PROPERTIES OF WELDED JOINTS OF RAIL STEEL IN ELECTRIC ARC WELDING

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The results of investigations of effect of thermodeformational cycles of welding on structural changes, strength and ductility properties of HAZ metal of welded joints of rail steel with carbon content of 0.72 % are given. Influence of preheating temperature and value of welding heat input on delayed fracture resistance of HAZ metal and cold crack formation in the joints was studied.

Keywords: *arc welding, railway rails, welded joints, heat-affected zone, delayed fracture, cold cracks*

At manufacturing of railway rails the high-carbon silicon-manganese steel with carbon content of 0.71–0.82 % and manganese of 0.75–1.05 % is used. The adding of manganese in such amount into rail steel in comparison with carbon steel sharply decreases critical rate of hardening and increases considerably the depth of its heat treatment. Therefore, the welding of such type of steels is connected with considerable difficulties which lie in development of measures on prevention of occurrence of crystalline (hot) and delayed (cold) cracks in weld metal and near-weld HAZ metal [1, 2].

Initiation of hot cracks in weld metal takes place as a result of increase of carbon content at its stirring with a base metal in the process of arc welding. To increase resistance of weld metal against hot cracks is possible due to application of electrode materials with decreased carbon content, welding at conditions providing minimal penetration of base metal and also increasing a coefficient of deposition [1]. At mechanized methods of welding the best results are achieved using wires of small diameter at straight polarity and decreased heat inputs.

The largest difficulties during welding of high-carbon steels appear due to formation of cold cracks in joints. Their formation is predetermined by tendency of high-carbon steels to hardening and correspondingly determined by peculiarities of structural transformations in HAZ metal under the influence of thermodeformational cycle of welding. It is especially difficult to prevent the cold cracks formation when a joint could not be subjected to special heat treatment directly after welding.

As to the main value of steel weldability and resistance of welded joints against cold cracks formation the high-carbon rail steel is very close to high-strength medium-alloy steels, the carbon content of which is 0.3–0.4 %. The value of carbon equivalent for these steels is approximately the same ($C_{\rm eq}$ = 0.8–1.0 %) [2]. Therefore, to prevent the cold cracks formation in welded joints of rail steel the similar technological solutions as in welding of medium-alloyed steels can be applied.

During investigations of weldability of medium-alloyed steels the most efficient methods of preventing the cold cracks formation in HAZ metal of joints are established [2, 3]. They include control of thermal cycle of welding and temporary welding stresses, application of welding wires with a low melting temperature, decrease of content of diffusive hydrogen in weld metal, application of additional technological procedures like preliminary surfacing of groove edges of a joint, special technology of welding and other.

The most simple and convenient method is control of thermal cycle using preliminary and concurrent heating of the joint along with the optimal selection of welding conditions. In many cases the welding of medium-alloyed carbon steels at such approach allows almost complete eliminating the danger of cold cracks formation in the joint. The perfect thermal welding cycle is considered to be that one which excludes overheating of metal in the near-weld HAZ area as a result of its rapid heating and cooling at temperatures above the temperature A_{c_1}. The delayed cooling below A_{c_1} temperature facilitates the development of pearlite and intermediate transformations of overcooled austenite. Here the amount of hardening structures is considerably decreased and resistance of HAZ metal against fracture is increased.

As to investigations of weldability of rail steel, then these data are limited. They concern mainly the problems of increase of quality of rails during their manufacture and also welded joints, performed using the resistance method of welding [4–6].

The purpose of this work was to study the influence of thermodeformational cycle of welding (TDCW) on the formation of structure, change of strength and ductile properties of metal, resistance of HAZ metal to delayed fracture and resistance of welded joints of high-carbon rail steel to cold cracking.

At the first stage of investigations the simulation method of TDCW was used on the basis of installation

Table 1. Cooling rate in HAZ metal in mechanized welding of rail steel joints

Q_w, kJ/cm	T_{preh}, °C	$w_{6/5}$*, °C/s
8.6	20	20–25
27.5	20	11–13
8.6	100	13–15
8.6	150	10–12
8.6	200	4.5–6.0
8.6	250	3.0–4.2

*The cooling rate after the first pass is given.

MSR-75 using electronic programming devices [7]. Structural transformations in the metal under the influence of TDCW were studied using thermal differential analysis. The specimens of 120 × 12 × 12 mm size of rail steel with carbon content of 0.72 % were used which were heated using electric current (maximal temperature of heating was 1320 °C, rate of heating was 220–250 °C/s, cooling rate in the range of temperatures 600–500 °C was 3–22 °C/s). The investigated range of cooling rates is mostly characteristic of butt joints of rail steel of 300 × 150 × 15 mm size, performed using mechanized welding in shielding gas and wire Sv-08G2S of 1.2 mm diameter (Table 1).

Figure 1 shows the diagram of transformation of overcooled austenite of rail steel, and Figure 2 shows the typical areas of microstructure of simulated HAZ metal. It is seen that transformation of overcooled austenite at cooling rates 10–22 °C/s occurs mostly in martensite area (Figure 2, *a, b*). The temperature of beginning of martensite transformation is 220 °C. The hardness of hardened metal is *HRC* 60–65. The decrease in cooling rate in this range does not lead to considerable changes in the structure. The further delay in cooling ($w_{6/5} \leq 10$ °C/s) facilitates decrease in hardness of metal, which is connected with kinetics of austenite decay. At the cooling rate of 3–5 °C/s the hardened structures are absent, the transformation in HAZ metal occurs mostly in pearlite area, and hardness of metal decreases to *HRC* 35–40 (Figure 2, *c*).

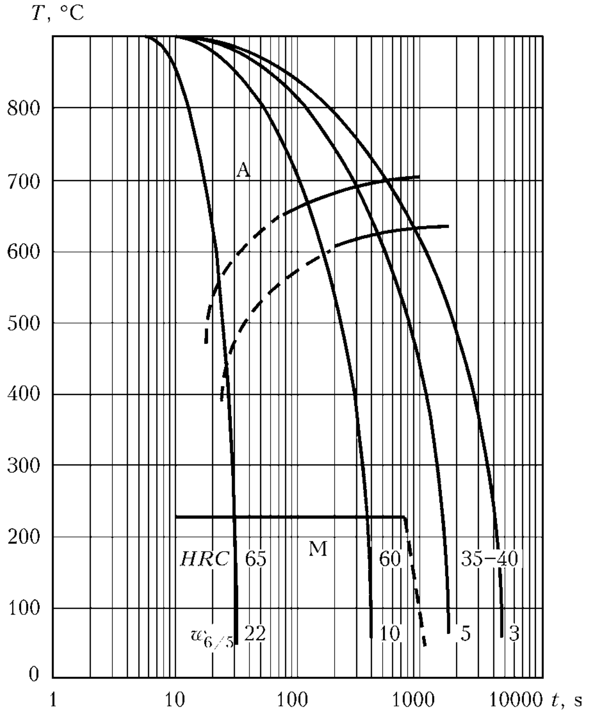

Figure 1. Transformation of overcooled austenite in HAZ metal of rail steel with carbon content of 0.72 % (T_{max} = 1320 °C, t_h = 6 s)

Thus, in HAZ metal of rail steel with carbon content of 0.72 % the formation of hardened structures occurs at the cooling rates above 5 °C/s. To avoid conditions of hardening of HAZ metal in welding is possible by applying the preheating of joints of up to 200 °C (see Table 1). Considering that carbon content in rail steel can be higher (up to 0.82 %) and martensite transformation can take place at lower cooling rates ($w_{6/5} \leq 5$ °C/s), the temperature of preheating T_{preh} in welding of rails should be not less than 250–300 °C.

The strength and ductile properties of HAZ metal of rail steel were evaluated by standard methods. For this purpose special specimens were manufactured

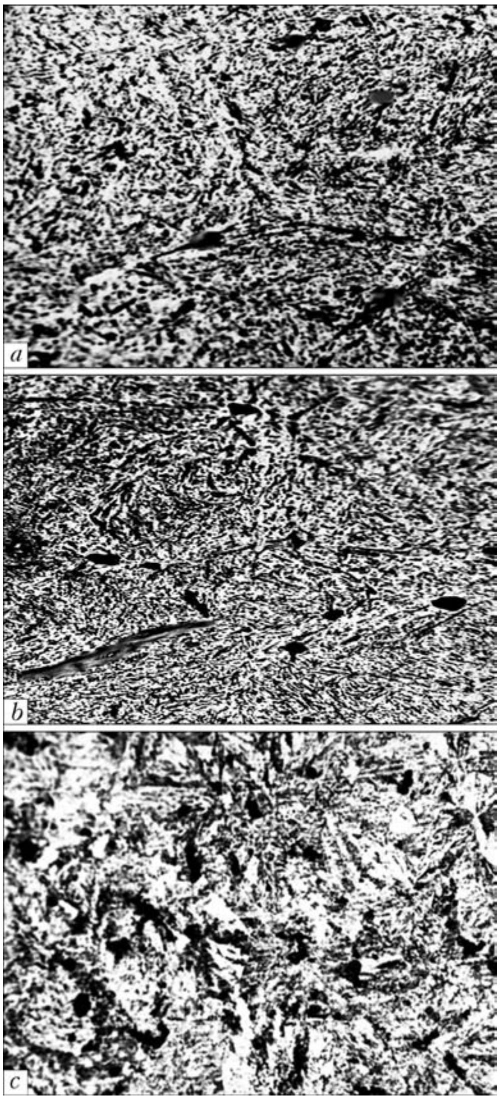

Figure 2. Microstructure (×300) of HAZ metal of rail steel: *a* — $w_{6/5}$ = 22; *b* — 10; *c* — 3 °C/s

Table 2. Mechanical properties of HAZ metal of rail steel with carbon content of 0.72 %

$w_{6/5}$, °C/s	σ_y, MPa	σ_t, MPa	δ_5, %	ψ, %	KCU_{+20}, J/cm^2
5	830	1120	7.7	21.4	6.7
10	880	1250	5.0	12.6	6.2
22	920	1280	4.7	12.6	5.8

from simulated pieces for static tensile tests of metal according to GOST 1497–84 and impact bend tests according to GOST 9454–78. The generalized results of tests are given in Table 2.

As is seen, at high cooling rates when transformation of overcooled austenite occurs mainly in the martensite region, the structure of hardened metal with increased properties of strength and low ductility is formed in HAZ metal of joints. Such metal has low deformability and relatively increased tendency towards delayed fracture. To improve the ductile properties of HAZ metal is possible due to delayed cooling of welded joints. With decrease of cooling rate to $w_{6/5} \leq 5$ °C/s the values of ductility of metal are 1.5–2 times increased.

It is obvious that due to a low ductility of HAZ metal of rail steel the relaxation of stresses in the joint will be complicated. Therefore, in welding of rails without application of preheating it is practically impossible to avoid cold cracks formation in joints. At low cooling rates ($w_{6/5} \leq 5$ °C/s) the transformation of austenite occurs with formation of more ductilec structures, but also with extremely high level of strength. Such metal is more capable to microplastic deformations, and resistance to delayed fracture of joints should be comparatively higher.

The quantitative estimation of resistance of single-pass welded joints of rail steel to delayed fracture was performed using Implant method [2]. In the course of experiments the cylinder specimens-inserts of 6.0 mm diameter without screw thread were used. Figures 3 and 4 present results of investigations of resistance of single-layer welded joints of rail steel to delayed fracture.

It is seen from the given data that during conventional welding conditions using wire Sv-08G2S at heat input Q_w = 8.6 kJ/cm without application of preheating (T_{preh} = 20 °C) HAZ metal of joints has very low level of resistance to delayed fracture. The critical stresses of fracture σ_{cr} = 60 MPa, which amounts only to $0.07\sigma_y$. The preheating up to 250 °C facilitates the increase of resistance of HAZ metal to delayed fracture of more than 7 times ($\sigma_{cr} = 0.55\sigma_y$). At preheating of up to 300 °C the delayed fracture of Implant specimens was not observed.

The increase in heat input of welding up to 27.5 kJ/cm (T_{preh} = 20 °C) also facilitates the increase in resistance of joints to delayed fracture. The level of σ_{cr} is 280 MPa. The welding at the given heat input positively influences the change of HAZ metal structure which is comparable with welding at heat input of 8.6 kJ/cm using preheating up to 150 °C. Using both variants of welding the cooling rate in joints (see Table 1) and formed structure of metal of near-weld HAZ area are almost the same. Therefore, single-layer welded joints are fractured approximately at the same level of loading.

The application of preheating in welding delays cooling. In HAZ metal of joints of rail steel the more ductile structures are formed. As is known, it facilitates development of local microplastic deformations in hardened HAZ metal, which results in more intensive proceeding of relaxation processes and increase of resistance of welded joints to delayed fracture [8, 9].

In welding using wire Sv-08Kh20N9G7T (A + F) at heat input of 8.6 kJ/cm without preheating (T_{preh} = = 20 °C) critical stresses of fracture amount only to 100 MPa. This is a bit higher than at similar conditions of welding using ferrite-pearlite wire Sv-08G2S (F +

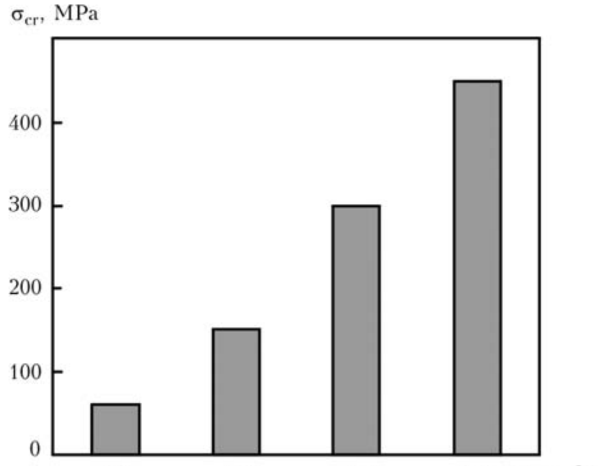

Figure 3. Influence of temperature of preheating on resistance to delayed fracture of welded joints of rail steel in welding using wire Sv-08G2S (Q_w = 8.6 kJ/cm)

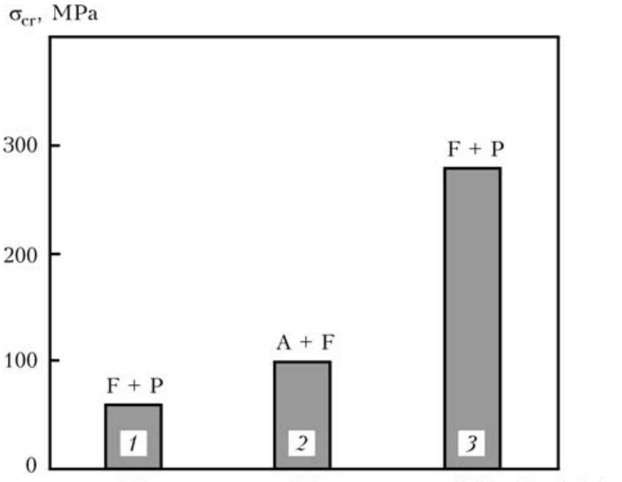

Figure 4. Influence of heat input of welding and weld metal type on resistance to delayed fracture of welded joints of rail steel: T_{preh} = 20 (*1*, *2*) and 250 (*3*) °C

Table 3. Characteristics of cold cracks in the joints of rail steel in welding of technological samples «rigid boxing»

No.	Welding conditions	Longitudinal crack	Transverse crack
1	Q_w = 8.6 kJ/cm T_{preh} = 20 °C	Crack along the fusion line, 100 % in the height of a joint During welding a crack escaped to the surface of a joint after overlapping of each layer	Crack crosses the weld into HAZ and further to the base metal for the depth up to 10 mm During welding a crack escaped to the surface of a weld after overlapping of each layer
2	Q_w = 27.5 kJ/cm T_{preh} = 20 °C	Crack along the fusion line, 50 % in the height of a joint During welding there was no crack on a surface of a joint	Crack propagation into the weld for the depth of up to 30 % Crack on the surface of a weld escaped after welding of the second layer
3	Q_w = 8.6 kJ/cm T_{preh} = 250 °C	No cracks	No cracks

+ P), however, considerably lower than the level of σ_{cr}, which is provided by application of preheating of metal up to the temperature of 250 °C.

It is known that in welding of high-strength alloyed steels with carbon content of up to 0.4 % the austenite-ferrite weld metal positively influences the formation of HAZ metal structure. Using given materials it is possible to considerably increase resistance of joints to delayed fracture [2, 3]. However, using such welds in welding of high-carbon rail steel due to formation of low-ductile structures in HAZ metal at high cooling rates no considerable increase of resistance of joints to delayed fracture occurs.

The further investigations were directed to study of influence of technological factors on the peculiarities of cold cracks formation in multi-layer welded joints of rail steel.

The resistance of joints of high-strength rail steel against cold cracks formation was investigated in welding of technological samples «rigid boxing». The technological samples represent butt joints which are prewelded-in to massive base along the contour. To evaluate the resistance of joints against formation of longitudinal cold cracks, the butt joints of the size 300 × 100 × 45 mm were used, and for transverse cracks the butt joints of 300 × 300 × 15 mm size were used. Concentrators of stresses in samples are corre-

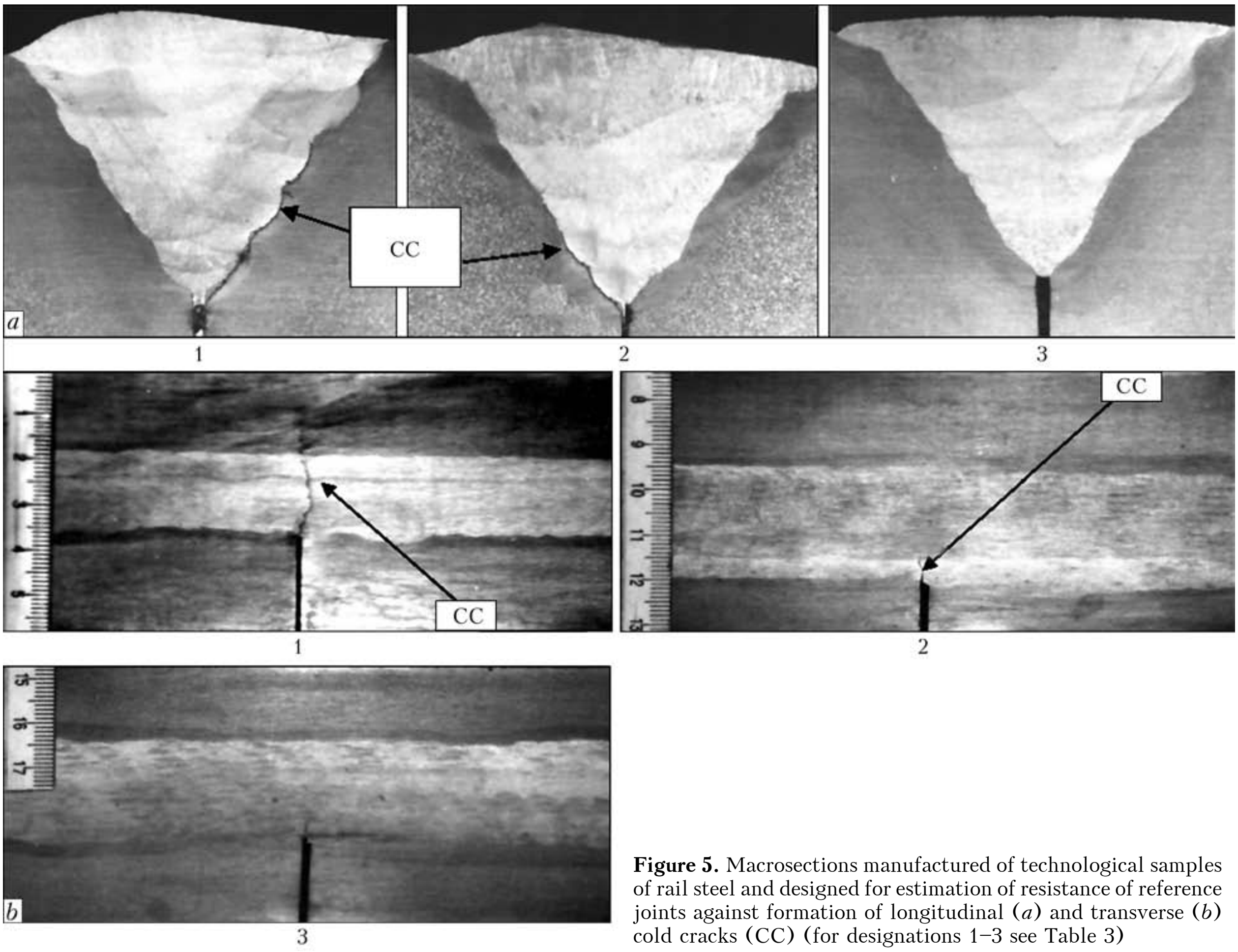

Figure 5. Macrosections manufactured of technological samples of rail steel and designed for estimation of resistance of reference joints against formation of longitudinal (*a*) and transverse (*b*) cold cracks (CC) (for designations 1–3 see Table 3)

spondent design lacks of penetration in longitudinal or transverse directions. The multilayer welding of such samples was performed using wire of the type Sv-08G2S of 1.2 mm diameter in shielding gas. To fix the moment of formation and process of cold cracks propagation in welding of reference butt weld of technological samples the method of acoustic emission was applied. After completion of welding the samples were subjected to holding at room temperature up to 3 days. Further the reference butt weld was separated from the base and sections were cut of it for visual inspection for the presence of cold cracks in the joint.

Table 3 presents the generalized results of investigations in welding of technological samples, and Figure 5 shows macrosections of the reference joints. As is seen, the welded joints of rail steel at conventional conditions of mechanized welding without application of preheating have low resistance against formation of both the longitudinal, as well as transverse cold cracks. To increase resistance of welded joints of rail steel against cold cracks formation is possible by applying preheating and increasing heat input of welding.

The results of carried out investigations on the influence of TDCW on the structure and properties of welded joints are basic for development of reliable technology of electric arc welding of railway rails. The main technological requirement in electric arc welding of high-strength rail steel is the application of preheating of joints up to the temperatures of not lower than 250 °C.

CONCLUSIONS

1. The complex of investigations was carried out for establishment of influence of TDCW on formation of structure and mechanical properties of rail steel with carbon content of 0.72 %. It was found that at the cooling rates $w_{6/5} > 5$ °C/s the martensite structure is formed in metal. The hardened metal with such structure has increased values of strength ($\sigma_t \geq$ ≥ 1250 MPa) and low ductility ($\delta_5 = 5.0$ %, $\psi =$ $= 12.6$ %). To increase ductile properties of metal (1.7 times) is possible at delayed cooling ($w_{6/5} \leq 5$ °C/s). The resistance of metal to delayed fracture is considerably increased (σ_{cr} are increased from 60 to 450 MPa).

2. In electric arc welding of rail steel the HAZ metal is most dangerous from the point of view of cold cracks initiation. Without application of preheating up to the temperature of 250 °C it is impossible to prevent cold cracks formation in the joints. The increase in heat input of welding facilitates only delay of processes of cold cracks propagation in welded joints, but it does not prevent their initiation.

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