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Flash-butt welding of high-strength rails

The article features the results of research in the field of welding high-strength rails. The scope of the research combined not only monitoring of the welding process as such but also the assessment of the achieved results. The recommendations how to carry out welding operations are part of the results too.

Key words: *welding, rails, breaking force analysis, flash-butt welding.*

1. INTRODUCTION

Over the recent years, high-strength R260 and R350HT rails have been laid on the railroads of Poland. In accordance with the contract between the railroads of Poland, the PJSC Kakhovka Plant of Electric Welding Equipment (PJSC KZESO) and the E.O. Paton Electric Welding Institute (PWI), stationary rail welding machines K1000 and mobile complexes (on the wheelbase of the MAZ and Tatra vehicles or rail base of MRWM (mobile rail welding machines)), equipped with the machines K922-1, were delivered to Poland.

The E.O. Paton Electric Welding Institute has been cooperating fruitfully with the PJSC KZESO for over 50 years. These rail welding machines were designed by the E.O. Paton Electric Welding Institute and have been successfully produced by the PJSC KZESO for many years. In addition, the industrial technology was developed for welding high-strength R260 and R350HT rails with the use of the mentioned machines. To fulfill this work, the batches of the mentioned rails were delivered to PWI and KZESO. The chemical composition of rail steel and its mechanical properties are given in Table 1. PWI has been cooperating with the Institute of Innovative Technologies EMAG in Katowice since 2015, whereas KZESO is represented on the Polish and European markets by KZESO Machinery in Katowice within the scope of trade and production.

Table 1

Chemical composition of rail steel

Steel grade	Chemical composition, %								
	C	Mn	Si	V	Ti	Cr	P	Al	S
R260	0.62…0.82	0.70…1.20	0.15…0.58	0.03	–	0.15	0.025	0.004	0.025
R350HT	0.72…0.82	0.70…1.20	0.15…0.58	0.03	–	0.15	0.020	0.004	0.025

The welding of rails was performed at the plant using the welding machine K922-1. Two reference batches of R260 and R350HT rails were welded. Preliminarily, the weldability of the mentioned rails was tested and metallographic examinations were carried out. The tests of welded rails were carried out in accordance with the requirements of the European Standard [4]. The welded joints of all the batches were monitored using non-destructive testing methods (ultrasonic [US] and capillary methods of control). They were also tested for static mechanical bending in accordance with the requirements of the European Standard.

The metallographic examinations of welded joints according to the order of KZESO MACHINERY Ltd. were carried out at the E.O.Paton Electric Welding Institute in the light microscope Neophot 32, while fractographic studies and X-ray spectral microanalysis of fractured surface were performed in the Auger microprobe JAMP 9500F of the JEOL company (Japan). The aim of the conducted works was to develop an industrial technology for welding high-strength R260 and R350HT rails to meet the requirements of the European Standard and to provide stable quality of welded joints of different grades of steel without changes in the welding mode.

In Poland the technologies and equipment for welding not heat-hardened R260 rails, developed by PWI, have been applied for many years. In this case the technology of flash-butt welding with continuous flashing (CF) is used. This technology is characterized by lower power consumption, provides uniform heating of rails across the whole cross section and stable reproduction of preset welding cycles. Its many-years' application under different conditions has demonstrated stable and high quality of joints of not heat-hardened rails. Therefore, the preliminary tests of welding R350HT rails were performed at the canonical modes accepted in welding of non-hardened rails using continuous flashing.

The program of welding with the use of continuous flashing is given in Figure 1, and the temperature field in the heat affected zone (HAZ) corresponding to this mode is shown in Figure 2, curve 1. The results of tests on static bending are given in Table. 2.

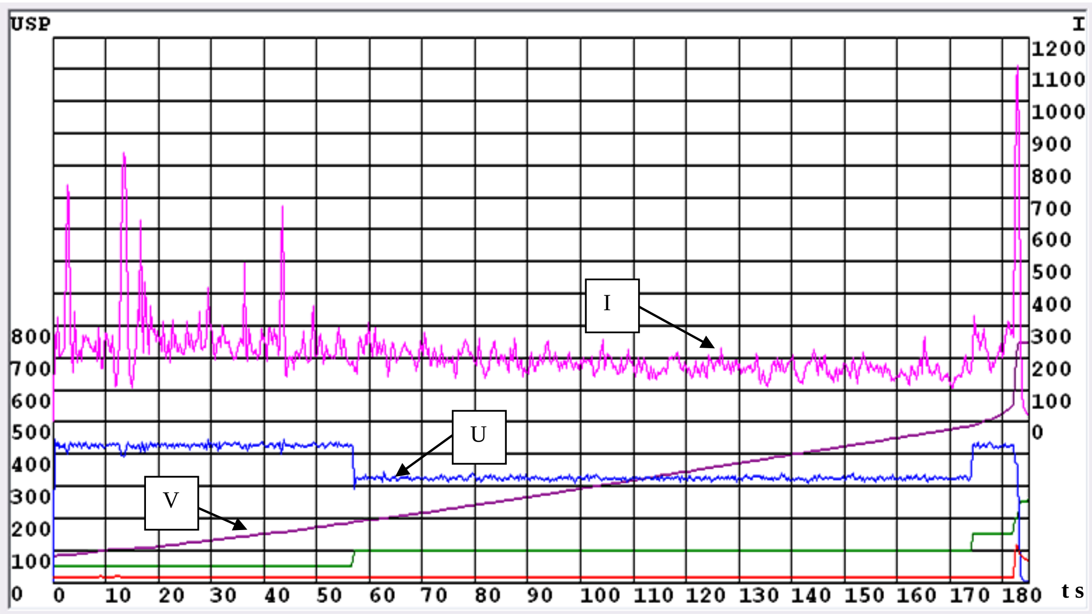

Fig. 1. Programs of changing the main parameters U, I, Vf in welding rails R65 with continuous flashing

Table 2

Results of mechanical tests on static bending

Number of mode	Rail grade	Fracture load, kN	Bending deflection, mm	Remarks
Requirements of TS	Ukraine	160	≥30	TS U 24.1-40075815-002:2016
	European standard	160	≥20	EN 14587-1:2007 E
1.	R350HT	1800-2500 2100	14 – 30 18	CF
2.	R350HT	1700-2250 1900	12 – 22 16	CF
5.	R350HT	2770-3050 3000	58 – 66 60	PF

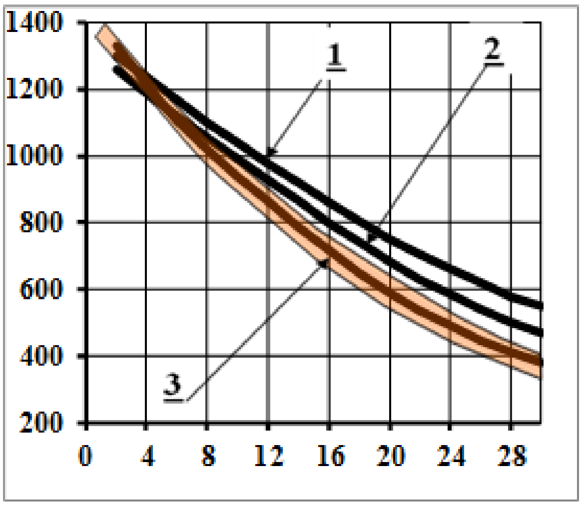

Fig. 2. Distribution of temperature in HAZ before upsetting in welding of rails R65 at different modes: 1 continuous flashing at a canonical mode; 2 continuous flashing at a low heat input; 3 pulsating flashing at an optimum heat input

The values of tests of welded joints of R350HT rails concerning the fracture load are close to standard values while the values of ductile properties are instable and predominantly lower than the requirements of the Technical Specifications. Figure 3 shows the microstructure of joints (weld center). In the weld center we can observe a coarse-grain (grain number 2-3) perlite-sorbite structure with ferrite precipitations along the boundaries of primary austenite grains.

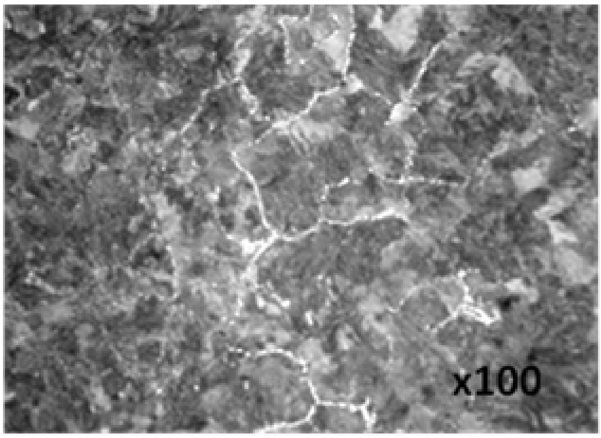

Fig. 3. Microstructure in the center of the welded joint made by continuous flashing

From the experience of flash-butt welding of rail steel [7] it is known that the presence of such a structure in welded joints of rails has a negative effect on the values of mechanical properties of joints, especially on ductility. It is shown in the works [6,7] that the reduction in energy input in welding of such steel allows to improve the structure of metal along the joint line.

The batches of specimens were welded with the use of CF, but with a lower energy input due to reduced duration of flashing (see Figure 2, curve 2). During testing the specimens of that batch for bending, the obtained values on the deflection size were unstable (Table 2, mode 2), which is caused by formation of some dull spots in the plane of the joint defined in flash-butt welding as dull spots (DS) (Figure 4).

Fig. 4. Dull spots on the fractured surface of the welded joint

They represent thin oxide films of up to 10 μm thickness. Their composition includes mostly oxides of alloying elements of nonmetallic inclusions contained in the base metal of rails. In the majority of standards, the DS of small sizes are conventionally considered to be acceptable if their total area at the fracture surface does not exceed 30 mm^2.

The appearance of such defects is considered to indicate the need to modify the welding technology. Therefore, further experiments for welding specimens of R260 and R350HT rails were carried out using the method of flash-butt welding with pulsating flashing [8]. Similarly to continuous flashing (CF), all the welding parameters of pulsating flashing (PF) are preset by the programs of changing the voltage, current and speed of flashing in the function of time or displacement (Figure 5).

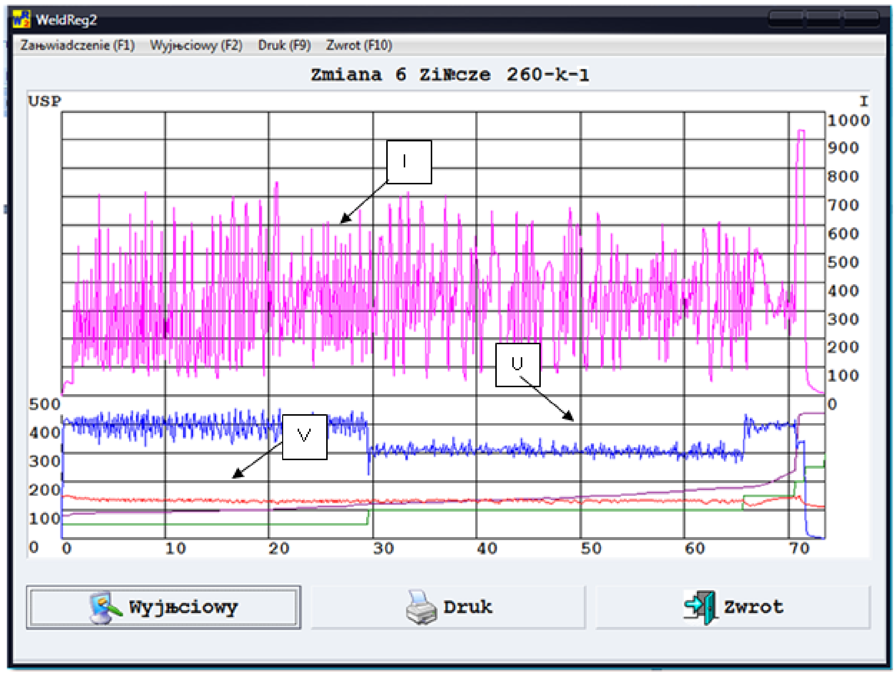

Fig. 5. Program of changing main welding parameters

At the same time, through the control of instantaneous values of these parameters in the process of flashing, it becomes possible to suppress, to a large extent, the explosion-like fracture of elementary contacts arising between the contacting parts and to transfer it to the melting process.

In this case the efficiency factor of the flashing process is significantly increased, the current for flashing is 2-3 times increased and the possibilities to vary the energy input during welding are significantly widened.

In particular, it provides feasibility to heat the near-contact layers of metal of welded parts to the temperature required for quality welding at a minimum width of the common heat-affected zone. The curves, characterizing the temperature distribution in the heat-affected zone at PF and CF are given in Figure 2.

In both cases, the near-contact layers are heated to the temperature above 1,200°C, but the gradient of the temperature field during PF is considerably higher, thus contributing to the formation of a fine-grained structure in the weld center. In addition, the application of PF opens new opportunities to prevent the formation of DS-type defects in welding with the reduced energy input.

In the work [5] it is shown that the higher is the probability of formation of DS-type oxide films in the plane of joints, the smaller is the thickness of melt on the surface of flashing. As it can be seen from the comparison of plots in Figure 6, the melt at PF has a more stable value than at CF, its minimum values are 2-3 times higher. Therefore, it seems to be possible to use the welding modes in PF, characterized by the minimum energy input without the risk of the DS-type defects occurring in the joint plane.

The main investigations were carried out on specimens of R350HT rails, characterized by higher strength. On their basis the optimum mode of PF welding was determined, preset by the program (see Figure 5) and the distribution of temperature in HAZ, curve 3 in Figure 2. In such heating mode the welding duration is 70-80 seconds (Fig. 5). This means that it is reduced 3 times compared with the canonical mode taken for not heat-strengthened rails (Figure 1). The average power at melting increased 2 times, but the maximum short-term power consumption remained at the same level of performance as in discontinuous fusion welding, so when using pulsating flushing there is no need to adopt energy sources of rail welding machines.

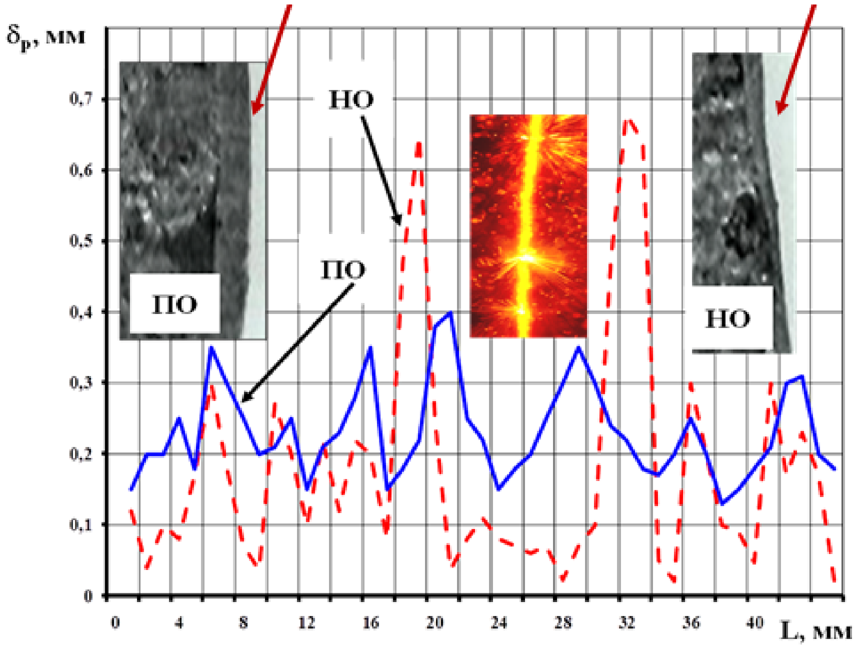

Fig. 6. Distribution of melt on the surface in welding with pulsating flashing (PF) and continuous flashing (CF)

During the investigations it was found out that obtaining the required mechanical properties of the joints in welding of R260 rails can be done at the same energy input as in R350HT rails. Therefore, the reference batches of R260 and R350HT rails were welded at the same mode. Each reference batch had 10 specimens of 1.22 m length with a weld in the center. The welded specimens, mounted on the supports at a distance of 1 m from each other, were tested for static bending by means of applying a load in the weld center in accordance with the European Standard [4].

All the specimens after mechanical treatment of welds were subject to capillary and ultrasonic testing. The results of bending tests are given in Table 3. The tested specimens are characterized by high strength and ductility. The batches of R260 rails were not fractured during the tests, and the loads were at the level of base metal values, therefore the concentrator (notch) was made in the weld center and the specimens were brought to the fracture to check the defects along the fusion line. In the batches of specimens of R350 rails, 100% of specimens were fractured in welds, meantime the load and the bending deflection significantly exceeded the established requirements. In the fractures of specimens no defects were observed. In all the tested specimens of reference batches no defects were revealed after capillary and ultrasonic testing.

Table 3

Results of mechanical tests on static bending

No.	Marking of weld butts	Load, кN	Bending, m	Test results
1.	260-к-2	**2440**	**46**	Not fractured
2.	260-к-4*	**2430**	**47**	Not fractured
3.	260-к-5*	**2440**	**48**	Not fractured
4.	260-к-6*	**2445**	**49**	Not fractured
5.	260-к-7*	**2380**	**44**	Not fractured
6.	260-к-16	**2250**	**37**	Not fractured
7.	260-к-17	**2480**	**48**	Not fractured
8.	260-к-18	**2380**	**45**	Not fractured
9.	260-к-20	**2410**	**46**	Not fractured
10.	260-к-21	**2380**	**43**	Not fractured
11.	350-к-11	**2700**	**58**	Fractured
12.	350-к-12	**3050**	**66**	Fractured
13.	350-к-13	**3000**	**64**	Fractured
14.	350-к-14	**3000**	**58**	Fractured
15.	350-к-15	**3050**	**63**	Fractured

The analysis of the microstructure in the weld center and HAZ (see Figure 7) shows that the grain size in the weld center is 2...3 times reduced and the level of ferrite decreased significantly as compared to the data in Figure 3 shown for CF welding. The structure in the weld center and the adjacent area of HAZ remains sorbite-perlite and sorbite, there are no dangerous hardening structures there.

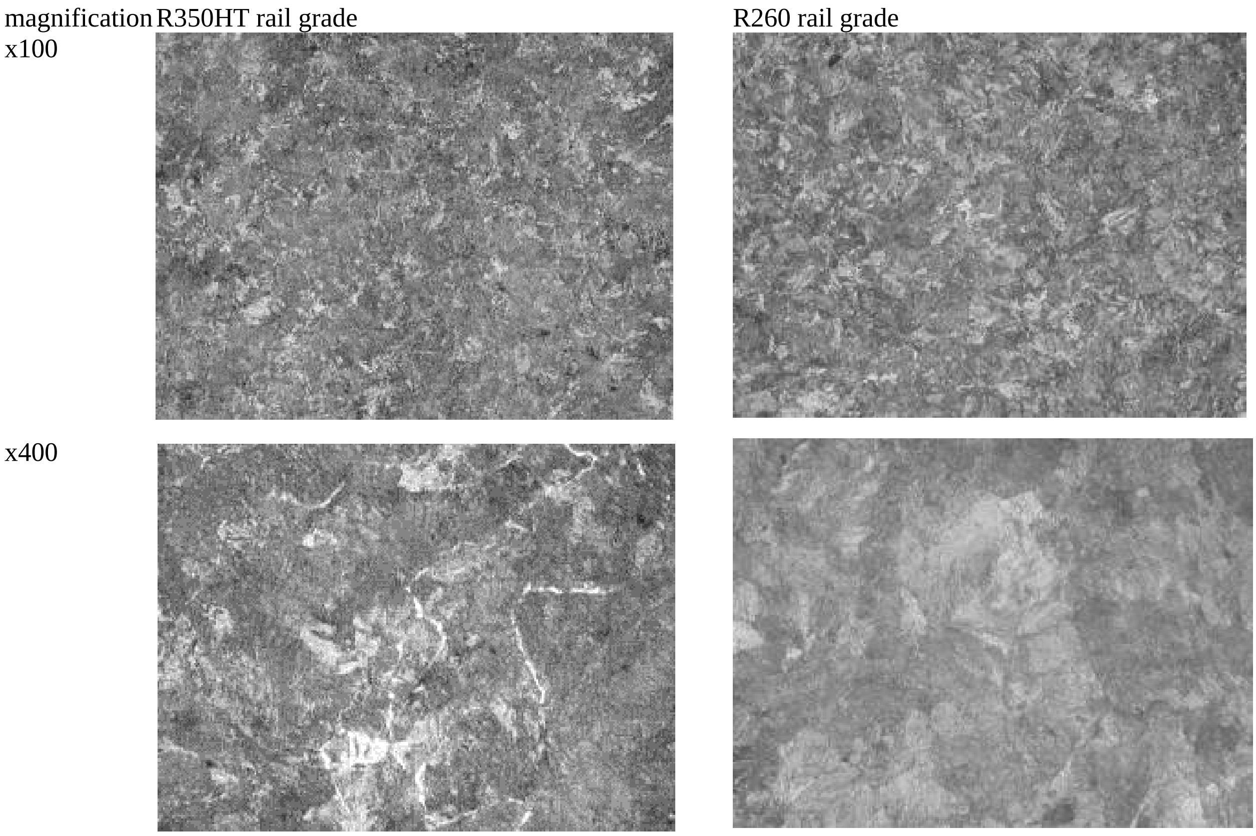

Fig. 7. The welded joint microstructure in the heat affected zone

Figure 8 presents the results of measurements of hardness in the joints of reference batches. The measurements were carried out at the depth of 5 mm from the rolling surface of the rail head. In R350HT rails the hardness is decreased in certain areas of HAZ at the length of 1-2 mm in the places where heating reached the temperature of steel tempering. While in the center, due to reduction in carbon content in the near-contact layers of the metal, subjected to heating to the temperature close to the melting temperature of steel, the structure of tempered sorbite with high ductile properties was observed in the areas with reduced hardness. The length of such areas does not exceed 2 mm, therefore they cannot negatively affect the wear resistance of joints in the rail-wheels contact.

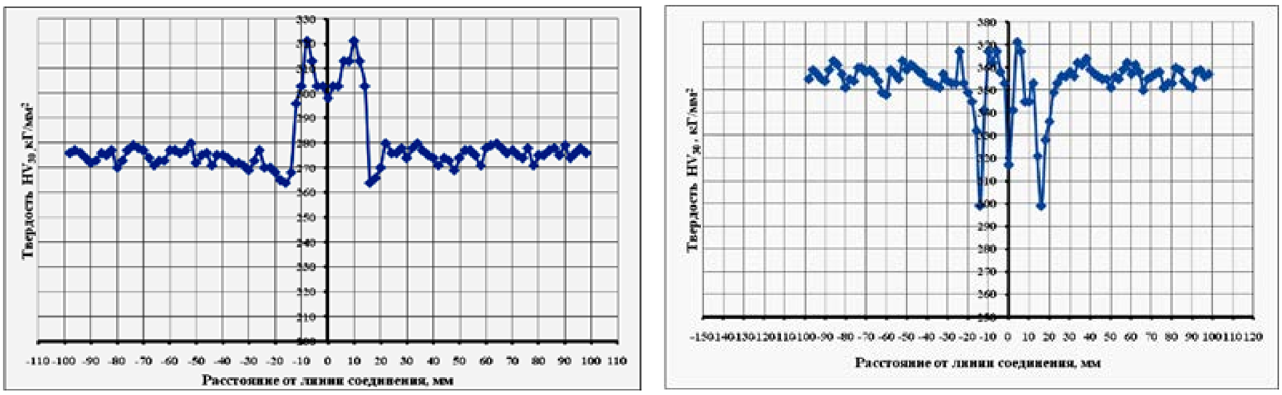

Fig. 8. Diagram of distribution of hardness HV30 in welded joint of rails: R 260 (left), R 350HT(right)

In the joints of R260 rails a 23% increase of hardness in HAZ is observed as compared to the base metal. The structure of metal in this area represents the sorbite with the grain 3...4 (see Figure 7b) and hardening sorbite. Such increase is admissible according to the conditions laid in [9]. The increase was caused by rapid cooling of HAZ during welding at the rigid mode. During the investigations the limiting admissible deviations from the optimal value of energy input (marked area of curve 3, Figure 2) were also determined, at which the required values of mechanical tests of welded joints can be provided. It should be noted that the given limits of energy input are based on many-years experience in the application of the PF technology in welding of high-strength rails at the railroads of Ukraine, Russia and other countries. The further gained experience of using this technology in welding high-strength R260 and R350HT rails allows to specify the limit conditions. In the process of welding the test specimens at the energy inputs lower than the specified limits, the increase in hardness of welded joints of R260 and R350HT rails was observed together with the increase in the values of strength and ductility. With the increase in energy input the decrease in hardness in HAZ and values of strength and ductility of joints was manifested to a larger extent.

The conducted investigations show that while welding high-strength R260 and R350HT rails it is possible to obtain high values of mechanical properties of welded joints due to keeping the main condition, i.e. significant reduction in energy input as compared to the technologies accepted in welding non-hardened rails. At the same time the range of acceptable deviations of energy input is narrowed with respect to the preset value. This specifies a number of increased requirements to the systems of automatic control of the welding process, providing accuracy of reproduction of the preset welding programs, as well as the accuracy of rail ends preparation before welding, cleaning their surface in the places of contact with current-carrying electrodes.

At the E.O.Paton Electric Welding Institute a great amount of experience was gained in the application of technology for PF welding of high-strength rails of different manufacturers in the railroads of Ukraine, Russia, CIS countries, China, USA, where welding machines, designed by PWI, are used. These machines apply systems of in-process monitoring of parameters, which are preset by the programs of process control. After completion of welding of each butt, a computer control system registers all the data about changing parameters, compares them with the preset values and provides information about the existing deviations in real time (see Figure 9). This information comes to the operator's panel and to the diagnostic center, where the evaluation of joints quality is made considering the results of non-destructive and destructive testing. The EMAG Institute has got long-term experience within the scope of monitoring machines and devices, whereas KZESO MACHINERY deals with production and implementation of complex solutions.

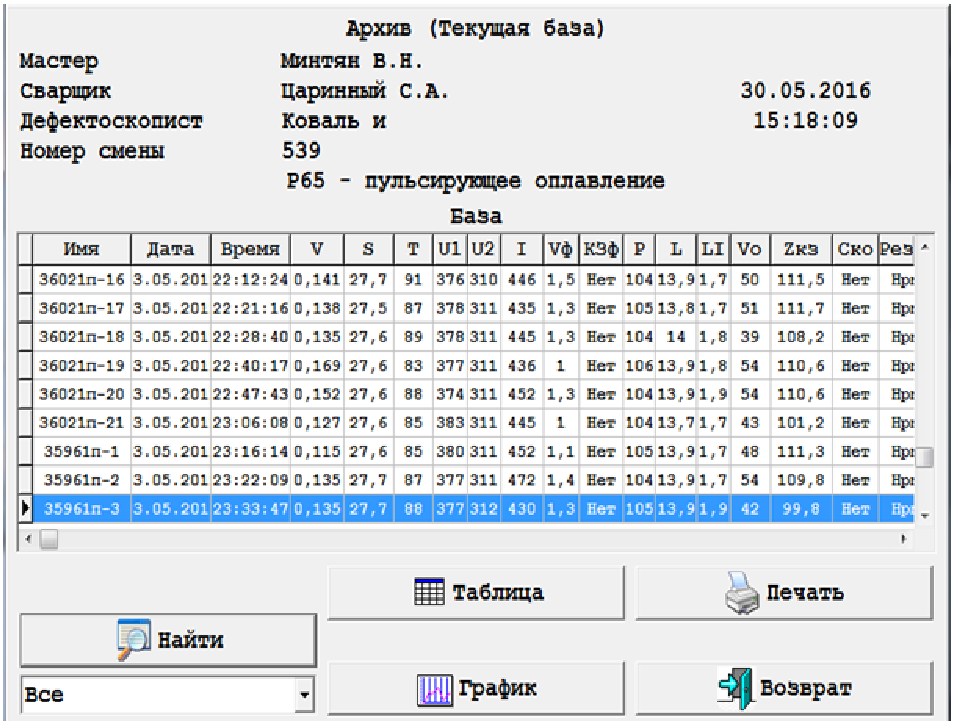

Fig. 9. The report on welded joints with welding parameters

The in-process monitoring provides very accurate determination of possible violations of the preset modes of energy input and evaluates the degree of their effect on the quality of joints. In addition, the in-process monitoring system detects deviations of flashing parameters influencing the formation of joints in the final stage of flash welding and upsetting.

In the real conditions of the rail welding equipment operations, particularly in the field conditions, the deviations from the preset parameters are possible. In order to minimize their negative effect on the quality of joints, an adaptive system of automatic control of the preset welding parameters was developed. On the basis of the data accumulated during the in-process monitoring the algorithms of feedbacks were determined in the systems of control of main parameters of the flashing process, which provide stable reproduction of the preset welding programs by their correction. For example, during an unexpected change in the mains voltage and increase in the resistance of welding circuit of the machine due to its overheating, the flashing process may be stopped if the program of voltage changes is rigidly preset. In this case the system of adaptive control will correct the program at which the flashing is continued and the energy input will remain at the preset level.

2. WELDING OF RAILS IN TRACK WITH TENSION

In the construction and repair of continuous welded tracks it becomes necessary to stabilize the stressed state of rail sections. In continuous welded track rails, rigidly fixed on the sleepers, stresses occur, caused by changes in the ambient temperature. In the middle latitudes the changing interval is 90°C (-45 + 50°C). To reduce the stresses, the tension of the track should be relieved periodically by replacing the rail inserts of the corresponding length 2 times a year (in spring and autumn) [3]. A similar problem arises while relieving stresses when a repair of the continuous welded track is needed Then instead of cutting out the defective area a new rail is inserted which is welded-on to the section in 2 places (Figure 10). In flash-butt welding the rails are shortened and to obtain the necessary allowance for welding of the closing butt, the rail is bent to provide a proper value of the allowance. At the same time the drive of the welding machine should provide high accuracy of rail shortening in the final stage of welding. Such a technology of repair of continuous welded tracks with the use of flash-butt welding is applied at the railroads of Ukraine [2] and other countries.

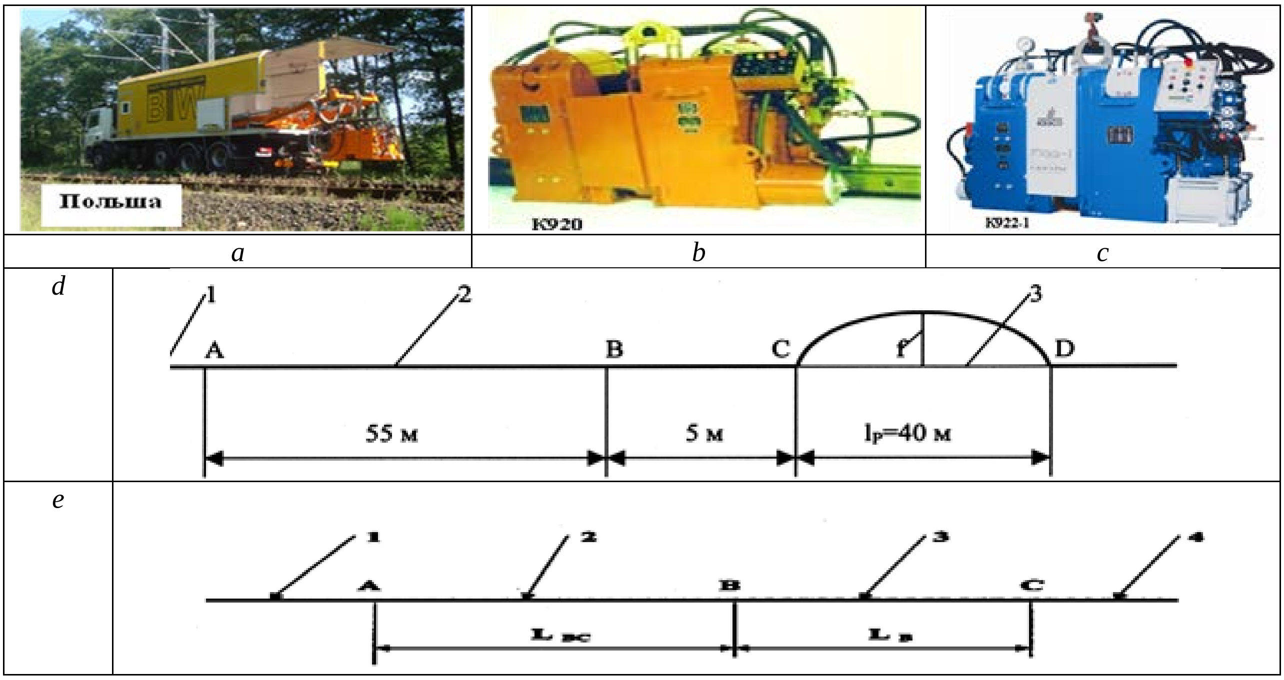

Fig. 10. Scheme of rail welding in track:
a – mobile rail welding machine K922-1; b – rail welding machine K920; c – rail welding machine K922-1; d – scheme of bending of a rail section before welding with its restoration by means of the method of partial disassembly; e – scheme of rail section unfastening before welding with its restoration by means of the tension method

In the process of carrying out such works it was proposed to perform this operation without bending the welded-on rail insert and to obtain the necessary allowance for welding due to the tension of the welded rail sections. The application of pulsating flashing allows to save a two-times bigger allowance for flashing than in continuous flashing. This greatly facilitated the solution of the specified problem.

On the basis of the pulsating flashing process, a complex system for automatic multifactor control of welding parameters, combined with the program, presetting the tension force in the rail sections, was developed at the E.O.Paton Electric Welding Institute. It provides a stable performance of the preset welding modes regardless of the tension force of rail sections. The operator only enters to the computer the data about the temperature at which the welding is carried out.

A successful application of the technology of rail welding with tension during the repair of continuous welded tracks made it possible to offer a more radical solution to stabilize the stressed state of continuous welded tracks. It is based on the suggestion to create constant tensile stresses in welding long rail sections of such a value that no compressive stresses should occur in them during the changes of ambient temperature in the range of 90°C. The calculations show that the tensile stresses were constantly maintained, their maximum rated value exceeded 14 kg/mm^2 and such a level of stresses is quite acceptable for high-strength rails. The technology of welding with tension is successfully applied by the American company Norfolk which uses the equipment designed by PWI. Hundreds of kilometers of continuous welded tracks were welded.

3. EQUIPMENT FOR WELDING OF HIGH-STRENGTH RAILS

In the recent decades, at PWI a new generation of mobile rail welding machines was designed, which are manufactured by the Kakhovka plant of electric welding equipment according to the documentation of PWI. The final assembly, implementation as well as guarantee and post-guarantee service of these mobile rail welding machines in Poland are provided by KZESO MACHINERY Ltd. In Table 4 their technical characteristics are given. All the machines are equipped with modern computerized systems of multifactor control of main parameters and fast-response hydraulic drives which allow to perform the technology of welding with the use of pulsating flashing and tension. The drives of the machine develop the upsetting force of 90-150 tons, which allows to use them for welding high-strength rails at different energy input and with tension. The machines are equipped with built-in flash removers which remove flash in a hot state without unclamping the rail section. This is necessary in welding with tension. The weight of the machine was increased by 10-20% as compared to the machines of previous generations used in rail welding. Therefore, they can be used on the available mobile rail welding complexes.

Table 4

Characteristics of welding machines

Welding parameters	Types of machines							
	K355A-1	K900A-1	K920-1	K921	K922-1	K922-2	K930	K950
Rated primary current (duty cycle=50%), A	395	395	540	540	540	540	540	540
Rated power (duty cycle=50%), kVA	150	170	210	210	210	210	210	210
Transformation coefficient	60	60	54	54	54	54	54	54
Rated upsetting force, kN (kgf)	450 (45000)	500 (50000)	1000 (100000)	1500 (150000)	1200 (120000)	1200 (120000)	1200 (120000)	1200 (120000)
Rated clamping force, kN (kgf)	1250 (125000)	1200 (120000)	2500 (250000)	3750 (375000)	2900 (290000)	2900 (290000)	2900 (290000)	2900 (290000)
Upsetting speed at idle mode, mm/s, not less than	20	25	35	35	40	50	50	50
Machine travel, mm	70	70	90	150	100	150	200	250
Mass of welding head, kg, not more than	2375	2500	2900	4200	3450	3500	3500	3500
Mass of delivery set, kg, not more than	4000	4100	4500	6000	5100	5150	5200	5250
Dimensions (B × H × L), mm	810 × 1059 × 1140	1030 × 1140 × 1550	1060 × 1195 × 1600	1190 × 1400 × 2430	1060 × 1300 × 1895	1060 × 1300 × 2050	1060 × 1300 × 2095	1060 × 1300 × 2145

4. CONCLUSIONS

The technology of flash-butt welding of high-strength R260 and R350HT rails was developed to provide the properties of welded joints required by the standards of the EU and the railroads of Poland. The technology is based on a welding method using pulsating flashing, developed by the E.O. Paton Electric Welding Institute.

It was found out that, while welding high-strength rails, to obtain the required mechanical properties of welded joints, it is necessary to reduce the energy input in welding as compared to the existing technologies accepted for the joints of not heat-treated rails.

In welding with the reduced energy input the requirements to admissible deviations from the preset optimal welding conditions become more rigid.

In rail welding machines of a new generation K922 the systems of automatic multifactor process control flashing are installed, providing the accurate reproduction of the preset technologies of welding high-strength rails during the repair and construction of railway tracks.

The use of the machine K922 allows to perform a new technology for the stabilization of the temperature-stressed state of continuous welded tracks by using welding with tension.

The cooperation between PWI and EMAG enables to develop complex solutions within the scope of automation, control and visualization of machine operations and processes. These solutions will be implemented in Poland by KZESO MACHINERY Ltd.

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