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INFLUENCE OF COMPOSITION OF DEPOSITED METAL AND THERMODEFORMATION CYCLE OF SURFACING ON STABILITY OF JOINTS OF WHEEL STEELS WITH DISPERSION NITRIDE AND SOLID SOLUTION STRENGTHENING TO COLD CRACK FORMATION

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Current trends in the development of railway transport increase the load on the axle and speed of freight trains. The relevant task is to create technologies for the production and restoration of railway wheels, which provide the extension of their service life in different operating conditions. To solve the specified problem, it is necessary to study the influence of different factors on the technological and operational strength of welded joints of wheel steels with dispersion nitride and solid solution strengthening and develop the technology for restoring the rolling profile of all-rolled wheels of freight cars. It was established that the change in resistance of the HAZ metal of wheel steels with dispersion nitride and solid solution strengthening to delayed fracture is significantly influenced by the carbon content in steel and cooling rate during welding. Diffusion hydrogen, contained in the deposited metal, getting into HAZ, significantly reduces its resistance to delayed fracture. In the new wheel steel, the carbon content should not exceed 0.55 %. Under other conditions, it will be impossible to provide the proper level of resistance of joints to the cold crack formation during surfacing of new railway wheels. 11 Ref., 3 Tables, 4 Figures.

Keywords: arc surfacing, wheel steel with dispersion nitride and solid solution strengthening, heat-affected-zone, structure, cooling rate, diffusion hydrogen, cold cracks

Today in Ukraine to manufacture wheels of freight cars, wheel steel of grade 2 with a carbon content of 0.55–0.65 % is used [1, 2]. Having a relatively low cost, wheels made of such steel have a sufficiently high reliability during operation. The level of loading on the axle of the wheel pair of freight cars during operation on the railway tracks of Ukraine and the CIS countries amounts up to 23.5 t.

Current trends in the development of mainline railway transport in Ukraine are aimed at increasing the load on axle to 27.5 t and the speed of freight trains to 150 km/h, which leads to the use of wheels of improved strength and wear resistance. In this regard, today several directions of creation of new wheel steels are considered. First, it is proposed to increase the carbon content in steel to 0.75 %, as it is done during the manufacture of wheels in the EU, USA and Japan. This is the simplest way, which does not require additional costs and changes in the technological process of manufacturing railway wheels. However, during operation of such wheels on the main tracks of Ukraine, this can lead to a sharp increase in defects on the rolling surface.

The second direction is based on microalloying of the existing wheel steel with carbide- and nitride-forming elements, due to which it is possible to provide the dispersion of the metal structure. This will promote the improvement of ductile properties of the wheel metal at a higher level of its strength [3–5]. At the same time, to reduce the probability of «shelled treads» formation on the rolling surface of the wheel, the carbon content in the steel should be limited.

All directions of creation of new wheel steels are actively worked out today. However, to increase the strength of railway wheels, the most promising area of development is microalloying of wheel steel with carbide- and nitride-forming elements. At the same time, while creating new railway wheels of higher strength, it is also necessary to predict whether it will be possible to restore them after wear by surfacing in the conditions of domestic production.

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Investigation procedures. *Investigation of the influence of cooling rate during surfacing on the resistance of HAZ metal to delayed fracture.* The investigations were carried out using the method Implant [6, 7] in a specialized installation developed at the PWI. Cylindrical specimens-inserts made of experimental steel were subjected to tests. They did not have a stress concentrator in the form of a notch. The specimens were cut out along the rolled metal. From the same steel the plates with a size of 300×250 mm were prepared, in the hole of which specimens–inserts were placed on the yield fit, which during the tests were welded-on to the plate.

As the object of investigations experimental wheel steels with dispersion nitride and solid solution strengthening (conditional reduction of KS-DnTR3) were used, having the following composition with different carbon content, wt.%:

No.1 — 0.52 C; 0.70 Si; 0.81 Mn; 0.37 Cr; 0.17 V; 0.0173 N; 0.030 S; 0.025 P.

No.2 — 0.64 C; 0.70 Si; 1.30 Mn; 0.42 Cr; 0.15 V; 0.0174 N; 0.030 S; 0.025 P.

For comparison, wheel steel of grade 2 with a carbon content of 0.54 % and steel 65G (0.65 % C) were used.

Welding of the specimens was performed using a wire of a solid cross-section of grade Sv-08G2S with a diameter of 1.2 mm and a flux-cored wire of grade PP-AN180MN/98 (12GSKhNFT alloying system). During welding using wire Sv-08G2S the conditions were as follows: I_w = 180–200 A; U_a = 28–30 V; v_w = = 13–15 m/year, wire PP-AN180MN/98: I_w = 250–280 A; U_a = 28–30 V; v_w = 15–18 m/year. The input energy of surfacing in both cases was approximately at the same level and amounted to 8.6–10.0 kJ/cm.

The cooling rate of HAZ metal was changed due to preheating of the plates, which depending on the technological variant of welding varied from 20 to 250 °C. This approach allowed changing the cooling rate $w_{6/5}$ of welded joints in the range from 25 to 10 °C/s.

Static loading of the specimens was started after cooling to a temperature of 50 °C. The speed of loading to its constant value was approximately 10 MPa/s. As the index of resistance of HAZ metal of welded joints to delayed fracture, critical stresses (σ_{cr}) were taken, at which the specimen did not break for 24 h.

Investigation of effect of diffusion hydrogen on resistance of HAZ metal to delayed fracture. As in preliminary investigations, the quantitative evaluation of the effect of the diffusion hydrogen content in the deposited metal ($[H]_{dif}$) on the resistance of the HAZ metal to delayed fracture was performed applying the Implant method. As the object of investigations, the experimental wheel steel KS-DnTR3 No.1 with a carbon content of 0.52 % was used. During the tests a mechanized method of surfacing in a mixture of gases 82 % Ar + 18 % CO_2 was used applying the flux-cored wire PP-AN180MN/98. The specimens were deposited during preheating to a temperature of 100 °C. Under such conditions of surfacing, the cooling rate $w_{6/5}$ amounted to 12–15 °C/s, and in the HAZ metal a martensitic-bainitic structure was formed, where the volume fraction of martensite was approximately 85 % and the hardness of the quenched metal was in the range of 4440–4640 MPa.

The hydrogen content in the deposited metal was regulated by changing the temperature and time of the flux-cored wire annealing. To determine the number of $[H]_{dif,}$ the method of «pencil» test was used, which consisted in the following. A specimen of weld metal with the size of approximately 60×14×14 mm was deposited into a copper water-cooled mold. Then, directly after surfacing it was extracted from the mold and additionally cooled in the water flow till the room temperature (cooling time is 10 s) and placed to the eudiometer, where as a locking medium a hydrogen solution of glycerol was used, preheated to the temperature of 40–45 °C. The process of evolution of diffusion hydrogen from the deposited metal specimens lasted for 72 h until its complete cessation. The amount of diffusion hydrogen was calculated by the following formula

$$[H]_{\mathrm{diff}} = \frac{ah}{P} \cdot 100 \ \mathrm{ml/g},$$

where α is the coefficient of the eudiometer; *h* is the height of the column in the eudiometer, mm; *P* is the weight of the specimen of deposited metal, g.

Investigations of resistance of joints to cold crack formation. Investigations of the stability of joints of wheel steels with dispersion nitride and solid solution strengthening to cold crack formation were performed during welding of technological specimens «rigid seal welding» [6, 8].

The rigid specimen represents a massive plate with a size of 300×400 mm and a thickness of 45 mm, to which around the whole perimeter the plates of the butt joint with a V-shaped opening (angle is 60°) of the investigated steel with 20 mm thickness, 300 mm length and 100 mm width are welded-on with the leg of 10–12 mm. The total 200 mm width of the joint corresponds to the maximum level of the specimen rigidity — the level of residual tensile stresses in the HAZ metal is approximately 400 MPa [9]. Further, the butt joint is welded with a constructive lack of fusion (gap is 1.5–2.0 mm, blunting is h = 4 mm), which is a stress concentrator for cold crack formation. Welding of specimens during testing of welded joints of experimental wheel steels for resistance to cold crack

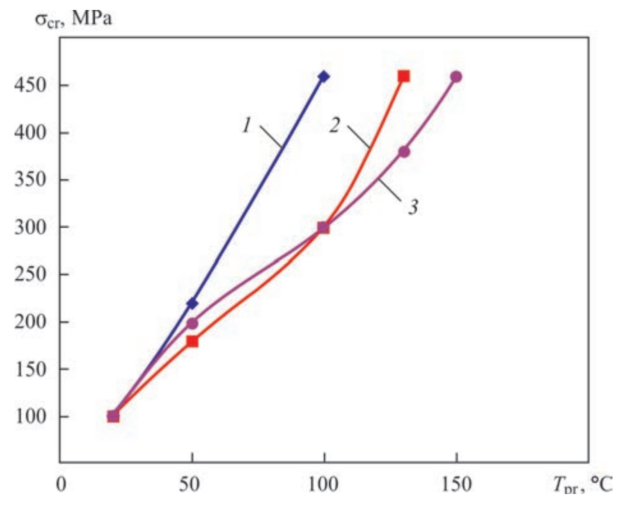

Figure 1. Resistance of HAZ metal of wheel steels of grade 2 (*1*) [11] and KS-DnTR3 No.1 (*2, 3*) to delayed fracture: *1, 2* — Sv-08G2S; *3* — PP-AN180MN/98

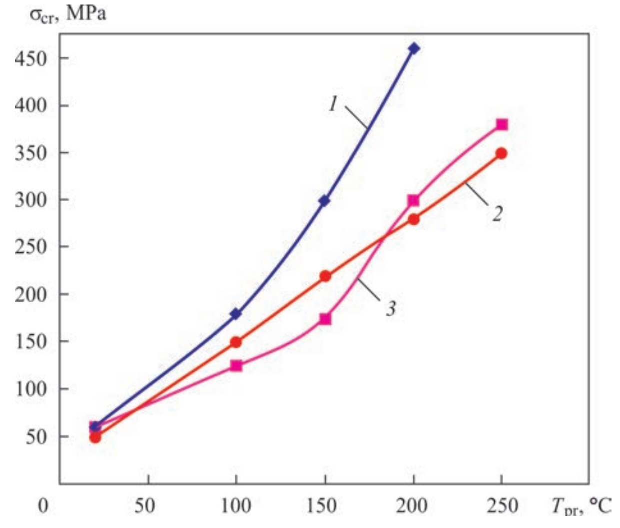

Figure 2. Resistance of steel of grade 65G (*1*) [11] and wheel steel KS-DnTR3 No.2 (*2, 3*) to delayed fracture of HAZ metal: *1, 2* — Sv-08G2S; *3* — PP-AN180MN/98

formation was performed applying the mechanized method in shielding gases (82 % Ag + 18 % CO_2) using flux-cored wire PP-AN180MN/98 with a diameter of 2.0 mm on the following conditions: welding current is 250–300 A, arc voltage is 28–30 V, welding speed is 15–18 m/h.

Table 1. Parameters of thermal cycle in the HAZ metal during arc surfacing of specimens applying the Implant method

Input energy Q_{surf}, kJ/cm	Preheating T_{pr}, °C	Thermal cycle parameters		
		$w_{6/5}$, °C/s	$\tau_{8/5}$, s	$\tau_{8/1}$, s
8.6–10.0	–	25–30	8	170
	50	20–25	10	230
	70	15–20	11	250
	100	12–15	12	450
	150	8–10	14	760
	200	5–7	18	890
	250	3–4	25	1050

Multilayer welding was performed under the conditions when after each layer of deposited metal the joint was cooled to a temperature of 20–30 °C, after which filling of the groove was continued. To fix the moment of formation and the process of cold crack propagation during cooling of a butt after welding, the method of acoustic emission was used [10]. After welding, the specimens were subjected to 3 days exposure. Further, the reference butt joint was separated from the plate and mechanically cut on templates, from which macrosections were later made to carry out visual inspection for the presence of cold cracks. The templates were cut out in the places of welded joints, where the most intense acoustic signals were recorded.

Results of experiments and their analysis. The generalized results of testing specimens applying the Implant method on determination of the effect of preheating temperature (cooling rate in HAZ) on the resistance of the deposits of the experimental wheel steel with a carbon content of 0.52 and 0.64 % to delayed fracture are presented respectively in Figures 1 and 2.

During surfacing with preheating of metal to 100 °C, the cooling rate in HAZ is reduced to 12–15 °C/s (Table 1). Under such conditions of cooling, the formation of the metal structure in the comparable wheel steels is already significantly different. Thus, in the HAZ metal of wheel steel of grade 2 a bainitnic-martensitic structure is formed, in which the share of martensite does not exceed 30 %, and in the experimental wheel steel KS-DnTR3 No.1 the martensitic-bainitic structure is formed, in which the volume fraction of martensite is already predominant and amounts up to 80 %. According to structural differences, the resistance of steels to delayed fracture also changes. During preheating at a temperature of 100 °C, the critical fracture stresses for KS-DnTR3 No.1 are approximately 1.5 times lower. For the wheel steel of grade 2 (0.58 % C) this preheating temperature is already optimal to prevent the development of delayed fracture processes in the HAZ metal during surfacing, and for wheel steel with dispersion nitride and solid solution strengthening (0.52 % C) is still insufficient.

It is possible to increase the critical fracture stresses for the HAZ metal of the experimental wheel steel KS-DnTR3 No.1 to the level of the wheel steel of grade 2 (σ_{cr} = 460 MPa) by increasing the heating temperature to 130 °C. Under such conditions, the cooling rate is reduced to 8 °C/s and in the HAZ metal of the experimental steel a strengthening structure is formed, in which the share of martensite does not exceed 50 %. According to the preliminary data, such share of martensite in the structure is critical for a significant probable increase in resistance of the quenched HAZ metal of high-carbon steels to delayed fracture [11].

It should be noted that during surfacing using the flux-cored wire PP-AN180MN/98 similar results were obtained. In contrast to the variant of welding using the wire Sv-08G2S, it was possible to significantly inhibit the development of delayed fracture processes (σ_{cr} = = 460 MPa) in the HAZ metal of the wheel steel KS-DnTR3 with a carbon content of 0.52 % (experimental steel No.1) at a temperature of preheating of 150 °C.

The indices of critical fracture stresses during the tests of specimens of the experimental wheel steel KS-DnTR3 No.2 with a carbon content of 0.64 % as compared to steel 65G (0.65 % C), differ more significantly (Figure 2) than in the previous case while comparing wheel steels of grade 2 and KS-DnTR3 No.1 (0.52 % C).

The critical cooling rate, at which up to 50 % of martensite is formed in the HAZ metal structure of steel 65G, amounts to 6–7 °C/s, which can be achieved by surfacing with an input energy of 8.6–10.0 kJ/cm using preheating to a temperature of 200 °C. At such a cooling rate in the HAZ metal of the experimental wheel steel KS-DnTR3 No.2, the share of martensite is predominant and amounts to approximately 99 %. Therefore, the critical fracture stresses of the HAZ metal of the experimental wheel steel are more than 1.5 times lower. Even at an increase of preheating temperature to 250 °C, the level of resistance of the HAZ metal of steel KS-DnTR3 No.2 to delayed fracture increases to 350–380 MPa, but still does not reach the level (σ_{cr} = 460 MPa), when the development of processes of a delayed fracture is impossible.

The data on the content of diffusion hydrogen in the deposited metal, depending on the conditions of preparation of the flux-cored wire PP-AN180MN/98 before surfacing are given in Table 2.

The generalized results of investigations of influence of the content of diffusion hydrogen in the deposited metal on the indices of the HAZ metal resistance of the experimental wheel steel KS-Dn-TR3 No.1 to the delayed fracture are given in Figure 3.

As is seen from the abovementioned data, at a proper heat treatment of flux-cored wire before surfacing, as it is recommended during its use (annealing at T = 230 °C for 2.5 h), when the content of diffusion hydrogen in the deposited metal is minimal ($[H]_{diff}$ = = 0.3 ml/100 g), the critical fracture stresses are the highest and amount to σ_{cr} = 300 MPa. Increasing the amount of diffusion hydrogen in the deposited metal to 1.5 ml/100 g leads to a sharp decrease in the resistance of the HAZ metal to delayed fracture. Critical fracture stresses are reduced by almost 2.5 times (to 125 MPa). At a further increase in the diffusion hydrogen in the deposited metal to 2.2 ml/100 g, the processes of delayed fracture proceed even more rapidly and the critical stresses amount to only 75 MPa. As compared to the initial state, when the flux-cored wire was annealed at 230 °C for 2.5 h, the overall decrease in the resistance of the HAZ metal to delayed fracture amounted to 4.5 times.

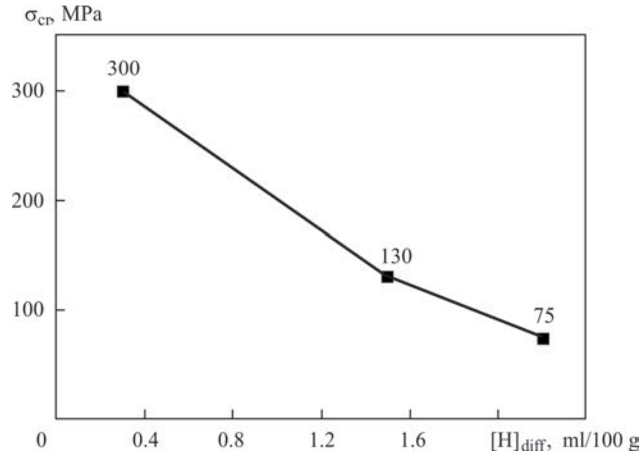

Figure 3. Influence of diffusion hydrogen content on resistance of HAZ metal of wheel steel KS-DnTR3 No.1 (0.52 % C) to delayed fracture

Therefore, while performing investigations, it was found that in the case of mechanized surfacing of the wheel steel with dispersion nitride and solid solution strengthening, diffusion hydrogen, which is contained in the deposited metal, getting into HAZ, significantly reduces its resistance to delayed fracture. The process of nucleation and propagation of microcracks is accelerated, and the critical fracture stresses at an increase in the content of diffusion hydrogen from 0.3 to 2.2 ml/100 g are reduced to 4.5 times.

The generalized results of tests of technological specimens on resistance of welded joints of experimental wheel steels to cold crack formation are presented in Table 3 and typical examples of cold crack formation are in Figure 4.

While performing tests, it was found that during welding without preheating in welded joints of experimental wheel steels with dispersion nitride and solid solution strengthening, the probability of cold cracks is 100 %. However, depending on the carbon content of wheel steel, there are differences in the nature of cold crack formation and propagation. In welded joints of the wheel steel KS-DnTR3 No.1 (0.52 % C)

Table 2. Content of diffusion hydrogen in the deposited metal (wire PP-AN180MN/98)

Conditions for preparation of flux-cored wire before surfacing	$[H]_{diff}$, ml/100 g
Annealing at T = 230 ° C for 2.5 h	0.3
Annealing at T = 200 ° C for 2.5 h	1.5
Without annealing	2.2

Table 3. Cold cracks in welded joints of experimental wheel steels KS-DnTR3 No.1 (0.52 % C) and KS-DnTR3 No.2 (0.64 % C) (arc method of welding rigid specimens)

Steel	Welding wire, welding modes	T_{pr}, °C	Presence and nature of cold crack (CC) formation
KS-DnTR3 No.1, δ = 20 mm	PP-AN180MN/98 with a diameter of 2.0 mm, I_w = 250–300 A, U_a = 28–30 V, v_w = 15–18 m/h	Without preheating	CC from the concentrator in HAZ and the weld along the fusion line for the entire thickness of the joint
		100	CC were not detected
		150	
KS-DnTR3 No.2, δ = 20 mm		Without preheating	CC from the concentrator in HAZ to a depth of 5 mm, then along the weld for the entire thickness and length of the joint
		150	
		200	
		250	

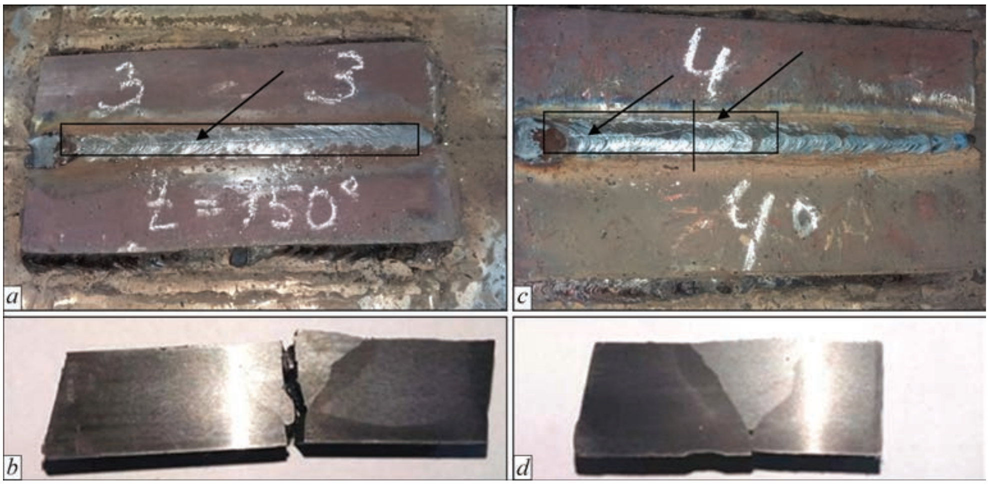

Figure 4. Examples of cold crack formation in welded joints of experimental wheel steels with dispersion nitride and solid solution strengthening in welding using flux-cored wire PP-AM180MN/98: *a* — KS-DnTR3 No.2, T_{pr} = 150 °C, through CC (HAZ, weld); *b* — KS-DnTR3 No.2, T_{pr} = 200 °C, through CC (HAZ, weld); *c* — KS-DnTR3 No.1, welding without preheating, CC from concentrator in HAZ along the fusion line for the entire thickness of the joint; *d* — KS-DnTR3 No.1, T_{pr} = 100 °C, CC are absent

a cold crack is formed from the concentrator and propagates in two directions. As is seen from Figure 4, *c* a cold crack propagates along the weld metal (area from the crater of up to 100 mm long), passing further into the HAZ along the fusion line (area of up to 50 mm long) and extends to the joint surface. In both cases, a crack originates in the HAZ metal. At the same time, the total length of a crack amounts to approximately 50 % of the length of the welded joint.

In welded joints of the wheel steel KS-DnTR3 No.2 (0.64 % C) a cold crack is formed from the concentrator, it has the beginning in HAZ, as in the previous case, propagates to the depth to 5 mm, and further — exclusively along the weld to the entire thickness of the joint, also coming to the surface. In this case, the fracture occurs along the entire length of the welded joint.

It is possible to avoid the cold crack formation in welded joints of the wheel steel KS-DnTR3 No.1 (0.52 % C) by applying preheating of the metal to a temperature of 100 °C. During welding of the wheel steel KS-DnTR3 No.2 (0.64 % C), cold cracks are formed even at preheating to a temperature of 250 °C. Welding of the technological specimen of this steel at a higher preheating temperature was not performed.

Conclusions

1. The change in resistance of the HAZ metal of wheel steels with dispersion nitride and solid solution strengthening to delayed fracture is significantly influenced by the carbon content in steel and cooling rate during welding. In surfacing using a wire of a solid cross-section of grade Sv-08G2S or a flux-cored wire of grade PP-AN180MN/98 (12GSKh1NFT) at an input energy of 8.6–10.0 kJ/cm, an increased resistance to delayed fracture is provided under the conditions when the carbon content in the wheel steel does not exceed 0.55 %. Here, the preheating temperature should be up to 150 °C. At a higher content of carbon, the preheating temperature should be increased to not lower than 250 °C.

2. In mechanized surfacing of the wheel steel with dispersion nitride and solid solution strengthening, diffusion hydrogen, which is contained in the deposited metal, getting into HAZ, significantly reduces its resistance to delayed fracture. Therefore, the content

of diffusion hydrogen in the deposited metal should be limited to not more than 0.3 ml/100 g, which is possible at a preliminary annealing of a flux-cored wire PP-AN180MN/98 (12GSKh1NFT) before its use at a temperature of 230 °C during 2.5 h. At a higher content of diffusion hydrogen in the deposited metal, the process of nucleation and propagation of microcracks in the HAZ metal is accelerated, and the critical fracture stresses are reduced by up to 4.5 times.

3. During welding of experimental wheel steels with dispersion nitride and solid solution strengthening, the formation and propagation of cracks in the deposits is significantly affected by the structural state of HAZ metal, which depends on the carbon content in steel and cooling rate. It is possible to avoid cold crack formation under the conditions when the carbon content in steel does not exceed 0.55 % by applying preheating of metal to 100–150 °C.

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