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URGENT PROBLEMS OF WELDING RAILWAY RAILS UNDER MARTIAL LAW IN UKRAINE

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ABSTRACT

Rail joining in stationary and field conditions is mainly performed by flash butt welding (FBW), which has been successfully used for many years on the railways of Ukraine and abroad. The article analyzes the critical challenges for ensuring the operability of the railway infrastructure under martial law in Ukraine. To solve urgent problems, the E.O. Paton Electric Welding Institute of the NAS of Ukraine (PWI) together with the Branch "Center for Track Construction and Repair" of the JSC "Ukrainian Railways" have developed a set of measures to ensure high-quality welding of rails in stationary and field conditions during the repair and construction of continuous welded rails in accordance with the requirements of acting regulatory documents. The results of works (research, technological, scientific and technical expertises) on the implementation of these measures for the period of 2022–2025 are presented. In particular, the technical condition of rail welding machines was successfully audited, the technology was improved and technological modes of FBW of railway rails were practiced, the system of quality assurance of joints during FBW of railway rails was improved, new revisions of regulatory documents for FBW of railway rails were prepared, the works are being conducted to update the design of FBW machines, cooperation with companies is developed to renew the production of rail welding equipment in Ukraine.

KEYWORDS: railway rails, welded joint, flash butt welding, railroad frog

INTRODUCTION

Continuous welded rail (CWR) is considered a progressive construction method for railway track superstructures in modern operations [1]. Rail joining in stationary and field conditions is mainly performed by flash butt welding (FBW), which has been successfully used for many years on the railways of Ukraine and abroad [2]. Since the 1950s, the PWI has been a world leader in the field of development of technologies and equipment for FBW of railway rails [3–5].

Under the general supervision of Academician B.E. Paton and the direct supervision of Academicians of the NAS of Ukraine V.K. Lebedev and S.I. Kuchuk-Yatsenko, PWI created the world's first highly efficient mobile equipment for FBW of railway rails in the field conditions. It is based on the original design of the secondary circuit of welding transformers with reduced short-circuit resistance and the technology of continuous flash butt welding with a programmable variation of the FBW process basic parameters. The unique welding equipment was created [4, 5], which, unlike the best foreign analogues, was distinguished by significantly smaller dimensions, lower weight and power consumption, high efficiency, and full automation of the welding process, which provided the ability to weld rails at the track laying location.

The first mobile rail welding machines were produced by PWI, and since 1961, the Kakhovka Electric Welding Equipment Plant has mastered the serial production of mobile (K155, K255, K255L, K355) and stationary (K190, K190M, K190PA) rail welding machines, which have successfully operated in Ukraine and dozens of countries on all continents [4]. The equipment and licenses for technological developments of PWI were purchased by a number of leading foreign companies, including Plasser & Theurer (Austria), Holland and Progress Rail Services (USA), Network Rail (UK). When travelling by rail in Ukraine, the USA, China, the European Union and many other countries, most passengers do not realize that the welded rail butts are made using technologies and equipment developed at PWI. This also applies to subway tracks in Kyiv, Washington, New York, Singapore, Shanghai, Beijing, Bangkok and other cities. Rail welding enterprises of the JSC "Ukrainian Railways" use exclusively technologies and equipment for FBW developed by PWI.

In the 2000s, based on the results of fundamental research, PWI developed and implemented the technology for FBW of rails with pulsating heating mode (pulsating flashing), designed and mastered the production of a new generation of mobile (K900, K920, K921, K922, K930, K945, K950, K960, K963, K1045) and stationary (K1000, K924) rail welding machines. They are the first in the world to implement a number of innovative technical solutions protected by international patents in the field of welding technology, design of welding machines, principles of rail alignment, FBW process control systems and quality testing of rail welded joints [6–10].

The russian military invasion of Ukraine in 2022 led to a number of critical challenges for ensuring the operability of the railway infrastructure under martial law. These challenges include the suspension of domestic rail production by Azovstal Metallurgical Combine as a result of the occupation, which has raised the issue of welding used [11]and new [12–17] rails of different grades and manufacturers, with various heat treatment modes, in particular, in a heterogeneous combination; suspension of production of domestic rail welding equipment by Kakhovka Electric Welding Equipment Plant (KZESO PJSC), which led to the disruption of the delivery of a stationary K924 machine for FBW of railroad frogs to JSC "Dnieper Railway Switch Plant" and eight newest KSM007 rail welding complexes equipped with K922-1 machines to the JSC "Ukrainian Railways", and necessitated an urgent solution to the problem of extending the operational life of existing welding equipment.

To solve the above problems, PWI together with the Branch "Center for Track Construction and Repair" (CTCR) of the JSC "Ukrainian Railways" developed a set of measures to ensure high-quality rail welding in stationary and field conditions during the repair and construction of CWR in accordance with the requirements of acting regulatory documents [11–13]. The mentioned set of measures includes organizational, research, design and technological works, scientific and technical expertise.

The following tasks were identified as the most urgent and priority ones:

- establishing the causes for the non-compliance of some welded joints of railway rails of different grades and plants-manufacturers with the requirements of regulatory documents;
- audit of the technical condition of rail welding equipment available at the JSC "Ukrainian Railways" and development of measures to extend its operational life;
- improvement of technology and optimizing technological modes for FBW of railway rails of converter production;
- improving the quality assurance system for joints during FBW of railway rails;
- preparation of recommendations and amendments to existing regulatory documents, development of a new revision of technical specifications for FBW of railway rails;
- improving the design of mobile rail welding machines;
- search for companies that have the production capacity to renew the production of FBW equipment.

THE AIM

of the article is to provide brief information on the results of works for the period of 2022–2025 to implement the developed set of measures for ensuring high-quality welding of railway rails under martial law in Ukraine.

ESTABLISHING OF THE CAUSES OF NON-COMPLIANCE OF SOME WELDED TO JOINTS OF RAILWAY RAILS WITH THE REQUIREMENTS OF REGULATORY DOCUMENTS

At the request of the Branch "CTCR" of the JSC "Ukrainian Railways", PWI specialists performed scientific and technical expertise of the causes for non-compliance of welded joints of rails of various grades from different manufacturers with the requirements of regulatory documents, in particular, during their mechanical tests in accordance with the requirements of acting standards [11–13]. Based on the results of in-process control, analysis of welding protocols, macroanalysis and metallographic examinations of rail joints, fractographic examinations of fractures of rail welded joints, the causes of their fracture during mechanical tests for static bending and under cyclic loads during the operation of the railway track were determined. The methods of macroanalysis, microanalysis, hardness (NOVOTEST TC-GPB) and microhardness (M400, Leco) measurements, optical microscopy (Neophot-32), scanning electron microscopy (SEM), energy dispersive X-ray microanalysis (EDXMA), Auger electron spectroscopy (Auger-microprobe JAMP-9500F, JEOL with built-in EDS spectrometer OXFORD EDS INCA Energy 350) were used [18].

As an illustration of the scope of the complex of works carried out in this area, below is a fragment of the report of the scientific and technical expertise of the causes for non-compliance with the requirements of regulatory documents (fracture during static bending tests) of the welded joint of R65 type rails of E76F grade, made by continuous FBW using K355 mobile rail welding machine. The subject of the study is the defects in the rail foot according to code 66.3 and the defect in the rail web according to code 56.3 detected at the fracture (Figure 1) of the rail welded joint [19].

The fracture of a rail welded joint butt is heterogeneous in terms of the macrogeometry of the fracture surface [20], since it has geometric zones with different macrorelief of the fracture surface. According to the surface condition and fracture micromechanism, the fracture in the head and the bulk part of the web and foot is crystalline, quasi-brittle and intergranular [21, 22].

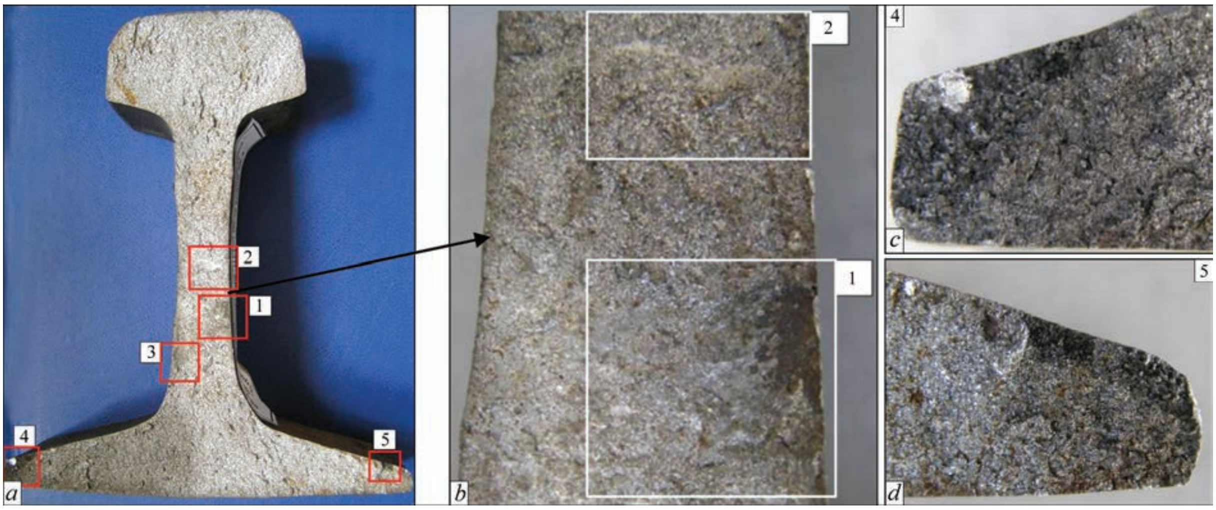


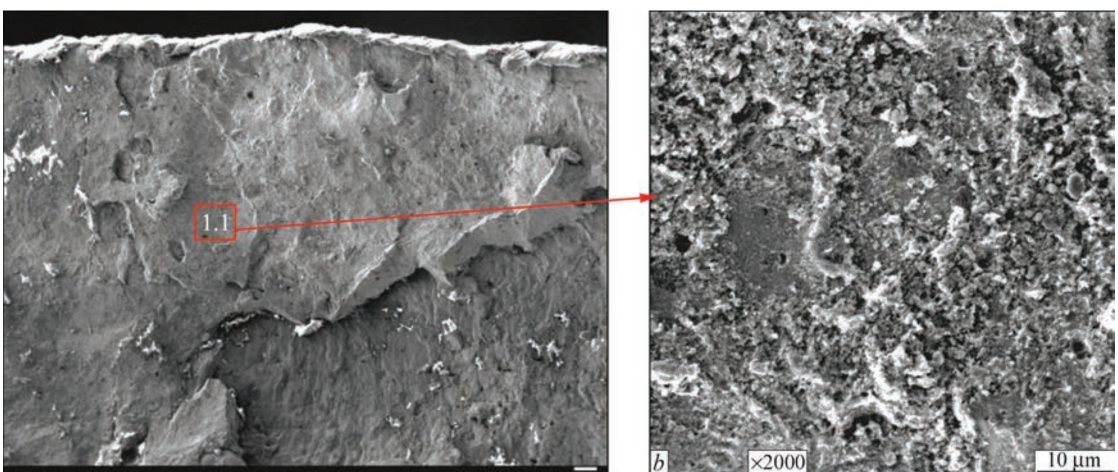
Figure 1. Fracture of welded rail (*a*), defects in the rail web (*b*) and foot (*c*, *d*)

Defects in the form of dark spots without metallic luster and signs of crystalline fracture (Figure 2) are observed in the rail web at fracture regions Nos 1, 3 (see Figure 1, *a*). The total area of these defects is about 60 mm^2, which indicates that the rail welded joint does not meet the requirements [11–13].

The chemical composition of the dark areas approximately corresponds to the composition of iron oxide FeO (Figure 2, *b*). According to [21], this type of defect can be attributed to group 4 "Lack of fusion" of subgroup P401 "No weld» or subgroup P403 "Insufficient fusion (stuck weld)". The most probable cause for the formation of such defects is a violation of the flashing process before upsetting at the stage of intensive flashing.

In region 2 of the fracture, a defect of 0.3–2×10 mm in size was found in the rail web (Figure 3, *a*) in the form of a light spot with a metallic luster without signs of crystalline fracture. The defect is elongated in the transverse direction of the web; its total area is about 18 mm^2, which exceeds the admissible maximum value according to [11–13]. The fracture surface in regions 2 and 3 has no signs of crystalline fracture, has the appearance of a locally melted surface with a slight metallic luster, the main component is iron (about 85 %) with a small oxygen content (about 6 %). In terms of chemical composition, numerous inclusions located on the surface of the defect correspond to ferromanganese silicates present in the base metal of rail steel, which indicates their metallurgical origin [23].

Metallographic examinations of regions of the heat-affected zone (HAZ) adjacent to the welded butt fracture revealed that the total width of the HAZ significantly exceeds the requirements of [17], which regulates the admissible value of the HAZ width within 20–45 mm. The significant increase in the HAZ width compared to the requirements of [17] could be caused by several factors, namely: rails overheating (excessive heat input into the welded butt), long-term



Spectrum, at.%	C	N	O	Fe	Ca	S
2	6.0	1.5	48.8	43.0	0.6	0.1

Figure 2. SEM images of fracture regions No. 1 (*a*) and No. 1.1 (*b*) after ion etching with Ar+ ions at 3 keV to a depth of 60 nm, Auger spectrometry results of region No. 1.1

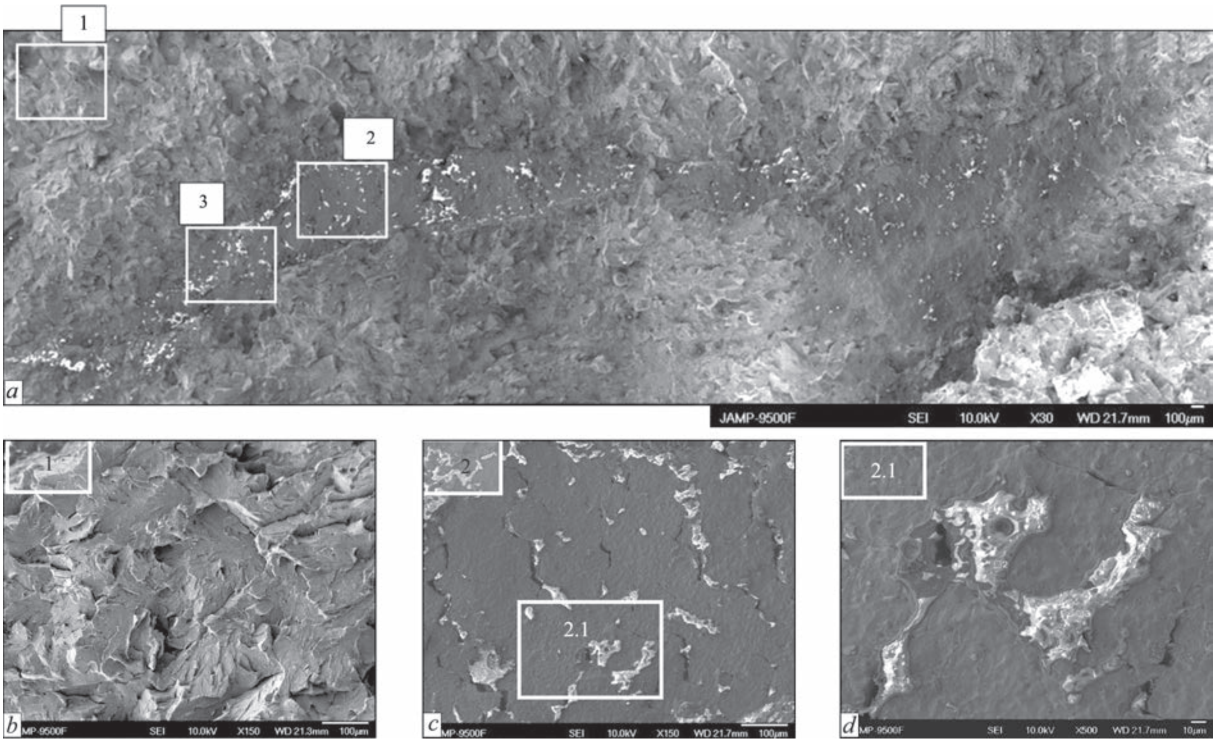


Figure 3. SEM images of the fracture surface in region 2 (see Figure 1): (*a*) and locations 1, 2 and 2.1 (*b*, *c*)

short circuit of rail ends during flashing, excessively long flashing process.

Defects were detected in the fracture regions of the rail foot (Figure 1, *c* — regions 4, 5), which are defects of group 3 “Solid inclusions”, P306 “Inclusion of cast metal (Solidified residual molten material enclosed in the joint including impurities)” [21].

Defects in rail foots (group 3, P306) are relatively hard to detect with existing ultrasonic flaw detectors after welding a joint, as they have a monolithic structure of overheated metal oxidized along the grain boundaries without any cavities. During ultrasonic inspection with existing flaw detectors, such defects can be interpreted as structural noise.

The probable causes for the formation of the above defects and the non-compliance of the rail welded joint with regulatory requirements [11–13, 17] are the combination of several factors, in particular, excessive heat input into the rail welded joint, local oxidation of rail ends at the stage of intensive flashing, and the penetration of overheated metal into the joint plane when cutting burr. It was revealed that the zone of initial crack propagation and welded rail welded joint fracture were caused by defects in the rail foot; rail welded joint fracture was caused by the location of defects in the tensile stress zone.

The main results of scientific and technical expertises of the causes for non-compliance of rail welded joints with the requirements of regulatory documents are presented in the conclusions, which include the classification of rail welded joint fracture by macrogeometry of the fracture surface, fracture characteristics by surface condition and fracture micromechanism, classification of defects, conclusions on compliance of the rail welded joint with regulatory requirements, substantiation of probable causes of defects and causes of rail welded joint fracture, assessment of the possibility of detecting existing defects by ultrasonic inspection methods.

Based on the results of scientific and technical expertises of welded joints of R65 type rails of various grades (E76F, K76, K76F, R350HT) and of different plants-manufacturers, produced by mobile rail welding machines K355, K900, K922-1 during 2024–2025, PWI experts developed recommendations to prevent arising of defects in rail welded joints and to reliably detect probable defects during non-destructive testing of joints, as well as a list of practical measures for their implementation. The main measures to prevent defective welded joints in the CWR are the improvement of technology and optimizing technological modes of FBW of rails of different grades, strict compliance by personnel with the requirements [11–13] for auxiliary and welding works; the use of welding machines equipped with systems for recording the basic parameters of the FBW process; monitoring of rail welding technology based on electronic reports from rail welding enterprises of the JSC “Ukrainian Railways”. The use of phased array technology for ultrasonic inspection of rail welded joints is also recommended.

AUDIT OF THE TECHNICAL CONDITION OF RAIL WELDING EQUIPMENT

During the reporting period, PWI specialists conducted an audit of the technical condition of welding ma-

Figure 4. Mobile K922-1 machines as part of rail welding KZM 005 (*a*), KZM 007 (*b*) and KRZ 1 (*c*) complexes

chines at all rail welding enterprises (RWE) of the JSC "Ukrainian Railways", in particular, stationary K1000 and mobile K355A, K900, K920 and K922-1 machines. As a result of the performed works, the existing problems listed in the technical condition reports of the equipment were identified; together with the Branch "CTCR" of the JSC "Ukrainian Railways", a set of measures was developed to maintain the specified technical characteristics and extend the operational life of rail welding machines as part of KZM 005, KZM 007, KRZM 3, KRZM 4 and KRZ 1 complexes (Figure 4), new contracts for similar works were concluded, and fruitful cooperation in this area continues.

IMPROVEMENT OF TECHNOLOGY AND OPTIMIZING TECHNOLOGICAL MODES OF FBW OF RAILWAY RAILS OF CONVERTER PRODUCTION

After Azovstal Metallurgical Combine suspended the production of domestic rails in 2022 as a result of the occupation of Mariupol, Ukrainian railways began the use of R65 (60EI) rails of converter production of various grades with different heat-treatment modes, which are purchased from different manufacturers and received as humanitarian aid. Rail welding enterprises of the JSC "Ukrainian Railways" together with PWI had to solve the problem of improving the technology and optimizing technological modes of FBW of rails of different grades (R350HT, R350LHT, R400HT), in particular, in a heterogeneous combination, in short terms. A similar problem arose with used rails of open-hearth and converter production of M76, E76, E76F, K76 and K76F grades, which, when laying in the railway track, must be welded together and in a heterogeneous combination.

In previous years, the technological modes of FBW of rails were determined experimentally for the available type of rails and a specific rail welding machine. The requirements of acting regulatory documents [11–13] regulate the admissible ranges of variation in certain parameters of FBW of rails, in particular, the voltage of the primary circuit of welding transformers and the value of displacement at different stages of the FBW process, upsetting pressure, displacement rate during flashing, forcing and upsetting, time of upsetting under current, etc. Based on the analysis of the results of many years of practical experience in FBW of rails at rail welding enterprises of the JSC "Ukrainian Railways", mechanical tests and metallographic examinations of welded joins, it was found that ensuring the technological parameters of FBW within certain limits is a necessary but not sufficient condition for producing welded joints of rails that meet the requirements [11–13].

Moreover, ensuring the compliance of rail welded joints with the requirements of the national standard [17], harmonized with the relevant European regulatory document, provides for certain parameters of the HAZ, namely: the admissible range of HAZ width values (minimum $H_{\mathrm{HAZ\ min}}$ and maximum $H_{\mathrm{HAZ\ max}}$ values) and its nonuniformity along the length and cross-section of the rails, and additionally contains

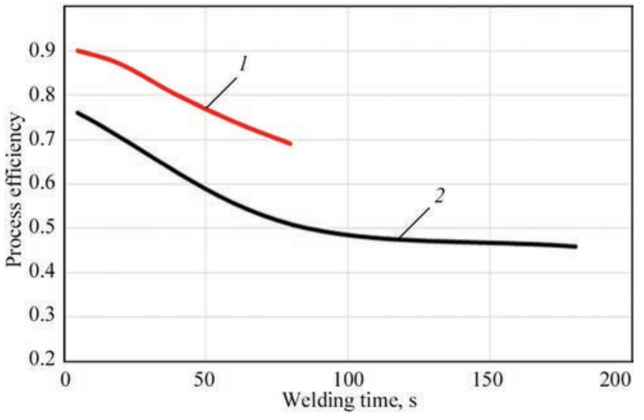


Figure 5. Variation in efficiency over time at FBW: *1* — PF; *2* — CF (calculated data)

requirements for the microstructure of the metal in the HAZ — there shall be no evidence of martensite or bainite at 100× magnification in the visible heat affected zone.

The development and approval of the FBW mode for each rail grade in a specific rail welding machine required conducting a complex of works, including mechanical testing, metallographic and factographic examinations, non-destructive testing, determination of hardness distribution, etc. Until now, no reliable algorithm has been determined to ensure the quality of welded rail joints at varying external factors (condition of the welding machine, diesel generator parameters, quality of rail end preparation, etc.). The development of the mentioned algorithm for rail joint quality was based on the idea of Academician of the NASU S.I. Kuchuk-Yatsenko to use the value of the total heat input Q_{fl} in the rail flashing process as a complex parameter that takes into account the influence of other energy parameters of the FBW process on the temperature distribution in the HAZ, microstructure formation and mechanical properties of welded rail joints. The implementation of this idea consisted in determination and scientific substantiation of the range of changes in Q_{fl} during FBW of modern rails of converter production, which ensures that welded joints meet the requirements of acting standards. From a practical point of view, this will

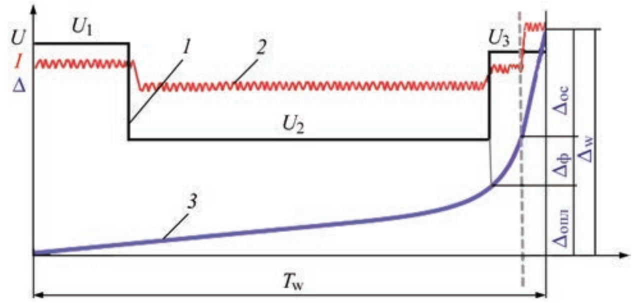


Figure 6. FBW process cyclogram with a programmable primary voltage variation: *1* — voltage, *2* — current, *3* — welding allowance

significantly reduce the time and scope of research and testing when developing and optimizing FBW process modes for different rail grades, regardless of the electric mains parameters, condition of the rail welding machine, etc. Below is a brief description of the conducted research and the obtained results.

The calculations of variation in the thermal efficiency of the rail heating processes at continuous flashing (CF) and pulsating flashing (PF) established that at CF of rails, the value of the efficiency decreases from 0.7 (in the initial period) to 0.45 at t_{fl} = 180 s, and at PF, the efficiency decreases from 0.9 in the initial flashing period to 0.7 at t_{fl} = 80 s (Figure 5). Our calculations substantiate the use of PF as a basic process in the development of an efficient FBW technology for modern railway rails of converter production.

A computational study of heating R65 (60E1) type rails at PF with a programmable voltage U variation (Figure 6) at different stages of the flashing process was carried out.

Mathematical models and appropriate computer simulation tools for the kinetics of temperature fields during FBW of railway rails were developed jointly with the Department 34 of PWI. The numerical solution of the nonstationary thermal conductivity equation was used along with a set of necessary laboratory measurements of the influence of FBW process parameters on temperature cycles in the welded rails. This made it possible to take into account the multiphysical processes of rail end flashing and determine the characteristic thermal efficiency of the FBW process.

The mathematical model was used to calculate the thermal cycles and temperature distribution in the HAZ during FBW of R65 type rails of K76F grade. When performing the calculations, the values of the basic parameters of FBW modes (Table 1) were set within the limits provided for in [13].

To assess the reliability of the mathematical model, experimental studies of thermal cycles were carried out and the temperature distribution in welded joints produced by FBW was determined according to Table 1. Experiments to study thermal cycles at FBW were performed in stationary K1000 and mobile K922-1 machines (Figure 7). A system of thermocouples was used, mounted in the rail head at different distances from the rail end in a step of 5 mm. The first thermocouple was placed at a distance of 18 mm from the rail end, which involved placing it at a distance of 5 mm from the joint line (JL) after the FBW process.

A comparative analysis of the calculated and experimental data of the study of thermal cycles during flashing (Figure 8) shows that the mathematical model has a calculation error of about 8 %, which makes it possible to predict the kinetics of the temperature field

Table 1. FBW mode of K76F rails

Parameter	Value
Primary voltage at different stages of flashing *U*, V	$U_1 = 400$, $U_2 = 305$, $U_3 = 400$
Mean value of the primary current I at different stages of flashing, A	$I_1 = 420$, $I_2 = 380$, $I_3 = 420$
Total flashing time t_{fl} ($t_{1,2,3}$ – by stages), s	$T_{fl} = 80$ ($t_1 = 30$, $t_2 = 45$, $t_3 = 5$)
Upsetting time under current, s	1
Total displacement for total flashing Δ_{fl} ($\Delta_{1,2,3}$ – by stages), mm	14 ($\Delta_1 = 3$, $\Delta_2 = 7$, $\Delta_3 = 4$)
Upsetting value Δ_{ups}, mm	12
Calculated heat input value Q_{fl}, MJ	12.8

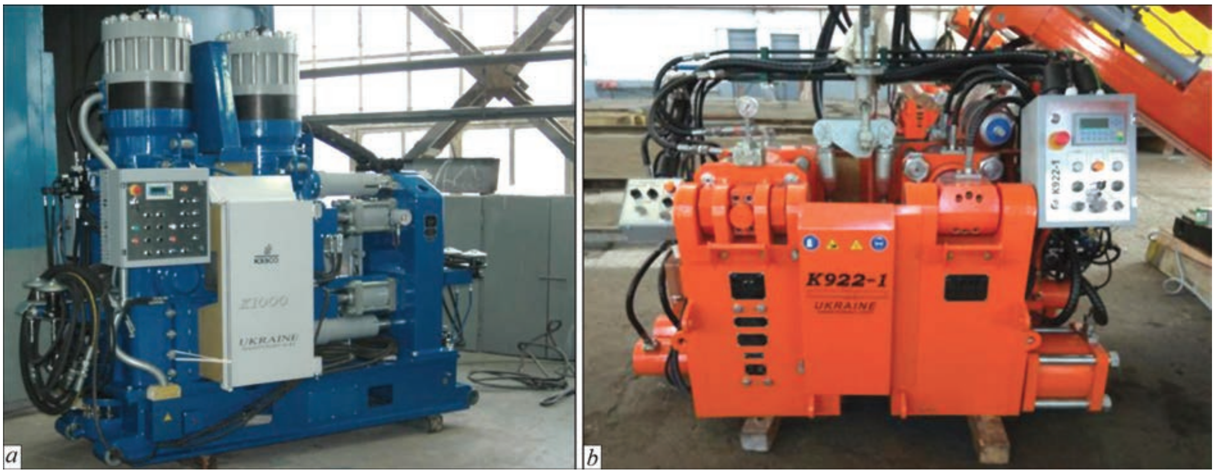


Figure 7. Rail welding K1000 (*a*) and K922-1 (*b*) machines

in rails at FBW with satisfactory accuracy. This makes it possible to use a mathematical model to study the influence of the basic FBW parameters on the heating and cooling processes of rail welded joints. It was found that the maximum value of the cooling rate in the welded joint and HAZ is achieved along the JL, where the heating temperature in the FBW process was maximum.

Using the developed mathematical model, the effect on the efficiency of the heating process and the temperature distribution in the welded joint zone of R65 (60E1) type rails of the FBW process parameters was studied, namely: the primary voltage *U* of the power source at different stages of the flashing process (U_1–U_3), the allowance Δ_f of the progressive flashing stage, the flashing duration t_{fl}, and the value of the heat input Q_{fl}). The temperature distribution along the axis of the rail welded joint at FBW with different values of voltage *U* at stage 2 of the process is shown in Figure 9.

Based on the obtained results, the use of the FBW process with a programmable variation of the power supply voltage in time is substantiated, the cyclogram of the flashing process is specified, which provides for a stage-by-stage variation of *U* in the range U_1 = 355–440 V at the first stage of flashing, in the range U_2 = 250–300 V at the second stage (quasi-stationary heating), and within U_3 = 355–440 V at the third stage (progressive flashing).

The temperature distribution along the axis of the welded rail joint at FBW at different flashing process duration t_{fl} was determined. The calculation results for t_{fl} = 90 and 120 s are shown in Figure 10. The criteria for selecting the minimum allowable t_{fl} was to achieve a temperature distribution along the axis of the flashed rails, at which the conditions for upsetting by a set

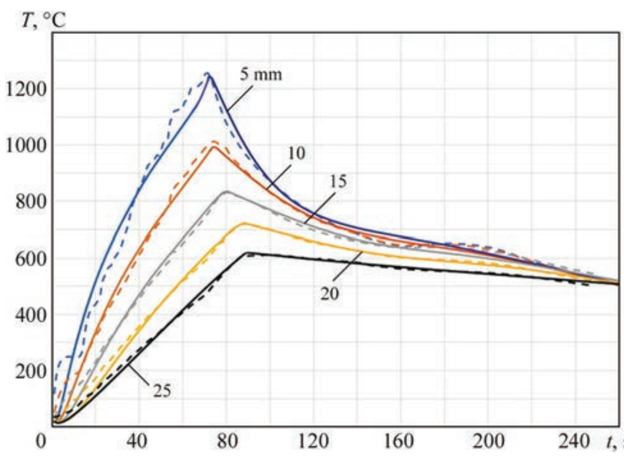


Figure 8. Calculated (dashed lines) and experimental (solid lines) thermal cycles at FBW of R65 (60E1) rails of K76F grade at different distances from the JL

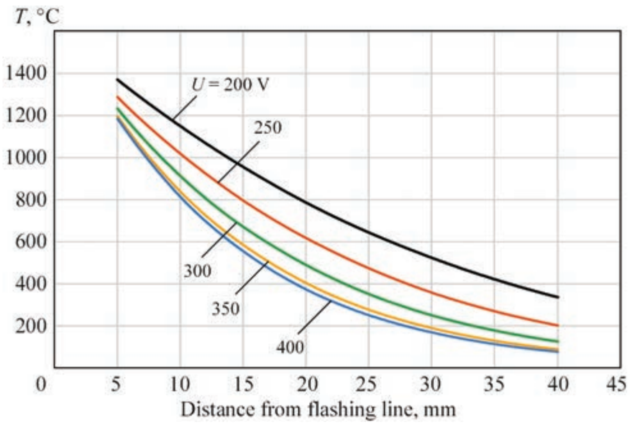


Figure 9. Temperature distribution along the axis of the welded rail joint at FBW with different voltage U at stage 2 of the flashing process (see Figure 6)

value of upsetting displacement Δ_{ups} = 12 mm (the width of the HAZ with a heating temperature of up to 1000 °C should exceed Δ_{ups} = 12 mm) are ensured. As is seen from the obtained data, for t_{fl} = 90 s and more, the above condition is met.

The dependence of the minimum $H_{HAZ\ min}$ and the maximum $H_{HAZ\ max}$ values of the welded joint HAZ width (according to the requirements of [17]) on the duration of the flashing process t_{fl} in the range from 50 to 140 s was determined by calculations. It was established that during PF of railway rails of R65 (60E1) type, with an increase in t_{fl} in the range from 50 to 140 s, the value of heat input Q_{fl} varies in the range of Q_{fl} = 9–18 MJ, while the value of $H_{HAZ\ min}$ increases from 16 to 22 mm, and the value of $H_{HAZ\ max}$ — from 36 to 54 mm.

An important parameter of the thermal cycle in FBW of rails is the cooling rate $W_{8/5}$ of the welded joint metal in the temperature range of 800–500 °C. This parameter determines the presence or absence of hardening structures, pearlite dispersion, strength and hardness indices in the HAZ of the welded joint. The dependence of the cooling rate $W_{8/5}$ of welded joints

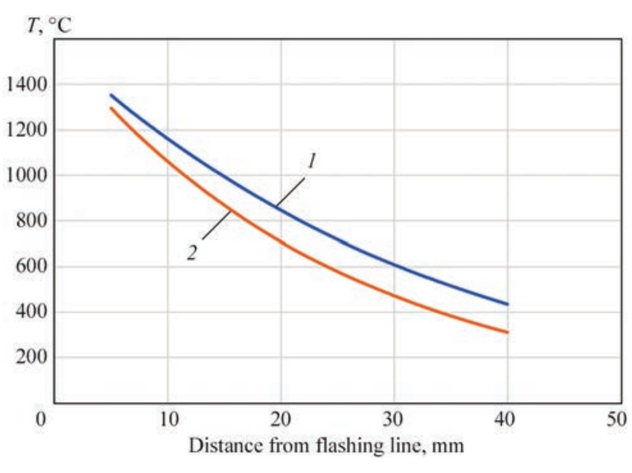


Figure 10. Temperature distribution along the axis of the welded rail joint at FBW with different value of flashing time t_{fl}, s: *1* — 120; *2* — 90

after FBW of R65 (60E1) type rail of K76F grade on the value of Q_{fl} was studied by calculation. When calculating the cooling rate $W_{8/5}$ of metal in the HAZ of the joints, the value of Q_{fl} varied within the above limits, namely: t_{fl} = 50–140 s, Q_{fl} = 9–18 MJ.

To evaluate the structural state of the metal in the HAZ of R65 rail joints of K76F grade, the continuous cooling transformation diagram (CCT diagram) of K76F rail steel was used [14]. The aim of the study was to determine the range of changes in the value of heat input Q_{fl}, in which there are no hardening structures (martensite) in the welded joint of rails, the pearlite structure of the HAZ metal is ensured, and hardness values are achieved in accordance with the requirements [11–13, 17]. During the calculations, the values of current, flashing displacement and time, upsetting displacement and heat input were set for three different FBW modes (Table 2). The calculated temperature distribution in the HAZ of joints at FBW of R65 (60E1) rails of K76F grade for modes 1–3 is shown in Figure 11.

To assess the structural state of the metal in the HAZ of rail joints, the calculated cooling curves (logarithmic time scale) for different FBW modes were superimposed on the continuous cooling transformation diagram of K76F rail steel. The CCT diagram of K76F steel with the maximum carbon content within the regulatory requirements [24] and the calculated cooling curves of joints for the value of heat input Q_{fl} = 9.0, 9.7, 12.6 and 16.2 MJ at FBW are shown in Figure 12. Analysis of the data in Figure 12 shows that for Q_{fl} = 9 MJ (within mode 1), the maximum cooling rate along the JL is $W_{8/5}$ = 8.7 °C/s, the cooling curve is partially contained within the bainite region, and the hardness value reaches 395 *HV*30. The presence of bainite in the structure of the to ints of rail welded joint metal is not allowed, therefore, mode 1 at a value Q_{fl} = 9 MJ is unacceptable according to the criterion of the structural state of the metal in the joint zone when examining the microstructure [17]. For Q_{fl} = 12.6 MJ (within mode 2), the cooling rate along the JL is $W_{8/5}$ = 3.75 °C/s, the cooling curve is within the pearlite transformation region, the hardness value reaches 380 *HV*30, which meets the

Table 2. FBW modes of R65 rails of K76F grade

Parameter	Values for FBW modes		
	Mode 1	Mode 2	Mode 3
Flashing time t_{fl}, s	50–60	70–90	110–140
Flashing current I, A	370-390		
Flashing displacement Δ_{fl}, mm	7–8	9–12	14–15
Value of heat input Q_{fl}, MJ	9–10.8	11.5–14.0	14.4–18

requirements of acting regulatory documents. For Q_{fl} = 16.2 MJ (within mode 3), the cooling rate along the JL is $W_{8/5}$ = 2.75 °C/s, the cooling curve is completely within the pearlite transformation region, and the hardness value reaches 368 *HV*30. Consequently, during FBW at modes 2 and 3, rail welded joints meet the regulatory requirements in terms of the structural state of the metal in the joint zone [17].

Thus, the minimum values of the flashing time $t_{fl.mi}$ = 55 s and heat input $Q_{fl.min}$ = 9.7 MJ at FBW of heat-strengthened K76F rails with a maximum carbon content within the regulatory requirements, at which the cooling rate along the JL does not exceed $W_{8/5}$ = 7.0 °C/s and the absence of bainite and martensite in the joint zone is ensured, were determined by calculation.

The technological modes of FBW of R65 (60E1) type rails of K76F and R350HT grades were optimized based on the results of mechanical tests and metallographic examinations. Bend testing [11–13, 17] of welded rail joints made using different FBW modes were performed (see Table 2). The test results are shown in Tables 3 and 4.

Obviously, only mode 2 meets the regulatory requirements for the values of bend test deflection and force of welded K76F and R350HT rail joints. After the bend testing of welded K76F rail joints produced by FBW at mode 1, fracture analysis was performed. Defects are observed in the fractures (Figure 13), which are defined as “flat spots” [23, 25, 26] with a total area of more than 15 mm^2, which do not correspond to [11–13]. FSs are distinguished on the fracture surface by an undeveloped relief and are gray in color. In the structure of FSs, there are numerous

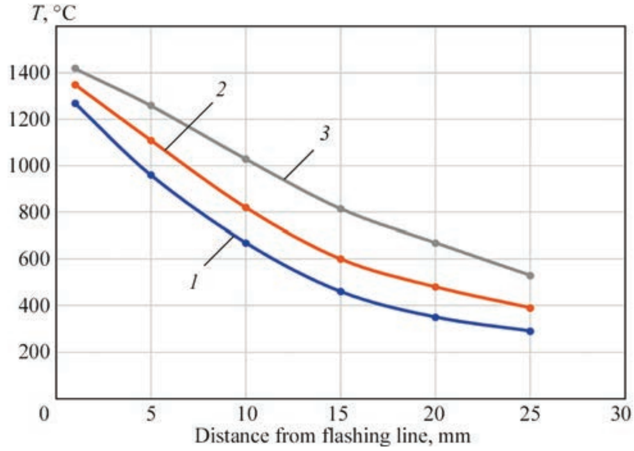


Figure 11. Temperature distribution in the HAZ before upsetting at PF of R65 (60E1) rails at modes *1–3*

melted inclusions (Figure 13), which are based on particles of complex oxides several microns in size, which include manganese, silicon.

An increase in the heat input during FBW (mode 3) leads to a decrease in indices of bend test rail welded joints. This is primarily predetermined by an increase in the grain size along the JL and in the HAZ and the development of the process of pre-eutectoid ferrite precipitation along the boundaries of primary austenitic grains [25]. Thus, mode 3 (t_{fl} = 110–140 s, Q_{fl} = 14.4–18 MJ) does not meet the requirements [11–13], although it is acceptable according to the micro examination requirements of the rail welded joints [17]. At FBW at mode 2, the regulatory requirements for welded joints of rails of K76F and R350HT grades are met by both criteria: structural state of the metal and indices of mechanical properties of joints during bending tests.

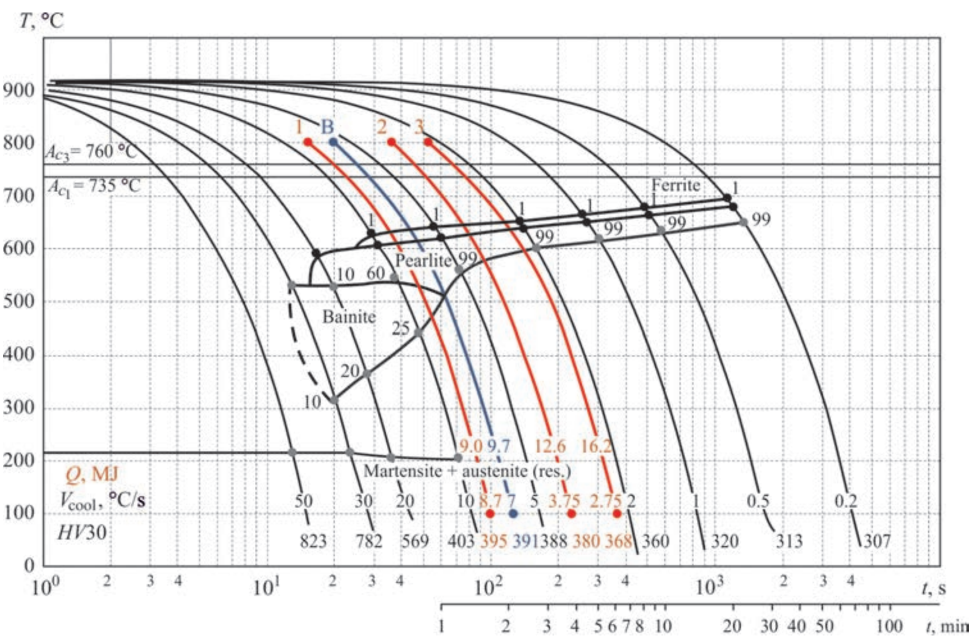


Figure 12. CCT diagram of K76F steel [24] and calculated curves of cooling rails made by FBW with different value of heat input Q_{fl}, MJ

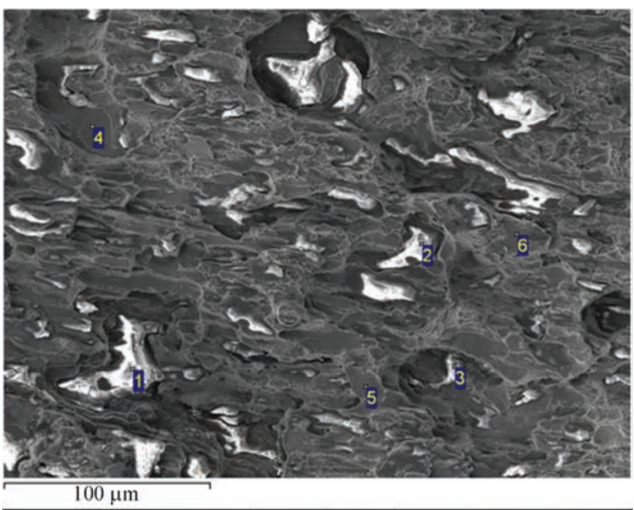
Table 3. Test results of welded joints of R65 rails of K76F grade

Mode number	Bend test force, kN	Bend test deflection, mm
Requirements [13]	≥1650	≥30
Mode 1	1950–2250 1950	27–32 28
Mode 2	2000–2300 2150	35–45 38
Mode 3	1800–2000 1900	25–34 29

Table 4. Test results of welded joints of 60E1 rails of R350HT grade

FBW mode	Bend test force, kN	Bend test deflection, mm
Requirements [13]	≥1650	≥30
Mode 1	1900–2100 1900	27–31 28
Mode 2	2100–2350 2200	34–41 37

Metallographic examinations of welded joints of K76F and R350HT rails produced by FBW at mode 2 were performed. The macrosection, microstructure, SEM image of the metal in the joint zone and the hardness distribution for the joint of R350HT rails are shown in Figure 14. Within the HAZ, a decrease in hardness to 280 *HV* 30 is observed, which is predetermined by the process of cementite spheroidization in the zone of partial recrystallization. This is typical



Spectrum	C	O	Al	Si	Cr	Mn	Fe
1	1.51	46.66	0.00	22.15	0.00	24.77	4.90
2	20.02	43.54	0.23	15.99	0.11	17.14	2.96
3	1.50	37.53	0.06	20.94	0.08	33.93	5.73
4	1.83	0.54	0.00	0.40	0.00	0.76	96.47
5	2.12	1.49	0.08	0.46	0.06	1.65	94.13
6	0.87	0.52	0.00	0.27	0.00	0.08	98.26

Figure 13. SEM image and micro EDXMA results of a flat spot in the fracture of K76F rail joints at FBW, mode 1

for welded joints of heat-strengthened rails made of eutectoid grade steels [26–30]. The length of such areas on both sides of the JL does not exceed 4 mm, the total width of the HAZ is 24–29 mm, which meets the requirements of [17].

Based on the results of calculations and experimental studies of thermal cycles at FBW, macroanalysis, metallographic examinations, and mechanical tests of welded joints of rails, the general range of changes in Q_{fl} at FBW of heat-strengthened rails of K76F and R350HT grades was determined, which ensures the formation of high-quality joints that meet the requirements of acting regulatory documents for rail welded joints, namely the value of heat input during flashing should be Q_{fl} = 11.88–14.0 MJ. Varying the value of heat input Q_{fl} within certain limits ensures a set cooling rate of welded rail joints in the austenite transformation temperature range and causes the formation of highly dispersed lamellar pearlite without structural components of martensite and bainite.

The determined range of optimal Q_{fl} values was used in developing and optimizing technological modes of FBW of rails of different grades and manufacturers, regardless of the parameters of the power mains and the condition of the rail welding machine. Based on the research results, the FBW technology for heat-strengthened rails was improved [31], a unit of measuring transducers was developed [32], and an algorithm for controlling the FBW process with a regulated cooling mode for welded joints [33] was adapted to the existing programs of the control system of K922-1 and K1000 rail welding machines. Due to the dosed heat input in the flashing process during FBW, the ability to regulate cooling of to rail welded joints was implemented to ensure their compliance with the requirements of acting standards for the indices of hardness and structural state of the joint zone metal (absence of martensite and bainite).

The above procedure of calculation and experimental studies was used to determine the admissible ranges of variation in the technological parameters of the FBW process of railroad frogs. Replacing M76 rails of open-hearth steel with heat-strengthened K76F and R350HT rails of converter steel required improvement of the FBW technology of the frog core of 110G13L steel with rail ends of K76F steel through a transition element (TE) of austenitic chromium-nickel 08Kh18N10T steel. The problems typical of welding dissimilar steels are associated with structural and chemical heterogeneity of the joint zone, the probability of forming a brittle interlayer of variable chemical composition, in particular, areas with a martensitic structure. The problem was solved by applying FBW technology by pulsating flashing, which ensures the

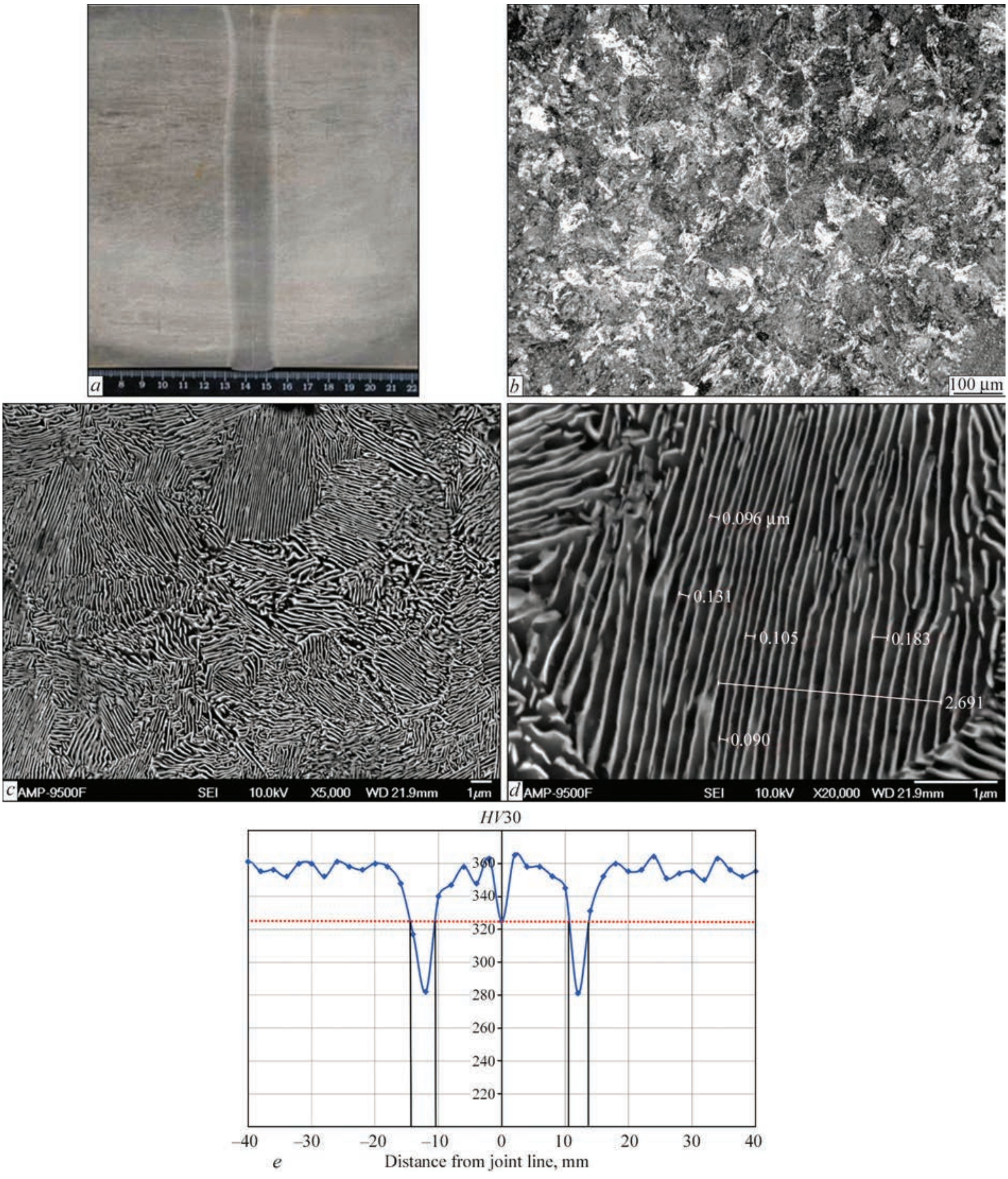


Figure 14. Macrosection (*a*), microstructure ×100 (*b*), SEM images, ×5000 (*c*), ×20000 (*d*) and hardness distribution in the R350HT rail welded joint at FBW (*e*), mode 2

implementation of specified thermal cycles to prevent the formation of brittle structural components in the combined joint of 110G13L, 08Kh18N10T and K76F steels and to produce a regulated pearlite structure in the HAZ of K76F rail steel [32].

Using the algorithm for numerical solution of the three-dimensional thermal conductivity equation under initial and boundary conditions corresponding to the actual welding conditions for the specimens, thermal cycles during FBW of K76F steel with the TE from 08Kh18N10T austenitic steel (joint 1) and 110G13L steel with the TE from 08Kh18N10T steel (joint 2) were obtained. The ranges of variation in the basic technological parameters of the FBW process were determined, at which, in the process of flashing rails of K76F, 110G13L, and 08Kh18N10T steels, their uniform heating along the cross-section and length is ensured, sufficient to perform deformation by a specified value during the upsetting.

The influence of the thermal cycle of FBW of the second joint on the structural stability of the metal in the HAZ of the first joint was evaluated using calcu-

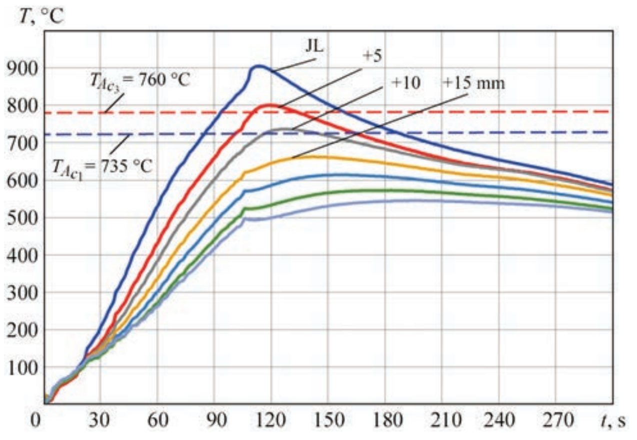


Figure 15. Thermal cycles in the first joint on the side of K76F steel at FBW of the second joint at h_{TE} = 10 mm width (experimental data)

lated and experimental data. It was found that the absence of brittle chromium carbides in the HAZ of both joint of the railroad frog is ensured by implementing the set temperature and time conditions of FBW by pulsating flashing, under which there is no significant diffusion of carbon in the joint zone of K76F and 08Kh18N10T steels, provided that the width of the TE of 08Kh18N10T steel is optimized.

Possible structural changes were evaluated in the metal of the first joint on the side of K76F steel at the TE width of h_{TE} = 10 mm at different distances L from the JL of K76F + 08Kh18N10T steels: L = 0, 5, 10 and 15 mm [33]. In particular, it was found that the thermal cycle of FBW of the second joint at a set value of heat input Q_{fl} can lead to heating of K76F steel in the joint zone of the first butt to a temperature below or above the temperature of structural transformations $T_{A_{c1}}$ = 735 °C, $T_{A_{c3}}$ = 760 °C (Figure 15), depending on the width of the TE of 08Kh18N10T steel.

For a set FBW mode of the second joint, the minimum width of the TE of 08Kh18N10T steel was determined, at which no heating of joint 1 to temperatures $T > T_{A_{c1}}$ occurs and negative structural transformations in joint 1 are excluded. In particular, it was found that for the FBW mode of the second joint with the heat input value Q_{fl} = 14.4 MJ at the TE width $h_{TE} \geq 21$ mm, the first joint is heated to a temperature lower than $T_{A_{c1}}$ = 735 °C, which potentially does not lead to the formation of hardening structures in the joint of K76F+08Kh18N10T steels, and the heating mode corresponds to a short-term "tempering" for K76F steel [33].

Using the improved FBW technology, a pearlite structure of a set dispersion (sorbitic-troostite) is produced in joint 1 on the side of K76F rail steel; welded railroad frogs meet the requirements of acting standards [34].

IMPROVEMENT OF THE QUALITY ASSURANCE SYSTEM FOR FBW OF RAILWAY RAILS

The FBW Department of PWI has developed, put into production, and has been successfully using computerized systems for quality assurance of joints using various pressure welding methods for many years. For FBW of railway rails, a three-level quality assurance system for rail welded joints was developed, which provides for:

- level 1 — development of an effective technology and approval of FBW modes for specific types and grades of railway rails in accordance with the requirements of acting regulatory documents;
- level 2 — in-process control of the basic parameters of the FBW process under actual production conditions, comparison with the established admissible limits of their deviations, issuance of a report (protocols) on the compliance of welded joints with the established requirements;
- level 3 — statistical analysis of rail FBW protocols performed at all FBW machines and submitted to the diagnostic center of the JSC "Ukrainian Railways".

The implementation of level 1 of the quality assurance system is based on the requirements for welded joints of railway rails provided in [11–13, 17]. When developing FBW technology and modes for the existing type and grade of railway rails, as well as a specific rail welding complex, the specialists of the FBW Department use the results of destructive and non-destructive testing, metallographic examinations of rail welded joints produced at PWI testing laboratory certified in accordance with the requirements of DSTU EN ISO/IEC 17025:2019.

In order to implement level 2 of quality assurance, i.e. to ensure stable reproduction of the rail welding process and testing of its basic parameters, a computerized FBW process monitoring and control system was developed, which allows maintaining the optimal flashing mode under actual production conditions largely regardless of operating conditions. The system is based on the use of an industrial computer, controller and appropriate sensors. During welding of each joint, the process parameters can be self-adjusted, which ensures optimization of programs for their variation at all stages of flashing and in general during the welding period. The computerized control system records the basic parameters of the FBW process, determines their admissible deviations from the set values and, in accordance with the established algorithms, assesses the quality of the joints immediately after welding [37].

Statistical analysis of rail welding protocols (level 3) ensures timely detection of systematic deviations of the basic FBW parameters, process optimization and the ability to diagnose the operating rail welding equipment.

The results of calculations are presented in the form of tables, diagrams and histograms and visually represent the progress of the welding process, as well as its dependence on a particular rail welding machine, FBW modes and rail grade. Statistical analysis of rail FBW protocols was successfully implemented in cooperation with the JSC "Ukrainian Railways".

In 2024–2025, remote monitoring for compliance of FBW technology of all welded rail joints with electronic welding reports sent to the Diagnostic Center of the JSC "Ukrainian Railways" from each rail welding machine equipped with a computerized quality control system was established.

PREPARATION OF RECOMMENDATIONS AND AMENDMENTS TO ACTING REGULATORY DOCUMENTS, DEVELOPMENT OF A NEW REVISION OF TECHNICAL SPECIFICATIONS FOR FBW OF RAILWAY RAILS

In 2024, based on the results of research works and contracts, PWI specialists developed recommendations for amending and supplementing the acting technical specifications for welding railway rails [11–13], which were fully taken into account in the new revision of the regulatory documents [36, 37]. An assessment of the results of the joint works is described in a letter from the Director of the CTCR Branch of the JSC "Ukrainian Railways", which states that "as a result of the implementation of the agreements, the technical condition of rail welding machines has been significantly improved to ensure train safety and the sustainable operation of the railway infrastructure under martial law in Ukraine".

UPDATING THE DESIGN OF FBW MACHINES, RENEWAL OF PRODUCTION OF RAIL WELDING COMPLEXES

To meet the needs of the JSC "Ukrainian Railways" and other partners, the problem of renewal of production of rail welding machines developed by PWI is extremely relevant. The successful solution of this problem is inseparably associated with updating the design of mobile and stationary machines for FBW of rails to meet the technical requirements of the customer and the production capabilities of equipment manufacturing companies.

In 2023, the Czech company SaZ s.r.o., in close cooperation with PWI, launched the serial production of double-track WELDERLINER rail welding complexes (Figure 16) equipped with K922-1 mobile machines that implement pulsed FBW technology. This event was preceeded by a significant improvement in the design documentation of the K922-1 machine to meet the manufacturer's technical requirements, design and technological support for the production of rail welding machines, which was carried out by PWI specialists.

The WELDERLINER complexes have successfully passed the comprehensive tests required by the European standard EN 14587-2:2009 for FBW of rails. The K922-1 mobile machine, which is an original development of PWI, is equipped with a modern computerized system for multifactor control of welding parameters, high-speed hydraulic drives, as well as a device for burr removing in the hot state without unclamping the welded rail section to cool the welded joint to a set temperature.

In 2024, PWI developed the design documentation for RW Equipment & Consulting LLC (USA) for the RW1060 mobile rail welding machine, which is an updated version of the K1045 machine for FBW of railway rails in hard-to-reach locations. A batch of K1045 machines was previously produced by the SE "Pressure Welding Engineering Center" (PWEC) of the STC "The E.O. Paton Electric Welding Institute" by order of the Progress Rail Services, USA. The RW1060 machine has an updated design of the current supply circuit, which provides significant advantages in the operation of equipment in subway tunnels, when welding railroad frogs with rails in the railway track. For example, by using unique new design of transformers, including a new approach to the design of current leads, it became possible to reduce the outer width of the opened machine when setting on rails to be welded from 597 mm to 438 mm (in the plane of the head of the rail being welded), which is a critical moment for this type of welding machines. During the production of the RW1060 welding head (Figure 17) at the PWEC, specialists from the Flash Butt Welding Department of PWI provided a design support during the production, and improvements were promptly made to enhance the manufacturability of the machine's components and mechanisms. The main design solutions implemented in the K1045 and RW1060 machines are patented in Ukraine [40–43].

In 2024, PWI launched cooperation with the French Company Yardway Railquip France SAS to provide services on the technology support and maintenance of mobile equipment for FBW of rails. The successful development of cooperation is expected to open up additional opportunities for expanding the use of PWI developments abroad.

In order to renew the production of stationary K1000 rail welding machines to meet the needs of the JSC "Ukrainian Railways", PWI and the Company "Rail Systems" signed a license agreement to grant the right to use the design, manufacturing technology and operation of FBW machines in stationary conditions. In 2024, "Rail Systems" has already gained

Figure 16. Mobile K922-1 machine (*a*), double-track WELDERLINER rail welding complex (*b*, *c*)

Figure 17. Welding head of the RW1060 machine for FBW of railway rails in hard-to-reach locations

successful experience in overhauling K1000 machines by order of rail welding enterprises of the JSC "Ukrainian Railways".

Long-term cooperation with the Dnieper JSC "Railway Switch Plant" continues to support the technological process of manufacturing railroad frogs, in particular, using the FBW technology for frog cores of high-wear 110G13L steel with rails made of eutectoid grade steel through TE of austenitic chromium-nickel stainless steel. In 2023–2025, PWI successfully performed works on consulting support of the technology for FBW of frogs, audit of the technical condition of the K924M machine, manufacturing of welding circuit elements, development of a set of measures to ensure the specified technical characteristics of the K924M machine and extend its operational life.

Thanks to the joint efforts of the JSC "Ukrainian Railways", PWI and foreign partner companies, critical challenges are being successfully overcome to ensure the operability of the railway infrastructure under martial law in Ukraine and to expand the use of PWI developments abroad.

CONCLUSIONS

1. The critical challenges for ensuring the operability of the railway infrastructure under martial law in Ukraine were analyzed. The suspension of domestic rail production by Azovstal Metallurgical Combine as a result of the occupation has raised the issue of welding used rails and new rails of different grades, from different manufacturers and with various heat treatment modes, in particular a heterogeneous combination. The prob-

lem of extending the service life of existing welding equipment is also relevant.

2. To solve the existing problems, a set of measures was developed to ensure high-quality welding of rails in stationary and field conditions during the repair and construction of continuous welded rails in Ukraine in accordance with the requirements of regulatory documents.

3. Implementation of the developed set of measures in 2022–2025 allowed solving a number of problems related to the FBW of railway rails:

● the causes for non-compliance of some rail welded joints of different grades with the requirements of regulatory documents were identified, recommendations were developed to prevent defects and reliably detect probable defects during non-destructive testing of rail welded joints;

● an audit of the technical condition of rail welding equipment available at the JSC "Ukrainian Railways" was conducted and measures were developed to extend its operational life;

● the technology was improved and the process modes of FBW of heat-strengthened railway rails of converter production were optimized;

● quality assurance systems for joints during FBW of railway rails were optimized;

● designs of mobile rail welding machines were updated, production of equipment for FBW of rails was renewed.

4. Thanks to the joint efforts of PWI of the NAS of Ukraine, structural units of the JSC "Ukrainian Railways", domestic and foreign partner companies, critical challenges are being successfully overcome to ensure the operability of the railway infrastructure under martial law in Ukraine and expand the use of domestic developments abroad.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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