaluation of the joint quality directly after welding in accordance with the established algorithms [49, 51].

Figure 12. Mobile machines K960 (*a*), K945 (*b*), rail welding complex with K945 machine (*c*) for FBW of rails with “tension”

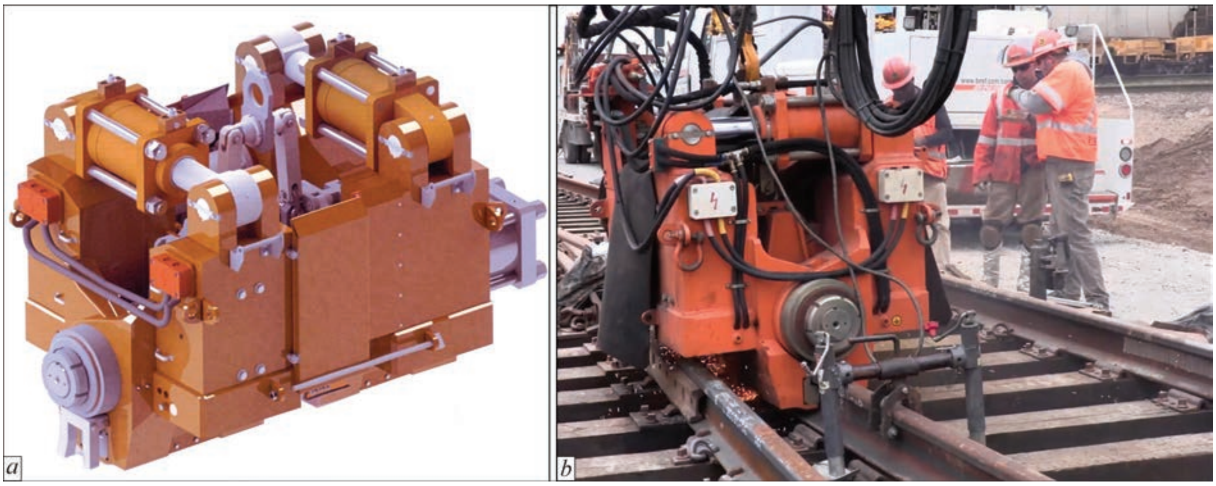

Figure 13. Prototype of machine K1045 (*a*) and welding complex with machine K1045 for FBW of rails in difficult-to-access locations (*b*)

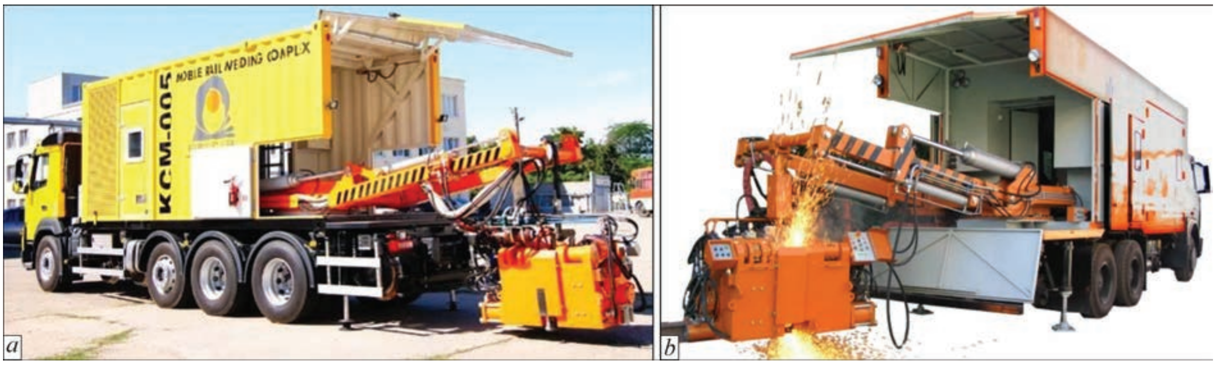

Figure 14. Rail welding complex KCM 005 on a combined chassis equipped with machine K920 (*a*), K922-1 (*b*)

The scientific, technological and design developments of PWI were realized in a series of stationary (K1000, K1100, K924) and mobile machines (K900, K920, K921, K922-1, K930, K945, K950, K1045), which are included into the mobile rail welding complexes (Figures 10–14). The distinctive characteristics of these machines are the kinematic diagram, peculiarities of design of the clamping and axial displacement mechanism, upsetting force (650–2000 kN), etc. The advantage of most of the models of the machines is presence of a built-in flash remover with a separate drive for flash removing in the hot condition without unclamping the rails being welded.

These machines realize a series of internationally patented innovative technical solutions in the field of welding, control systems, designing the assemblies of welding machines, fast-acting hydraulic drives and principles of rail alignment. In recent years several hundred stationary and mobile rail welding machines were manufactured and delivered to different countries (USA, Canada, Austria, Great Britain, China, Singapore, Thailand, Malaysia, Taiwan, Kazakhstan, Slovakia, etc.).

Current scientific, technological and design developments of PWI are focused on maximum adaptation to the customer requirements from the point of view of efficiency of welding of rails of different categories, grade and composition (in particular, of hypereutectoid class and those alloyed by Cr, Mn, Ti, V) [52, 53], design solutions and technical characteristics of the machines, increase of manufacturability of separate assemblies and mechanisms, and they are implemented in the design of new mobile rail welding machines.

CONCLUSIONS

1. Permanent joints of railway rails are performed by fusion welding (thermit, electric arc, electroslag) and pressure welding methods (gas-pressure, electric resistance, induction, linear friction).

2. Thermit, electric arc, gas-pressure and flash-butt welding methods found practical application in construction and repair of railway tracks. The flash-butt welding method has the following variations, namely FBW with continuous flashing, FBW with resistance preheating and FBW with pulsed flashing.

3. Despite a comparatively low productivity, impossibility of process automation, thermit welding, due to its high mobility and versatility, has been used for more than 100 years for joining rails for different applications (on tram and railway tracks), as well as welding railway crosses.

4. Developed at PWI technology of automatic electric arc bath welding using a consumable nozzle is suitable for welding of rail tracks of industrial enterprises,

tram and crane tracks, as well as for performance of operative repair on the railways in the future.

5. Despite a comparatively low level of process automation, gas-pressure welding with availability of qualified staff and correct organization of auxiliary and welding operations provides reliable welding of rails. It is proved by successful experience of application of this technology in Japan.

6. Practical experience of application of FBW with resistance preheating, in particular from Schlatter Company, demonstrates the correspondence of quality characteristics of welded joints of rails to the requirements of current standards. The main limitation for application of this technology is a relative complexity, large dimensions and high cost of rail welding equipment.

7. Technology of FBW with pulsed flashing allows providing optimum thermal cycles in welding of steels of different composition and properties and guarantees joint quality specified by current standards. Scientific, technological and design developments of PWI were realized in a series of stationary and mobile rail welding machines, which are included into mobile rail welding complexes successfully introduced in many countries of the world.

8. Development of FBW technology and equipment is driven by the need for their maximum adaptation to modern requirements of efficient welding of rails of different categories, strength classes and composition, requirements to design solutions and technical characteristics of rail welding machines, increase of manufacturability of separate assemblies and mechanisms.

REFERENCES

1. Paton, B., Kostyuk, M., Kuchuk-Yatsenko, S. (2010) Innovative cluster «Velvet road» and scientific-technical breakthrough of Ukraine into world market of construction of high-speed railways. *Nauka ta Innovatsii*, 6(**2**), 69–86 [in Ukrainian].
2. Cantos, P., Pastor, J., Serrano, L. (1999) Productivity, efficiency and technical change in the European railways: A non-parametric approach. *Transportation*, **26**, 337–357. DOI: https://doi.org/10.1023/A:1005127513206
3. Kuchuk-Yatsenko, S., Yakovlev, V., Didkovskyi, O. et al. (2016) Development of technologies and equipment of rail welding is the key for widening of all-welded seamless tracks in Ukraine. *Ukrainska Zaliznytsya*, **1**, 56–59 [in Ukrainian].
4. Kuchuk-Yatsenko, S. (2018) Technologies and equipment for flash-butt welding of rails: 60 years of continuous innovations. *The Paton Welding J.*, **11–12**, 25–40. DOI: https://doi.org/10.15407/tpwj2018.12.03.
5. DSTU 4344:2004: *Rails common to broad gauge railways. General specifications*. UkrNDIMet, Kyiv, Derzhspozhyvstandart [in Ukrainian].
6. EN 13674-1:2011+A1:2017: *Railway applications – Track – Rail.* Pt 1: Vignole railway rails 46 kg/m and above. European Committee for Standardization.
7. DSTU EN 13674-1:2018 (EN 13674-1:2011+A1:2017, IDT) (2018) *Railway transport. Track. Rails.* Pt 1: Vignole railway rails 46 kg/m and above. DP UkrNDNTs [in Ukrainian].
8. TUU 24.1-40075815-002:2016: *New welded rails for railways. Specifications* [in Ukrainian].
9. (2012) *Technical recommendations on technology of tension welding of rails.* VND UZ 32.7.02.012-2012 TsP-0280. Kyiv, Poligraphservis [in Ukrainian].
10. EN 14587-1:2018 (E): *Railway applications — Infrastructure — Flash butt welding of new rails.* Pt 1: R220, R260, R260Mn, R320Cr, R350HT, R350LHT, R370CrHT and R400HT grade rails in a fixed plant.
11. EN 14587-2:2009 (E): *Railway applications – Track – Flash butt welding of rails.* Pt 2: New R220, R260, R260Mn and R350HT grade rails by mobile welding machines at sites other than a fixed plant.
12. Tachikawa, H., Uneta, T., Nishimoto, H. (2000) Steel welding technologies for civil construction applications. *Nippon Steel Techn. Rept*. 82(**7**), 35–41.
13. Xiao-Fei, L.I., Langenberg, P., Münstermann, S. et. al. (2005) *Recent developments of modern rail steels*. HSLA Steels. 2.
14. Tatsumi, K., Mineyasu, T., Minoru, H. (2011) Development of SP3 rail with high wear resistance and rolling contact fatigue resistance for heavy haul railways. *JFE Technical Report*, **16**.
15. Pointner, P. (2008) High strength rail steels — The importance of material properties in contact mechanics problems. *Wear*, 265(**9–10**), 1373–1379.
16. Kuziak, R., Zygmunt, T. (2013) A new method of rail head hardening of standard-gauge rails for improved wear and damage resistance. *Steel Res. Int.*, 84(**1**), 13–19. DOI: https://doi:10.1002/srin.201200140
17. Morant, S. (2015) Next-generation super-premium rail steels hit the tracks. *Inter. Railway J.* http://www.railjournal.com/index.php/track/next-generation-super-premium-rail-steels-hit-the-tracks.html?channel=531
18. Lonsdale, C. (1999) *Thermite rail welding: History, process developments, current practices and outlook for the 21st century. Altoona, PA 16601: Conrail Technical Services Laboratory Altoona.*
19. Micenko, P., Muruganant, M., Huijun, L. et al. Double dip *hardness profiles in rail weld heat-affected zone literature and research review report*. CRC Project Report, R3.121. Brisbane, Australia.
20. Wang, Y., Zhou, H., Shil, Y.-j. et al. (2012) Mechanical properties and fracture toughness of rail steels and thermit welds at low temperature. *Inter. J. of Minerals, Metallurgy and Materials*, 19(**5**), 409. DOI: https://doi.org/10.1007/s12613-012-0572-8.
21. Dahl, B. (1995) Repair of rails on-site by welding. *Svetsaren*, 50(**2**), 10–14.
22. Okumura, M. et al. (1995) Development of field fusion welding technology for rail-roadrails. *Nippon Steel Techn. Rept*., 65(**4**), 41–49.
23. Saita, K., Karimine, K., Ueda, M. (2013) Trends in Rail Welding Technologies and Our Future Approach. *Nippon steel and Sumitomo Metal Technical Report*., 105, 84–92.
24. Poznyakov, V., Kiriakov, V., Gajvoronsky, A. et al. (2010) Properties of welded joints of rail steel in electric arc welding. *The Paton Welding J.*, (**8**), 16–20.
25. Kuzmenko, G., Kuzmenko, V., Galinich, V. et al. (2012) New technology of electric arc bath welding of rails on tram and crane tracks. *The Paton Welding J.*, **5**, 33–36.
26. Bajic, D., Kuzmenko, G., Samardzic, I. (2013) Welding of rails with new technology of arc welding. *Metalurgija*, **3**, 399–402.
27. Yamamoto, R. (2007) Advances in gas pressure welding technology for rails. Railway. *Technology Avalanche*, **17**, 99–105.
28. Yamamoto, R., Komizu, Y., Fukada, Y. (2014) Experimental examination for understanding of transition behaviour of oxide

inclusions on gas pressure weld interface: Joining phenomena of gas pressure welding. *Welding Inter.*, **7**, 510–520. DOI: https://doi.org/10.1080/09507116.2012.753237.

29. *Induction rail welding plant*. www.mirageservices.co.uk
30. *Railway rail induction-welding device*: Pat. US2019330805: E01B29/46, B23K13/01, B23K37/04, E01B29/04, E01B29/44. Publ. on 06.12.2022.
31. Maalekian, M (2007) *Friction welding of rails*. PhD Th., Graz University of Technology.
32. Gould, J., Johnson, W. *Translational friction weld rail repair — Phase i final report*. EWI Project No. 52765GTH, FRA Contract No. DTFR53-11-C-00004.
33. Shira, S. *The use of translational friction welding for constructing and repairing rail for high speed and intercity passenger rail* — Phase II design report EWI Project 54368GTH Task 1–3, FRA Contract No. DTFR53-13-C-00041.
34. Zhang, H., Li, C., Zhu, Z. (2022) Influence of CDFW process parameters on microstructure and mechanical properties of U75V rail steel welded joint. *Metals*., 12(**5**), 711. DOI: https://doi.org/10.3390/met12050711
35. *Schlatter Group. Rail welding systems* (2016) www.schlatter.ch.:www.schlatter.ch/en/welding-machine
36. Kuchuk-Yatsenko, S., Krivenko, V., Didkovsky, A. (2012) Technology and new generation of equipment for flash butt welding of advanced high-strength rails for construction and reconstruction of high-speed railway lines. *The Paton Welding J.*, **6**, 22–26.
37. *INNOTRACK — Innovative track systems.* Concluding Technical Report. http://www.innotrack.eu
38. Kuchuk-Yatsenko, S., Didkovsky, A., Shvets, V. (2016) Flash-butt welding of high-strength rails of nowadays production. *The Paton Welding J.*, **5–6**, 4–12. DOI: https://doi:10.15407/tpwj2016.06.01
39. Kuchuk-Yatsenko, S., Didkovsky, A., Shvets, V. (2016) Flash-butt welding of high-strength rails. *Mining, Informatics, Automation and Electrical Engineering*, **528**, 4.
40. Turpin, B., Danks, D. (2003) *Electroslag field welding of railroad rail — Final report for high-speed rail IDEA Project* http://onlinepubs.trb.org/onlinepubs/archive/studies/idea/finalreports/highspeedrail/hsr-37final_report.pdf
41. Danks, D., Turpin, B. (2005) Recent advances in field electroslag rail welding. In: *Proc. of AREMA 2005 Annual Conf.* www.arema.org/files/library/2005_Conference_Proceedings/00049.pdf
42. Grigorenko, G., Kostin, V., Zhukov, V. et al. (2016) Peculiarities of structural transformations in HAZ metal of rail steel M76 joint produced by flash-butt welding. *J. of Physical Sci. and Appl.*, 6(**5**), 54–652. DOI: https://doi:10.17265/2159-5348/2016.05.0
43. Weingrill, L., Krutzler, J., Enzinger, N. (2016) Temperature field evolution during flash-butt welding of railway rails. *Materials Sci. Forum*., **879**, 2088–2093. DOI: https://doi:10.4028/www.scientific.net/MSF.879.2088
44. Micheletto, A., Cookson, J., Pang, Y. et al (2020) The structural integrity of flash-butt welded premium rail steel — Evaluation of strength, microstructure and defects. *J. of Rail and Rapid Transit* (IF 1.87). DOI: https://doi:10.1177/0954409720973138
45. Mousavizade, M., Farhangi, H. (2009) Characterization of surface defects associated with flash butt-welded pearlitic rails and their contribution to overload and fatigue failures. *Advanced Materials Research*., **83–86**, 1262–1269.
46. Porcaro, R.R., Faria, G.L., Godefroid, L.B. et al (2019) Microstructure and mechanical properties of a flash butt welded pearlitic rail. *J. Mater. Process. Tech*., **270**, 20–27.
47. (2008) D4.6.1: *The influence of the working procedures on the formation and shape of the HAZ of flash butt and aluminothermic welds in rails*. INNOTRACK Project TIP5-CT-2006-031415. http://www.innotrack.eu
48. Rudenko, P., Gavrish, V., Kuchuk-Yatsenko, S. (2017) Influence of flash butt welding process parameters on strength characteristics of railway rail butts. *The Paton Welding J.*, **5–6**, 75–78. DOI: https://doi:10.15407/tpwj2017.06.14
49. Kuchuk-Yatsenko, S., Didkovsky, A., Antipin, E. (2017) Real-time operational control information management system for flash-butt welding of rails. Mining — Informatics. *Automation and Electrical Engineering*, **529**, 4. DOI: http://dx.doi.org/10.7494/miag.2017.1.529.35.
50. Kuchuk-Yatsenko, S., Milenin, A., Velikoivanenko, E. (2018) Mathematical modeling of metal heating process in continuous flash-butt welding. *The Paton Welding J.*, **10**, 2–8. DOI: https://doi:10.15407/tpwj2018.10.01
51. Kuchuk-Yatsenko, S. I., Rudenko, P. M., Gavrish, V. S. et al. (2016) Statistical control of process of flash-butt welding of rails. Two-level control system. *The Paton Welding J.*, **6**, 13–16. DOI: https://doi:10.15407/tpwj2016.06.02.
52. Shvets, V.I., Didkovsky, O.V., Antipin, Y.V. et al. (2022) Features of microstructure of butt joints of hypereutectoid AREAL-136HE-X rail steel in flash-butt welding. *The Paton Welding J.*, **3**, 33–40. DOI: https://doi.org/10.37434/tpwj2022.03.04
53. Shvets, V.I., Didkovsky, O.V., Zyakhor, I.V. et al (2023) Study of the structure of joints of rails of R260MN grade in flash-butt welding. *The Paton Welding J.*, **1**, 3–10. DOI: https://doi.org/10.37434/tpwj2023.01.01

ORCID

I.V. Ziakhor: 0000-0001-7780-0688,
Ye.V. Antipin: 0000-0003-3297-5382,
O.V. Didkovskyi: 0000-0001-5268-5599,
O.V. Kavunichenko: 0000-0002-5164-9796,
A.M. Levchuk: 0000-0002-0361-7394,
Yu.A. Shylo: 0000-0002-6174-5925

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

I.V. Ziakhor
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: zyakhor@paton.kiev.ua

SUGGESTED CITATION

I.V. Ziakhor, Ye.V. Antipin, O.V. Didkovskyi, O.V. Kavunichenko, A.M. Levchuk, Yu.A. Shylo, Yan Truska (2023) Modern technologies of welding railway rails (Review). *The Paton Welding J.*, **8**, 4–16.

JOURNAL HOME PAGE

https://patonpublishinghouse.com/eng/journals/tpwj

Received: 10.04.2023
Accepted: 07.08.2023