metals

Article

Study of Melting Methods by Electric Resistance Welding of Rails

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Abstract: An analysis of the results of rail operation shows that up to a third of all rail breaks in the railway line and up to 12.9% of all withdrawn acute defective rails are associated with welded joints. This is largely explained by the formation of structures with martensite sections in the welded joints of rails and the formation of burns. This work presents the results of studying welded joints, obtained under three welding modes (continuous flash welding, pulsating flash welding and combined flash welding). The conducted studies have shown that the flash welding mode significantly influences both the cooling rate value and the very nature of the thermal cycle of the welded joint as a whole. Changes in the cooling rate under different modes exert a significant influence on the structure and properties of the weld. Resistance welding of rails from the steel grade E76HGF by pulsating flash welding can result in the appearance of needle martensite areas, which is the reason for increased embrittlement of the weld and a decrease in its properties. The conducted field experiments have reliably shown that in the conditions of the combined welding mode it becomes possible to avoid these problems. Moreover, a slight increase in the mechanical properties of the weld in the range of 2–4% has been experimentally recorded, and the destructive load of the welded joint of the rail increases by 2–3% at high values of the bending deflection. In turn, these factors allow a significant reduction in the number of cases of rail welded-joint failures in real conditions of their operation.

Keywords: rails; welded rail joints; martensite; lamellar pearlite; hardness; microhardness; impact hardness

1. Introduction

At present, the current stage of development of the entire rail track complex of the Russian Railways (OAO (RR)) is characterized by an increasing spread of progressive technologies for the repair and maintenance of railway tracks, high-performance track equipment, and the introduction of more efficient track designs, which include a continuous welded rail track. The main direction of strengthening the track superstructure is the replacement of bolted joints with welded ones. The strength and reliability of the rails welded by the contact method is determined by the correct choice of the welding technology, thermal and mechanical treatment of welded joints [1]. At the same time, welded joints remain the weak link of the continuous welded rail track; welded joints account for 12.9% of all the rails, removed in a single order, including 27.1% of all the cases of rail failures in the railway lines. Local irregularities in the area of welded joints constrain the possibilities for increasing the travelling speed of passenger and freight trains.

In conditions of increasing freight traffic density, speed and axle loads, high demands are placed on the quality of rail steel of both domestic and foreign manufacturers [2].

The conducted analysis of the existing welding technologies and heat treatment of welded joints revealed their significant disadvantages, related to the formation of structures with martensite sections in the welded joints of the rails made of low-alloy steels. Another disadvantage is the formation of burns in the places of contact with welding machine electrodes and appearance of two new zones of thermal influence during local heat treatment of welded joints. This leads to the fact that up to a third of all rail failures in the railway line and up to 12.9% of all the withdrawn defective rails are associated with welded joints. In this regard, serious requirements are imposed on the welded joints of rail bars laid in the main track, ensuring the quality along the plane of the joint of the welded joint and the complete absence of welding defects. Defects formed during the welding and processing of a welded joint, even of insignificant sizes, can be a spot of the origin and further development of fatigue cracks [3]. A failure of the welded joint of the rails threatens traffic safety; therefore, special attention is paid to the quality of the welded joint, its reliability and durability [4].

The construction of high-speed railways is currently actively underway, where the rails of the P65 type manufactured by EVRAZ ZSMK and PAO ChMK are widely used in the track superstructure. Based on this, at present, the method of resistance welding of rails, which is used in both stationary circumstances and in the field, has become the most widespread in the rail welding industry. This method allows regulating and conducting flash welding at maximum useful power during the welding process [5]. The method of resistance welding is more economical and technologically advanced, as it allows for control of the largest number of technological parameters directly in the production process [6,7].

Innovative stationary rail-welding machines are currently used for welding the rails of the P65 type at rail-welding enterprises, in which the welding process is carried out in continuous and pulsating flash welding. The most promising method for welding rails is the resistance welding by pulsating flash welding. For the first time, this method was applied in 1997 at switch plants for welding switch parts [8]. Owing to new computer control systems and high-speed hydraulic drives, modern contact machines, for welding rails in RSP stationary technological lines of the K-1100, K-1000, MSR 63.01, MSR 63.01A types (Figure 1) and for operating as part of track rail-welding machines (TRWM) of the K-900, K-922, MSR-8001 and MSR-12001 types, are able to operate in the flash welding mode [9,10].

With all the positive effects of pulsating flash welding during contact welding of rails on the welded joint quality, it is necessary to take into account the fact that the metal heating degree and the nature of heat and deformation distribution in the product depend on the structural and phase transformations, mechanical, technological and service properties of welded joints. At the same time, if the cooling rate exceeds the critical rate, the formation of hardening structures in the heat-affected zone (HAZ) is inevitable. Hardened structures are prone to crack formation.

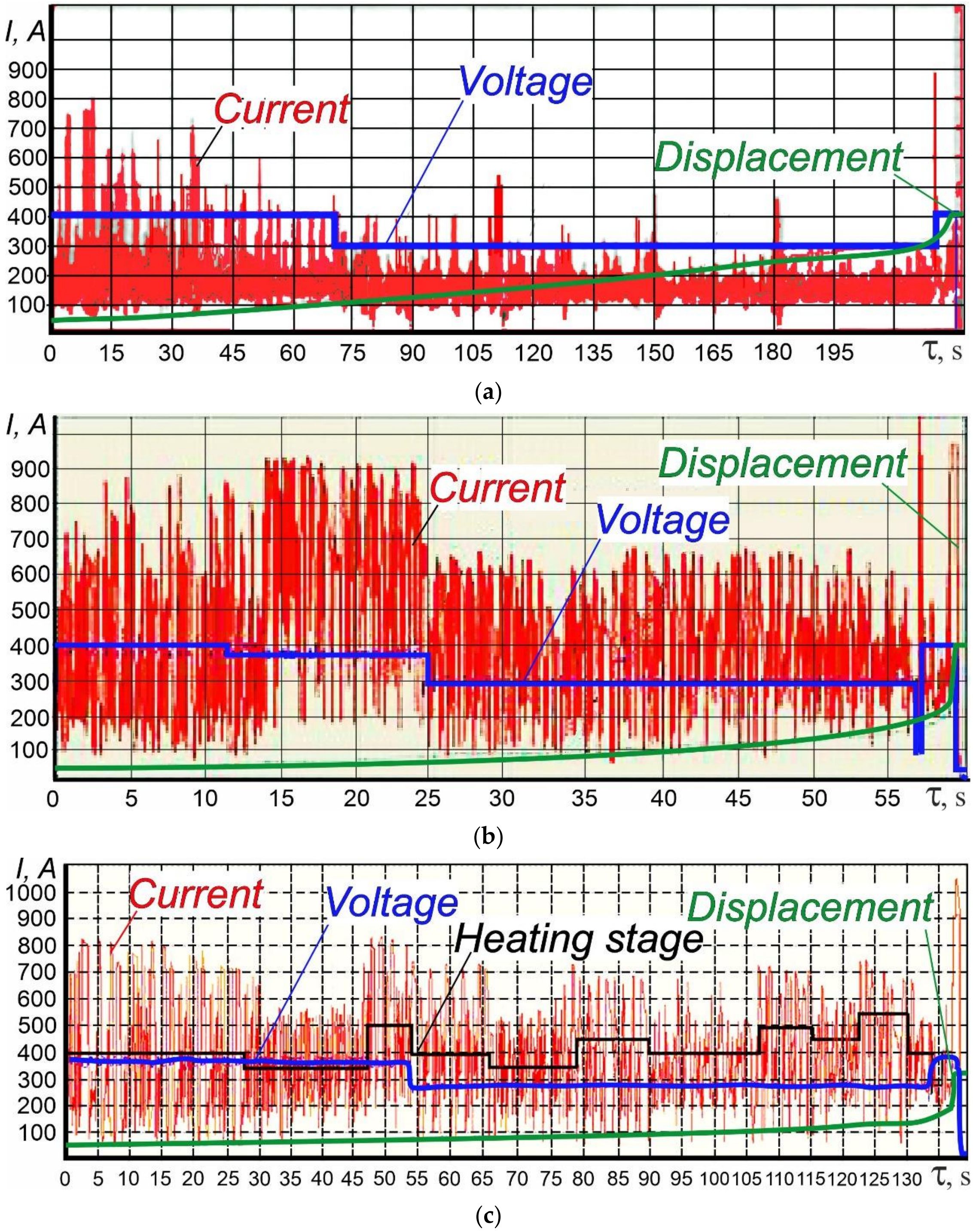


Figure 1. Oscillograms of the recording of the main welding parameters: average values of current, voltage and displacement. (**a**) continuous flash welding; (**b**) pulsating flash welding; (**c**) combined flash welding.

In contact welding, the main factors affecting the quality of the welded joint are the temperature in the heat-affected zone (THAZ) and the pressure at the stage of metal deformation (settling–deformation of the metal in a plastic state). It can be assumed that at any temperature, there is the pressure that ensures the production of a welded joint [5], and lower compression forces correspond to higher temperatures. At the melting point of the metal, the pressure required for welding equals zero, the elements of the parts are connected spontaneously without external influence, but solely due to the liquid phase formation. Pressure welding in this case turns into fusion welding. On the other hand, pressure welding can be performed without using supplementary heating, i.e., at ambient temperature. In this case, the connection is made by cold welding. During cold welding, maximum compression pressures are applied.

However, in the circumstances when it is necessary to weld large-section parts, especially from hard and low-plastic metals and alloys (carbon and alloy steels, bronze, brass and others), so-called thermal and press welding methods are used, such as: gas-pressure welding; vacuum welding; friction welding or contact welding. With all the thermal and press welding methods, relatively low compression forces are applied during significant heating of the welded elements of the part at the junction.

The experimental studies show that with each method of thermal and press welding and with each material being welded, there is a certain narrow temperature range within which, at a certain pressure and the corresponding amount of plastic deformation, the welded joint of high quality is obtained with high values of mechanical characteristics. Beyond this interval, at any values of pressure and deformation, it is either very difficult or impossible to obtain a good joint. The most important value is the temperature corresponding to the lower boundary of the temperature range under consideration. This temperature at a certain compression pressure and the amount of plastic deformation is the energy threshold [11], overcoming which is necessary to obtain a high quality welded joint.

According to A.S. Falkevich [12], the permissible temperature range of good weldability of carbon steels is in the range of 1200–1500 °C.

At the same time, welding is accompanied by a complex of simultaneously proceeding processes, the main one of which is the thermal influence on the metal in the heat-affected zone. The metal structure in this zone changes according to the thermal cycle of heating and cooling and depends on the chemical composition of the base metal and its previous heat treatment.

The metal softening in the HAZ after contact welding of rails can lead to uneven wear during operation and increases the likelihood of brittle damage [13,14].

Therefore, in the welded joint area, the head metal hardness should correspond to the hardness of the base metal to prevent local increased wear when operating the rail track.

To increase the hardness level in the head and fatigue strength of the welded joint metal of the rails after their welding on rail-welding trains and on the way, local heat treatment of welded joints is performed [15].

For example, the Japanese companies Nippon Steel Corporation (Yawata, Japan) together with Mitsui & Co. Ltd. (Tokyo) constantly work in the field of improving the technology of welding and heat treatment processes [16]. At the present time, in Japan, welding is carried out by several methods. The 200-m rail bars from 25 and 50-m rails at stationary enterprises are produced by the methods of contact flash-butt welding (FBW) and gas pressure welding (GPW) of rails.

In addition, methods of aluminothermite (Termite Welding (TW)) and electric arc welding (Enclosed Arc Welding (EAW)) are used in the manufacture of 1500-m rail bars.

In Switzerland, the Schlatter and Windhoff companies are working on improving the technical characteristics of stationary and suspended rail-welding machines. The machine has been developed in combined operation with an AMS 100 suspended rail-welding machine, which is able to move by road and rail.

The developed equipment and technologies allow for the production of welded plates with high productivity. Howeverm at the same time, one of the main problems of such production from low-alloy steels is the instability of the results when testing control samples for three-point bending. Such tests are carried out after welding by continuous (NO) and pulsating (PO) flash welding without local heat treatment of the welded joint. In comparison with the technology of manufacturing welded rails of the Russian production, when welding rails of the European production, a mandatory requirement has been introduced for local heat treatment after welding rails with a pulsating flash welding method. This allows eliminating the disadvantage associated with the formation of a layer with separate martensite sections on the spot of micro-volumes with an increased content of chromium, nickel and carbon. The method of continuous flash welding, during which a long technological heating process takes place, leads to an increase in the linear magnitude of the heat-affected zone (HAZ). This exerts a negative influence on the structural strength of the welded joint [17–19].

The work is devoted to solving the problem of improving the performance of welded rail bars by improving welding by flashing and heat treatment. Now, there are a very large number of defects in the rails throughout the railway network precisely because of violating the hardness of the welded joints on the surface of the rolling rails (crumpling, flaking, destruction of weld seams). The relevance of the chosen topic is conditioned by the need to ensure the transportation safety and trouble-free operation of railway transport. This is determined by the reliability of welded joints in long-welded rails.

In view of this, the purpose of this work is to prepare recommendations for improving the rail welding technology based on the results of the conducted tests. To achieve this purpose in the work, the authors tried to solve the following tasks:

- construction of temperature fields of the weld seam for three welding modes of rail joints;
- investigation of the structure of welded joints after continuous flash welding, pulsating flash welding and combined flash welding;
- investigation of the mechanical properties of welded joints after continuous flash welding, pulsating flash welding and combined flash welding.

2. Methods and Materials

In this article, rail steels E76HGF and E78HSF were taken as the study material. These steels are widely used for the manufacture of rails. In the first stage of experimental work, we welded rails from these steels in various modes (continuous flash welding, pulsating flash welding, and combined flash welding) and plotted cooling curves. In the second stage, samples were obtained for microstructural and mechanical tests during rail welding in the modes of continuous flash welding, pulsating flash welding and combined flash welding.

2.1. Chemical Composition of the Studied Materials

The work analyzes the welded structures made of E76HGF and E78HSF steels. The chemical composition of the used materials is shown in Table 1.

Table 1. Chemical composition of steel.

Steel Grade	**Content, %**							
						P	**S**	**Al**
	C	**Mn**	**Si**	**V**	**Cr**	**Not More Than**		
E76HGF	0.73	0.83	0.37	0.06	0.75	0.017	0.007	0.0003
E78HSF	0.69 0.83	0.70 1.10	0.28 0.62	0.05 0.15	0.35 0.85	0.030	0.025	0.005

The initial material was identified using an optical emission spectrometer ARL 3460.

2.2. Welding Equipment and Welding Modes of Rail Joints

The joints, welded by the contact method from rails of the DT350 category according to GOST R51685-2013 manufactured by PAO ChMK (Chelyabinsk, Russia) and EVRAZ ZSMK (Moscow, Russia), were used as the main objects of the study.

Butt-seam contact welding of the workpieces was carried out using a K-1100 machine (ELEKTROTERMOSVAR, OAO, Moscow, Russia). The technological parameters included the rated voltage of the supply mains of 380 V; nominal frequency of 50 Hz; upset force of 770 kN; linear settling of 16 mm; preliminary settling rate of 0.1–0.3 mm/s; initial settling rate of 25–30 mm/s; settling duration of 3 s. The cross-sectional area of the workpieces with the rail profile was 12,000 mm^2.

To obtain samples, we used three welding modes: continuous flash welding; pulsating flash welding and combined flash welding. To understand the difference between these modes, in Figure 1 we have shown oscillograms of the recording of the main welding parameters: average values of current;, voltage and displacement.

2.3. Analysis of the Sample Microstructure

After forming the welded structures to perform structural studies, metallographic specimens were made from the samples, obtained using conventional technology. To identify the carbon steel structure, a 3% solution of nitric acid in ethyl alcohol was used. The surfacing layer structure was detected by means of a solution of HNO_3 and HCl acids contained in a ratio of 1:3. Structural studies were carried out using a Carl Zeiss AxioObserver Z1m light microscope and a Carl Zeiss EVO 50 XVP scanning electron microscope (Jena, Germany). The phase composition was studied using an ARL X'TRA (Thermo Fisher Scientific, Waltham, MA, USA) X-ray diffractometer in the CuKα radiation.

To identify defects in the welded joints, the following methods were used: a visual-optical method using a Carl ZeissAxio Observer A1m microscope; a capillary method; an eddy current method using a VD–70 eddy current flaw detector.

2.4. Mechanical Testing of the Samples

The microhardness of the materials was assessed using a Wolpert Group 402 MVD device (Bretzfeld, Germany). The load on the diamond indenter was 0.98 N. The hardness of the samples, obtained in the work, was measured by the Brinell method in accordance with GOST 9012.

The resulting welded joints were held under normal conditions for 72 h. Uniaxial tensile test samples were cut from the joints in the transverse direction so that the welded joint was located in the center of the working part of the sample. Uniaxial tensile tests were carried out using a universal testing machine UTS-110M-100 with a pick-up movement rate of 10 mm/min.

Impact bending tests along with determination of impact toughness values were performed on the samples with a U-shaped notch in accordance with GOST 9454-78 using a KM-5T pendulum copra.

The experimental research results were statistically processed in the Statistica, Table Curve 2D and Table Curve 3D software.

For each value (each point on the diagram), tests were conducted for at least 5 samples.

2.5. Plotting Cooling Curves of the Samples

To obtain information on the thermal cycle and its influence on the metal structure, a technique for measuring temperatures in the heat-affected zone during welding was developed. The temperature was measured directly in the metal deformation zone. The dimensions of the assumed heat-affected zone vary under different modes in the range from 10 to 30 mm from the center of the seam, which corresponds to the maximum distance of the thermocouple installation. Since it was not possible to measure the temperature in the seam center, the temperature data in this zone were measured by means of a thermal imager of the SDS HotFind-D model. To measure the temperature of the metal, CA (chromel–alumel) thermocouples are used. The standard calibration of CA thermocouples was provided in accordance with GOST 3044–84 (ST CEV 1059–85). Thermocouples were made of thermoelectrode wire 0.1–0.5 mm in diameter by soldering (when using a protective quartz cap) or by twisting (when measuring with a naked joint). Quartz straws were used to isolate thermoelectrodes from each other (0.5–1.0 mm in diameter), two-channel corundum and porcelain tubes (the outer diameter was 3.5 mm). The data, obtained from the thermocouples, were recorded and statistically processed using the WeldingTemp measuring complex, whose microprocessor modules allow measuring an analog signal in the range from 15 mV to 2.5 V. The functioning and regulation of the measuring complex were carried out by means of the developed software under Windows 7/8/10/11. The technical capabilities of the measuring complex allowed for the collection, registration and storage of analog signals on the hard disk of a personal computer with a scalability of up to 2048 channels. At the same time, depending on the research tasks, the software allowed for conversion of the obtained data array into a graphic image at the end of the measurement process. The SDS HotFind-D thermal imager allows measuring temperatures up to 1500 °C. The thermal imager was equipped with an uncooled microbolometric matrix in the focal plane of the lens with a resolution of 160 × 120 pixels. The video image of the thermograms was transmitted to a personal computer using an analog signal capture board in the NTSC format with a frequency of 60 Hz.

3. Factors Affecting Electric Resistance Welding in the Metal Plastic State

The distribution of temperature fields in the zone of metal deformation (ZMD) and heat affected zones (HAZ) is the main factor determining the quality and mechanical properties of the welded joint of electric resistance welding of rails. Figure 2 shows thermal cycles at various melting methods during electric resistance welding of E76HGF steel rails.

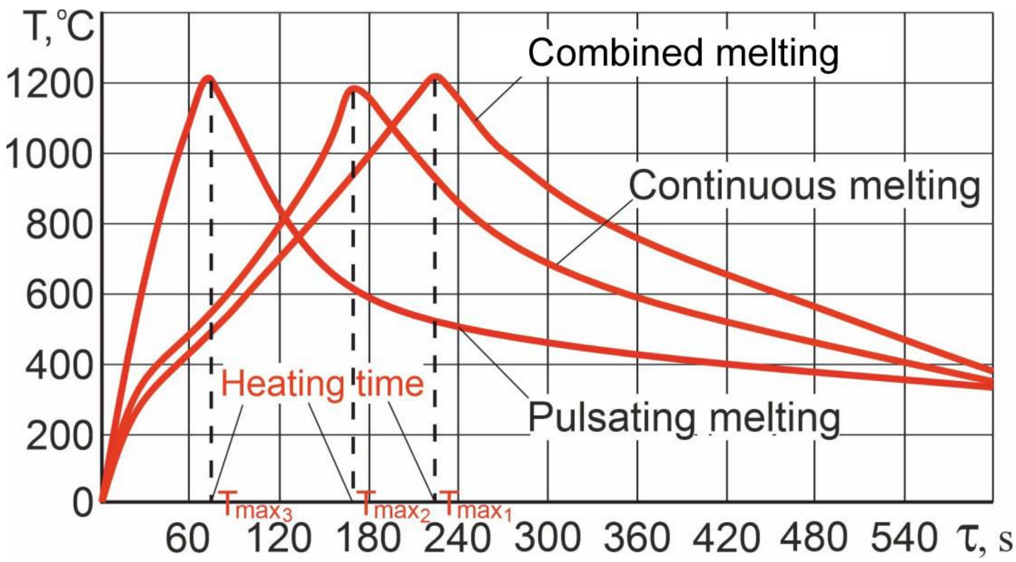


Figure 2. Thermal cycles using different methods of flashing contact welding of rails.

The work carried out on the construction of cooling curves for three welding modes showed the dependence of thermal cycles on the intensity of heating in the welding process.

The method of continuous melting, where the heating process lasts about 170–240 s, increases the length of the heat affected zones (HAZ), which negatively affects the structural strength of the welded joint. However, the cooling curve becomes gentler, which eliminates the possibility of forming quench structures in the HAZ.

Intense cooling of the metal in the HAZ occurs with rapid heating, which is provided by pulsed or pulsating melting used in the control algorithm on modern rail-welding machines. When welding with heating from 70 to 130 s, the cooling curve has a steeper shape due to the fact that the heat does not have time to propagate along the length of the rail. At the same time, it is possible to form high-strength sections with the martensite structure, especially in microvolumes with a high content of chromium, nickel and carbon.

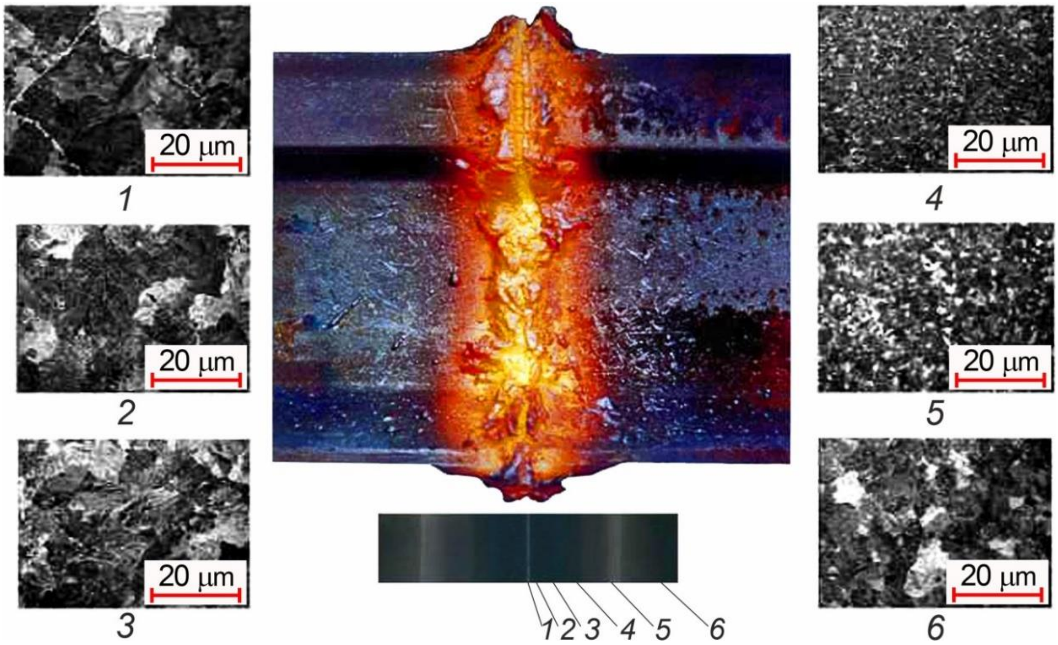
The combined heating method has a gentler cooling curve compared to continuous and pulsating melting, but the long heating process, about 230–340 s, and the uneven heating of the heat-affected zone deteriorates the mechanical properties of the welded joint.

The use of the combined heating would be more effective in a combined form when welding rails by melting with preheating under low temperatures.

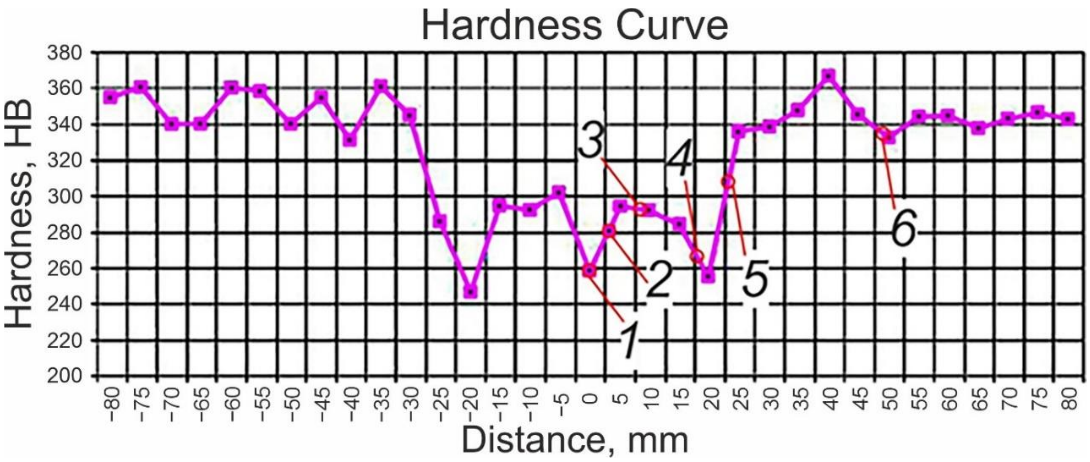
It can be assumed that when welding rails using continuous and pulsating melting, thermal cycles will have a similar character, but with different cooling rates.

3.1. Structure and Properties of the Welded Seam of Rails Obtained under Standard Conditions

Thermal cycles of various layers of the welded zone, distant from the weld seam boundary at different distances, have different characteristics, which is the reason for the formation of the welded joint in the form of an aggregate of layers with a heterogeneous structure and mechanical properties (Figure 3). Figure 3 shows the structure of the welded rail of the E76HGF steel in the mode of pulsating flash welding and presents the hardness values for the zones of different distances from the center of the seam. The pulsating flash welding mode is the standard mode used for welding rails according to the regulatory documents of LLC RZD companies (Russia).



(**a**)



(**b**)

Figure 3. Macro- and microstructure in pulsating flesh welding (**a**), hardness distribution of the welded joint of rails; (**b**): 1—weld seam; 2, 3, 4, 5—zones of incomplete metal melting, respectively, formation of a fine eutectoid mixture of pearlite and cementite after overheating, formation of a fine eutectoid mixture of pearlite and cementite without overheating of high tempering; 6—base metal.

The microstructure of welded joints along the length is divided into six zones:

1. The 0.5–1 mm wide seam is characterized by a light decarbonized bend and the transverse rotation of fibers;
2. In the zone of incomplete melting of 1–1.5 mm wide metal, low-melting accumulations and looseness are possible;
3. The zone of the finely dispersed eutectoid mixture of pearlite and cementite after overheating, 10–15 mm in thickness, is formed as a result of overheating and recrystallization (formation and growth of grains due to initial deformed grains);
4. The zone of the fine eutectoid mixture of pearlite and cementite without overheating, 10–15 mm in thickness, appears after recrystallization of the metal (formation of new crystals from crystals of the previous modification during cooling–from an austenite structure to a pearlite one);
5. High 5–10 mm wide tempering zone with transition to base metal;
6. Base metal: for heat-strengthened rails–fine pearlite (troosto-sorbite or quenching sorbite), for non-heat-strengthened rails–lamellar pearlite.

Thermal modes mainly prevent cold cracks caused by a number of factors, such as the formation of quenching structures (martensite and bainite), which leads to the appearance of additional stresses due to the volumetric effect. Diffusion and concentration of hydrogen, which is adsorbed in microvoids, causes additional embrittlement of the metal [20].

In the case of thermal impacts on the metal in the heat-affected area, the nature of structural transformations largely depends on the mass fraction of elements included in the chemical composition of steel, and the cooling rate. With an increase in the cooling rate, the resulting structure in the heat-affected area is crushed and its hardness increases. If the cooling rate exceeds the critical rate, the formation of quenching structures is inevitable. Quenching structures may also form quenching cracks.

Plastic, well-treated structures, such as pearlite or finely dispersed eutectoid mixture of pearlite and cementite, are most desirable in the heat-affected area.

The conducted experiment on welding a rail made of the E76HGF steel showed that the heat-affected zone was approximately 30–40 mm, which corresponds to standard values. Zone 1 in Figure 3 is the center of the weld seam with the structure of coarse-grained lamellar pearlite with a ferritic mesh around the former austenitic grains. Such a structure will provide a relatively low hardness and good plasticity. Zone 2 is a zone of incomplete melting and its structure is similar to the structure of the first zone; however, the ferritic grid is not solid, but in the form of fragments. Pearlite grains are smaller and less decarbonized steel. As a result, the hardness drop gradient magnitude is not as large as in the first zone. The structure of zone 3 is a coarse-grained lamellar eutectoid mixture of pearlite, cementite and alloyed ferrite. In zone 4, this eutectoid mixture of pearlite and cementite turns into austenite. During recrystallization, a relatively fine grain is formed. The hardness in zones 2–4 is practically at the same level. In zone 5, high tempering occurs, which significantly reduces the steel hardness and provides a ferrite–pearlite structure.

The main technological method that reduces the likelihood of cracks is heating. The heating temperature is determined depending on the carbon equivalent and the cross-sectional area of the rail. The required heating temperature increases with the increase in steel alloying and the rail cross-sectional area. Heating promotes pearlite conversion and is an effective means of eliminating quenching structures. Therefore, it serves as a preliminary heat treatment of welded joints (heating before and during welding). If we change the heating process, we can control the cooling rate and obtain the desired hardness in the HAZ.

Temperature and pressure cannot be considered regardless of time; all three factors are interrelated. The higher the applied pressure, the lower the required temperature at the specified welding time.

3.2. Metallographic Studies of the Rail Weld Obtained by Various Methods of Flash Welding

Currently, the most widespread method in rail welding is the electric resistance welding of rails used in both stationary and field conditions. This method allows adjusting and performing melting at the maximum useful power during the welding process [21]. The electric resistance welding is more economical and technological, since it allows for the control of the largest number of process parameters directly during operation. The electric resistance welding heats and continuously cools the rails in the HAZ. Depending on the melting method (open-hearth, converter or electrical steel) and on the mass fraction of elements included in the chemical composition of steel, the welding process is selected using the existing methods of melting: continuous or pulsating; determining the dimensions of characteristic areas of the HAZ and thermal cycles of the welded joint [22]. The choice of thermal modes mainly aims to prevent the formation of quenching structures (martensite and bainite) leading to additional stresses due to the volumetric effect. The choice of modes during electric resistance welding is determined depending on the melting method, type of rail and steel grade.

A metallographic study of the welding joints of rails made of non-thermally reinforced E76KhGF steel (Table 1) showed the formation of sections with a martensite quenching structure on sections in the HAZ after electric resistance welding by melting. The chemical analysis of the composition of the tested steel is given in Table 1.

No welding defects were found in the study of the macrostructure of metal, welded rails by continuous and pulsating melting of electric resistance welding.

The microstructure of the base metal of the E76HGF rail is lamellar pearlite (Figure 4).

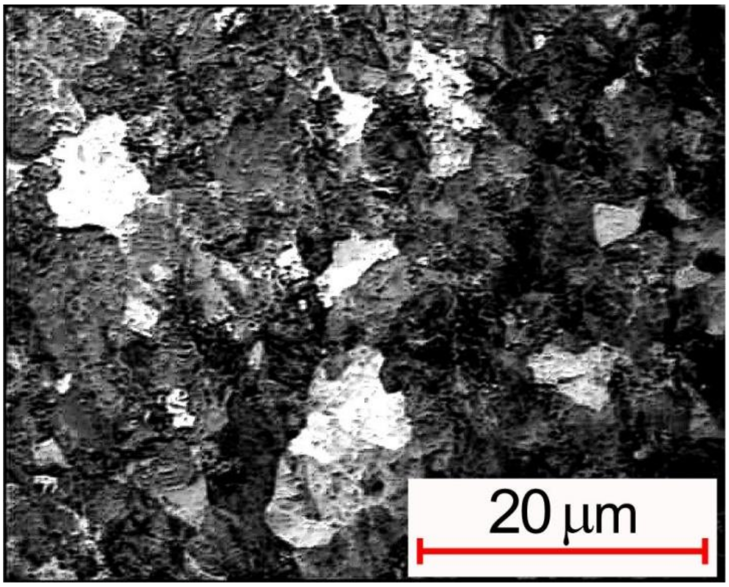


Figure 4. Microstructure of the base metal of the E76HGF rail.

The microstructure of the welded seam of the investigated samples of rails welded by continuous and pulsating flash welding is generally identical and is a coarse-grained lamellar pearlite with a ferrite network around the former austenite grains. Figure 5a shows the microstructure of the weld after resistance welding by continuous flash welding.

It should be noted that the ferrite network in the welded joint of rails welded by pulsating melting is thinner and less branched (Figure 6a).

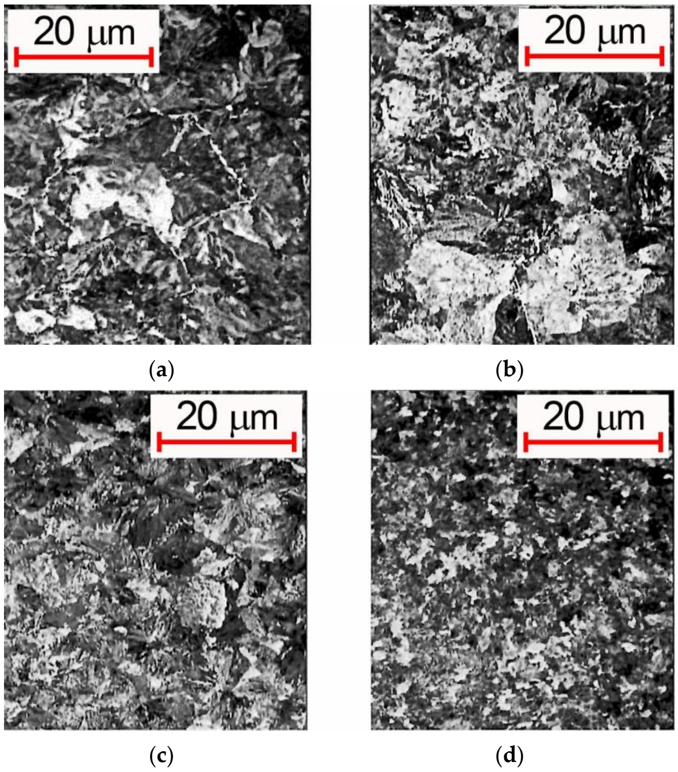


Figure 5. Microstructure of the rail head metal (E76HGF) welded by continuous melting where (**a**) welded joint; (**b**) partial melting zone; (**c**) zone of forming the eutectoid mixture of pearlite and cementite after overheating; (**d**) zone of forming the eutectoid mixture of pearlite and cementite without overheating.

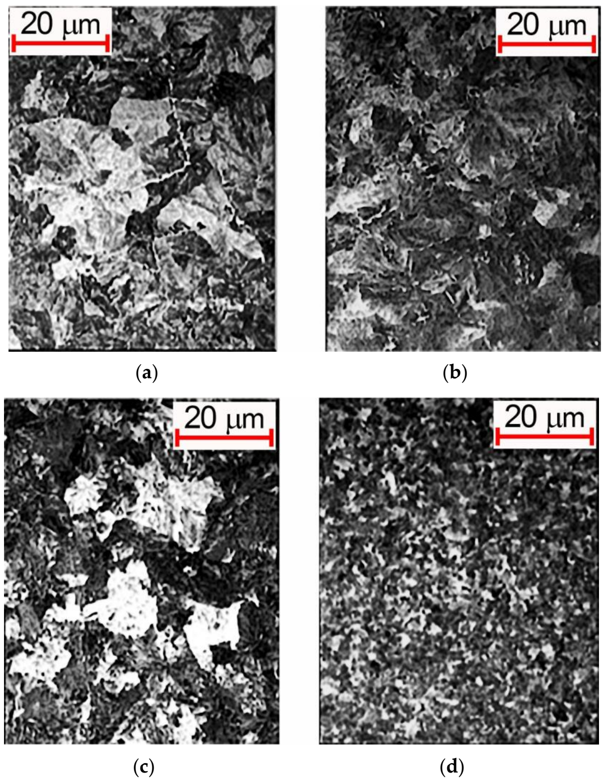


Figure 6. Microstructure of the rail head metal (E76HGF) welded by pulsating melting where (**a**) welded joint; (**b**) partial melting zone; (**c**) zone of the eutectoid mixture of pearlite and cementite after overheating; (**d**) zone of the eutectoid mixture of pearlite and cementite without overheating.

In the zone of incomplete melting, the structure of the metal is similar to the structure of the weld, and the ferrite network is present in the form of separate fragments (Figures 5b and 6b). Accumulations of non-metallic inclusions along the boundaries of grains and looseness are possible with insufficient sediments during metal deformation. Therefore, the joint is most often broken along the incomplete melting zone if there are welding defects.

Figures 5b and 6b show the microstructure of the zone of forming the eutectoid mixture of pearlite and cementite after overheating. The structure is presented in the form of a coarse-grained lamellar eutectoid mixture of pearlite and cementite and alloyed ferrite. The structure is represented as coarse-grained lamellar sorbite and doped ferrite. The transformations in this zone take place according to a combined-type diffusion and diffusionless mechanism, since not only heating, but also pressure which causes deformation of the austenitic grain, contributes to the formation of this zone.

In the zone of the eutectoid mixture of pearlite and cementite without overheating (Figures 5d and 6d), pearlite completely transforms to austenite occurring with the formation of very fine grains during reverse recrystallization.

However, the pulsating melting when welding rails by the electric resistance method of E76KhGF steel reveals the small areas of needle-type martensite (Figure 7).

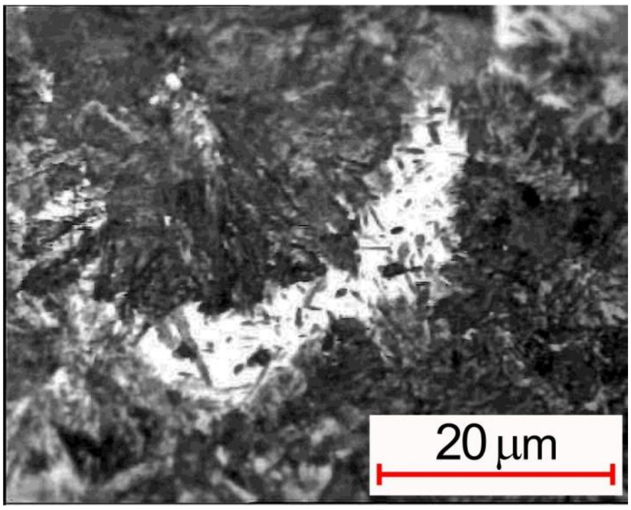


Figure 7. Martensite in the zone of forming the eutectoid mixture of pearlite and cementite after overheating.

The microhardness of martensite sections is HV_{50} = 6450–7150 MPa. The study of the microstructure of the welded joint showed that with welding rails made of steel with a chromium content of 0.35 to 0.85% in certain areas of the HAZ, the cooling rate in the welding cycle exceeds the critical rate of quench structures. In this case, a mixed structure consisting of plate sorbite and martensite structures is formed, which is unacceptable, since fatigue cracks are formed in the HAZ during the operation of the weld joint.

The choice of thermal modes mainly prevents the formation of quenching structures (martensite and bainite) leading to the appearance of additional stresses due to the volumetric effect.

To avoid the possibility of failure of the welded rails during operation, due to the presence of a martensitic structure, it is necessary to study the welding cycles in different melting methods of electric resistance welding.

The main objects of the study are welded joints (Figure 8), welded by the contact method from rails of DT350 (Table 2) category according to GOST R51685-2013 manufactured by PJSC Chelyabinsk Metallurgical Plant and EVRAZ West Siberian Metallurgical Complex.

Figure 8. Welded joint.

Table 2. Chemical composition of the tested steel.

Rail Category	Steel Grade	Content, %										
		C	Mn	Si	V	Cr	Ni	Cu	Ti	P	S	l
										Not More Than		
DT350 Chelyabinsk Metallurgical Plant	K76F	0.79	1.13	0.34	0.10	0.04	0.03	0.02	0.002	0.012	0.009	0.003
	according to GOST P516852013	0.71 0.82	0.75 1.25	0.25 0.60	0.03 0.15	not more than 0.20–0.80	–	–	–	0.020	0.020	0.040
DT350 EVRAZ West Siberian Metallurgical Complex	E76HF	0.76	0.79	0.55	0.04	0.38	0.07	0.1	0.002	0.019	0.007	0.002
	according to GOST P516852013	0.71 0.82	0.75 1.25	0.25 0.6	0.03– 0.15	0.20–0.80	–	–	–	0.020	0.020	0.040

3.3. Mechanical Properties of the Rail Weld Obtained by Various Methods of Flash Welding

Table 3 presents the mechanical characteristics of the rail weld metal after continuous melting, pulsating melting and combined melting. For comparative tests, typical mechanical characteristics were selected: tensile strength; conventional yield strength; impact toughness; specific elongation/contraction and Brinell hardness.

Table 3. Mechanical properties of metal of welded rail head by different methods of electric resistance welding.

Mechanical Properties	Melting Method			GOST P 51685-2000 Rail Category T1	
	Continuous Melting	Pulsating Melting	Combined Melting		
Ultimate tensile strength σ_u, H/mm^2	1022	1016	1019	at least	1180
Yield stress $\sigma_{0,2}$, H/mm^2	595.7	622.6	620.7		800
Impact hardness, KCU, J/cm^2	4	4	4		25
Percentage extension δ, %	9.8	9.2	9.3		8.0
Reduction of area, ψ, %	42.2	46.5	45.7		25.0
Brinell hardness, HB	262–370	251–365	261–366	341–401	

Analysis of the results of the mechanical properties of welded joints after continuous flash welding, pulsating flash welding and combined flash welding shows slight differences in the parameters of the mechanical characteristics. A decrease in the yield strength in relation to the initial material, as well as an increase in the values of specific elongation and contraction, evidence the high plastic properties of the welded joint, which can be explained by the formation of coarse-grained lamellar pearlite with a ferritic network around the former austenitic grains. The reasons for the reduced impact toughness of the near-seam zones in welded joints may be the heterogeneity of the chemical composition (liquation) and significant overheating of the metal, characteristic of this type of welding. If liquation leads to unevenness in the mechanical properties along the cross-section of the welded joint, then overheating, accompanied by grain growth, significantly increases the tendency of the weld to brittle fracture.

The analysis of testing results of welded joints of rails for static strength was carried out after welding by electric resistance welding by different methods of melting. Table 4 shows the results after processing the statistical data obtained at the rail welding plants (RWP) during the tests of rail samples over 2013–2018 with the minimum, maximum and average values for the static bending test:

Table 4. Results of statistical tests of rail samples.

MeltingMethod	Indicators	
	DestructiveLoad, kN	BendDeflection, mm
Pulsating melting	(2000–2450)/2230	(30–45)/42
Continuous melting	(2000–2400)/2200	(33–50)/38
Combined melting	(2100–2500)/2300	(30–50)/40
Technical requirements Russian Railways 1.08.002-2009	2000	27

- RWP–1 Oktyabrskaya Railway Station, total number of tested samples–66 pcs. (weld stretching zone–36 pcs., head–30 pcs.);
- RWP–3 Moscow Railway, total number of tested samples–20 pcs. (weld stretching zone–12 pcs., head–8 pcs.);
- RWP–13 Yuzhno-Uralskaya Railway, total number of tested samples–26 pcs. (weld stretching zone–15 pcs., head–11 pcs.);
- RWP–8 Northern railway station, total number of tested samples–30 pcs. (weld stretching zone–15 pcs., head–15 pcs.);
- RWP–19 Far Eastern Railway, total number of tested samples–22 pcs. (weld stretching zone–10 pcs., head–12 pcs.);
- RWP–29 West Siberian Railway, total number of tested samples–60 pcs. (weld stretching zone flange–32 pcs., head–28 pcs.);
- RWP–32 East Siberian Railway, total number of tested samples–26 pcs. (weld stretching zone–13 pcs., head–13 pcs.).

To calculate the average destructive load and the bend deflection, 148 results were processed out of the total number of experiments performed, of which 75 samples were processed during pulsating melting, 63 samples were processed during continuous melting and 10 samples were processed during combined melting. The strength and ductility graphs of welded joints, the studied methods of melting electric resistance welding were built based on the obtained data (Figure 9).

It can be clearly seen that the combined melting of electric resistance welding slightly improves the ductility indicators at high strength values, which is especially important at present, since the largest number of ductility failures is observed at the highest strength indicators of welded joints welded by pulsating and continuous melting.

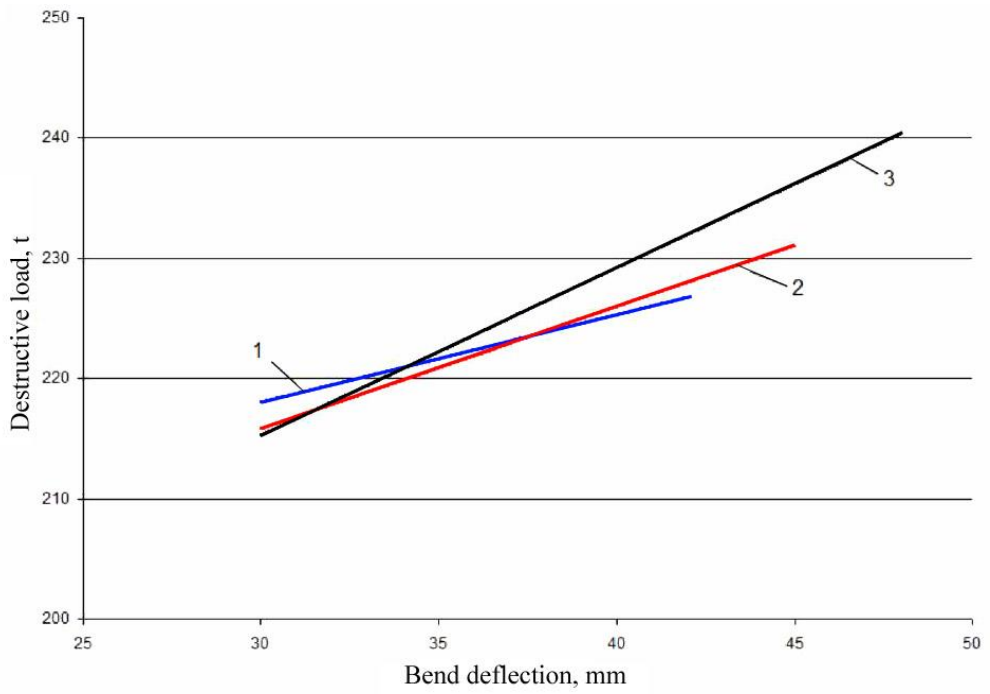


Figure 9. Strength and ductility of welded joints tested for static bending: 1—continuous melting; 2—pulsating melting; 3—combined melting.

The conducted experiment showed that the mechanical properties changed significantly along the seam section. There was a significant decrease in the weld seam hardness, but at the same time its plasticity increased significantly. The reason for this is significant changes in the weld structure caused by the influence of the formed temperature field. In the central part of the seam, steel decarbonization occurs, and at a distance from the central part of the seam, the eutectoid mixture of pearlite, cementite is formed and steel recrystallization occurs. In turn, the welding mode type (continuous, pulsating or combined flash welding) has an insignificant effect on the mechanical characteristics, which is confirmed by the experimental data results. The differences in the ultimate strength between these modes are no more than 1%, the impact toughness does not change, the specific elongation is no more than 5% and the hardness is no more than 3%. At the same time, such small changes in the properties have a very significant impact on operational characteristics. The destructive load of the welded joint of the rail at high values of the bending deflection (Figure 9) increases by a value within 2–3%. Since in real conditions of rail operation, the load on the joint very rarely exceeds the limit values, even such a slight increase in the mechanical properties can significantly reduce the number of cases of failures in welded rail joints.

4. Conclusions

1. The conducted studies have shown that the flash welding mode significantly affects both the value of the cooling rate and the very nature of the thermal cycle of the welded joint as a whole. The highest cooling rate is reached when welding in the pulsating mode. The cooling rate and cooling curves for continuous and combined modes are almost identical. Changes in the cooling rate under different modes have a primary influence on the structure and properties of the weld seam;
2. The results of studying the rail top during local heat treatment of welded joints confirmed the need for intensification of quenching cooling in the central zone of the rail seam. In this zone, the maximum decrease in the hardness of the weld seam occurs owing to the formation of coarse-grained lamellar pearlite with a ferritic network

around the former austenitic grains. In turn, a decrease in hardness in the central zone occurs due to its decarbonization;

3. Welding rails of the E76HGF steel grade by the contact method by pulsating flash welding can lead to the appearance of needle martensite areas, resulting in embrittlement of the weld seam and a decrease in its properties. As a result of conducting field experiments, it was reliably shown that in the conditions of the combined welding mode it becomes possible to avoid the mentioned problems;
4. The use of the combined welding mode of rail joints provides a slight increase in the mechanical properties of the weld seam in the range of 2–4%. Along with this, such slight changes in the properties exert a very significant impact on the operational characteristics. The destructive load of the welded joint of the rail at high values of bending deflection increases by a value within 2–3%. Since in real conditions of rail operation, the load on the joint very rarely exceeds the maximum values, even such slight increase in the mechanical properties can significantly reduce the number of cases of welded rail joint failures.

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