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HEAT TREATMENT OF WELDED JOINTS OF HIGH-STRENGTH RAILWAY RAILS (REVIEW)

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In construction of high-speed continuous welded railway lines the high-strength rails, welded by different methods, have a mass application. With the appearance of high-strength rails with a high carbon content, the necessity of implementation of heat treatment operation of butt welded joints in a cycle of rail section manufacture became urgent. The aim of the presented review is the analysis of problems and forecasting the prospects of nowadays technologies of heat treatment of high-strength rail butt welded joints. Different methods of heat treatment used in industry were considered. Different schemes of heating and cooling of rail weld and their effect on formation of microstructure and mechanical properties of joint metal were analyzed. A review of references showed that the technology of high-frequency current heating with further hardening of a head is the most requested during heat treatment of butt welded joints of high-strength rails. 31 Ref., 6 Figures.

Keywords: *continuous rail track, high-strength rails, butt welded joints, heat treatment, hardness, microstructure, high-frequency currents, defects*

The world experience shows, that the promising development of railways requires the creation of high-speed railway lines. The solution of this task puts forward new requirements to the railway track and its main element: rails and their continuous joining along the entire length of the track.

In the last decade, a tendency to increase the intensity, speed and traffic density on railways is observed in the world, which makes it necessary to increase the reliability and service life of rails and causes a high level of requirements to them as to the hardness, contact-fatigue strength, resistance to formation of contact-fatigue defects and brittle fracture [1].

With an increase in the traffic speed and an increase in the mass of the transported cargoes, the dynamic effect both on the wheel pair, as well as on the railway track is increased. One of the main disadvantages of the link track is the presence of a butt joint. The rail butt joint is the place, where the «break» of the rail line occurs, which, despite the butt cover plates, reduces stiffness and increases deflection. This leads to the fact that when the rolling stock moves through the butt joint, the wheel hits the head of the receiving end of the rail. Shocks and impacts at the joints lead to intense wear on both the running gears of the rolling stock and the rails themselves. As a result of wheel strikes on the oncoming rail, crumpling and spalling of the rail head in the joint zone at a distance of 60–80 mm from the butt gap, fractures of rails across the bolt holes, fractures of cover plates and butt bolts occur [2].

In this regard, there is a tendency in the world to replace the butt bolted joints of railway rails by welded joints. The continuous welded track is free from disadvantages of butt joints and has several advantages [3]:

- saving of metal due to reducing the number of butt joining;
- up to 30 % reduction in the costs for repair of track and rolling stock;
- increase in the service life of the upper structure of the track, as well as the rolling stock due to a decrease in the number of wheel strikes of cars and locomotives at the joint point of rail sections;
- reduction of the main specific resistance to the traffic of trains to 12 % and, in this regard, saving of diesel fuel and electricity for traction;
- reducing the volume of works on the straightening the track associated with deflections in the butt joints;
- absence of rail breaks across the bolt holes, one of the main types of breaks in the link track;
- improving the comfort conditions of passenger travel, reducing noise levels;
- reducing the pollution of the track with bulk cargoes and the environment with dusty cargoes;
- improving the reliability of electric rail circuits of automatic blocking, etc.

Nowadays, high-strength rails of such leading manufacturers as Voestalpine (R350NT, Austria), Nippon Steel (VS-350Ya, VS-350LDT, Japan), Corus British Steel (BS113A, Great Britain), PIETC (U75V, China), Azovstal Iron and Steel Works (K76F, Ukraine), OJSC Nizhny Tagil Metallurgical Plant (E76F, Russia), Novokuznetsk Metallurgical Plant (K76T, Russia) are widely applied. High-strength rails have characteristics of metal strength being 1.3–1.5 times higher than that in ordinary rails (Fig-

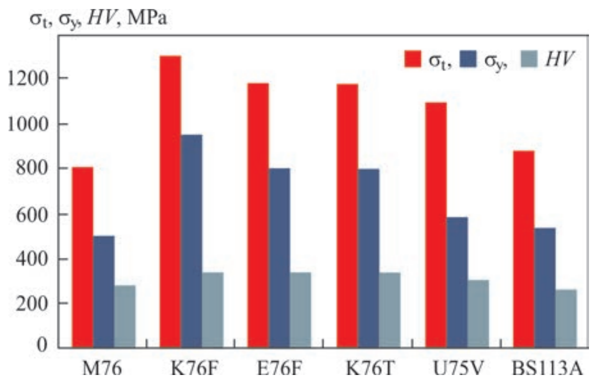

Figure 1. Strength characteristics of rails

ures 1, 2), while the requirements to ductile properties in accordance with standard indices remained at the same level [4]. In the production of high-strength rails, the production technology is used with continuous casting of steel and continuous rolling. Figure 3 shows the distribution of hardness in the base metal of high-strength rails in the vertical plane [5].

High-strength rails have a significant carbon content (0.9–1.1 %) for improvement of wear resistance. In the production of such rails, coarse carbides remain inside the austenite grains, thus reducing the ductility and impact toughness of pearlite structure after accelerated cooling. From the point of view of the structure of rail steel, the increase in its carbon content drastically changed the weldability of such steel. At the present stage of development of equipment for welding production technology, in terms of the main factor of steel weldability, high-carbon steel is close to high-strength medium-alloyed steels with a carbon content of 0.3–0.45 %. The value of indicates of carbon equivalent, calculated by the formula [6] for these steels, is approximately the same — S_{eqv} = = 0.80–1.0 %. Thus, high-carbon rail steels are fair by the quality criterion of weldability, i.e. when it is impossible to provide metallic integrity of the joint without special technological measures and rational modes of welding [7].

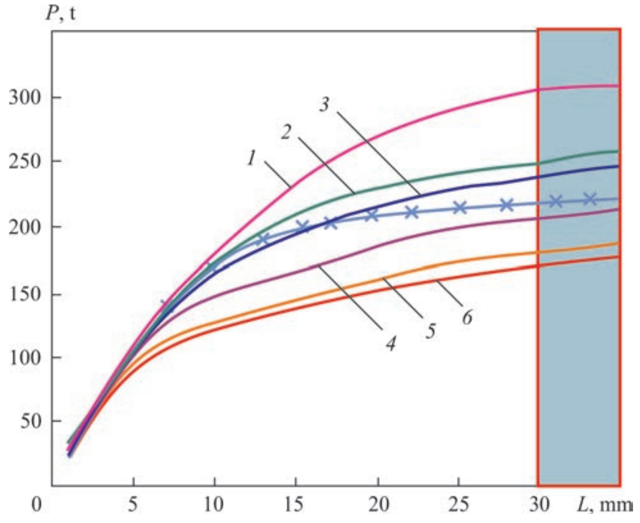

Figure 2. Dependence of loading during testing on static bending from deflection of rail [4]: *1* — NKMK E78KhS (Russia); *2* — NKMK, NTMK E76F, K76F (Russia, 2012); *3* — NKMK, NTMK E76F, K76F (Russia, 2003); *4* — Azovstal KF (Ukraine); *5* — U75V (PRC); *6* — Azovstal M76 (Ukraine)

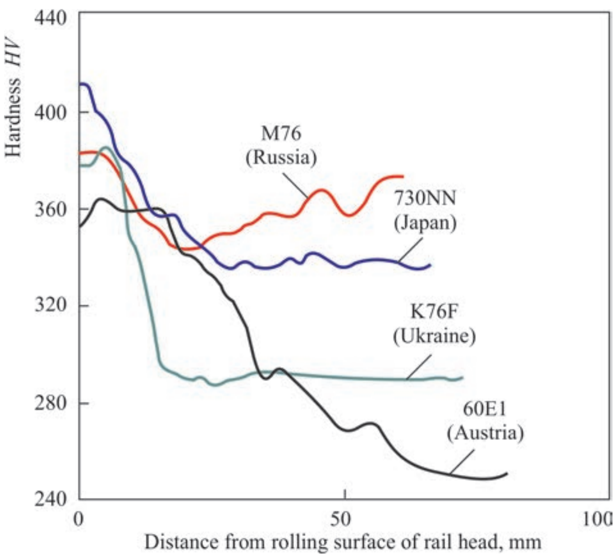

Figure 3. Distribution of hardness in base metal of high-strength rails in the vertical plane [5]

Nowadays, in the world practice, the rails are welded by the following methods during the construction of continuous welded track [8]:

- pressure methods: flash-butt welding, gas pressure welding, induction welding, laser welding, friction welding;
- aluminothermic methods;
- electric arc methods: welding with stick electrodes, submerged-arc welding, shielded-gas welding, electroslag welding, welding with flux-cored wires, etc.

The method of pressure welding is based on heating the rail ends to the temperature of plastic state and their pressing at a certain force. The ends of rails can be heated by electric current, gas torches, high-frequency currents, laser, plasma and heat evolved by friction. During pressure welding a filler material is not used, the ends of rails are welded together. When using pressure welding, the strength and reliability of welded rail joints is primarily determined by the correct choice of welding technology and modes.

Aluminothermic and electric arc methods differ significantly from pressure welding methods by the fact that a weld is 15–25 mm wide, and consists mostly of a filler material, having a cast structure [9]. The quality of welded rail joints and their life also depend on the properties of filler materials.

Among the abovementioned methods of rails welding, the electric flash-butt welding method became the most widely used [10]. This method provides a high quality of welded joint, high process efficiency, high automation and mechanization of the process and availability of a system to monitor welding mode parameters.

For all welding methods the presence of heat-affected zone (HAZ) is typical. The resulting residual stresses in the HAZ metal lead to decrease in strength characteristics of welded joint. The width of the HAZ effect depends on the time of exposure of high temperatures to the base metal, mass of the filler material, method and welding parameters [11].

Every year the number of defect-proof welded rail joints increases, the number of rail breaks in welded joints also increases. These welding defects are observed in recent years when the rails of electric steel are used for construction of a continuous track [3, 12].

The zone of welded butt joints is a weak area of rail track. As practice shows, the number of defects in removed defective rails reaches 30 % in welds at a total weld length of not more than 2 % of rail section length. This is caused by varying homogeneity of microstructure in the regions of the weld and HAZ, as well as by creating an unfavorable residual stress diagram. During welding, the conditions are created for the formation of inner defects, which are stress concentrators and weaken the rail section with a weld, as well as for distortion of the rail in the weld zone with subsequent formation of deflections during service of saddles. Most of the rail defects occur in the head region. In the head, defects in the form of transverse cracks make up 33 %. They occur due to insufficient contact-fatigue strength of the metal, violations of technology of welding rails and inner defects. At the same time, the defects, caused by horizontal delamination of the rail head due to the presence of clusters of nonmetallic inclusions, amount to 17 %. Defects, resulting from vertical delamination of the head because of remnants of shrinkage cavity, are 19 %. The remaining volume of defects is caused by chipping of the layer deposited on the head rolling surface, side wear and crumpling of the rail head in the welded butt joint. Figure 4 shows the location of rail defects in the cross-section [6].

The main disadvantages which reduce the service life of rails are [11]:

- presence of residual stresses in the rail head, which occur as a result of cold straightening operation during manufacture;
- creation of weak areas with a lowered resistance to wear and crumpling in the HAZ after welding and local heat treatment of welds;
- noticeable decrease in impact toughness, crack resistance and critical size of fatigue cracks during hardening from rolling heating as compared to hardening after separate recrystallization heating.

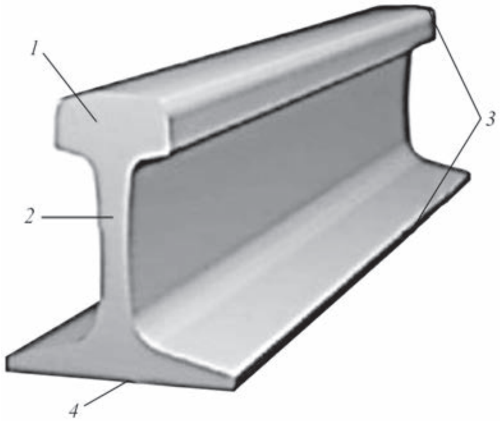

Figure 4. Location of rail defects across the cross-section [6]: *1* — in the rail head (74 %); *2* — in the web (7 %); *3* — other defects outside the joint (16 %); *4* — in the rail flange (3 %)

It is known [13], that a welded joint of rails has a coarse-grained structure and lower values of mechanical properties than the base metal. The metal of a welded joint zone, as compared to the metal of rolled rails differs by lower ductility, toughness and higher tendency to brittle fractures. In welded butt joints of high-strength rails, dips of hardness are observed, including the hardened metal layer of a rail head. In the rails of usual strength, the scattering of hardness in the welding zone varies within a small range of *HV* 10–30, and during welding of rails of increased and high strength, in the joints a significant decrease in hardness (on *HV* 100–150), and accordingly, wear resistance and fatigue limit of metal in the rail head are observed.

In the world practice, additional heat treatment (HT) of rail joints is increasingly used, which minimizes the results of high-temperature heating of high-strength rail steels during the process of welding [14, 15]. Additional HT of a rail joint increases its strength properties and refines the microstructure of a welded joint. The use of HT has a positive effect on service life of a welded joint of rails, since the fatigue strength limit is higher than the strength of a welded joint which was not subjected to HT. Brittle strength and impact toughness of the metal of welded rails is increased after local HT of joints, the increase in resistance to brittle fractures of welded rails of regular, enhanced and high strength increases the reliability of their operation in the track. This is especially important in the mass application of rails from the steels of new grades of continuous welded sections and rails in the regions with a severe climate, in express and high-speed lines [16].

In this regard, the problem of determining the optimal modes of HT of welded joints of high-strength rails is relevant. The solution of this problem will increase the service life and reliability of railway lines.

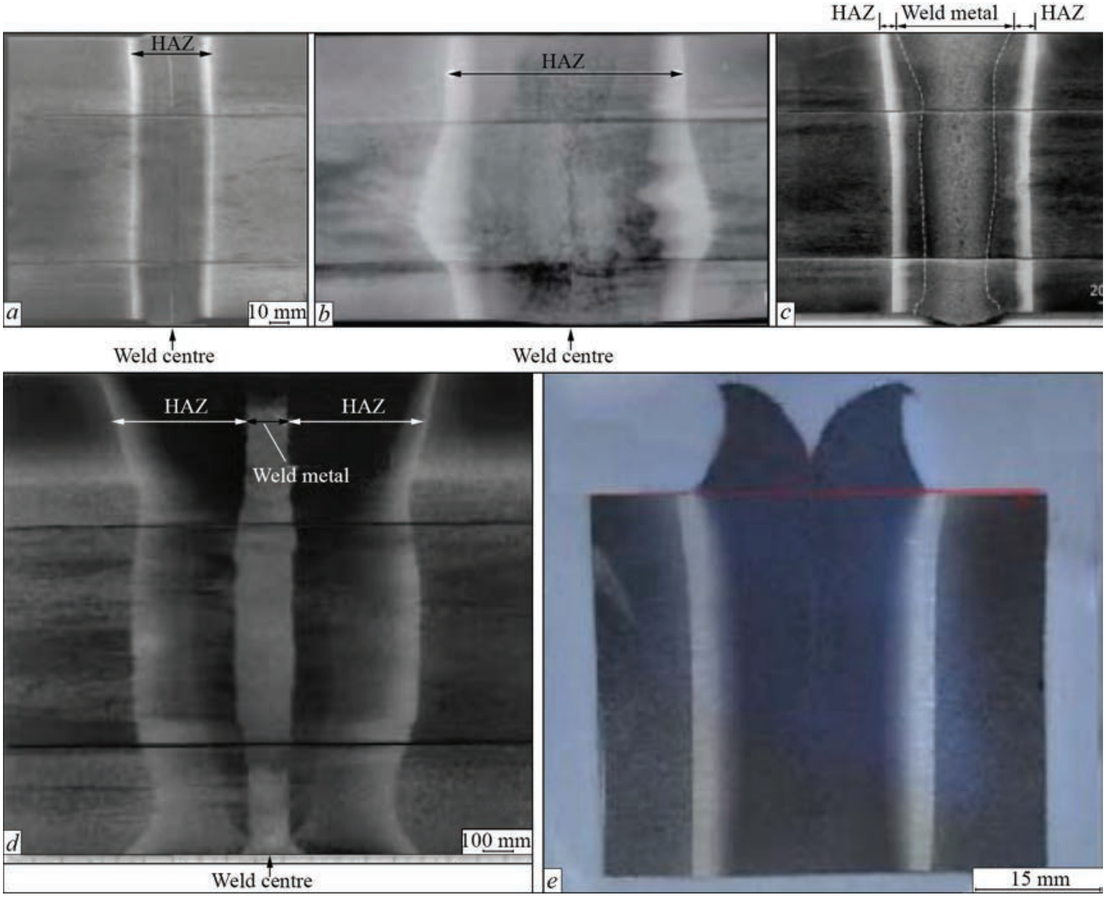

Figure 5. Macrostructures of welded rail joint made by different methods [17]: *a* — flash-butt welding; *b* — gas-pressure welding; *c* — aluminothermic welding; *d* — hidden arc welding; *d* — linear friction welding

The highest designed strength is in the rails with a homogeneous sorbite hardened structure of maximum dispersion with a hardness of *HV* 331–388, or rails with a homogeneous structure of tempered martensite or bainite. The service life of the rails is directly related to their hardness. Such parameters of rails microstructure as the value of distance between plates in pearlite, size of pearlitic colonies, presence of excessive ferrite also have a great influence on the properties of rails. It is known that pearlite structure is formed during diffusion transformation of austenite in a wide range of temperatures: from about 720 to 450 °C and, as a result, it has a different dispersion, estimated by the value of distance between plates, which can vary by more than an order: from about 1.0 to 0.05 µm. Accordingly, the steel hardness and other characteristics of mechanical properties are changed [17].

It is known (Figure 5) that flash-butt welding and arc welding have minimal zones of cast metal and HAZ. The aluminothermic joint has the largest zone of cast metal and HAZ, gas-pressure method has the largest HAZ of rail steel. In linear friction welding, the cast metal zone is minimal, and HAZ consists of several zones.

Figure 6 presents comparative results on distribution of hardness in a welded joint during welding using different methods without and with heat treatment of the joint. It is seen that aluminothermic and gas-pressure welding have a dip of hardness in a larger area of a rail joint as compared to other methods [18].

Nowadays, a lot of works has been carried out to determine the rational technology of HT of rail joints of high-strength rails. In different countries of the world, the technologies of HT of welded joints have a radical difference. In Germany, to conduct the HT after welding a joint, the heating is performed by an exothermic powder, which is poured into the steel clinker, surrounding a welded joint, and ignited, burning of powder occurs at a temperature of 370–430 °C. A controllable cooling of a joint takes about 30 min, providing a complete pearlite transformation. In the recommendations of the Ministry of Rail Roads (India), in flash-butt welding of high-strength rails a controllable HT after welding should be performed. The HT process takes place in an asbestos pipe of 300 mm diameter, a length of 1 m, which is installed on the rail section with a weld and the joint is heated up to the temperature of 850 °C by four kerosene torches with a holding of about 10 min, after which the welded joint is moved to hardening device with a compressed dry air. The specialists of the Austrian Company Voestalpine Schienen GmbH recommend apply

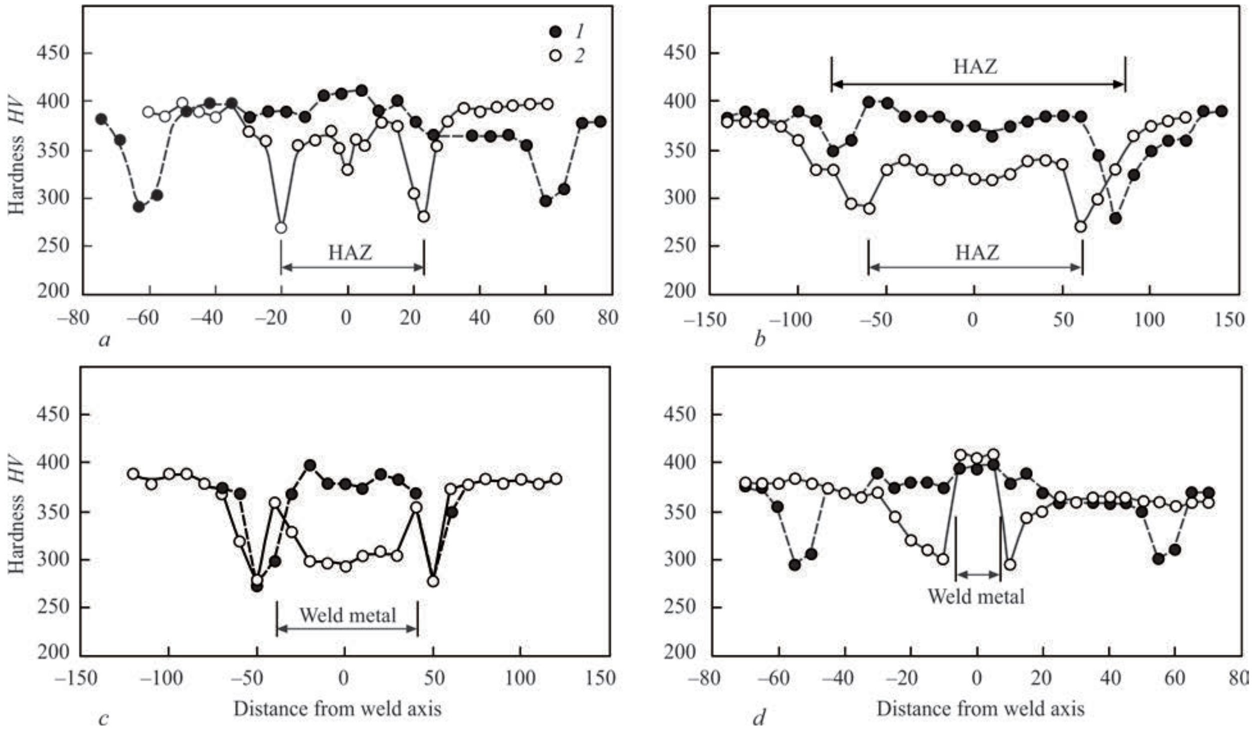

Figure 6. Distribution of hardness in the area of rail welded joint made by different methods [13]: *a* — flash-butt welding; *b* — gas-pressure welding; *c* — aluminothermic welding; *d* — hidden arc welding; *1* — after HT, *2* — welded joint

different HT after welding of high-strength rails of the own production of the type R350HT, R370CrHT, R400HT in the form of subsequent heating of a joint, accelerated cooling holding, etc. In the UK, the works were carried out to determine the optimal heating rate, influence of hardening conditions on distribution of residual stresses in a welded joint of high-strength rails and search for an acceptable cycle time. A welded joint was heated with a different heat flux from 75 to 120 kW/m^2 to the temperature of 650 °C and cooled at different rates from 2–5 °C/s. In the course of investigations it was found that the level of residual tensile stresses can be reduced by rapid heating of a welded joint immediately after welding. The results of accelerated cooling showed an improved hardness distribution as compared to the natural air cooling. The Rail Road Research Institute of Japan developed the technology of gas-pressure welding and HT of high-strength rails. After welding, when the temperature of a joint reaches 600 °C, it is reheated by special torches about 90 s up to the temperature of 1000 °C. Then the cooling by a special hardening device to a temperature of 300 °C occurs. In the USA, there is an experience in the construction of railways, using high-strength rails of Japanese production of hypereutectoid steel HE-X with a carbon content of 1.1 % and a length of 146 m, which are welded into 440-meter sections. Then, the entire welded section is passed through passing-by induction device for HT, which provides a uniform hardness and homogeneity of the structure over the entire length of a welded section. At Qinghua University (China), research was carried out on the effect of HT on welded joints of U75Mn rails. HT was carried out by induction heating of the joint to a normalization temperature of 880 °C and tempering temperature of 600 °C. The research results showed that during normalization, the grain size in the welded joint is changed and the mechanical properties of the metal are improved, and the hardness is increased. At a temperature of 600 °C, the hardness parameters were even lower than those of a welded joint without HT [19–25].

In a number of works, it was proved that it is necessary to use a differentiated HT of welded joints, which consists in hardening of a rail head from repeated recrystallization induction heating of its entire cross-section with subsequent normalization of rail flange and web. As a result, the hardness in a rail head increases as well as the fatigue and brittle strength due to the welded joint metal structure refinement. According to the authors' opinion, the differentiated HT of welded rail joints eliminates the zonal heterogeneity of a weld metal [26].

In the opinion of specialists of Tomsk University (Russia), the technology with hardening using air-water mixture is unreliable, because an unfavorable hardened structure of martensite is formed in the metal of the head of a rail welded joint, exceeding the standard hardness of rail steel, which sharply decreases the resistance of rails to fatigue and brittle fracture. Such structural heterogeneity over the rolling surface of a joint leads to crumbling of these areas of metal [27].

The result of the carried out works on HT of welded joints in induction installations of the type ITSM-250/2.4 of the Russian production with a current frequency of 2.4 kHz is a restored hardness to the level of the base metal strength, moreover, a structure of hardened sorbite is formed in the rail head. The yield and fatigue strength of the metal of welded rails is not lower than that of the rolled ones. According to the authors of these works, to provide the strength and reliable operation of the tracks, HT of welded joints of rails of modern production with a high content of carbon and other alloying elements is obligatory [13, 27].

The Tomsk Company MagnitM developed a method of HT of welded rail joints, based on heating of the welded joint by the optimal scheme of temperature field distribution. This method of HT allows eliminating the self-tempering of the rail head after its cooling. Rail hardening is performed by a forced cooling with a compressed air, which is characterized by a more uniform and stable distribution of hardness at the rolling surface in the welded joint zone than during hardening with an air-water mixture. To carry out HT, an effective design of inductor was developed for heating the installation of UIN-100/RT-P type and different frequency of current of the induction heating source of 8.0–16.0 kHz was used [28].

The authors of the work [29] carried out investigations of the effectiveness of different HT methods. It was determined that the use of one-sided hardening cooling scheme, when the air hardening medium acts only on the rail head, leads to the fact that the joint zone, heated to a temperature above the critical one, sharply reduces the volume during cooling, which leads to its compression. The remaining high temperature in the flange leads to a plastic deformation, which causes the rail deformation and deflection on the flange. To eliminate the negative effect of stress in the rail flange, the authors propose a technology with the applying of a differentiated double-sided scheme of the hardening cooling. The scheme provides the hardening cooling of the rail head and subcooling of its flange to preserve the rail geometry and allows obtaining a favorable diagram of compressive stresses in the head and the flange and compensating tensile stresses in the web. After conducting HT, the microstructure of the weld metal in the rail head and flange is represented by sorbite, and in the web it is represented by lamellar and granular sorbite of a mixed morphology.

According to the author of the work [30], installations of the type UIN-001 have a design with an excessively wide inductor, which in the process of HT leads to an excessive increase in the HAZ, heating time and the effect of high temperatures on the rail metal. Since the rail profile has a complex cross-sectional shape with different volumes of metal, then to have a uniform distribution of the temperature field over the cross-section the specialists of the E.O. Paton Electric Welding Institute proposed to reduce the current frequency to 2.4 kHz and apply a special design of inductors with magnetic conductors. Due to that, a magnetic coupling between the inductor and welded joint is improved, and a uniform distribution of the power input into the heated rail joint occurs. A part of the power, transmitted to the head and to the flange is increased as compared to that to the web, and it is decreased in the rail tongues, thus preventing their overheating. As a result, a uniform heating of the entire cross-section of the welded joint of the rail is provided with the allowable gradient of the temperature field drop. As a result, HT of welded joints positively changed the microstructure of the welded joint metal; the hardness was uniformly distributed across the HAZ width.

Different modern equipment, developed for the process of HT of welded joints of rails, allows carrying out HT process in the form of a single technological operation in one and the same induction equipment for various steel grades and different types and sizes of rails. This is provided by a rational choice of heat treatment mode.

Some recommendations exist as to conducting HT of welded joints of high-strength rails. At induction heating of a joint treated below the critical point A_1 (690–730 °C) and a significant holding at this temperature, recrystallization and partial growth of grain sizes can occur. At such a holding, the carbides formed during welding can again dissolve in the ferrite matrix. At the same time, a slow cooling again promotes the formation of such carbides, which can lead to a decrease in the service life of rails. Therefore, during induction heating of rail steel it is recommended to perform a quick heating to a maximum temperature above the point A_1, with a minimum holding or without it, and to cool rapidly to the temperature of 600–650 °C. In this case, sorbite-shaped pearlite is formed with a degraded ferrite network, at the same time fine cementite dissolves in the ferrite matrix, which increases the weld hardness. In case of rapid cooling of steel, containing 0.71 % of carbon, in the temperature range $A_1 < T < A_3$, the austenitic grains transform into martensite and a hardened rail joint is formed. As is known, martensite has a high hardness and at the same time high brittleness. A slow cooling of <10 °C/s from the annealing temperature to A_1 and a forced cooling with compressed air to a temperature of 510–420 °C can form a bainite structure, which has a high strength and impact toughness, but the hardness of such a structure turns out to be higher than the standard hardness of rail steel [31].

It can also be said that the development of railways follows the path of construction of high-speed and cargo-intensive main lines, which make the operating conditions of a railway more severe and require the improvement of quality of both the rails themselves, as well as their welded joints. Manufacturers maintain trends to increase the carbon content in rail steel, develop new rail alloying systems and HT technologies, which improve their operational properties. To reduce damages of the rails, it is necessary to provide high hardness, wear resistance, contact-fatigue strength of the head metal and at the same time the plasticity and resistance to alternating loads in the web and flange. This review shows that despite great successes in the field of HT in improving the reliability of rail welded joints, the existing HT technologies do not provide a sufficient stability of service properties and do not fully allow obtaining the required operational characteristics of rail welds. Therefore, it becomes necessary to carry out further investigations and study the kinetics of phase transformations in a rail welded joint in the process of heating and cooling during HT, which will help to solve the specified problem. For today in the world there is no single established opinion on the performance of HT technological process by a number of parameters: heating source, power, type of hardening medium, temperature and time factors for welded joints of high-strength rails, with similar weight and geometry parameters. At HT there is no clear definition of the effect zone at HT, which, in turn, depends on the method of making welded joint of railway rails. Preferred are the methods for making welded joints with a minimum width of the HAZ, such as flash-butt welding of rails and subsequent HT of welded joint.

A widespread application in conducting HT of welded joints of high-strength rails was obtained by the method of high-frequency current heating, which has several advantages as compared to other methods. This method allows controlling the heating process, being controlled in terms of the required amount of energy input, including also at a certain metal depth, provides a more uniform heating of welded joint across the entire cross-section, reduces the heating time, and consequently, the effect of high temperatures on the welded joint metal. It should be noted that in the literature, the influence of the modes of induction heating and cooling on the structure of rail steel as well as the effect of the formed structure on the service life are almost not analyzed. Indeed, the cooling forms to a greater extent the structure of the metal and its properties.

One of the limiting factors for spreading of the technological process of HT with the high-frequency current heating of welded joints of railway rails is the complex process of determining the shape and design of the working member, i.e. inductor, which should meet all the requirements of the technological process of HT. The shape and design of the inductor depend on many characteristics: geometric (complex cross-sectional shape of rails, mass and dimensional indices of the components of a rail parts: heads, webs, flanges), electrical (operating frequency, electromagnetic parameters of the system), thermal (heating rate, holding time, cooling rate, distribution of heat fluxes in the complex geometry of metal volumes in the zone of welded joint and base metal), as well as the places of conducting HT of welded joints of railway rails (rail welding enterprise, field conditions, repair).

In this regard, an urgent task is to create a new complex of equipment for HT, which will meet the modern requirements to the determination of the optimal modes of HT of welded joints of high-strength rails to improve the life and reliability of railway lines.

In conclusion, let us note that the existing technologies of HT of welded joints of high-strength rails need further investigation of the process, as far as at the present stage the existing HT technologies do not fully provide a sufficient homogeneity of properties of welded joint and base metal.

Moreover, it is necessary to carry out further investigations on the effect of heating rates, holding and cooling time on the features of structure formation by controlling the thermal cycle modes in the temperature range of phase transformations and the effect on structural fraction of phase components in a welded joint, which determine its reliability and life.

The width of the zone of influence at the HT of welded joint is also not accurately determined. When studying the HT process, it is necessary to determine such a zone, which would maximize the homogeneity of welded joint with base metal of a rail and reduce its sensitivity to stress concentrators.

To solve the general problem, it is necessary to take into account the complex cross-sectional shape of welded rail and distribution of heat fluxes in the welded joint metal and along the rail axis. The application of methods of physical and mathematical modeling is important to determine the required heat fields, electromagnetic parameters of the system and phase transformations at HT of rail welded joint.

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