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INCREASE OF BRITTLE FRACTURE RESISTANCE OF METAL OF HEAT-AFFECTED ZONE IN RAILWAY WHEEL SURFACING

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Presented results are continuation of the complex investigations and refer to effect of low-temperature tempering, which is carried out in process of delayed cooling of products after welding, on mechanical properties and crack resistance of the joints of high-strength steel with 0.55–0.65 % carbon content. It is determined that tempering at 100 °C during four hours promotes rise of ductility property indices of quenched metal of heat-affected zone by 70 %, that of impact toughness 3 times, crack resistance 4.5 times, welded joint life duration 2 times. It is related with 1.5 times decrease of dislocation density in a volume of bainite and martensite laths as well as relaxation of stresses of II type. 14 Ref., 2 Tables, 7 Figures.

Keywords: *high-strength carbon steel, arc welding, heat-affected zone, low-temperature tempering, mechanical properties, brittle fracture, life*

One of the main problems in welding of high-strength steels is embrittlement of heat-affected zone (HAZ) metal due to formation in it of the quenching structures with low capacity to microplasma deformation. It is well known fact [1, 2] that ductile properties of quenched HAZ metal predetermine the possibility of cold cracks formation in the joints during welding as well as further workability of welded joints under effect of operation loads. Different technological methods are used in order to increase metal resistance to brittle fracture. The most efficient among them are thermal methods of welded joint treatment. Thus, the joints are preheated before welding, that allows regulating cooling rate and structure-phase composition of quenched HAZ metal. As a rule, this technological operation permits welding high-strength steel joints without cold cracks formation in them [3, 4]. However, preheating does not always efficiently influence HAZ metal resistance to brittle fracture under effect of external loading. In order to solve this problem the products after welding are subjected to tempering at temperatures from 250 to 600 °C. Thermal mode of tempering (heating rate, temperature and duration of holding, cooling rate) depends on content and level of steel strength, geometry of the products. Tempering allows stabilizing structure of welded joint metal as well as significantly decreases level of stresses in the structure [5, 6]. The disadvantages of the method are large energy expenses and necessity in special equipment use.

Issue of increase of brittle fracture resistance of quenched HAZ metal is the most pressing in welding of high-strength steel joints with 0.55–0.65 % carbon content. Work [7] shows that the value of critical coefficient of stress intensity K_{1c} has 4–8 times reduction for HAZ in comparison with metal in initial state. Also, it was determined that 2–3 times increase of brittle fracture resistance of quenched HAZ metal requires welding conditions providing formation of structure with prevailing portion of lower bainite. At that, content of hydrogen in HAZ metal should not exceed 0.2 ml/100 g. However, brittle fracture resistance of HAZ metal of high-strength carbon steel joints is significantly lower than that in base metal even at such welding conditions.

Today high-strength carbon steels are widely used in manufacture of railway wheels and bands for main transport, urban passenger transport and enterprises' transport. Carbon content in steels varies from 0.55 to 0.70 % and main alloying elements are silicon (up to 0.60 %) and manganese (up to 1.20 %) [8]. The wheels are worn in process of long-term operation and their restoration is carried out using surfacing methods. Surfacing technology assumes application of preheating and delayed cooling of wheel after surfacing. Thus, in restoration of the wheels, made of wheel steel of grade 2 (0.55–0.65 % C), a temperature of preheating makes 150 °C and after surfacing the wheels are cooled in heat chambers to 20–30 °C temperature during 4–5 h [9–10]. Necessity of application of delayed cooling as technological operation for deposited wheels was experimentally determined back in the 1990th. It allowed eliminating formation of cracks in deposited wheels at their restoration. At the same time it was also shown that increase of preheating temperature to 250 °C, but without delayed cooling of wheel after surfacing, does not provide significant effect in rise of crack resistance of restored wheels.

Aim of the present work is to determine effect of cooling conditions on structure, mechanical properties, brittle fracture resistance of HAZ metal and life of welded joints of high-strength steels with 0.55–0.65 % carbon content.

Materials and investigation method. Wheel steel of grade 2 (wt.% 0.58 C; 0.44 Si; 0.77 Mn; 0.10 Ni; 0.05 Cr; 0.012 S; 0.011 P) and carbon steel of 65G grade (0.65 C; 0.19 Si; 0.91 Mn; 0.18 Ni; 0.16 Cr; 0.017 S; 0.010 P) were used as materials for investigation.

The investigations were carried out on model and welded specimens. Work [7] in details describes the methods of preparation and testing of the specimens. Cooling rate of the model specimens in simulation of thermal-deformation welding cycle in 600–500 °C temperature interval ($w_{6/5}$) made 6 °C/s. Bainite structure (100 %) is formed at this cooling rate in HAZ metal of grade 2 wheel steel and bainite-martensite structure in steel 65G at relationship of portion of structural constituents 66/34. At that, part of the specimens were subjected to continuous cooling to room temperature, and another ones after reaching specific temperature were put in a furnace, hold at this temperature during set time and then they were cooled in air to 20 °C under natural conditions. Tempering (holding) mode of the specimens in the furnace was selected based on temperature of wheel tread after surfacing, which made approximately 260 °C, and time of wheel cooling in the heat chamber. Effect of tempering temperature of 200, 150, 100 and 50 °C at specimens' holding in the furnace during 1–4 h was investigated. Further they were used for making the specimens for static tension (GOST 1497), impact (GOST 9454), three-point bend (GOST 25.506) and metallographic investigations. 3 specimens for each mode of heat treatment were produced for mechanical tests, the results were averaged.

Structure of heat treated metal, distribution, dislocation density and specimen fractures were examined using optical microscopy, scanning and electron microscopy methods (SEM-515 of Philips Company, JEM-200CX of JEOL Company). Further, local deformation (ε_{loc}) and structural stresses of II type (τ_{loc}) were determined using experimentally found parameters of substructure depending on metal cooling conditions.

Fatigue fracture resistance of welded joints, cooling of which took place under different conditions, was evaluated at cyclic bending loading with symmetric cycle according to generally accepted methods [12]. The tests were carried out with the specimens of butt joints of 400×85 mm size, 10 mm (65G) and 20 mm (KS2) thickness, which were welded by mechanized submerged arc welding in 3 and 6 passes, respectively. Welding of the specimens was performed using Sv-08KhM wire of 2 mm diameter on the following mode, namely welding current 240–280 A, arc voltage 28–30 V and welding rate 24 m/h.

Specific welding heat input at such modes made 10 kJ/cm. Preheating of the joints up to 150 °C was carried out before welding in order to eliminate the possibility of cold crack formation. After cooling the welded specimens were tested on UMP-1 unit at symmetric loading cycle with 14 Hz frequency. Cycle stresses (σ_a) were measured in 60–120 MPa range. A criterion of evaluation was the maximum stresses (fatigue limit σ_{-1}) , at which welded joint has no fatigue cracks after 2 mln cycles of loading.

Results of investigation and their discussion. Influence of temperature and time of tempering on change of mechanical properties of HAZ metal was evaluated using model specimens of steel 65G. Figure 1 shows generalized results of carried tests. A zero point on diagram abscissa scale is a value of mechanical properties of HAZ metal, cooling of which was carried out continuously on welding thermal cycle.

It is determined that tempering in 50–200 °C temperature range during four hours does not have significant effect on change of strength properties of quenched HAZ metal (Figure 1, *a*). Short-term strength of metal lies in 1120–1090 MPa range and conventional yield strength of metal made 745–760 MPa. But, as can be seen from presented data, the temperature value of low tempering has more significant influence on ductility properties and impact toughness of HAZ metal, and this is nonequivalent (Figure 1, *b*, *c*). Relative elongation rises 1.3 times (from 6.7 to 9 %) and contraction increases 1.7 times (from 15 to 25.6 %) at tempering temperature 100 °C. At 150–200 °C tempering these indices gradually decrease to initial level. The same tendency is observed with impact toughness indices of HAZ metal, at that their rise is more significant. There is 3.1 times (from 7 to 22 J/cm^2) increase of *KCU* value at 20 °C testing temperature, 2.7 times (from 6 to 16 J/cm^2) at –20 °C and 2.5 times (from 5 to 12.3 J/cm^2) at –40 °C.

Taking into account received data, the further evaluation was performed as for influence of time of holding at 100°C temperature on change of ductility and toughness of HAZ metal of steel 65G. Figure 2 shows generalized results of these investigations. It is determined that significant increase of indices of ductile properties and impact toughness has already been observed at two hours tempering. Increase of time of

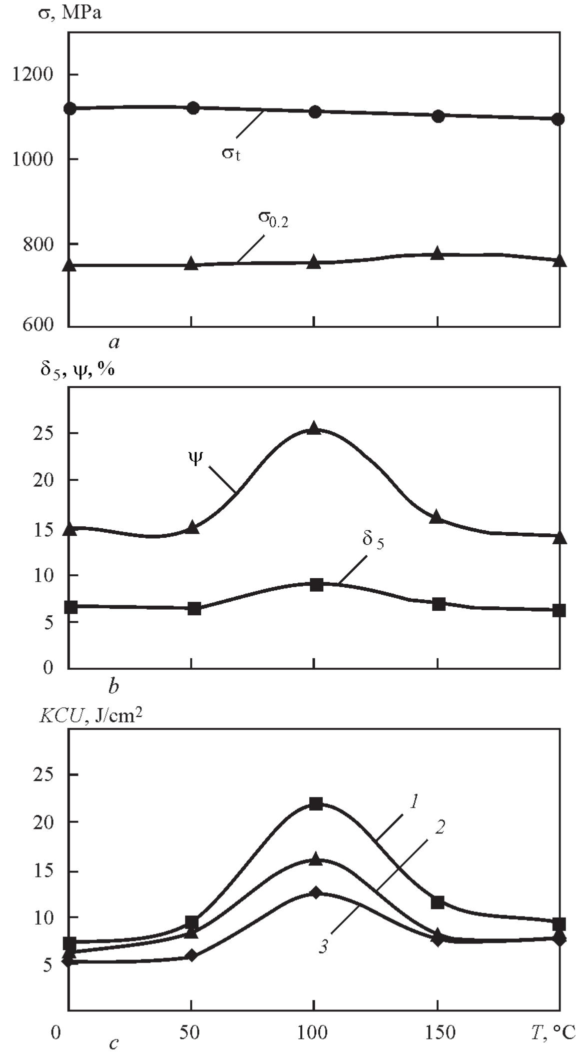

Figure 1. Effect of tempering temperature of 4 h duration on indices of strength (*a*), ductility (*b*) and impact toughness (*c*) of HAZ metal of steel 65G at testing temperature: *1* — 20; *2* — –20; *3* — –40 °C

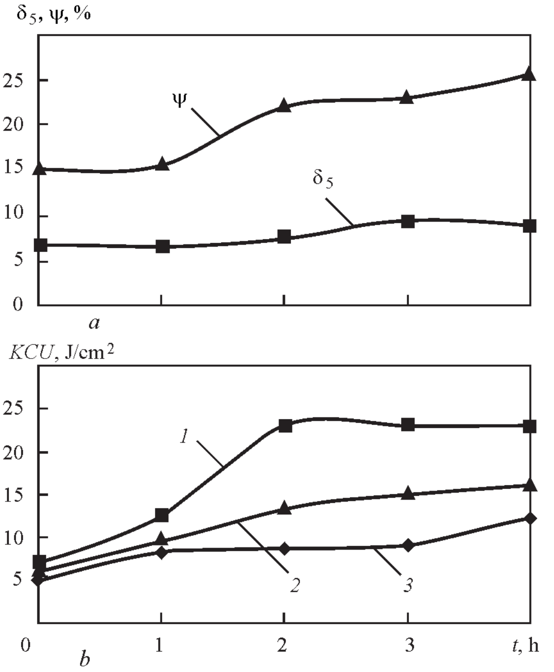

Figure 2. Effect of holding time at 100 °C tempering on indices of ductility (*a*) and impact toughness (*b*) of HAZ metal of steel 65G at testing temperature: *1* — 20; *2* — –20; *3* — –40 °C

metal holding at 100 °C to four hours promotes rise of its ductility by 16–22 %, indices of impact toughness at testing temperature 20 °C virtually do not change and at negative temperatures they increase by 21 and 40 %, respectively.

Obviously that enhancement of HAZ metal ductility as a result of delay of its cooling at 100 °C for 2–4 h can be related only with changes on substructural level since phase transformations to this moment in the majority of cases have already finished (temperature of start of martensite transformation 240 °C) [7]. Reduction of its ductility at higher tempering temperature (150–200 °C), apparently, takes place as a result of development of processes of carbon redistribution and precipitation of carbides in form of fine plates at bainite and martensite laths boundaries [5].

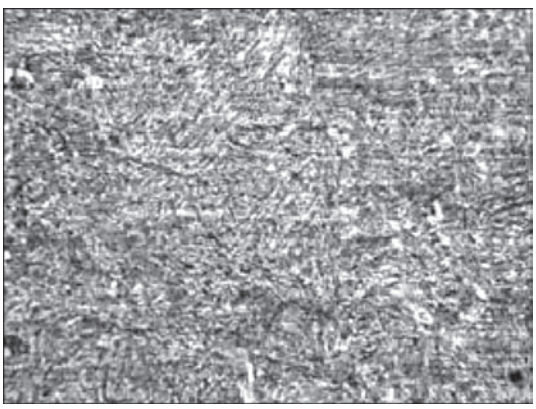

Figure 3. Microstructure of HAZ metal of steel 65G (×500)

Optical metallography methods did not detect substantial difference in the structure of quenched metal of the specimens, which were cooled under different conditions (Figure 3). For all cooling variants the structure is presented mainly by lower bainite (B_L) with *HV*0.1-3620–3860 MPa microhardness and martensite (M) (4120–4410 MPa). Volume fraction of upper bainite (B_U) with 3030–3210 MPa microhardness does not exceed 10 %. Separate areas of pearlite (2570–2710) and residual austenite (2700 MPa) of total volume not more than 2 % were also found.

Special electron-microscopy examinations of fine structure of the specimens were carried out for confirmation of changes in substructural level in HAZ metal, which take place at low-temperature tempering. The specimens that were continuously cooled on welding thermal cycle and specimens with four hours holding at 100 °C were selected for this. Table 1 shows generalized results of the investigations.

It is determined that tempering of HAZ metal during its cooling provoked changes in the substructural level, and they lied in the following. Dislocation density ρ in the elements of structure decreased approximately 1.5

Table 1. Parameters of fine structure, calculation values of local deformation and second type stresses (HAZ, steel 65G)

Cooling conditions	Structure elements	Lath width h, μm	Dislocation density ρ, cm^{-2}	Local deformation ε_{loc}, %	Second type stresses τ_{loc}, MPa
Continuous cooling on WTC	B_U	0.2–0.5	$4–5\cdot10^{10}$	2.8–9.0	739–924
	B_L	0.4–0.7	$6–7\cdot10^{10}$	8.4–17.5	1109–1294
	M	0.8–1.2	$7–8\cdot10^{10}$	17.5–33.6	1294–1474
On WTC from 100 °C, tempering 4 h, further in air	B_U	0.2–0.5	$3–3.5\cdot10^{10}$	2.1–6.3	554–646
	B_L	0.4–0.7	$4–4.5\cdot10^{10}$	5.6–11.25	739–830
	M	0.8–1.2	$5–6\cdot10^{10}$	14.0–25.0	924–1109

times (Table 1). At that width of the laths h of structural constituents does not change. Besides, together with simple quenching martensite (Figure 4, *b*) there were local areas of tempering martensite (Figure 4, *d*) in the metal. A calculation method, using substructure parameters, determined local deformations and stresses of II type. It is determined that local deformations and stresses in the volume of upper bainite laths showed 1.4 times reduction, that for lower bainite made 1.5 times and 1.3–1.4 times for martensite. Obviously, that these changes in the substructural level are the main factor of increase of indices of ductile and impact toughness properties of HAZ metal. These positive changes should, as a consequence, promote increase of its brittle fracture resistance.

Work [7] notes that the critical coefficient of stress intensity K_{1c} for HAZ metal of steels 65G and KS2 at cooling rate $w_{6/5}$ = 6 °C/s and hydrogen content $[H]_{dif}$ = = 0.5 ml/100 g makes 11 and 17.5 MPa √m, respectively, that is 6.5 and 3 times lower than the indices for steels in their initial state. These indices of metal brittle fracture resistance were received in testing of the specimens in course of not more than 0.5 h after their hydrogenation. K_{1c} indices increased 1.9 and 1.5 times (Figure 5), respectively, in testing of the similar specimens after aging (recovery) during 72 h at room temperature. Obviously, it is related with diffusion processes and partial removal of hydrogen from quenched metal.

K_{1c} index during two hours tempering at 100 °C for KS2 steel HAZ increased 1.8 times (from 17.5 to 32 MPa√m). More significant 4 times rise of brittle fracture resistance (from 11 to 45 MPa√m) under these conditions of cooling is noted for steel 65G HAZ metal. In our opinion, these changes can be explained by effect of two factors. First of all, it is complete removal of diffusion hydrogen from metal, that can be experimentally proved using «pencil tests» with model specimens after their fracture. Secondly, as it was determined earlier, due to relaxation of stresses of II type in the quenched metal structure. Mutual effect

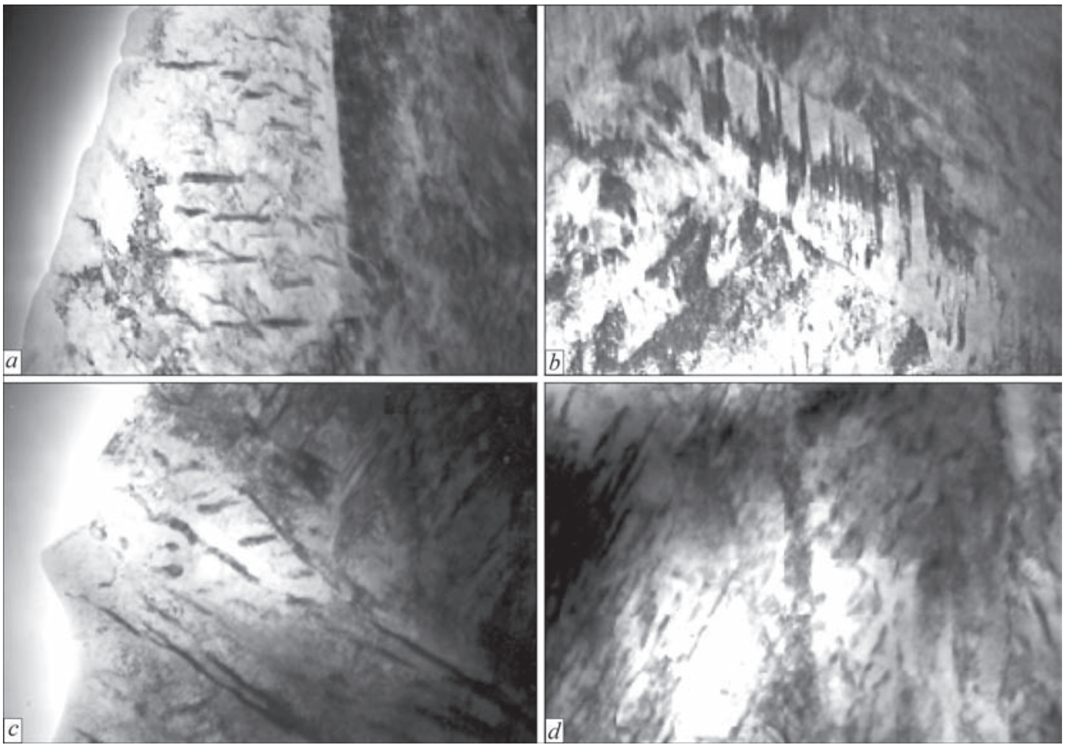

Figure 4. Elements of fine structure of HAZ metal of steel 65G at continuous cooling on welding thermal cycle (*a*, *b*) and with tempering at 100 °C during four hours (*c*, *d*) (×30000): *a*, *b* — B_L; *c*, *d* — M

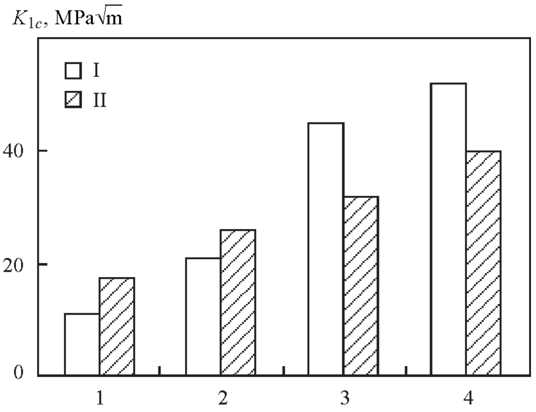

Figure 5. Brittle fracture resistance of HAZ metal of steels 65G (I) and KS2 (II) ($[H]_{dif}$ = 0.5 ml/100 g) depending on cooling conditions (1–4 — numbers of experiments in accordance to Table 2)

of these two processes were more obvious in testing of HAZ metal with bainite-martensite structure. Increase of holding time in the furnace at 100 °C up to four hours promotes approximately 10 % (Figure 5) additional rise of crack resistance in HAZ metal of studied steels.

Structure of fractures was examined on HAZ metal of steel KS2. Table 2 shows generalized results of fracture examination in a zone of main crack propagation, and Figure 6 represents typical fracture types. It is determined that nature of the fracture will dramatically change at holding of HAZ metal at 100 °C during 2–4 h. There is no brittle intercrystalline fracture (BCF) on the fracture surface, portion of brittle intraglanular fracture (BGF) increases up to 80–90 %, length of secondary cracks (L_{sec}) significantly reduces (from 120 to 30 μm), and portion of tough constituent in the fracture rises up to 10–20 %.

Carried investigations showed that application of low-temperature tempering (at 100 °C) during 2–4 h in process of cooling of railway wheels after their surfacing allows dramatic up to 4.5 times increase of resistance of quenched HAZ metal to brittle fracture, approximating it to high-strength steel indices in initial state. Taking into account that the wheel tread in process of continuous surfacing is heated to 260 °C, these technological operations can be fulfilled without additional energy expenses at delayed cooling of railway wheels in the heat chambers. In order to keep metal temperature at 100 °C level during long time it is necessary to use heat-insulating materials in a heat chamber structure, being additionally applied to the wheels, or use heating to 50 °C in the general heat chambers, where wheel pairs are set after surfacing. It is experimentally determined that time of metal holding in the temperature range 130–90 °C rises up to four hours under such conditions of wheel cooling after surfacing.

Enhancement of resistance of HAZ metal of high-strength carbon steels to brittle fracture has positive effect on change of welded joint fatigue resistance (Figure 7). Fatigue limit of the joints increases 1.5–2.0 times applying tempering at 100 °C in course of four hours in process of cooling. Moreover, a tendency of change of welded joint fatigue limit differs depending on type

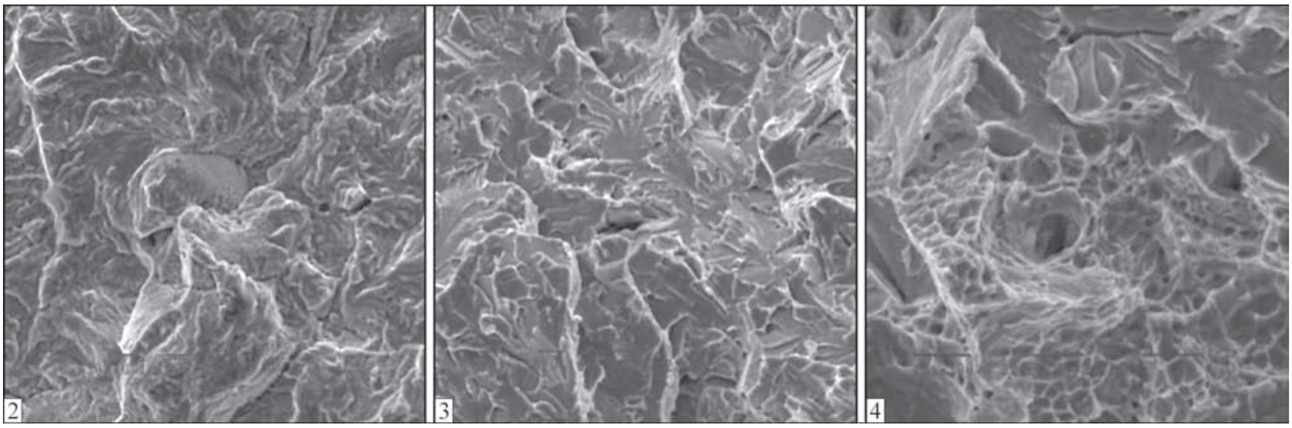

Figure 6. Fracture surface of HAZ metal of steel KS2 in zone of main crack propagation depending on cooling conditions (2, 3 — ×1010; 4 — ×2020); 2–4 — numbers of tests (see Table 2)

Table 2. Fracture nature in zone of main crack propagation (HAZ, steel KS2)

Number of experiment	Cooling conditions	K_{1c}, MPa√m	Fracture characteristics		
			BGF, %/ L_{sec}, μm	BCF, %/ L_{sec}, μm	Tough, %
1	Continuous cooling on WTC	17.5	70/120	30/120	–
2	Continuous cooling on WTC, holding 72 h	26	95/30	–	5
3	On WTC to 100 °C, tempering 2 h, further in air	32	90/30	–	10
4	On WTC to 100 °C, tempering 4 h, further in air	40	80/30	–	20

of investigated steel. Apparently, it is related with different structural state of quenched HAZ metal. Thus, cooling rate in HAZ of the joints with indicated welding conditions made $w_{6/5}$ = 13–15 °C/s. Bainite-martensite structure (relationship of structural constituents approximately 70/30) is formed in HAZ metal of steel KS2 at this cooling rate, and that in steel 65G is mainly martensite (volume fraction of bainite not more than 3 %) [7]. Therefore, fatigue limit of the joints of steel KS2 during two hours holding at 100 °C in comparison with four hours makes already 92 % of maximum value, 110 and 120 MPa, respectively, and only 67 % (80 MPa) for steel 65G. This indicates that two hours holding at 100 °C in formation of mainly martensite metal structure is not enough for relaxation of II type stresses. Realization of microplastic changes in such metal requires more time. It should also be noted that the same results [13] were obtained at H.V. Karpenko Phyciso-Mechanical Institute of the NAS of Ukraine (Lviv) during independent investigations on evaluation of changes at propagation of fatigue cracks in HAZ metal depending on cooling conditions.

In the conclusion it should be noted that carried investigations allowed improving surfacing technology in order to increase reliability of repaired wheels in railway transport operation. A novelty of the technology is proved by the patent of Ukraine [14]. It in addition to new requirements on cooling conditions of railway wheels after surfacing includes the requirements to value of preheating temperature depending on carbon content in wheel steel and level of welding consumables alloying.

Conclusions

1. It is determined that application of low-temperature tempering at 100 °C during two-four hours in process of cooling of welded joints of high-strength steels with 0.55–0.65 % carbon content promotes rise of indices of ductility properties of quenched HAZ metal up to 1.7 times and that of impact toughness up to 3 times at keeping its high strength level. Enhancement of HAZ metal ductility takes place due to positive changes in the substructural level. At that there is 1.5 times reduction of dislocation density in the lath volume of bainite and martensite as well as level of II type stresses in the structure of quenched HAZ metal.

2. Application of low-temperature tempering at 100 °C in surfacing of railway wheels in process of their cooling allows significant (up to 4.5 times) rise of resistance of quenched HAZ metal to brittle fracture, approximating its to as-delivered high-strength steel indices. Fatigue fracture resistance of welded joints rises up to two times at that.

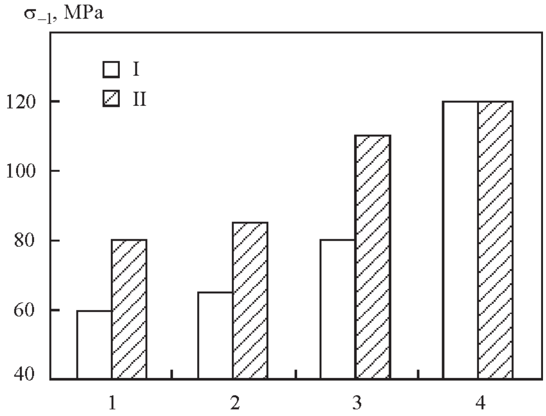

Figure 7. Effect of cooling conditions on fatigue strength of welded joints of steel 65G (1) and KS2 (II); 1–4 — numbers of experiments in accordance with Table 2

1. (1972) *New methods for assessment of resistance of metals to brittle fracture*. Ed. by Yu.N. Robotnova. Moscow: Mir.
2. Makarov, E.L. (1981) *Cold cracks in welding of alloy steels*. Moscow: Mashinostroenie.
3. Kasatkin, O.G., Mikhoduj, L.I., Kasatkin, S.B. et al. (1995) Resistance to delayed and brittle fracture of HAZ metal of 14Kh2GMR type high-strength steels. *Avtomatich. Svarka*, **2**, 7–10.
4. Skulsky, V.Yu. (2009) Peculiarities of kinetics of delayed fracture of welded joints of hardening steels. *The Paton Welding J*., **7**, 12–17.
5. Efimenko, M.G., Radzivilova, N.O. (2003) *Physical metallurgy and heat treatment of welded joints*. Kharkiv: NTU KhPI.
6. Anokhov, A.E., Korolkov, P.M. (2006) *Welding and heat treatment in power engineering*. Kyiv: Ekotekhnologiya.
7. Gajvoronsky, A.A., Poznyakov, V.D., Markashova, L.I. et al. (2016) Brittle fracture resistance of HAZ metal in arc-welded joints of high-strength steels with carbon content of 0.55–0.65 %. *The Paton Welding J*., **9**, 2–8.
8. Babachenko, A.I., Litvinenko, P.L., Knysh, A.V. et al. (2011) Improvement of chemical composition of steel for railway wheels providing of their resistance invrease to defect formation on roll surface. In: *Fundamental and applied problems of ferrous metallurgy: Transact., Dnepropetrovsk*, 226–233.
9. Matveev, V.V. (2007) *Restoration of railway wheels using surfacing*. Kiev: PWI.
10. Gajvoronsky, O.A. (2016) Conditions of quality assurance of railway wheels restored by surfacing. Science and progress of transport. *Visnyk DNUZT im. V. Lazaryana*, 5(**65**), 136–151.
11. Markashova, L.I., Poznyakov, V.D., Berdnikova, E.N. et al. (2014) Effect of structural factors on mechanical properties and crack resistance of welded joints of metals, alloys and composite materials. *The Paton Welding J*., **6/7**, 22–28.
12. (1990) *Strength of welded joints under alternating loadings*. Ed. by V.I. Trufyakov, Kiev: Naukova Dumka.
13. Haivoronskyi, O.A., Poznyakov, V.D., Markashova, L.I. et al. (2016) Structure and mechanical properties of the heat-affected zone of restored railway wheels. *Mater. Sci*., 51(**4**), 563–569.
14. Gajvoronsky, O.A., Poznyakov, V.D., Klapatyuk, A.V. (2014) *Method of restoration of high-carbon steel products*. Pat. 107301, Ukraine. Int. Cl. B23P 6/00.

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