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INFLUENCE OF THERMAL CYCLE OF SURFACING ON MECHANICAL PROPERTIES AND RESISTANCE OF HAZ METAL OF RAIL STEEL M76 TO BRITTLE FRACTURE

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Increasing the life of railway wheels is an urgent problem. The solution to this problem is associated with the optimization of the structural state of metal of railway wheels. In the work the influence of cooling rate during melting on mechanical properties, resistance to brittle fracture and structural changes of the HAZ metal of wheel steel with carbonitride strengthening with a carbon content of 0.63 % were investigated. It is shown that in the process of surfacing, a hardening bainite-martensitic structure is formed, the volume fraction of structural components in which is determined by the cooling rate. The hardened HAZ metal of wheel steel with carbonitride strengthening has a high strength and a low ductility with a high susceptibility to brittle fracture. 12 Ref., 2 Tables, 11 Figures.

Keywords: *arc surfacing, carbonitride strengthening, heat-affected-zone, thermal cycle, brittle fracture*

Today in Ukraine for manufacture of wheels of freight cars, wheel steel of grade 2 with a carbon content of 0.55–0.65 % is used [1, 2]. During operation, wheels wear out along the rolling profile. Due to the specifics of operation of the friction-rolling pair «wheel-rail», the working surface of a wheel flange has a more intensive wear, and on the rolling surface of a wheel, defects of a «shelled tread» type are often formed.

The modern trends in the development of mainline rail transport in Ukraine are aimed at increasing the axle load up to 27.5 t and the speed of freight trains up to 150 km/h, which predetermines the use of wheels of increased strength and wear resistance. The most promising direction for achieving this aim is based on microalloying of the existing wheel steel with carbide- and nitride-forming elements, due to which it is possible to provide a dispersion of the metal structure. This will promote the increase in ductile properties of a wheel metal at a higher level of its strength [3–5]. To reduce the probability of «shelled treads» formation on the rolling surface of a wheel, the carbon content in the steel should be limited.

It is necessary to foresee whether after the wear it will be possible to restore them by surfacing in the conditions of domestic production. Therefore, the development of a scientifically based technology for surfacing wheels manufactured of the new wheel steel, which would be based on the results of investigations of the influence of thermal deformation processes of arc surfacing on structural changes and properties of the new high-strength wheel steel, is an urgent problem.

The idea of the surfacing technology is based on the increased strength, hardness, ductile properties and cyclic crack resistance of the metal, deposited during restoration of a worn rolling profile of new rail wheels by forming a tiny bainite-martensite structure in the deposited metal, which has a good ability to resist wear during friction of a pair «wheel–rail».

Investigation procedures. *Investigation of influence of cooling rate during surfacing on mechanical properties of the HAZ metal.* The investigations were carried out using the simulation method in the installation MSR-75 [6]. As an object of investigations wheel steel with carbonitride strengthening (abbreviation is KS-TRZ — wheel steel — thermally hardened) with the following composition, wt.% : 0.63 C; 0.35 Si; 1.15 Mn; 0.16 Cr; 0.11 V, 0.019 S, 0.027 P was used. The results of investigations of wheel steel KS-TRZ were compared with the results of similar investigations of wheel steel of grade 2, GOST 10791–2004 (abbreviation is KS2) of the following composition, wt.% : 0.58 C; 0.44 Si; 0.77 Mn; 0.05 Cr; 0.01 V, 0.015 S, 0.020 P, which are given in [7].

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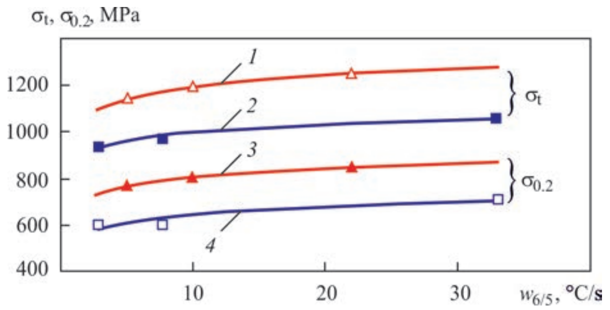

Figure 1. Influence of cooling rate on strength of HAZ metal of wheel steels KS-TRZ (*1*, *3*) and KS2 (*2*, *4*)

The specimens with the dimensions of 120×12×12 mm were used, which were heated by electric current according to a set cycle on the base of 60 mm. The maximum heating temperature of the specimens was 1200–1250 °C, the heating rate was 200–210 °C/s. In the central part of the specimens, a 40 mm wide area of metal was formed, which was homogeneous as to its structure. The cooling rate $w_{6/5}$ (in the temperature range of 600–500 °C) amounted to 5, 10 and 22 °C/s. Such cooling rates were selected based on the conditions of forming the most characteristic structures for the metal of the HAZ overheating region. After simulation of thermal cycle of arc surfacing, the special specimens were made from the specimens for evaluation of mechanical properties under static tension (specimen of type II, GOST 1497–84) and tests on impact bending (specimen of type 1, GOST 9454–78) were carried out. The investigations were carried out at a temperature of 20 °C and –40 °C.

Investigations of influence of cooling rate in surfacing on resistance of the HAZ metal to brittle fracture. Investigations were performed using model specimens of 100×20×10 mm, which were treated according to the thermal deformation cycle of arc surfacing. At the first stage of investigations, the specimens were subjected to heat treatment in the installation MSR-75. The heating rate of the notched specimens was 150 °C/s. The maximum heating temperature was 1250 °C. The cooling rates of the metal in the temperature range of 600–500 °C ($w_{6/5}$) were selected based on the conditions of forming the most characteristic metal structures of the HAZ overheating region of wheel steel KS-TRZ (according to the results of preliminary dilatometric investigations):

- $w_{6/5} = 5$ °C/s — bainitic-martensitic structure — 95 % B_l, 5 % M;
- $w_{6/5} = 22$ °C/s — martensitic structure — 18 % B_l, 82 % M.

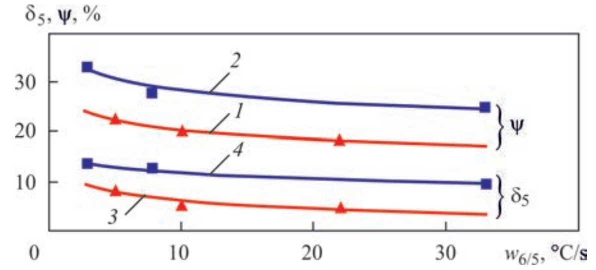

Figure 2. Influence of cooling rate on ductile properties of HAZ metal of wheel steels KS-TRZ (*1*, *3*) and KS2 (*2*, *4*)

Further, in the heat treated specimens a notch with a depth of 7 mm was mechanically made, from the top of which a fatigue crack with a depth of 3 mm was then grown. At the same time, a symmetrical load cycle with a frequency of 35 Hz and a stress cycle of 120 MPa were used. The load was performed in a low-power fatigue testing machine UMP-1. Then, the specimens with cracks were tested at a three-point bending in the Friedland installation.

The loading of specimens was carried out at a constant force when moving the punch at a speed of 1 mm/min. The value of the load at which the fracture of specimens occurs, was determined on indications of the dynamometer. The temperature of specimens during the tests was 20 °C. According to the obtained data, the critical factor of stress intensity K_{1c} was calculated [8, 9].

The fractures of specimens after testing were investigated by the methods of scanning electron emission in the scanning microscope SEM-515 of Philips Company, equipped with an energy-dispersive spectrometer of the «LINK» system.

Investigations of influence of thermal surfacing cycle on structural changes in the HAZ metal. The investigations were performed on the model specimens with a diameter of 6.0 mm and a length of 80 mm, which were made of wheel steel KS-TRZ, the chemical composition of which is indicated above. In accordance with the test method, the rigidly fixed specimens were heated to a temperature of 1250 °C at a rate of 210 °C/s (heating time is 6 s) and then cooled at different rates according to the thermal cycles of surfacing [8]. The time of staying of the metal at the temperatures higher than A_{c3}, depending on the cooling rate, was 7–10 s.

The temperature of beginning and end of the overcooled austenite transformation was determined according to the point of deviation of the tangent from the dilatometric curve, and the ratio of the phases formed as a result of transformations was determined by the method of sections [11, 12]. Subsequently, the structure of the specimens was examinated by optical metallography methods, and according to their results the correlations of structural components and their properties were specified.

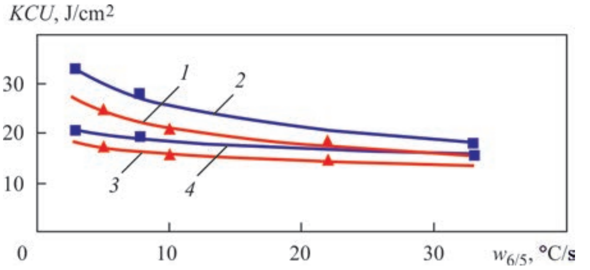

Figure 3. Influence of cooling rate on impact toughness of HAZ metal of wheel steels KS-TRZ (*1*, *3*) and KS2 (2, 4) at testing temperature of 20 °C (*1*, *2*) and –40 °C (*3*, *4*)

The metallographic examinations were performed by using Neophot-32 microscope, microhardness of separate structural components and integral hardness of the metal was measured in LECO M-400 hardness tester at the loads of 100 g (HV_1) and 1 kg (HV_{10}) respectively. The specimens for examinations were prepared by the standard method using diamond pastes of different dispersions, the reveal of microstructure was performed by chemical etching in the 4 % alcoholic solution of a nitric acid.

Results of experiments and their analysis. The generalized comparative mechanical properties of the HAZ metal of wheel steels KS-TRZ and KS2 are shown in Figures 1–3.

As is seen from the mentioned data, at high cooling rates, the hardened HAZ metal of wheel steel KS-TRZ has the highest values of strength and a low ductility. As compared to wheel steel KS2, the tensile and yield strength of the HAZ metal of steel KS-TRZ is approximately 21 % higher and the relative elongation and reduction in area are respectively lower by 50 and 26 %.

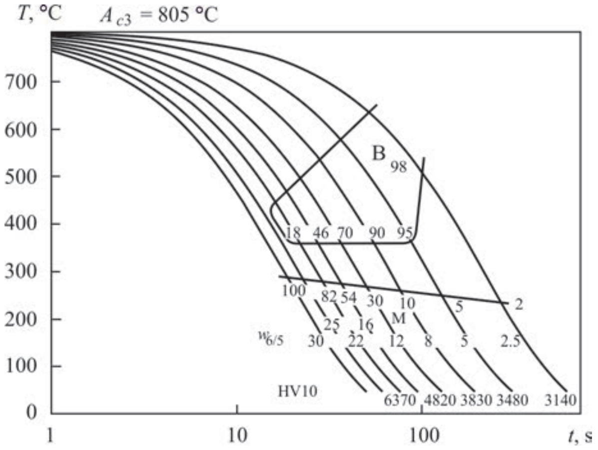

Figure 4. Diagram of transformation of overcooled austenite in HAZ metal of wheel steel KS-TRZ (0.63 % C) in arc surfacing

The strength and ductility of the HAZ metal of both wheel steel of grade KS2 as well as KS-TRZ are significantly affected by the cooling rate after heating. Thus, at $w_{6/5}$ = 22 °C/s, the strength of the hardened metal of KS-TRZ is 1250 MPa, the relative elongation is only 4.7 %, the reduction in area is 18.3 %. When the cooling is slowed down to $w_{6/5}$ = 5.0 °C/s, the values of ductility of the hardened metal can be improved by 1.2–1.8 times. But even under such cooling conditions, the values of impact toughness in the metal do not exceed 8.8 J/cm^2. It is obvious, that such a metal will have a relatively low deformation capacity under the action of external loading, and therefore an increased susceptibility to brittle fracture.

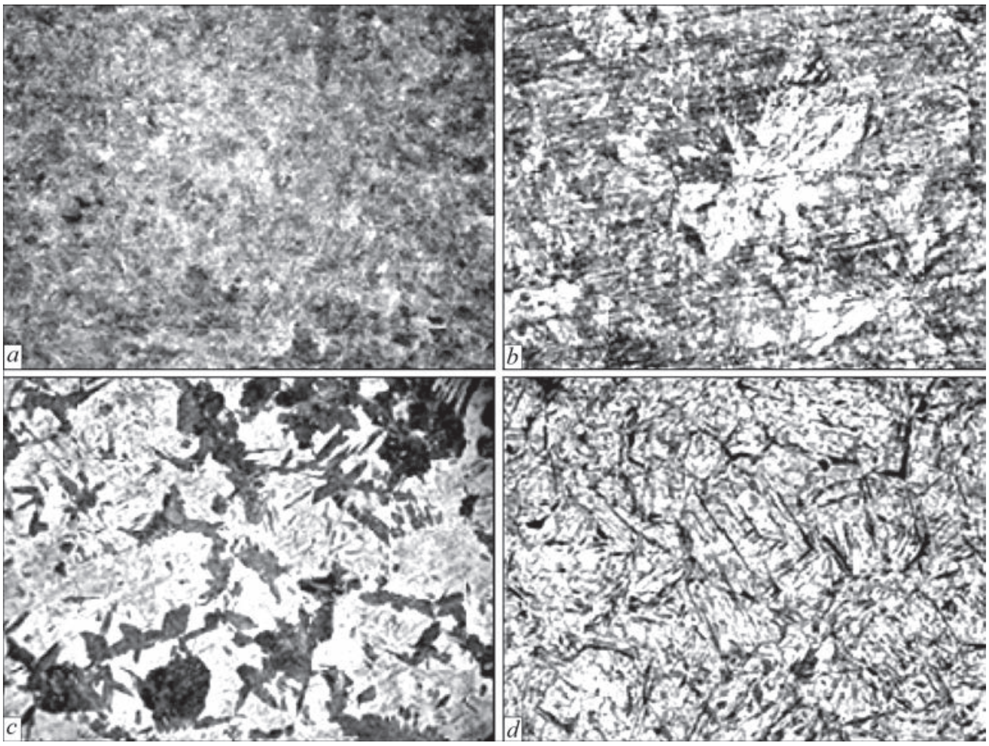

Figure 5. Microstructure (×500) of HAZ metal of wheel steel KS-TRZ: *a* — metal in the initial state; *b* — $w_{6/5}$ = 5; *c* — 22; *d* — 30 °C/s

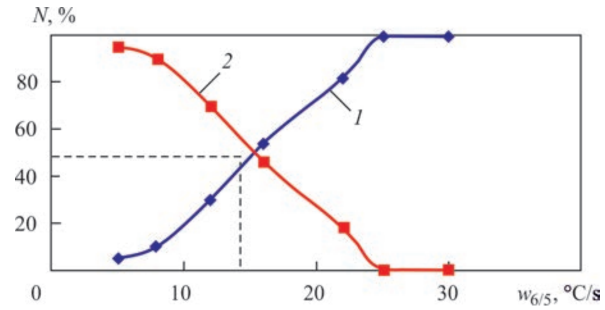

Figure 6. Influence of cooling rate on change of structure components in HAZ metal of wheel steel KS-TRZ: *1* — martensite; *2* — bainite

The mentioned changes in mechanical properties of the HAZ metal of steel KS-TRZ are most likely associated with the influence of continuous heating and cooling according to the thermal cycle of surfacing on the structure formation in the given metal. This is evidenced by the results of metallographic examinations.

In Figure 4, the generalized results of the investigations are shown in the form of a diagram of the overcooled austenite transformation in the metal of the HAZ overheating region, depending on the cooling rate in accordance with the thermal cycles of surfacing, and the metal structure is shown in Figure 5.

The structure of wheel steel KS-TRZ in its initial state is represented by a pearlite-ferrite mixture (Figure 5, *a*), the grain size is 16–32 μm, the microhardness of the structural components is HV_1–1990–2450 MPa. At the grain boundaries the ferrite fringes of 5–10 μm are located. Under the action of thermal cycle of surfacing, the structure of the metal changes significantly.

At a cooling rate of $w_{6/5}$ = 5.0–12.0 °C/s, a bainitic-martensitic structure is formed in the metal of the HAZ overheating region, in which the major part is formed by the bainitic component (Figure 4). It is mainly a lower bainite with the microhardness HV_1–3360–3780 MPa (Figure 5, *b*). As the cooling rate increases in this range, the fraction of martensite grows from 5 to 30 % and the hardness HV_{10} of the hardened metal increases from 3480 to 4820 MPa.

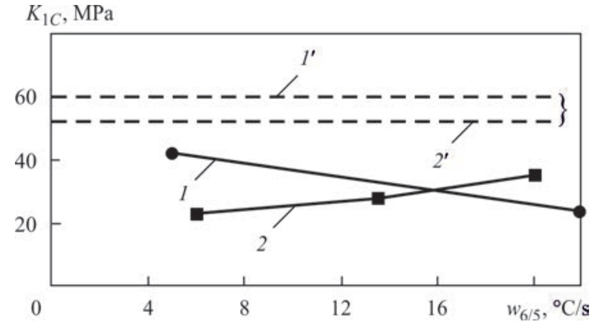

Figure 7. Resistance of HAZ metal of wheel steels KS-TRZ (*1*) and KS2 (*2*) to brittle fracture. Dashed lines — steel in the initial state

The upper bainite (HV_1–2970–3220 MPa) is the main component of the HAZ metal structure at a cooling rate of 2.5 °C/s. As the cooling rate increases to 5.0 °C/s, its fraction decreases to 20 % with a corresponding increase in the fraction of lower bainite.

Depending on the cooling rate, the martensitic transformation in the HAZ metal of wheel steel KS-TRZ begins at a temperature of 240–280 °C, and its microhardness varies from 4250 to 7830 MPa. As the cooling rate of the metal increases in the range $w_{6/5}$ = 12.0–22.0 °C/s, its fraction increases from 30 to 82 % (Figure 5, *c*). The amount of martensitic component of the structure at 50 % corresponds to the conditions of cooling, when the cooling rate will be approximately $w_{6/5} \approx 15.0$ °C/s (Figure 6). In this case the hardness of the hardened HAZ metal will be at the level of 5000 MPa.

The generalized results of investigations of the influence of cooling rate $w_{6/5}$ on the resistance of the HAZ metal of wheel steel KS-TRZ to brittle fracture are shown in Figure 7. For comparison, this Figure shows also the previously obtained results of investigations of resistance of the HAZ metal of wheel steel KS2 to brittle fracture [7].

Depending on the cooling rate of specimens, the factor K_{1c} during fracture of the HAZ metal of steel KS2 can vary in the range from 23 to 35 MPa√m. The base metal of the mentioned steel has the values of K_{1c} at the level of 51–52 MPa√m. The lowest value of stress intensity (K_{1c} = 23 MPa√m) is in the HAZ metal, whose cooling rate was 6.0 °C/s. At that time a structure was formed, consisting of upper bainite by 98 %.

At the increase in the cooling rate $w_{6/5}$ to 20 °C/s, the resistance of the HAZ metal of steel KS2 to brittle fracture grows by 1.5 times (K_{1c} = 35 MPa√m). Under the mentioned cooling conditions, a more dispersed structure of lower bainite and martensite is formed in an equal ratio.

The factor K_{1c} during the fracture of the HAZ metal of wheel steel KS-TRZ, depending on the cooling rate of specimens, i.e. their structural state, varies from 24 to 42 MPa√m. At this time, the metal with a structure of predominantly lower bainite ($w_{6/5}$ = 5.0 °C/s) has the highest resistance to brittle fracture, similar to the HAZ metal of steel KS2 at 20 °C/s. When forming a predominantly martensitic structure (at 22 °C/s), the value K_{1c} for the HAZ metal of wheel steel KS-TRZ is the lowest.

According to the results of studying fracture of specimens, the general and specific conditions of their fracture were established. The common feature for them is that in the fracture three characteristic areas are distinguished (Figure 8):

- area I — initiation and propagation of fatigue crack;
- area II — propagation of the main crack under the static bending load;
- area III — final fracture.

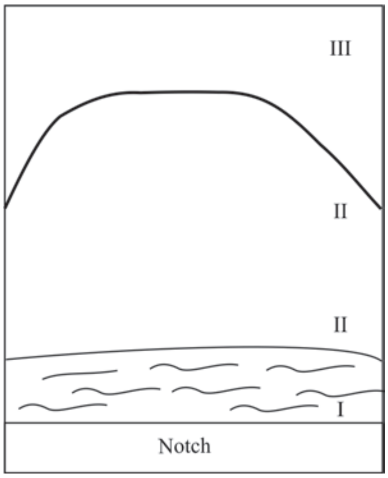

Figure 8. Conditional scheme of distribution of characteristic areas on the fracture surface of specimens during tests (description I–III see in the text)

The comparative analysis of fracture surfaces of the specimens showed that irrespective of the type of wheel steel and the structural state of the HAZ metal, the initiation and propagation of fatigue cracks has a brittle nature. In the zone of initiation of a fatigue cracks a brittle intergranular fracture was formed (Figure 9, *a*, *b*), and in the zone of propagation — a brittle transgranular fracture (Figure 9, *c*, *d*). The differences in the propagation of fatigue cracks depending on the type of wheel steel and a structural state of the HAZ metal are as follows. In the HAZ metal of steel KS2 with the structure of upper bainite ($w_{6/5}$ = 6.0 °C/s), the size of brittle fracture facets is 30–100 μm, and in the fracture of the HAZ metal of steel KS-TRZ during forming the structure of predominantly lower bainite $w_{6/5}$ = 5.0 °C/s) it is 30–70 μm. In the area I of the fractures, the secondary cracks were revealed, which were located along the boundaries of the grains, they are clearly seen in Figure 9, *a*, *b*. Their sizes also depend on the type of steel. It was established that in the metal of the HAZ overheating region of wheel steel KS2 at the mentioned cooling rates, the length of the

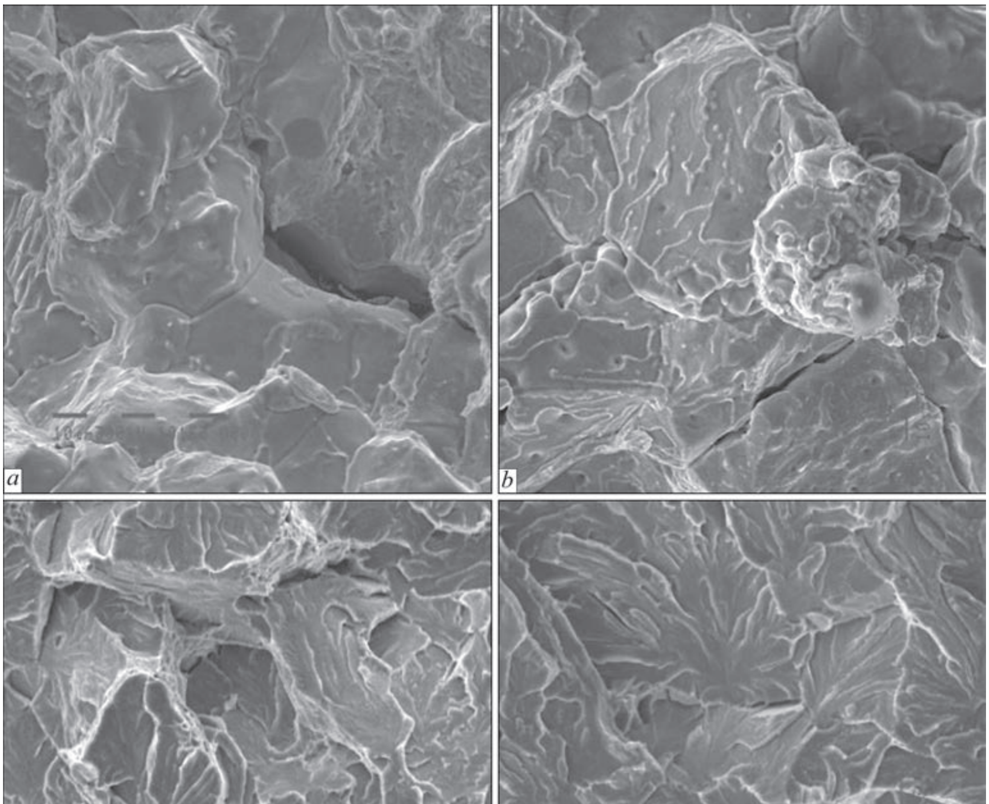

Figure 9. Typical surface of fracture of HAZ metal of wheel steels KS2 ($w_{6/5}$ = 6.0 °C/s) and KS-TRZ (5.0 °C/s) in the area of initiation (*a*, *b*) and propagation (*c*, *d*) of fatigue crack (x1010): *a*, *c* — KS2 [7]; *b*, *d* — KS-TRZ

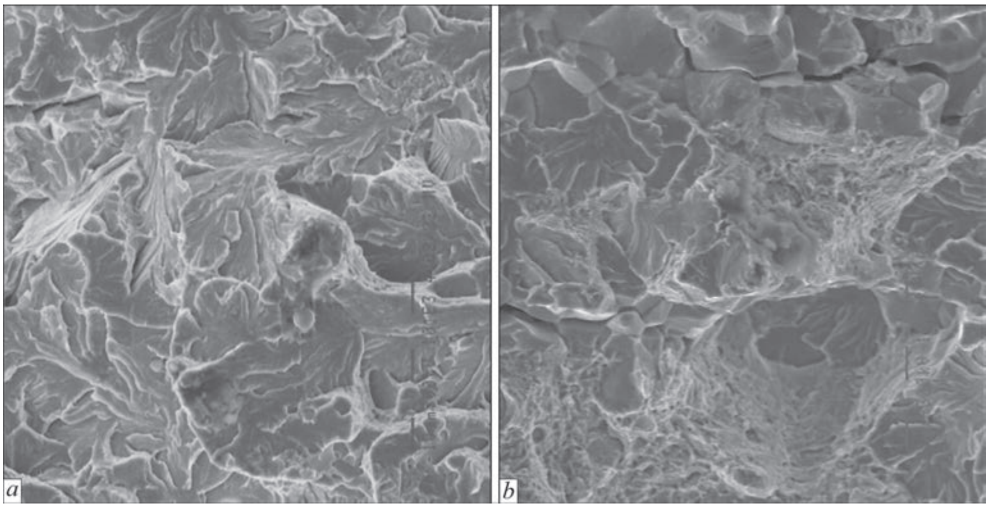

Figure 10. Typical fracture of HAZ metal of wheel steel KS-TRZ in the area of main crack propagation (×1010): *a* — $w_{6/5}$ = 5.0; *b* — 22 °C/s

Table 1. Character of fracture of HAZ metal of wheel steel KS2 [7] and steel KS-TRZ in the area of main crack propagation

Steel KS2 (C = 0.58 %)				Steel KS-TRZ (C = 0.63 %)			
$w_{6/5}$ = 6.0 °C/s		13.5 °C/s		5.0 °C/s		22 °C/s	
98 % B_u		25 % B_u, 50 % B_l, 23 % M		95 % B_l, 5 % M		18 % B_l, 82 % M	
$\frac{\text{BTF, \%}}{L_{sec}, \mu\text{m}} = \frac{100}{40}$	$\frac{\text{BIF, \%}}{L_{sec}, \mu\text{m}} - \text{N/D}$	$\frac{\text{BTF, \%}}{L_{sec}, \mu\text{m}} = \frac{100}{5}$	$\frac{\text{BIF, \%}}{L_{sec}, \mu\text{m}} - \text{N/D}$	$\frac{\text{BTF, \%}}{L_{sec}, \mu\text{m}} = \frac{100}{30}$	$\frac{\text{BIF, \%}}{L_{sec}, \mu\text{m}} - \text{N/D}$	$\frac{\text{BTF, \%}}{L_{sec}, \mu\text{m}} = \frac{85}{60}$	$\frac{\text{BIF, \%}}{L_{sec}, \mu\text{m}} = \frac{15}{60}$

secondary crack is L_{sec} = 50–100 μm, and that of steel KS-TRZ does not exceed 60 μm.

Unlike the fractures of the HAZ metal of steel KS-TRZ, which was heat treated at a cooling rate $w_{6/5}$ = = 5.0 °C/s, the secondary cracks in the zone of initiation and propagation of fatigue cracks of specimens, which predominantly had a martensitic structure (22 °C/s) were $L_{sec} \leq 200$ μm in length.

At the fracture area II, at a cooling rate $w_{6/5}$ at the level of 6.0 °C/s and 13.5 °C/s, the crack size is, respectively, not more than 40 and 5 μm [7]. In the HAZ metal of wheel steel KS-TRZ under the action of static loading, the crack propagates with a brittle nature on the grains body (brittle transgranular fracture — BTF) at $w_{6/5}$ = 5.0 °C/s, and also on the grain boundaries (brittle intergranular fracture — BIF) at 22 °C/s. The secondary cracks with the length $L_{sec} \leq 30$–60 μm were also found in the fracture structure (Figure 10).

In the area of final fracture (area III), irrespective of the type of wheel steel and structural HAZ metal, the fracture of specimens has a tough nature (Figure 10). On the fractures surface, the phase formations of up to 1–3 μm in size with a higher content of Mn, Ti, Si, Al and Ca are revealed.

Table 2. Parameters of thermal cycle in HAZ metal during arc surfacing of wheel steel (thickness is 20 mm, T_{max} = 1250–1350 °C) [10]

Input energy of surfacing Q_w, kJ/cm	Temperature of preheating T_{ph}, °C	Parameters of thermal cycle		
		Cooling rate $w_{6/5}$, °C/s	Cooling time from 800 to 500 °C $\tau_{8/5}$, s	Cooling time from 800 to 100 °C $\tau_{8/1}$, s
8.6	20	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
11.5	20	15–17	14	245
	50	12–14	16	360
	100	6–8	20	850
15.0	20	10–12	17	290

The generalized results of investigations of the HAZ metal fractures of steels KS2 and KS-TRZ are given in Table 1.

The carried out investigations showed that the HAZ metal of the studied wheel steel KS-TRZ due to the formation of hardening structures, has an increased susceptibility to brittle fracture. As compared to the initial state, the resistance of the HAZ metal to brittle fracture decreases by 1.4–2.5 times. At the same time, the change in the stress intensity factor K_{1c} during propagation of the main crack is significantly influenced by the structure-phase composition of the hardened metal. When forming predominantly the structure of the lower bainite in the HAZ metal, the K_{1c} value is the highest. Such conditions of structure formation in the HAZ can be provided in arc surfacing when the cooling rate is $w_{6/5} \leq 5.0$ °C/s.

The generalized parameters of the thermal cycle are given in Table 2.

Thus, during the investigations it was found that in the process of arc surfacing in the HAZ metal of the studied wheel steel KS-TRZ, the carbon content of which is 0.63 %, a hardening bainitic-martensitic structure is formed, the volume fraction of structural components in which is determined by the rate of cooling. As the rate of cooling of the metal increases from 5.0 to 22 °C/s, the fraction of martensite increases from 5 to 82 % , and the fraction of lower bainite decreases from 95 to 18 %. At the same time, the hardness of the hardened metal is increased by 1.8 times. The cooling rate $w_{6/5}$, when in the structure of HAZ metal 50 % of martensite is formed, is 15 °C/s. The formation of predominantly upper bainite in the structure during cooling, which is undesirable in terms of providing a relatively high level of resistance of the HAZ metal of wheel steel KS-TRZ to brittle fracture, is possible only at a cooling rate $w_{6/5} = 2.5$ °C/s.

Conclusions

During investigations, it was established that:

1. In the process of arc surfacing in the HAZ metal of the studied wheel steel with carbonitride strengthening, the carbon content in which is 0.63 %, a hardening bainitic-martensitic structure is formed, the volume fraction of structural components in which is determined by the cooling rate. As the cooling rate of the metal increases from 5.0 to 22 °C/s, the fraction of martensite increases from 5 to 82 % and the fraction of lower bainite decreases from 95 to 18 %. In this case, the hardness of hardened metal is increased by 1.8 times. The cooling rate $w_{6/5}$ during formation of 50 % of martensite in the HAZ metal structure is 15 °C/s.

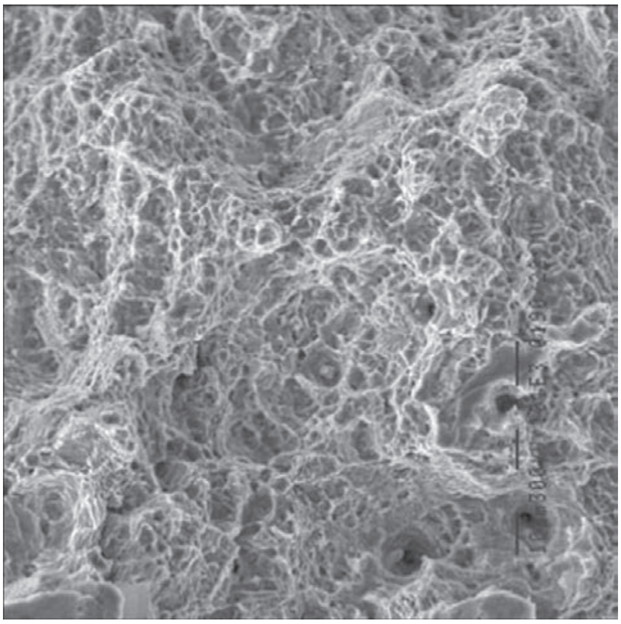

Figure 11. Fracture surface of specimens in the area of final fracture (×1010)

2. A hardened HAZ metal of wheel steel with carbonitride strengthening has a high strength and a low ductility. As compared to wheel steel of grade 2, the tensile and yield strength of the HAZ metal with carbonitride strengthening are approximately 21 % higher and the relative elongation and reduction in area are lower by 50 and 26 %, respectively.

3. To increase the ductility values of a hardened HAZ metal of wheel steel with carbonitride strengthening by 1.2–1.8 times is possible due to slowing down the cooling to $w_{6/5} = 5.0$ °C/s, when the structure of the lower bainite is predominantly formed in the metal.

4. HAZ metal of the studied wheel steel with carbonitride strengthening due to the formation of hardening structures has an increased susceptibility to brittle fracture. As compared to the initial state, the resistance of the HAZ metal to brittle fracture is by 1.4–2.5 times reduced. At the same time, the structural-phase composition of the hardened metal is significantly influenced by the change of the stress intensity factor during propagation of the main crack. When a predominant structure of the lower bainite is formed in the HAZ metal, the value K_{1c} is the highest. Such conditions of structure formation in the HAZ can be provided by arc surfacing, when the cooling rate will be $w_{6/5} < 5.0$ °C/s.

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