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FEATURES OF HEAT TREATMENT OF WELDED JOINTS OF RAILWAY RAILS

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Abstract. *The purpose of the work is to create inductors for heat treatment of welded joints of railway rails using induction heating with currents at a frequency of 2.4 kHz and to study the effect of heat treatment on the structure and hardness of the metal of welded joints made by contact butt and automatic submerged arc welding with a consumable nozzle. The inductors' inductive wires follow the shape of the rail profile and contain magnetic circuits installed above the rolling surface and the side faces of the head, neck and sole base. It has been established that the inductors provide a uniform distribution of the temperature field in the rail profile elements and a low temperature difference between the surface and deep metal layers. During heat treatment of welded joints of railway rails of type P65 made of steel K76F, made by contact butt-welding, the time for heating the joints to a temperature of 890 °C is 160 s. It is shown that after heat treatment of welded joints, the metal grain is crushed across the entire width of the heat-affected zone. The hardness of the metal approaches the hardness of the base metal in all rail elements. During heat treatment of welded joints made by automatic submerged arc welding with a fusible tip, the heating time to a temperature of 890 °C is 180 s. It has been established that under conditions of forced cooling of the head rolling surface with an air-water mixture, the uneven distribution of the width of the thermally affected zone in the rail profile elements decreases, the grain in the metal structure of the colossal zone and the zone of incomplete recrystallization is crushed, and the hardness of the metal of the colossal zone approaches the level of hardness of the base rail metal.*

Key words: *rails, inductors, induction heating, rail welds, heat treatment.*

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1. INTRODUCTION

The operational properties of seamless railway tracks largely depend on the quality of welded rail joints. The dominant rail joining process is contact butt-welding [1, 2]. The metal of welded joints, compared to the main rail metal, has zonal structural heterogeneity, foci of internal residual stresses and an uneven distribution of properties. To eliminate the negative impact of welding, heat treatment of welded joints is used. The mechanical properties of welded joints were found to be improved after heating to the normalizing temperature [3, 4]. A high heating rate is provided by the technology of induction heating of metals with high-frequency currents [5, 6, 7]. The purposeful distribution of the induced current density inherent in the heating technology allows taking into account the complex shape of the rail profile and the different mass of the head, neck and sole metal. The existing technology of heat treatment of welded joints of railway rails made by contact butt-welding involves heating the welded joints to a temperature of 850…950°C with currents with a frequency of 8…15 kHz and subsequent hardening of the head rolling surface with compressed air. The neck and sole of the rails are cooled in still air. The time of heating the welded joints to the heat treatment temperature exceeds 240 s [8]. The heating equipment contains inductors without magnetic cores. The inductors' inductive wires are oriented along the rails. The width of the heat-affected zone (HAZ) after heat treatment significantly exceeds the width of the HAZ of the welded joints.

The use of high-strength rails with increased wear resistance on railways necessitates the improving of the technology of heat treatment of welded joints and equipment for its implementation in the direction of creating the optimal width of the HAZ. It allows the increasing in the heating rate of welded joints; the distributing of the temperature field in the rail profile elements with a low temperature difference between the surface and deep layers of the metal; the ensuring a fine-grained structure of the metal across the width of the HAZ. To achieve such requirements and create an optimal distribution of the transmitted power in the rail profile elements, it is advisable to reduce the current frequency to 2.4 kHz and use magnetic circuits in inductors to increase the density of the induced current [9, 10, 11, 12].

Of considerable interest is the influence of heat treatment on the characteristics of welded joints of railway rails made by automatic arc welding by bath method with a fusible mouthpiece (AAWFM). The welding method developed at the E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine

Involves the use of self-shielding flux-cored wire fed through the longitudinal channel of a special fusible mouthpiece [13, 14]. The welding technology is intended for use in the conditions of construction, reconstruction, capital and current repair of tracks in light rail transport systems, subways, trams, industrial transport tracks, as well as for welding rail joints within switch points and intersections.

The objective of the work is to create inductors for heat treatment of welded joints of railway rails using induction heating with currents at a frequency of 2.4 kHz and to study the effect of heat treatment on the structure and hardness of the metal of welded joints made by resistance butt-welding and the AAWFM method.

2. MATERIAL AND METHODS

The work investigated welded joints of railway rails of type P65 made of steel K76F, performed by contact butt-welding on a stationary machine of type K1000 and welded joints of rails made by the AAWFM method in the laboratory of the E. O. Paton Electric Welding Institute of the NAS of Ukraine. The equipment for heat treatment of welded joints included a thyristor frequency converter TPChT-160/2.4 as a power source with currents of frequency 2.4 kHz, inductors, compensating capacitors, a liquid cooling system, and an air compressor. Inductors with a width of inducing wires of 55 mm performed heating of welded joints. The metal temperature was measured by chromel-alumel thermocouples. Metallographic studies were performed on longitudinal samples. The surface of the samples included the HAZ of welded joints and the base metal of the rails on both sides of the HAZ. To identify the microstructure of the metal, the method of chemical etching of polished surfaces of samples in a 4% alcoholic solution of nitric acid was used. The grain size of the metal was determined according to GOST 5639-82.1. The integral hardness of the metal HRC was measured on a TK-2M hardness tester with a load of 150 kg.

Inductors for heat treatment of welded joints of railway rails. Inductors for local heating of metal in the area of welded joints have the same design (Fig. 1). The inductors' inductive wires repeat the shape of the rail profile above the rolling surface and the side faces of the head, neck and sole. The air gaps are increased above the neck and greatly above the side faces of the sole, which prevents their overheating [15]. The inductive wires consist of two parallel wires, due to which the induced current density on the rail surface is brought closer to the total width of the wires. Magnetic circuits of the PL type of rod structure are installed above the rolling surface and the side faces of the head, neck and bottom of the sole. The magnetic circuits are designed to increase the induced current density and the efficiency of the inductor-rail system.

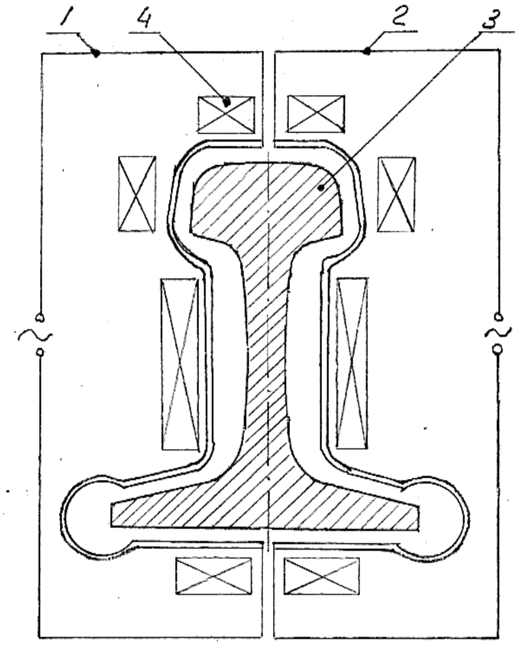


Figure 1. Inductors for heat treatment of welded joints of railway rails:
inducing wires – (1, 2); rail – (3); magnetic cores – (4)

Heat treatment of welded joints of railway rails performed by contact butt-welding. The width of the inductors' inducing wires exceeds the width of the HAZ of welded joints after welding of high-strength and high-alloy rails of the P65 type on stationary and mobile machines [16]. As tests have shown, the use of inductors provides a high heating rate of welded joints, a low temperature difference between the rolling surface of the head and the deep layers of the metal (Table 1). There is no overheating of the side faces of the sole. After heat treatment of welded joints, the HAZ width in the rail profile elements has a uniform distribution (Fig. 2). A slight decrease in the HAZ width in the areas of the transition of the head to the neck and the neck to the sole is explained by the absence of magnetic circuits in the inductors above such areas.

Table 1

Heat treatment parameters of welded joints of railway rails of type P65,
made by contact butt-welding

Parameter	Parameter value
Frequency converter power, kW	56…63
Rail head heating rate to magnetic transformation temperature, °C/s	9.1
Rail head heating rate above magnetic transformation temperature, °C/s	1.5
Heat treatment temperature, °C	890
Heating time to heat treatment temperature, s	160
Holding time at heat treatment temperature, s	20
Temperature difference between the rolling surface of the head and the layer at a depth of 23 mm, °C	40
Temperature of the side faces of the sole, °C	860…870
Cooling time of the rolling surface of the head with compressed air, s	180

3. RESULTS AND DISCUSSION

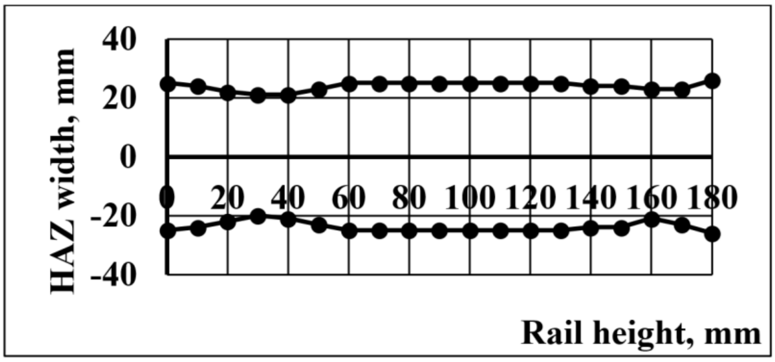
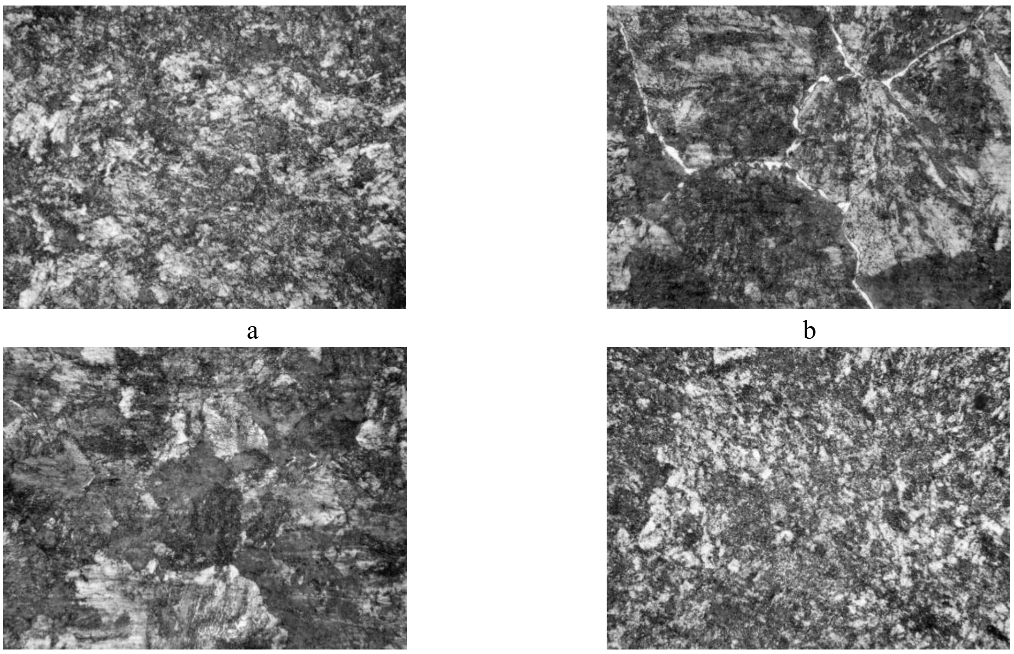


Figure 2. Distribution of the HAZ width along the height of railway rails of type P65 after heat treatment of welded joints

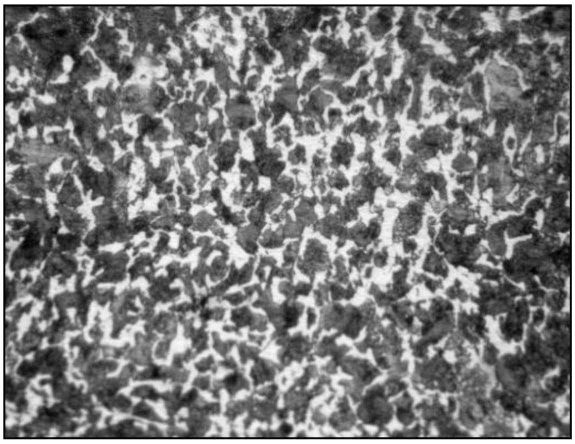
Studies of the metal microstructure have shown that the base metal of the rails at a depth of 25 mm from the rolling surface of the head has a sorbite microstructure (Fig. 3). After welding the rails, the microstructure of the metal along the joint line consists of sorbite with narrow ferrite fringes along the grain boundaries. In the coarse grain zone, located at a distance of 5 mm from the joint line, there is a purely sorbite structure. In the zone of incomplete recrystallization, at a distance of 14 mm from the joint line, there is a fine structure of sorbite in relation to the metal along the joint line. After heat treatment of the welded joints, the metal along the joint line has a sorbite microstructure (Fig. 4). At a distance of 5 mm from the joint line, a sorbite structure with areas of trostite is observed. In the zone of incomplete recrystallization, which after heat treatment is located at a distance of 27 mm from the joint line, there is a fine structure of sorbite. The metal structure in this area is no different from the joints after welding. A similar microstructure is characteristic of the rail neck and sole.



a b

c d

Figure 3. Microstructure (x500) of the metal in the welded joint zone at a depth of 25 mm from the rolling surface of the head: base metal – (a); joint line – (b); 5 mm from the joint line – (c); zone of incomplete recrystallization – (d)



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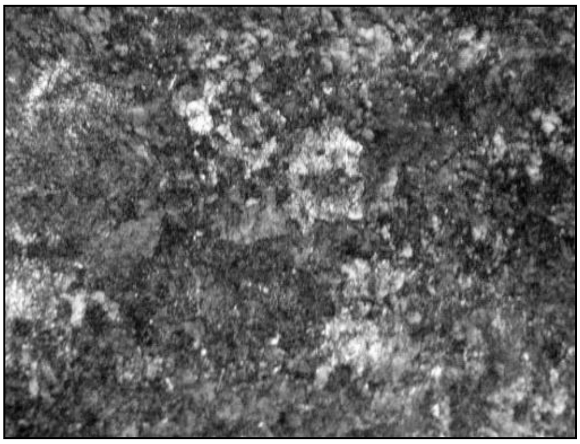
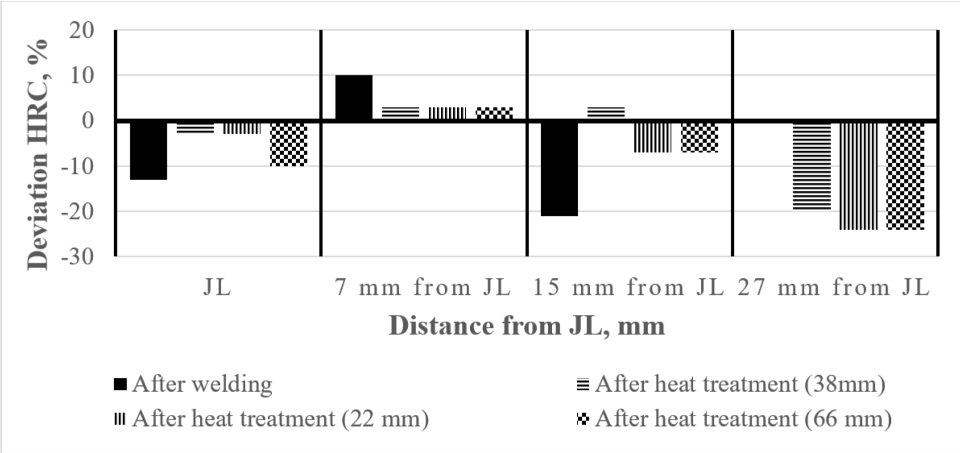


b

Figure 4. Microstructure (x500) of the metal at a depth of 25 mm from the rolling surface of the head after heat treatment of welded joints: joint line – (a); 5 mm from the joint line – (b)

The grain size of the base metal of the rails in all profile elements corresponds to 5–6 points. There are minor areas with a grain score of 7–8. After welding the rails, the grain size along the joint line corresponds to 2–3 points, and in the coarse grain zone at a distance of 5 mm from the joint line – 4–5 points. In the zone of incomplete recrystallization, located at a distance of 14 mm from the joint line, the grain score is 6-7. After heat treatment of the welded joints, the grain size along the joint line and in the coarse grain zone corresponds to 6–7 points in all profile elements of the rails. In the zone of incomplete recrystallization, the grain score is 7.

The hardness of the base metal of the rails at a depth of 25 mm from the head-rolling surface and a distance of 38 mm from the side face is HRC 28…29. The hardness in the center of the neck at a depth of 90 mm from the head rolling surface is HRC 27; in the sole at a depth of 10 mm from the bottom – HRC 29. After welding the rails, the hardness of the metal along the joint line is lower, and in the coarse-grain zone, it is higher than the hardness of the base metal in all elements of the rail profile (Fig. 5). In the zone of incomplete recrystallization, the hardness decreases to HRC 23. After heat treatment of the welded joints, the hardness of the metal along the joint line increases to HRC 28. From the joint line to the zone of incomplete recrystallization, the hardness of the metal is equalized in all elements of the rail profile. In the zone of incomplete recrystallization, located at a distance of 27 mm from the joint line, the hardness of the metal decreases to HRC 21…22. A similar distribution of metal hardness is observed at distances of 22 mm and 66 mm from the lateral face of the head, as well as at distances of 30 mm and 140 mm from the lateral face of the sole.



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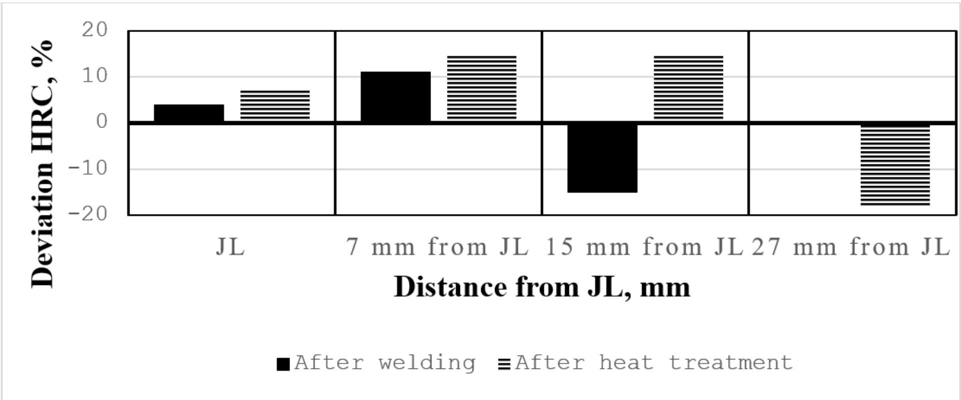

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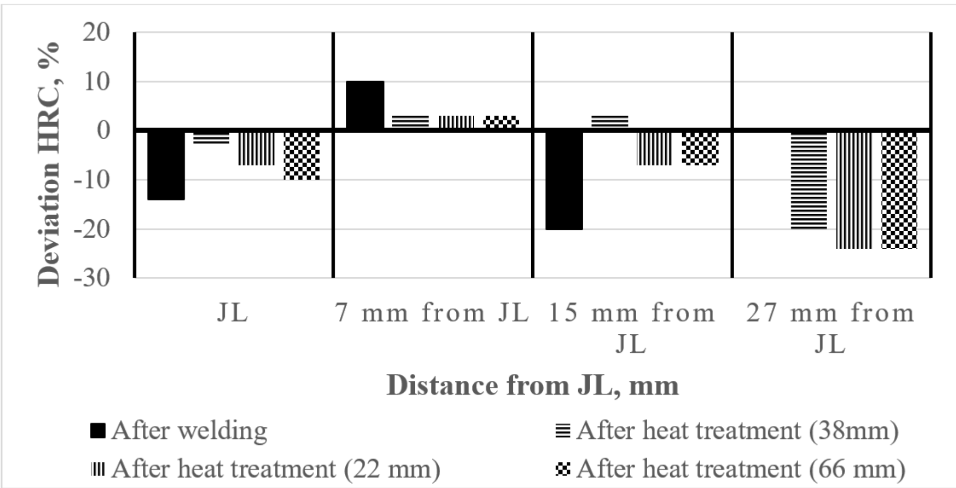


c

Figure 5. Deviation of the metal hardness of welded joints of railway rails of type P65, made by contact butt welding, from the hardness of the base metal of the rails: head at a depth of 25 mm from the rolling surface and at distances of 22 mm, 38 mm, 66 mm from the side face – (a); neck at a depth of 90 mm from the rolling surface of the head – (b); sole at a depth of 10 mm from the bottom and at distances of 30 mm, 140 mm from the side face – (c)

Heat treatment of welded joints of railway rails of type P65, made by the AAWFM method. In the process of heat treatment of welded joints of rails, cooling of the head rolling surface with an air-water mixture to a temperature of 450 °C and subsequent cooling in still air was used (Table 2). The cooling rate of the head-rolling surface increased. The heat treatment mode ensures the same temperature of the rail profile elements with a slight temperature difference between the head-rolling surface and the deep layers of the metal. There is no overheating of the side faces of the sole. However, unlike the process of heat treatment of welded rail joints made by contact butt-welding, the power of the frequency converter and the time of heating the joints to the heat treatment temperature increased.

In welded rail joints made by the AAWFM method, there is a significant uneven distribution of the width of the weld seam and the width of the HAZ in the rail profile elements (Fig. 6). The width of the HAZ in the neck and sole significantly exceeds the width of the HAZ in the railhead. The width of the toe zone in the railhead exceeds the width of the incomplete recrystallization zone. Their ratio reaches 5:1 at a depth of 23 mm from the head-rolling surface. After heat treatment of the welded joints, the width of the HAZ in the railhead increases and the uneven distribution of the HAZ width in the rail profile elements decreases. Some decrease in the HAZ width is noted in the areas of transition from the head to the neck and from the neck to the sole.

Table 2

Heat treatment parameters of welded joints of railway rails of type P65, made by the AAWFM method

Parameter	Parameter value
Joint clearance, mm.	15
Frequency converter power, kW	76…88
Heat treatment temperature, °C	890
The heating rate of the rail head to the magnetic transformation temperature, °C/s;	8.1
Heating time to heat treatment temperature, s	180
Holding time at heat treatment temperature, s	20
Cooling rate of the rolling surface of the head to a temperature of 450 °C, °C/s	4.75
Cooling rate of the rolling surface of the head in still air from a temperature of 450 °C, °C/s.	1.5
Temperature of the side faces of the sole, °C	860…870

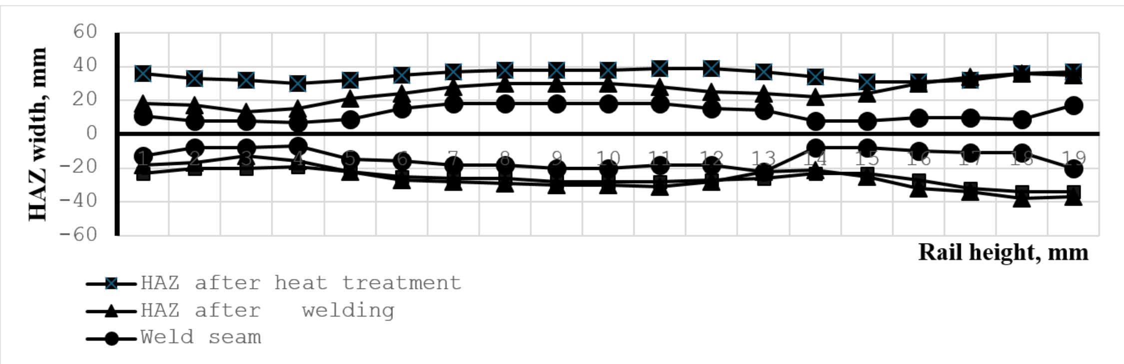


Figure 6. Distribution of weld width and HAZ width in welded joints of railway rails of type P65, made by the AAWFM method with a joint gap of 15 mm

Studies of the metal structure have shown that the base metal in the railhead has a sorbite microstructure and pearlite grains (Fig. 7). There is a slight coarsening of the base metal grain in the direction from the head-rolling surface to the head-neck transition area (Table 3). In the welded joints of the rails, at a depth of 20 mm from the head-rolling surface, coarsening of the metal grain in the circle seam zone is observed. The metal in the incomplete recrystallization zone has a homogeneous sorbite-type structure with trostite areas.

Table 3

Metal grain score of welded joints of railway rails of type P65, made by the AAWFM method

Depth from the head rolling surface, mm	Base metal	Circle seam zone	Zone of incomplete recrystallization
5	8–9	9	7–8
20	8–9	8	8–9
45	8	7–8	8–9

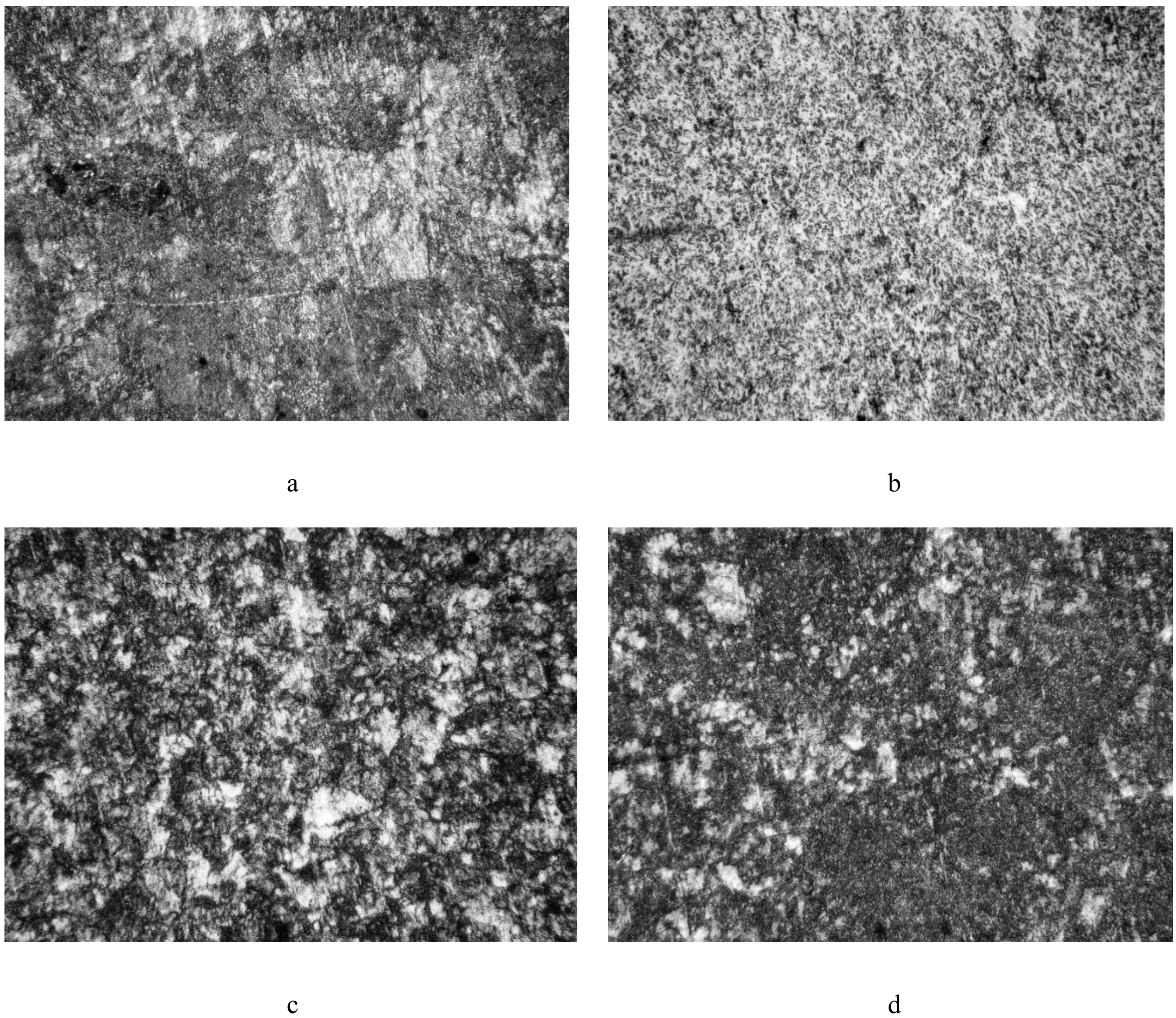


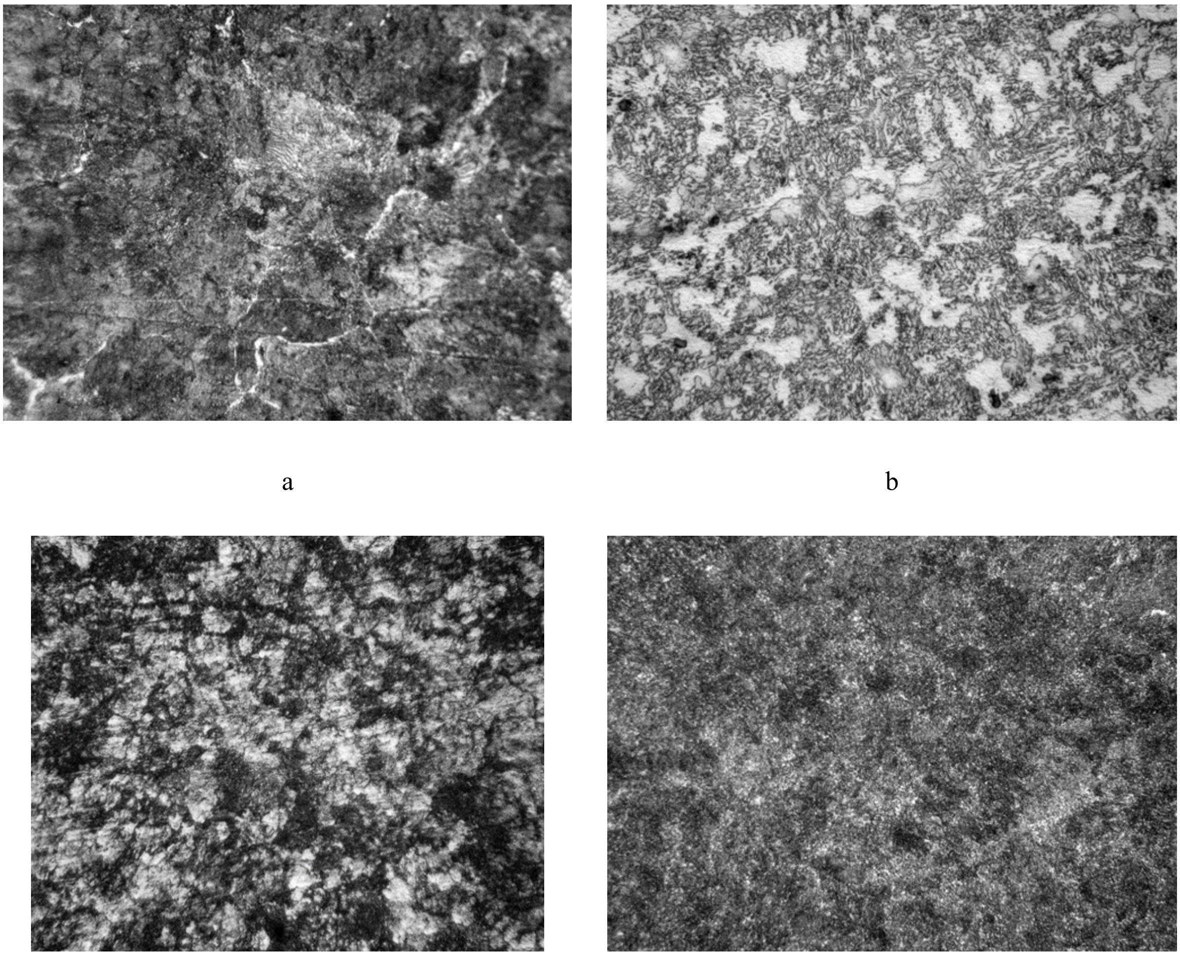
Figure 7. Microstructure (x500) of the metal in the zone of welded joints of railway rails of type P65, made by the ADZPM method, at a depth of 20 mm from the rolling surface of the head: base metal – (a); weld seam – (b); circle seam zone – (c); zone of incomplete recrystallization – (d)

Large grains of the base metal (Table 4) distinguish the rails used for heat treatment of welded joints. After heat treatment of welded joints, the weld in the railhead has a microstructure of the type of ferritic carbide mixture with large areas of ferrite in the center of the weld (Fig. 8). At a depth of 20 mm from the rolling surface of the head, grain crushing is observed in the metal of the head zone. The metal in the zone of incomplete recrystallization has a homogeneous structure of the sorbite type.

Table 4

Metal grain score of welded joints of railway rails of type P65, made by the AAWFM method, after heat treatment of welded joints

Depth from the head rolling surface, mm	Base metal	Circle seam zone	Zone of incomplete recrystallization
5	7–8	8–9	8–9
20	6–7	7–8	8
45	8	7–8	8–9



a b

c d

Figure 9. Microstructure (x500) of a welded joint of railway rails of type P65, made by the AAWFM method, at a depth of 20 mm from the rolling surface of the head after heat treatment of the welded joints: base metal – (a); weld seam – (b); circle seam zone – (c); zone of incomplete recrystallization – (d)

The hardness of the base metal in the head and sole of the rails is HRC 29, in the neck of the rails – HRC 27. After welding the rails, the hardness of the weld metal in the head and neck does not differ from the hardness of the base metal, but in the sole of the rails, it is much lower (Fig. 10).

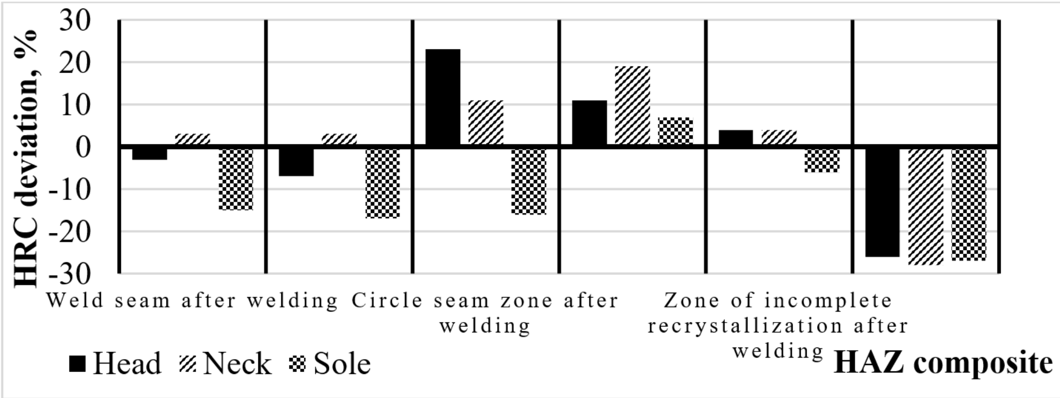


Figure 10. Deviation of the metal hardness of welded joints of railway rails of type P65, made by the AAWFM method with a joint gap of 15 mm, after welding and after heat treatment from the hardness of the base metal in the head at a depth of 25 mm from the rolling surface; in the neck at a depth of 90 mm from the rolling surface of the head; in the sole at a distance of 10 mm from the bottom

The hardness of the metal in the lug zone in the head and neck of the rails is higher than the hardness of the base metal, except for the sole. In the zone of incomplete recrystallization, the hardness of the metal in the head and neck is at the level of the base metal, except for the sole. After heat treatment of the welded joints, the hardness of the weld metal in the head and neck almost does not change, but remains low in the sole of the rails. The hardness of the metal in the lug zone increases in all elements of the rail profile and exceeds the hardness of the base metal of the rails. In the zone of incomplete recrystallization, the hardness of the metal remains low.

4. CONCLUSION

1. Inductors have been created for heat treatment of welded joints of railway rails made by contact butt-welding and welded joints made by the AAWFM method. Heating of welded joints is performed by induction method with currents with a frequency of 2.4 kHz. Inducing wires of inductors repeat the shape of the rail profile and contain magnetic circuits installed above the rolling surface and the side faces of the head, neck and bottom of the sole. Inductors provide uniform distribution of the temperature field in the head, neck and sole of the rails, low temperature difference between the surface and deep layers of the metal. The heating time of welded joints of railway rails of type P65 made of steel K76F performed by contact butt-welding to the heat treatment temperature of 890°C is 160 s. After heat treatment of welded joints, the metal grain is crushed across the entire width of the HAZ. The hardness of the metal across the width of the HAZ approaches the hardness level of the base metal in all elements of the rail profile.

2. The heating time of welded joints of railway rails of type P65 made of steel K76F, performed by the ADZPM method, to the heat treatment temperature of 890°C is 180 s. After heat treatment of welded joints of rails with the use of forced cooling of the rolling surface of the head with an air-water mixture, a decrease in the uneven distribution of the HAZ width in the elements of the rail profile occurs. There is a grain refinement in the structure of the metal of the ridge zone and the zone of incomplete recrystallization, and an approximation of the hardness of the metal of the ridge zone to the hardness level of the base metal.

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ОСОБЛИВОСТІ ТЕРМІЧНОГО ОБРОБЛЕННЯ ЗВАРНИХ СТИКІВ ЗАЛІЗНИЧНИХ РЕЙОК

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Резюме. *Мета роботи полягає у створенні індукторів для термічного оброблення зварних стиків залізничних рейок із використанням індукційного нагрівання струмами частотою 2,4 кГц та дослідженні впливу термічного оброблення на структуру та твердість металу зварних з’єднань, виконаних контактним стиковим та автоматичним дуговим зварюванням ванним способом плавким мундштуком. Індукуючи, дроти індукторів повторюють форму профілю рейок та містять магнітопроводи, що встановлені над поверхнею катання та бічними гранями головки, шийкою та основою підошви. Встановлено, що індуктори забезпечують рівномірний розподіл температурного* *поля в елементах профілю рейок та низький перепад температури між поверхневими та глибинними шарами металу. При термічному обробленні зварних стиків залізничних рейок типу Р65 зі сталі К76Ф, виконаних контактним стиковим зварюванням, час нагрівання стиків до температури 890°С становить 160 с. Показано, що після термічного оброблення зварних стиків, зерно металу подрібнюється по всій ширині зони термічного впливу. Твердість металу наближається до рівня твердості основного металу в усіх елементах рейок. При термічному обробленні зварних стиків, виконаних автоматичним дуговим зварюванням ванним способом плавким мундштуком, час нагрівання до температури 890°С становить 180 с. Встановлено, що в умовах примусового охолодження поверхні катання головки повітряно-водяною сумішшю зменшується нерівномірність розподілу ширини зони термічного впливу в елементах профілю рейок, подрібнюється зерно в структурі металу колошовної зони та зони неповної перекристалізації, твердість металу колошовної зони наближається до рівня твердості основного металу рейок.*

Ключові слова: *рейки, індуктори, індукційний нагрів, зварні з’єднання рейок, термічне оброблення.*