STRUCTURAL CHANGES IN OVERHEATING ZONE OF HAZ METAL OF RAILWAY WHEELS IN ARC SURFACING

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The objective of the work is investigation of the parameters of welding thermal cycle (WTC) in arc surfacing, including heating and cooling stages, on formation of metal structure and properties in overheating zone of the HAZ of high-strength wheel steel of grade 2, containing 0.58 % C. Gleeble 3800 complex was used to conduct heat treatment of model samples at heating rate of 25 to 210 °C/s up to the temperature of 1250 °C with subsequent cooling by WTC ($w_{6/5}$ = 2.5–64 °C/s), perform metallographic investigations of the structure and plot diagrams of overcooled austenite transformation. At testing by the Implant method influence of cooling rate and structural state of metal in overheating zone of HAZ on critical stress values at delayed cracking of wheel steel was assessed. It is established that incompleteness of the processes of metal austenite homogenizing in arc surfacing, because of its fast heating and limited time of soaking at the temperature above A_{c3}, has an essential influence on subsequent γ-α transformation in the HAZ metal. This leads to lowering of the critical cooling rate to 20 °C/s, at which not more than 50 % of martensite forms in the structure (w_{50M}). It is shown that the high delayed fracture resistance of HAZ metal on the level of $\sigma_{cr} \geq 0.45\sigma_{0.2}$ can be ensured, provided $w_{6/5} \leq w_{50M}$. Investigation results can be used at specifying the technology of building-up by surfacing of items from high-strength steels. 12 Ref., 4 Tables, 4 Figures.

Keywords: *arc surfacing, wheel steel, thermal cycle, HAZ, austenite transformation diagram, structure, martensite, bainite, delayed fracture*

Cracking in welded joints of high-strength steels depends on the state of the structure in the HAZ overheating zone, degree of metal quenching during the welding thermal cycle (WTC) and its plastic properties. This determines the quantity and density of dislocations, depth of running of diffusion and relaxation processes in the quenched metal that essentially influences the processes of crack initiation and propagation at loading and, eventually, the performance of welded joints and metal structures as a whole [1–5].

Problems at building-up by surfacing of items from high-strength wheel steels are similar to those arising in welding of alloyed steels. The main of them is prevention of cracking in the HAZ metal. Unlike high-strength alloyed steels, wheel steels do not contain any additional alloying elements, such as chromium, nickel, molybdenum, stabilizing the metal structure under the impact of thermodeformational cycle of welding. The main alloying element in wheel steel is carbon, the content of which is more than 0.50 %. Railway wheels made from such steel have ferrite-pearlite structure. Strength level of wheel metal exceeds 900 MPa at its comparatively low ductility and toughness [6, 7].

As is known, carbon forms an interstitial solid solution with iron, considerably strengthening the ferrite, and to a much greater extent than alloying elements forming the substitutional solid solution. Carbon solubility in iron is different, depending on the crystalline form, in which iron is present. So, carbon solubility in α-iron (BCC lattice) is equal to less than 0.02 %, and in γ-iron (FCC lattice) it is 100 times greater (up to 2 %) [1, 2]. At heat impact during heating and cooling changes of crystalline lattice will proceed in the metal. At cooling, depending on the degree of overcooling, γ-α transformation of austenite can proceed along two paths. At low cooling rates transformation will be accompanied by diffusion processes with formation of ferrite-pearlite mixture and upper bainite. At high cooling rate γ-α transformation will proceed without diffusion, with formation of hardening structures of lower bainite and martensite.

At the same time it is known that nature of γ-α transformation in the metal at cooling also depends on heating conditions and degree of austenite homogenizing [1, 2, 8, 9]. Shortening of the time of metal soaking at heating above A_{c3} temperature leads to compositional heterogeneity

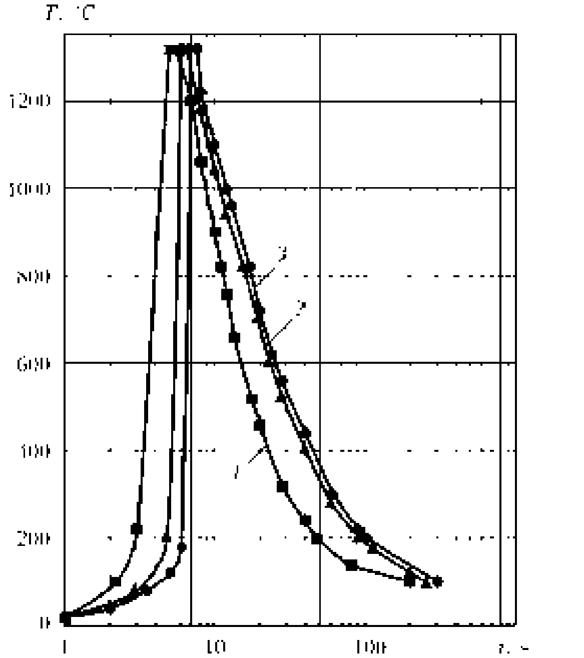

Figure 1. Thermal cycles in HAZ metal in arc surfacing of wheel steel 20 mm thick at heat input of 8.6 (*1*), 11.5 (*2*) and 15 (*3*) kJ/cm

of the structure of austenite forming from ferrite-pearlite mixture. Carbon-enriched austenite forms in the sections, where pearlite was located earlier, and where earlier there was pearlite, γ-α transformation runs at higher temperatures, and austenite contains much less carbon. This leads to metal structure containing austenite with varying carbon content. Presence of such an inhomogeneity in many cases leads to essential changes of austenite transformation kinetics at cooling, of metal structure and its properties. Therefore, the degree of austenite homogenizing in the metal of HAZ overheating zone will have an essential influence on structure formation and properties of railway wheels buildt-up by surfacing. Here, the main WTC parameters, on which metal structure and properties will depend, are not only maximum heating temperature T_{max} and cooling rate in the temperature range of 600–500 °C ($w_{6/5}$), but also heating rate (w_{heat}), as well as the time of metal staying at temperatures above A_{c3} (t_1).

Table 1. Main WTC parameters in HAZ metal in arc surfacing of wheel steel 20 mm thick

Surfacing heat input Q_w, kJ/cm	Thermal cycle parameters (T_{max} = 1320 °C)				
	w_{heat}, °C/s	t_1, s	$w_{6/5}$, °C/s	$t_{8/5}$, s	$t_{8/1}$, s
8.6	260	7	25–30	8	170
11.5	220	10	14–16	14	245
15.0	190	11.5	10–12	19	285

There is one more factor having an essential influence on structure formation in HAZ metal in welding. This is austenite grain growth, which leads to reduction of the area of intergranular boundary, and this, at other conditions being equal, reduces the probability of nucleation of ferrite and pearlite, increases austenite stability and promotes development of bainite and martensite transformation [1–3, 8].

Arc surfacing began to be extensively applied for reconditioning worn flanges of railway wheels of freight cars in repair enterprise of Ukraine and CIS countries comparatively recently. These are processes of single- and twin-arc surfacing under a layer of flux in modes ensuring heat input on the level of 10 to 14 kJ/cm. Mandatory technology elements are application of preheating of wheel treads to temperatures of 150–200 °C, depending on the used process of surfacing and slow cooling of wheels after surfacing in heat chambers. Meeting the requirements made to surfacing technology, guarantees a high quality of the deposited metal and service reliability of wheels. However, the question of the features of arc surfacing WTC parameters influence on the nature of structural changes in the overheating zone of HAZ metal of wheel steel still has not been clarified.

The objective of this work was studying the influence of WTC parameters in railway wheel surfacing, including the stages of heating and cooling, on formation of structure of HAZ metal overheating zone and its properties. Material used for investigations was high-strength wheel steel of grade 2 (GOST 10791) of the following composition, wt.%: 0.58 C; 0.44 Si; 0.77 Mn; 0.10 Ni; 0.05 Cr; 0.012 S; 0.011 P.

Characteristic thermal cycles in the HAZ metal in arc surfacing of wheel steel 20 mm thick, depending on heat input, are shown in Figure 1, and Table 1 gives the main WTC parameters. As is seen from the presented data, at arc surfacing heat input in the range of 8.6–15.0 kJ/cm, the time of metal heating in the HAZ overheating zone up to the temperature of 1320 °C is equal to 5–7 s, that corresponds to heating rate of 190–260 °C/s. Here the time of metal staying above A_{c3} temperature (800 °C) is equal to t_1 = 6.5–11.5 s.

HAZ metal structure at arc surfacing is heterogeneous, and dimensions of its individual zones are extremely small. Therefore, structural changes occurring under the impact of WTC in the metal were studied on model samples. Used for this purpose was research complex Gleeble 3800, fitted with a thermostat and high-speed dilatometer [10], and comparative studies were performed on cylindrical samples of 6 mm diameter and 80 mm length. In keeping with the testing procedure, they were heated up to the temperature of 1250 °C at the rate of 25 and 210 °C/s (heating time was 50 and 6 s, respectively), and then cooled at different rates in accordance with surfacing thermal cycles. Time of metal staying at temperatures above A_{c3}, depending on the cooling rate, was equal to 23–66 and 7–10 s, respectively. Cooling thermal cycles were selected so that in the temperature range of 600–500 °C, sample cooling rate $w_{6/5}$ varied in the range of 2.5–64 °C/s.

Temperature of the start and end of overcooled austenite transformation was determined by the point of tangent drifting away from the dylatometric curve, while the ratio of phases, formed as a result of transformations, was established by section method [11]. Furtheron, the structure of heat-treated samples was studied by the methods of optical metallography, which was followed by more precise determination of structural components ratio and critical cooling rate at γ-α transformations. Structural studies were performed using Neophot-32 microscope, microhardness of individual structural components and integral hardness of metal were measured in the LECO hardness meter M-400 at the load of 100 g ($HV0.1$) and 1 kg ($HV10$), respectively.

Generalized results of these investigations in the form of diagrams of overcooled austenite transformation in the metal of HAZ overheating zone, depending on heating rate, time of metal staying at temperatures above A_{c3} and cooling rate in keeping with WTC in arc surfacing, are given in Figure 2.

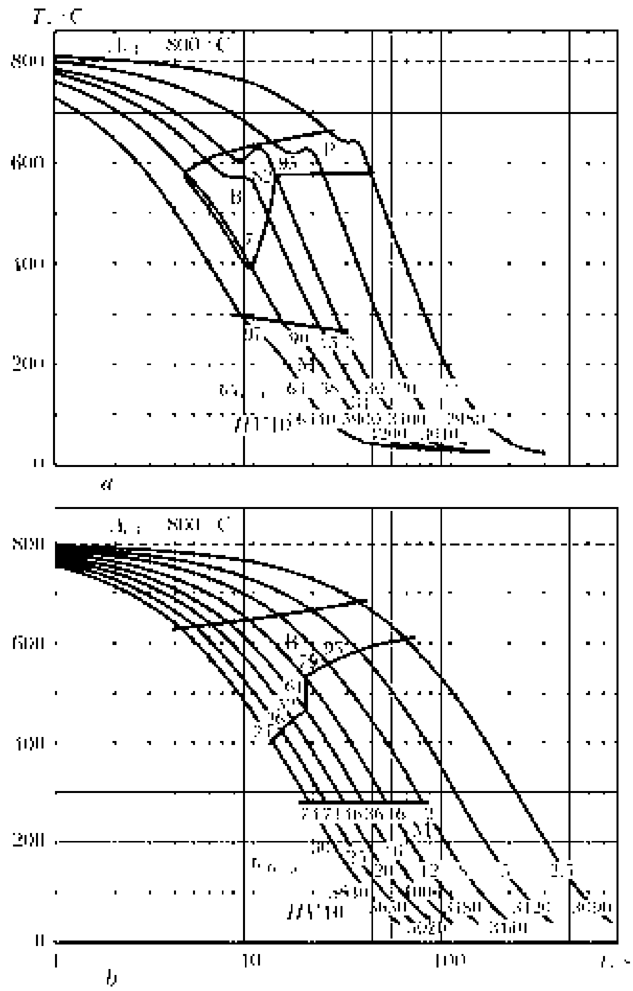

Figure 2. Diagram of overcooled austenite transformation in wheel steel HAZ metal in arc surfacing at w_{heat} = 25 °C/s, t_1 = 23–66 s (*a*) and w_{heat} = 210 °C/s, t_1 = 7–10 s (*b*)

Figures 3 and 4 show the characteristic microstructure of metal in HAZ overheating zone at different WTC parameters, and Tables 2 and 3 give the main structural parameters.

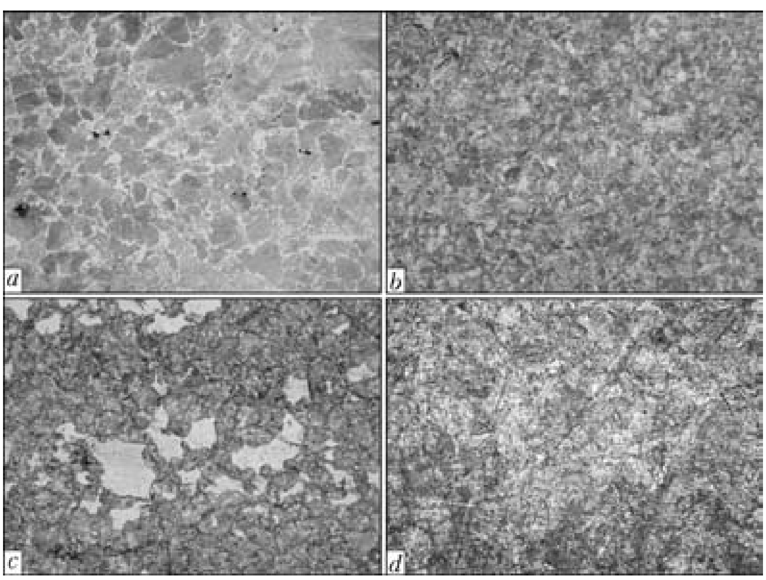

Figure 3. Metal microstructure (×320, 2 times reduction) in HAZ overheating zone at w_{heat} = 25 °C/s, t_1 = 23–66 s: *a* — base metal; *b* — $w_{6/5}$ = 20; *c* — 30; *d* — 64 °C/s

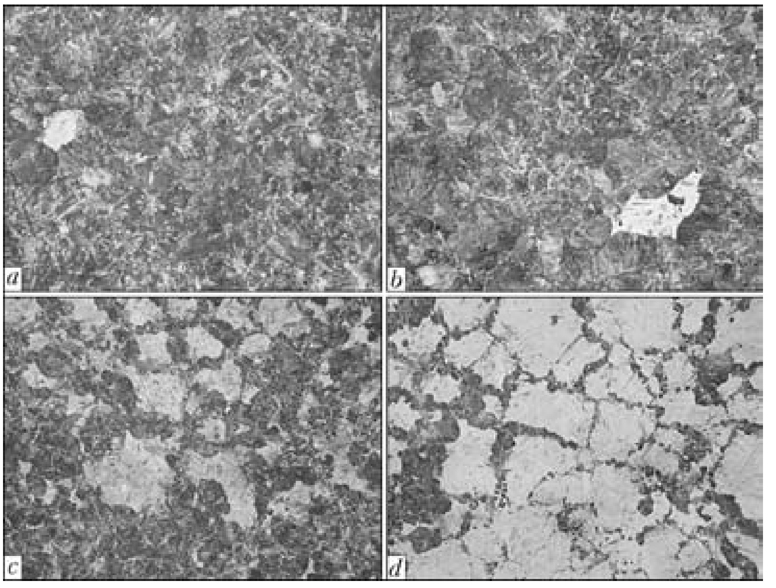

Figure 4. Metal microstructure (×320, 2 times reduced) in wheel steel HAZ overheating zone at w_{heat} = 210 °C/s, t_1 = = 7–10 s: *a* — $w_{6/5}$ = 8; *b* = 12; *c* = 16; *d* — 25 °C/s

Structure of grade 2 wheel steel in as-delivered condition is represented by pearlite-ferrite mixture (Figure 3, *a*), grain size is 16–32 μm and microhardness of structural components is *HV*0.1-1990–2450 MPa.

Located along grain boundaries are ferritic fringes of 5–10 μm size. Integral hardness of metal was *HV*10-2200 MPa.

At heating at w_{heat} = 25 °C/s transformation of overcooled austenite with cooling rate $w_{6/5}$ < < 30 °C/s (t_1 = 30–66 s), runs in the pearlitic-bainitic region (see Figures 2 and 3, *b*, *c*). Temperature range of pearlite transformation, depending on cooling rate, is equal to 660–630 °C. It is practically impossible to accurately determine the start of bainite transformation by dylatometric curves, tentatively it is approximately 630 °C. Therefore, in the diagram the region of pearlite and bainite formation is shown as a common pearlite-bainite one. Temperature of the end of bainite transformation in this range is equal to 580 °C. Metallographic investigations of sample microstructure revealed that microhardness of structural components of pearlite and bainite rises from 2450 up to 3220 MPa with increase of cooling rate from 11 up to 30 °C/s. By the features of structure and microhardness values bainite is identified as upper bainite structure,

Table 2. Structure parameters in overheating zone of HAZ metal in wheel steel (0.58 % C) at w_{heat} = 25 °C/s, t_1 = 65 s

$w_{6/5}$, °C/s	Metal structure	Structural components, %				Hardness *HV*0.1, MPa
		Pearlite	Upper bainite	Lower bainite	Martensite	
BM	Ferrite-pearlite	86	–	–	–	1990–2450
11	Pearlite-bainite	30	65	–	–	2450–2970
20	Pearite-bainite	16	80	–	–	2640–3220
30	Bainite	–	95	–	–	2970–6060
64	Martensite	–	–	–	97	4640–6420

Table 3. Structure parameters in overheating zone of HAZ metal in wheel steel (0.58 % C) at w_{heat} = 210 °C/s, t_1 = 10 s

$w_{6/5}$, °C/s	Metal structure	Structural components, %			Hardness *HV*0.1, MPa
		Upper bainite	Lower bainite	Martensite	
8	Bainite	95	–	2	2900–4420
12	Same	39	43	16	2900–5660
16	Bainite-martensite	–	61	36	3220–6060
25	Martensite-bainite	–	26	71	3360–6060

and its second name — sorbite as can be found in publications. In this range of cooling rates upper bainite content rises from 65 up to 95 %, and that of pearlite decreases from 30 % to 0 (see Table 2). Metal structure also reveals ferrite sections, located along grain boundaries, with total ferrite content not higher than 5 %. Grain size is 63–94 μm, and it is characteristic for metal at all rates of sample cooling.

Cooling rate, at which martensite formation starts, is equal to $w_{6/5}$ = 30 °C/s. At this cooling rate approximately 2 % of martensite was found in the metal structure, which is arranged as small isolated areas in the grain bulk. Temperature of the start of martensite transformation $T_{\rm Ms}$ is equal to approximately 265 °C, temperature of the end of martensite transformation could not be determined. Martensite microhardness was 5660–6060 MPa, that of upper bainite was 2970–3220 MPa. At cooling rate of 38 °C/s, the amount of martensite in the structure is equal to 90 %, and integral metal hardness rises up to 5900 MPa. When the structure contains 97 % of martensite ($w_{6/5}$ = 64 °C/s), metal hardness rises up to 6440 MPa (see Figure 3, *d*). Here, martensite formation starts at higher temperatures ($T_{\rm Ms}$ = 295 °C). As to its structure, martensite is less homogeneous, its microhardness varying in the range of 4640 to 6420 MPa. Bainite transformation in the range of cooling rates of 30 to 38 °C/s starts at $T_{\rm Bs}$ = 630–580 °C.

With increase of cooling rates in this temperature range, temperature of bainite transformation completion drops from 580 to 390 °C. It is obvious that at the cooling rate of 30 °C/s upper bainite structure forms (95 %), and at 34–38 °C/s — predominantly that of lower bainite, proceeding by diffusionless mechanism at lower temperatures. At cooling rate above 38 °C/s, bainite transformation is absent. In the metal structure, ferrite was also found along grain boundaries, its content not exceeding 3 %.

A metal heating and cooling by arc surfacing cycle ($w_{\rm heat}$ = 210 °C/s, t_1 = 7–10 s), austenite homogenizing proceeds not as completely, as in the previous case. This essentially affects also the structural transformations of overcooled austenite (see Figures 2 and 4, Table 3). Cooling rate, at which formation of martensite begins in the amount of 2 %, decreases to $w_{6/5}$ = 8 °C/s (Figure 4, *b*). Martensite microhardness is equal to approximately 4420 MPa. Now, at cooling rate of 30 °C/s, unlike slower heating, a martensite-bainite structure with 74 % of martensite forms in the metal of HAZ overheating zone. Integral hardness of metal here rises from 3140 up to 5830 MPa. Temperature of the start of martensite transformation $T_{\rm Ms}$ = 280 °C, and it remains constant in the studied range of cooling rates. At cooling rate of 12–25 °C/s, martensite microhardness is equal to 5660–6060 MPa.

During investigations it is also established that critical cooling rate, at which not more than 50 % of martensite ($w_{\rm 50M}$) forms in the metal structure, is equal to 20 °C/s. Coming back to previous data, obtained at heating with parameters $w_{\rm heat}$ = 25 °C/s and t_1 = 23–66 s, critical cooling rate is in the range of 34–38 °C/s, when 15 to 90 % of martensite forms. For slow heating we will assume this value to be equal to $w_{\rm 50M}$ = = 35 °C/s.

At heating at a high rate the nature of overcooled austenite transformation in the intermediate region changes accordingly. Temperature range of bainite transformation becomes wider. At $w_{6/5}$ < 8 °C/s the main γ-α transformation in the metal at cooling occurs in the pearlite-bainite region in the temperature range of 680–560 °C. By analogy with slow heating (at $w_{6/5}$ = = 11–30 °C/s) predominantly upper bainite structures form in the HAZ metal at heating by WTC (see Figure 4, *a*). Metal hardness is 3090–3140 MPa, grain size is 47.5–94.0 μm.

γ-α transformation with lower bainite formation starts at the cooling rate of 12 °C/s and higher. Temperature of the start of formation in the bainite region is $T_{\rm Bs}$ = 650–630 °C, and temperature of the end of bainite transformation drops to 540–400 °C with increase of the cooling rate. So, at $w_{6/5}$ = 12 °C/s the amount of lower bainite in the structure is equal to 43 %, and at 16 °C/s it is already 61 % (see Table 3). With increase of martensite content in the metal structure, which occurs at increase of cooling rate to $w_{6/5}$ = 25 °C/s, the amount of lower bainite decreases to 26 % (Figure 4, *d*), while microhardness of structural components rises from 2900–5660 up to 3360–6060 MPa.

The influence of WTC on HAZ metal properties was determined by the method of quantitative assessment of delayed fracture resistance, generally known as Implant method [4, 5]. Surfacing of technological plates with samples-inserts was performed by mechanized gas-shielded process with Sv-08G2S wire of 1.2 mm diameter in the following mode: welding current $I_{\rm w}$ = 160–180 A, arc voltage $U_{\rm a}$ = 26–28 V, surfacing speed $v_{\rm w}$ = 14 m/h. Heat input was equal to $Q_{\rm w}$ = = 8.6 kJ/cm. Diffusible hydrogen content in the deposited metal, determined by the «pencil» sample method, was $[{\rm H}]_{\rm dif}$ = 1/3 ml/100 g. Welding of Implant samples was performed with preheat-

Table 4. WTC parameters, structure and critical stresses at delayed fracture of HAZ metal at testing by Implant method (Q_w = = 8.6 kJ/cm)

T_{pr}, °C	Thermal cycle parameters			Structure in HAZ metal overheating zone*, %	σ_{cr}, MPa
	$w_{6/5}$, °C/s	$t_{8/5}$, s	$t_{8/1}$, °C		
20	25–30	8	170	Bl = 26–24, M = 71–74	100
50	20–25	10	230	Bl = 52–26, M = 46–71	220
70	15–20	11	250	Bl = 61–52, M = 36–46	320
100	12–15	12	450	Bup ≤ 39, Bl = 57–61, M = 16–36	>460

*Bup — upper bainite, Bl — lower bainite, M — martensite.

ing at $T_{pr} \leq 100$ °C. Cooling rate $w_{6/5}$ was varied in the range of 12–30 °C/s, and in zone of HAZ metal overheating a bainite-martensite structure with different content of structural components formed. Sample loading was performed after their cooling to 50 °C temperature. During testing maximum loading stresses σ_{cr} were determined, at which no delayed fracture occurs for 24 h. Generalized results of testing samples of grade 2 wheel steel by the Implant method are given in Table 4.

Presented data show that delayed fracture resistance of wheel steel HAZ metal at surfacing without preheating (T_{pr} = 20 °C) is the lowest, critical stresses being just 0.14 of HAZ metal yield point ($\sigma_{0.2}$ ~ 715 MPa [7]), and fracture proceeds in the brittle mode. Under such conditions of surfacing a martensite-bainite structure with higher dislocation density forms in the HAZ metal overheating zone. Amount of martensite in the structure is higher than 71 %, that of lower bainite is not more than 24 %, and the level of dislocation density is up to $\rho = 5–8 \cdot 10^{10}$ cm^{-2} [12]. As a result, the metal has a lower capacity for microplastic flow under loading, stress relaxation in it runs by formation of microcracks, and it fails at quite low stresses.

At application of preheating changes occur in the structure of the metal of HAZ overheating zone and σ_{cr} values rise. So, at T_{pr} = 50 °C lower bainite content in the structure is equal to approximately 26–52 %, and volume fraction of martensite decreases accordingly. At preheating up to 70 °C, further change of structural component ratio occurs towards increase of lower bainite up to 61 %. Here critical stresses rise 3 times up to the level of $0.45\sigma_{0.2}$. At preheating up to T_{pr} = 100 °C, when the cooling rate is equal to 12–15 °C/s and martensite content in the structure is not higher than 36 %, HAZ metal does not develop delayed fracture at stresses of 450 MPa. Implant sample could not be loaded to higher stress values during testing, as deposit metal starts flowing. Therefore, at preheating temperature of 100 °C, critical stresses were conditionally taken to be above 460 MPa.

Conducted testing by Implant method showed that in order to ensure an increased delayed cracking resistance of wheel steel HAZ metal at 0.58 % C, $w_{6/5} \geq w_{50M}$ condition has to be fulfilled, which is achieved at application of metal preheating to 100 °C.

It should be further noted that the presented results of investigation of the state of metal structure in the overheating zone of wheel steel HAZ at arc surfacing and testing by the Implant method are logically interconnected. It is practically impossible to explain these data by another method, without using the diagram of overcooled austenite transformation under the real conditions of impact of arc surfacing WTC, given in Figure 2, and investigations of HAZ metal microstructure. Classical diagrams of γ-α transformation plotted under the conditions of isothermal soaking, or at constant slow heating (see Figure 2) do not reflect the real changes in the structure of HAZ metal of welded joints on high-strength carbon steels.

Conclusions

1. It is established that incompletion of the processes of metal austenite homogenizing in arc surfacing as a result of its fast overheating and limited time of staying at temperature above A_{c3}, essentially affects the subsequent γ-α transformation in the HAZ metal of high-strength wheel steel. This leads to the situation, when in the metal of wheel steel HAZ overheating zone with carbon content of 0.58 %, the critical cooling rate in the range of temperatures of 600–500 °C, at which not more than 50 % of martensite forms in the structure, decreases 1.5 times and is equal to w_{50M} = 20 °C/s. Here the minimum cooling rate, at which formation of martensite component of the structure starts, is equal to $w_{6/5}$ = 8 °C/s.

2. At heating and cooling by the thermal cycle of arc surfacing, the nature of overcooled austenite transformation in the intermediate region changes. Temperature range of austenite transformation becomes wider, and upper and lower bainite structures form in the HAZ metal. γ-α transformation with formation of lower bainite starts at $w_{6/5} \geq 12$ °C/s. Its maximum amount corresponds to the cooling rate of 16 °C/s, being equal to 61 %. With increase of cooling rate to 25 °C/s, volume fraction of lower bainite drops to 26 %, and that of martensite rises up to 71 %. Microhardness $HV0.1$ of structural components rises from 2900–5660 up to 3360–6060 MPa, and metal hardness $HV10$ in the HAZ overheating zone — from 3480 to 5660 MPa.

3. High delayed cracking resistance of HAZ metal of wheel steel with 0.58 % C, at the level of $\sigma_{cr} \geq 0.45\sigma_{0.2}$, can be ensured at $w_{6/5} \leq w_{50M}$. Such conditions of cooling in surfacing at heat input of 8.6 kJ/cm correspond to application of preheating to 100 °C.

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