https://doi.org/10.37434/tpwj2020.05.01

STRUCTURE AND CRACK RESISTANCE OF SPECIAL STEELS WITH 0.25−0.31 % CARBON UNDER THE CONDITIONS OF SIMULATION OF THERMAL CYCLES OF WELDING

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The impact of thermodeformational cycle of welding on structural-phase transformations in the HAZ metal of armour steel of 30Kh2NMF type with different carbon content (0.25; 0.29 and 0.31 %) was studied. At the next stage, structural changes in model samples–simulators with 0.31 % carbon at different cooling rates (3.8; 12.5 and 21 °C/s) and their fracture mode after bend testing were studied. As a result of the performed studies, it was established that the structure ensuring the optimum level of strength and fracture toughness, forms when low cooling rates are used (below 3.8 °C/s). 13 Ref., 3 Tables, 6 Figures.

Keywords: special high-strength steel, thermodeformational welding cycle, thermokinetic transformation diagrams, heat-affected zone, microstructure, fracture mode, crack resistance

In the middle of the previous century, special armoured vehicles were made predominantly from steels of the following alloying systems: Cr−Mn−Mo; Cr−Ni−Mn−V, Cr−Ni−Mn−Mo, etc., which had 0.7–1.5 % Mn, 0.7–2.5 % Cr, 1.1–3.0 % Ni, 0.1–0.2 % V, 0.2–0.6 % Mo and 0.25–0.5 % carbon [1]. Further development of special steels followed the path of optimization of their chemical composition and application of special heat treatment modes that allowed increasing the hardness, ultimate strength and decreasing the content of carbon and sulphur, lowering the risks of cold cracking. Tempered martensite structure is the main structural component of these steels. Such steels are high-strength steels with $\sigma_{0.2} \geq$ 1300 MPa and $\sigma_t \geq \geq$ 1500 MPa.

Nowadays, heat-hardened high-strength steels alloyed by Cr, Ni, Mn and Mo with carbon content from 0.25 to 0.50 % which are additionally alloyed with V, Al, and B, are widely used during manufacture of welded components and bodies of wheeled armoured vehicles. Depending on their purpose, special steels can have medium ≥ 2850 MPa, increased ≥ 3350 MPa and high ≥ 3630 MPa hardness, which they develop after the respective heat treatment [2, 3].

One of the main requirements made of the welded joints of special steels, consists in that the hardness of metal in the joint HAZ should not be lower than that of base metal hardness. As structures from the mentioned steels are not hardened after welding, but are subjected to low-temperature tempering, it becomes obvious that the required values of HAZ metal hardness should be formed after welding.

It is known [4, 5] that the mechanical properties of metal are determined by its structural composition. Moreover, formation of the structure in the metal of welded joint HAZ depends not only on the chemical composition of steels, but also on the temperature-time cooling modes — thermal cycles of welding. Under certain conditions, when the metal is cooling down at a low rate after heating, it can be softened. And with increase of the cooling rate, its hardness and static strength usually increase.

However, welded joints of high-strength medium-carbon alloyed steels are prone to cold cracking. This is associated with formation of hardening structures and residual stresses in the HAZ metal [6−9]. Local preheating is used, in order to reduce the risk of cold cracking in the welded joints of these steels. On the one hand, it allows controlling the kinetics of phase transformations and forming structures with higher cold cracking resistance, and on the other hand — creating the conditions for active desorption of hydrogen from the welded joint metal. In a number of cases, however, welding high-strength special

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steels with more than 0.25 % C content becomes an insoluble problem for many developers of armoured vehicle design.

On the other hand, the problems in development of new high-strength steels for armoured vehicles still remains urgent. So, presence of defects in the welded joint zone was found recently in a number of cases at manufacture of armoured vehicle bodies from steel of 30Kh2N2MF type, even before their use [10]. This points to the fact that the problem of producing sound welded joints can be related not only to technological features of armoured welding, but also to the quality of the steel proper, namely uniformity of its structure, chemical composition and presence of defects.

In order to clarify the possible circumstances of appearance of low-quality welded joints of the bodies of armoured vehicles for the Ukrainian army, it is necessary to precisely determine the structural state of steel, applied in production, in as-delivered condition and possible structural-phase changes, occurring during welding of this steel. It is also necessary to take into account the rather broad range of carbon content (from 0.25 to 0.35 %), characteristic for this steel.

Brittle fracture resistance that is usually assessed by fracture mechanics criteria, also is a significant factor, determining the reliability of technical means from armoured steels.

Therefore, the main objective of the work, was evaluation of the impact of thermal-deformational cycles of welding (TDCW) on structural-phase transformations in the HAZ metal of armoured steel, determination of their structural inhomogeneity and establishing the relationship between the structure that forms and brittle cracking susceptibility (crack resistance) of this steel with different carbon content.

Materials and experimental procedures. At the first stage of the work, the structure-phase transformations in the HAZ metal of armoured steel of 30Kh2N2MF type with different content of carbon (Table 1) was studied at simulation of TDCW, using Gleeble 3800 complex [11, 12]. In keeping with the method, cylindrical steel samples of 6.0 mm diameter and 80 mm length were used, which were heated up to the temperature of 1250 °C in vacuum. Simulation cycles were selected in keeping with the established parameters of the thermal cycle in the HAZ of welded joints of 20 mm thickness at mechanized welding in shielding gas atmosphere. Accordingly, the rate of sample heating in Gleeble 3800 complex was equal to approximately 210 °C/s in the temperature range of 20−1200 °C, cooling rate was $w_{6/5}$ = 2.5–30 °C/s in the temperature range of 600–500 °C. When studying the kinetics of austenite decomposition the temperature of the start and end of transformation was determined by the tangent to the dilatometric curve, and the ratio of phases that formed as a result of transformation, was established by the random linear intercept method [13].

At the second stage, the structural changes and fracture mode of armoured steel with 0.31 % carbon were studied, depending on the cooling rate ($w_{6/5}$ = 3.8, 12.5 and 21 °C/s), using a complex of light metallography research methods (Versamet-2, Neophot-32) and analytical scanning microscopy (SEM-515, PHILIPS Company, Netherlands). The images were recorded, using Olympus digital camera. Microhardness of the structural components and integral microhardness of the HAZ metal were measured in the microhardness meter M-400 of LECO Company at the load of 100 g (*HV* 0.1) and 1 kg (*HV* 1) to GOST 2999−75).

Experimental results and their analysis. Base metal of armoured steel with 0.25 % carbon content in as-delivered condition without heat treatment (HT) is characterized by the rolled texture; its structure is mainly represented by upper bainite (Figure 1, *a*). Integral hardness of metal is HV_1 = 2830–2960 MPa.

The metal structure changes under the impact of TDCW. Generalized results of the studying the impact of the cooling rate on the structural-phase transformations in the HAZ metal of welded joints of armoured steel with 0.25 % carbon, are shown in Figure 2, *a* in the form of a thermokinetic diagram of transformation of overcooled austenite. As shown by the conducted studies, in the range of cooling rates $w_{6/5}$ = 2.5–30 °C/s the transformation of overcooled austenite in the HAZ metal of steel with 0.25 % carbon occurs exclusively in the martensite region. The temperature of the start of martensite transformation is equal to 360 °C, the temperature of its end is 150 °C (Figure 2). It should be also noted that at increase of the cooling rate the size of martensite packets is reduced from 34 to 12.5 mm, and integral hardness HV_1 rises from 3680 to 5070 MPa.

Studies of armoured steel with 0.29 % carbon content (after heat treatment) showed that the rolled texture in the metal is not as clearly manifested as in steel

Table 1. Chemical composition of armoured steel with different content of carbon, wt.%

Material	C	Si	Mn	Cr	Ni	Mo	Cu	V	Al	Ti	S	P
Armoured steel	0.25	1.24	0.71	1.68	2.20	0.24	<0.02	0.18	0.032	0.019	0.007	0.01
	0.29	0.78	0.73	1.68	2.0	0.30	<0.02	0.18	0.036	0.016	0.009	0.012
	0.31	93.3	1.16	0.74	1.16	2.26	0.3	0.2	0.04	0.024	0.01	0.016

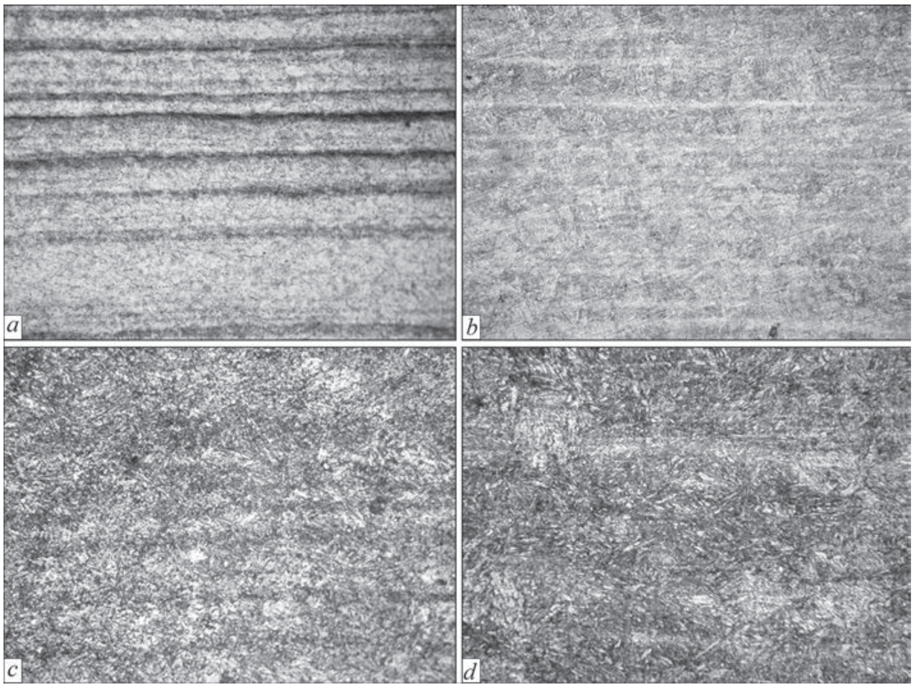

Figure 1. Structure of base metal of armoured steel with different carbon content, % C: *a* — 0.25; *b* — 0.29; *c*, *d* — 0.31 (×200, reduced two times at printing)

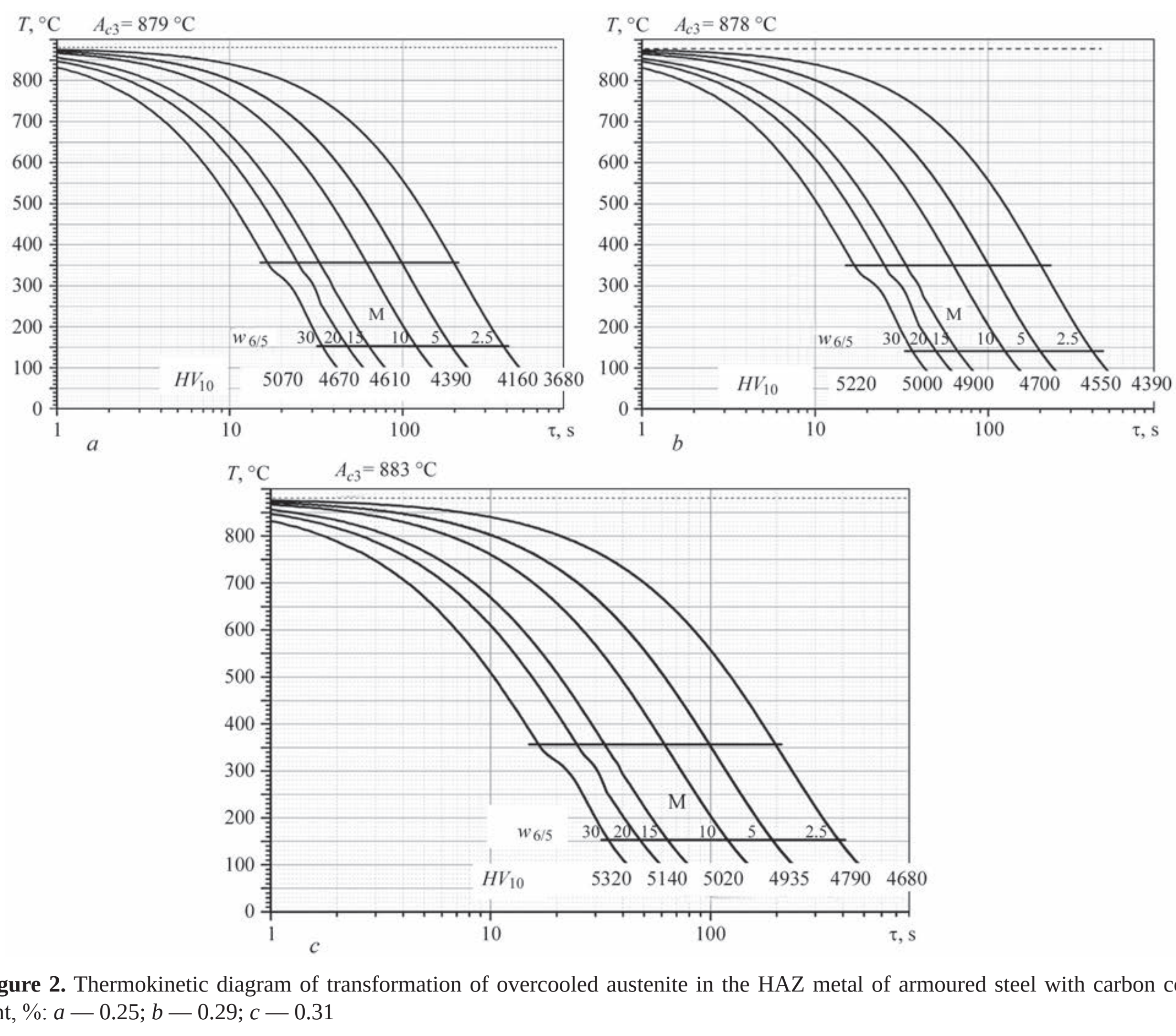

Figure 2. Thermokinetic diagram of transformation of overcooled austenite in the HAZ metal of armoured steel with carbon content, %: *a* — 0.25; *b* — 0.29; *c* — 0.31

Table 2. Structural parameters: packet size (D_p); volume fraction (V_{fr}, %); microhardness (*HV*) of structural components in the HAZ metal of samples of armoured steel (0.31 % C) at different cooling rates ($w_{6/5}$)

Parameter	Cooling rate $w_{6/5}$, °C/s		
	3.8	12.5	21
V_{fr}, %*	88−90 % M 10−12 % B_l	93−95 % M 5−7 % B_l	95−98 % M 3−5% B_l
D_p, μm	35−80	20−70	15−50
HV, MPa	4420 (B_l) 4980−5600 (M)	4880 (B_l) 5030−6060 (M)	4800 (B_l) 5360−6810 (M)

*Volume fraction of structural components was determined by the method of transmission electron microscopy (this material will be included into the next publication).

without HT. Metal structure is more uniform, and consists of dispersed martensite (Figure 1, *b*), integral hardness of metal is HV_1 = 4420–4560 MPa. Figure 2, *b* shows the generalized results of studying the impact of cooling rate on structural-phase transformations in the HAZ metal of welded joints with 0.29 % carbon, in the form of thermokinetic diagram of transformation of overcooled austenite.

In the HAZ metal of armoured steel with 0.29 % carbon, the overcooled austenite transformations in the range of cooling rates $w_{6/5}$ = 2.5–30 °C/s occurs also in the martensite region, similar to the previous case. Unlike steel with 0.25 % carbon, in steel with 0.29 % carbon the temperature of the start of martensite transformation is somewhat lower and is equal to 350 °C, that of the end of transformation is 140 °C (Figure 2, *a*, *b*). At increase of the cooling rate, the size of martensite packets decreases from 35.6 to 12.5 μm on average, integral value of microhardness increases from 4390 up to 5420 MPa.

Results of the conducted studies show that unlike steel, where carbon content is equal to 0.25 %, in the HAZ metal of steel with 0.29 % carbon, a martensitic structure of higher hardness and strength forms at cooling rate $w_{6/5} \geq 15$ °C/s.

Investigations of armoured steel with 0.31 % carbon in as-delivered condition (without HT) showed that the structure of predominantly upper bainite forms at a small amount of lower bainite (Figure 1, *c*). After HT (quenching and high-temperature tempering) the steel structure changes and consists of martensite and lower bainite (Figure 1, *d*).

Thus, in the considered range of cooling rates, the transformations of overcooled austenite in the HAZ metal of steel with 0.31 % carbon occur exclusively in the martensite region. Irrespective of the sample cooling rate, martensite transformation starts from the temperature of 360 °C, and ends at the temperature of 150 °C (Figure 2, *c*). With increase of the cooling rate, the size of martensite packets decreases, similar to the previous cases, from 34 to 12.5 μm on average.

With the purpose of further studying the structural-phase changes in the model samples-simulators from armoured steel, depending on the cooling rate ($w_{6/5}$ = 3.8; 12.5 and 21 °C/s), investigations of steel with 0.31 % C were conducted by the methods of light and scanning electron microscopy. At metallographic investigations the following structures: bainite, martensite, and their parameters: packet size (D_p), volume fraction of the structures (V_{fr}, %), which form in the metal of HAZ overheated zone, were studied, as well as the respective microhardness changes (Table 2).

It was established that at increase of the cooling rate from $w_{6/5}$ = 3.8 up to 12.5 °C/s and $w_{6/5}$ = 21 °C/s, the volume fraction of martensite becomes greater at reduction of the fraction of the bainite component, structure refinement (packet size is reduced 2 times)

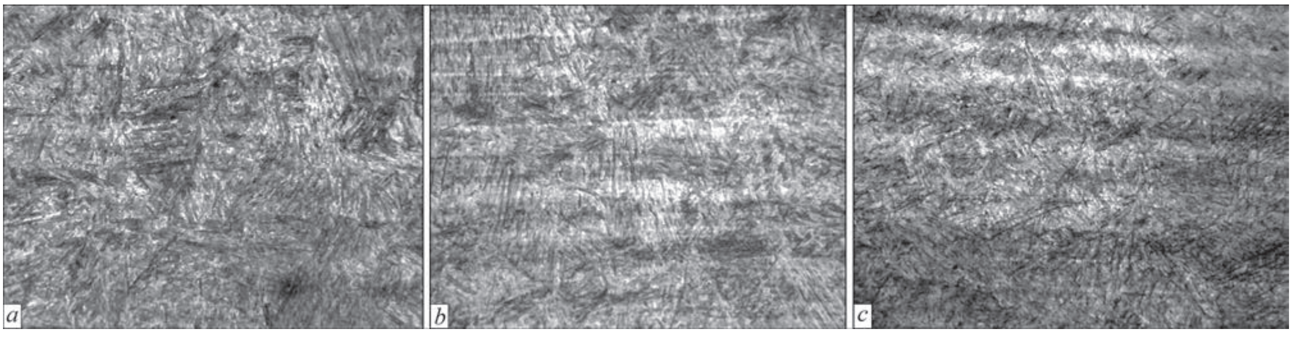

Figure 3. Microstructure (×500) of HAZ metal of model samples of armoured steel, cooled at different rates $w_{6/5}$, °C/s: *a* — 3.8; *b* —12.5; *c* — 21

Table 3. Results of fracture toughness testing of armoured steel (0.31 % C) at different cooling rates ($w_{6/5}$)

Critical coefficient of stress intensity	Cooling rate $w_{6/5}$, °C/s		
	3.8	12.5	21
K_{1c}, MPa·m$^{1/2}$	110	85	70

and increase of microhardness (by 13 % on average) (Table 2, Figure 3).

In order to evaluate the crack resistance of the HAZ metal of armoured steel samples at different cooling rates $w_{6/5}$, investigations of the impact of structural factors on the fracture mode at three-point bend testing at external load were conducted. Mechanical testing showed that the largest values of fracture toughness, namely the critical coefficient of stress intensity K_{1c} = = 110 MPa·m$^{1/2}$ of the metal was obtained at cooling rate $w_{6/5}$ = 3.8 °C/s (Table 3). K_{1c} value decreases at increase of the cooling rate up to $w_{6/5}$ = 12.5 and 21 °C/s. Such changes of fracture toughness are associated with the impact of the cooling rates on the structural-phase changes in the metal of the studied samples, namely reduction of the amount of lower bainite and increase of the amount of the martensite component.

Mechanical testing was followed by detailed fractographic analysis of the structure of sample fractures, taking into account the fracture modes, and parameters of microrelief elements of the fracture surface by the characteristic fracture zones: fatigue crack zone (near the notch); main fracture zone; final fracture zone (Figures 4−6).

Fractographic studies of the sample produced at cooling rate $w_{6/5}$ = 3.8 °C/s, showed the uniform type of quasibrittle fracture in the fatigue crack zone, with quasicleavage facet size d_f = 2–7 μm, and local areas of the tough component (d_{pit} = 2 – 5 μm), Figure 4 *a*, *b*. At transition to the main crack zone, the fracture mode is predominantly (V_{fr} = 90 %) ductile with pit size d_{pit} = 2–4 μm (Figure 4, *c*, *d*). The main crack zone is characterized by the presence of isolated secondary cracks of length L_{cr} = 10–15 μm (Figure 4, *e*). In the final fracture zone, the fracture mode is also ductile with pit size d_{pit} = 2–7 μm (Figure 4, *f*).

At increase of the sample cooling rate up to $w_{6/5}$ = = 12.5 °C/s, quasibrittle fracture with the size of quasicleavage facets d_f = 3–10 μm and local areas of the ductile component (d_{pit} = 2–5 μm) was found in the fatigue crack zone brittle fracture, Figure 5, *a*, *b*. At transition into the main crack zone the fracture mode is predominantly ductile (V_{fr} = 75–80 %) with pit size d_{pit} = 2–6 μm (Figure 5, *c*, *d*, *e*) and secondary cracks are absent. In the final fracture zone, fracture mode is ductile with pit size d_{pit} = 2–8 μm (Figure 5, *f*).

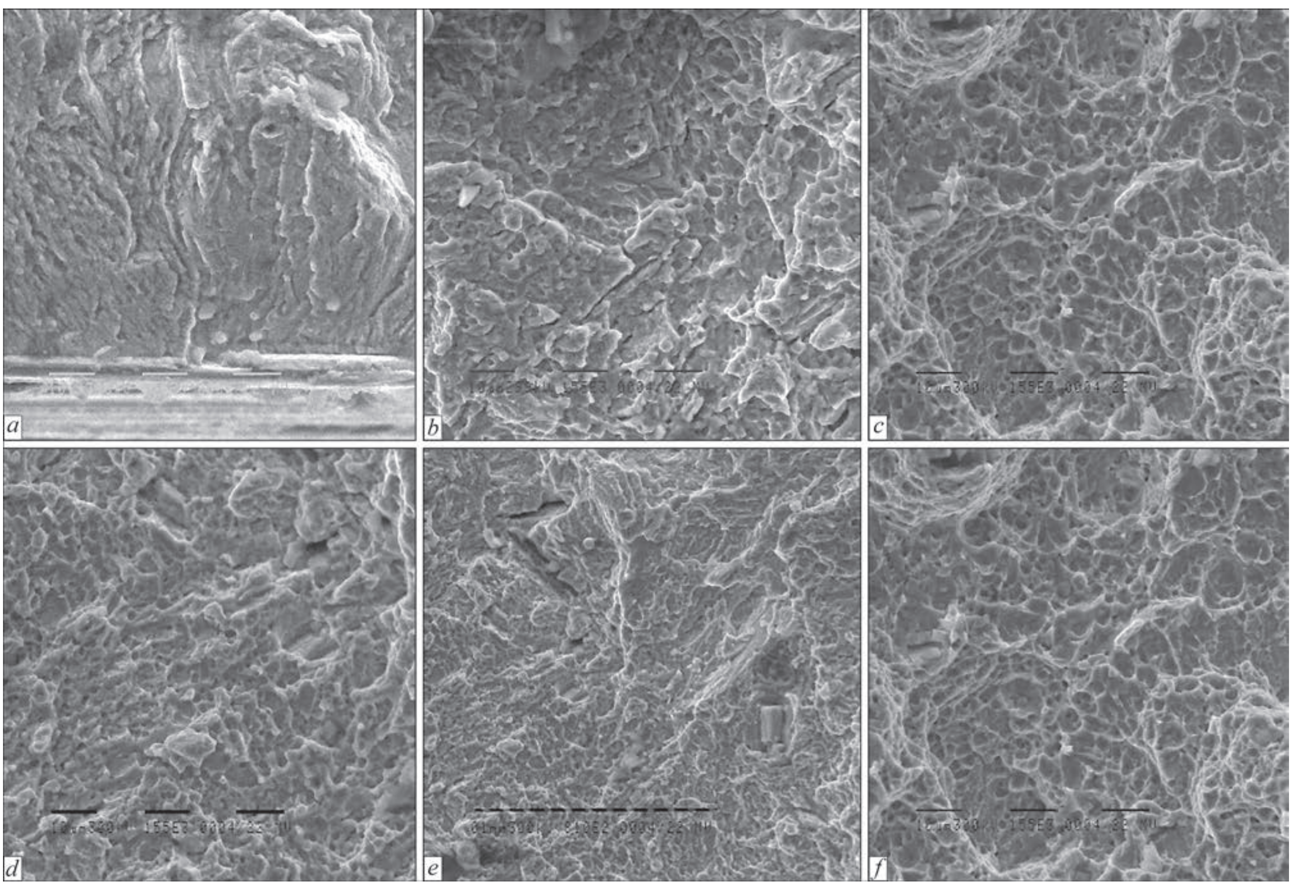

Figure 4. Fracture mode by fracture zones of armoured steel ($w_{6/5}$ = 3/8 °C/s): *a*, *b* — in the fatigue crack zone; *c*, *d*, *e* — in the zone of main crack propagation; *f* – in the final fracture zone (*a*–*d*, *f* — ×1550); *e* — ×810)

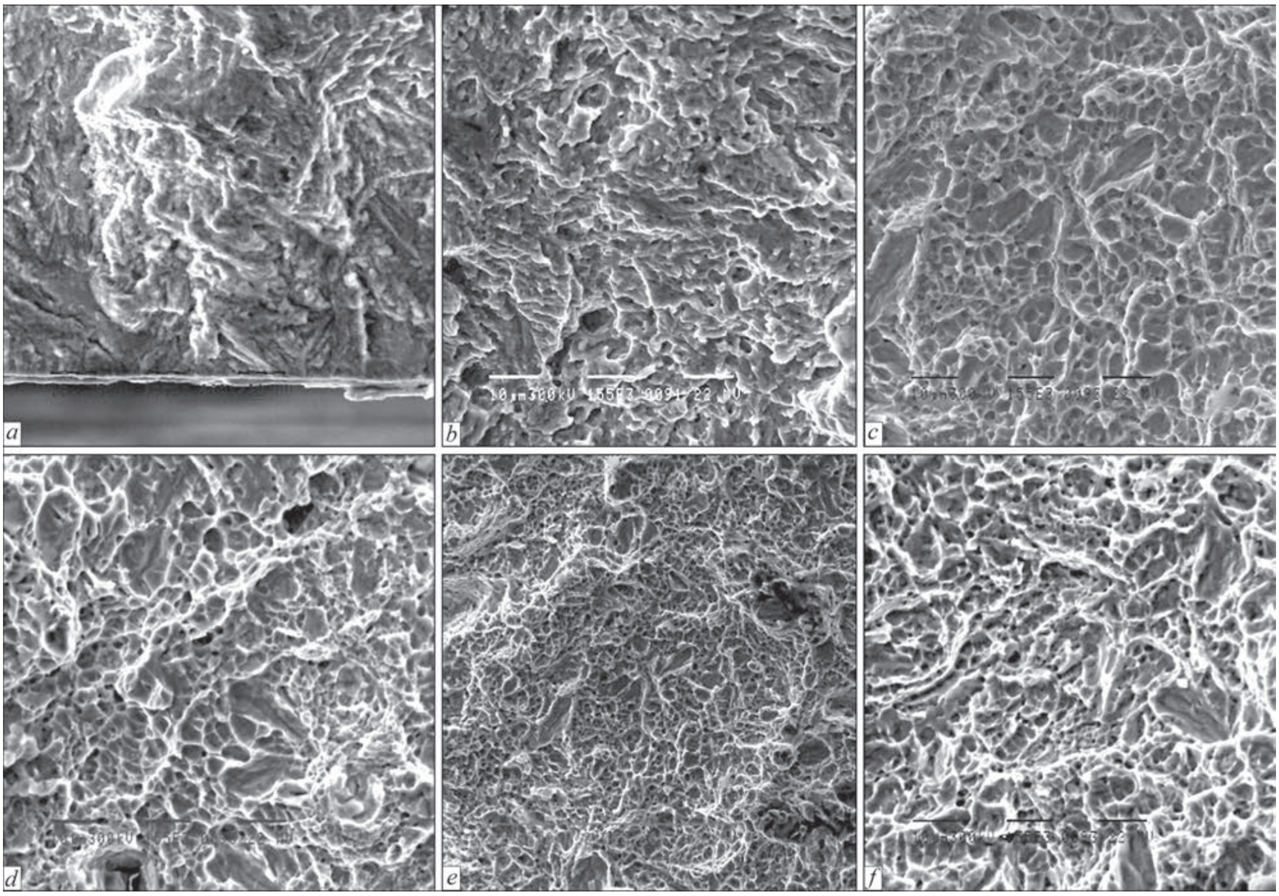

Figure 5. Fracture mode by zones of armoured steel fracture ($w_{6/5}$ = 21 °C/s): *a*, *b* — in fatigue crack zone; *c*–*e* — in the zone of main crack development; *f* — in final fracture zone (*a*–*d*, *f* — ×1550; *e* — ×810)

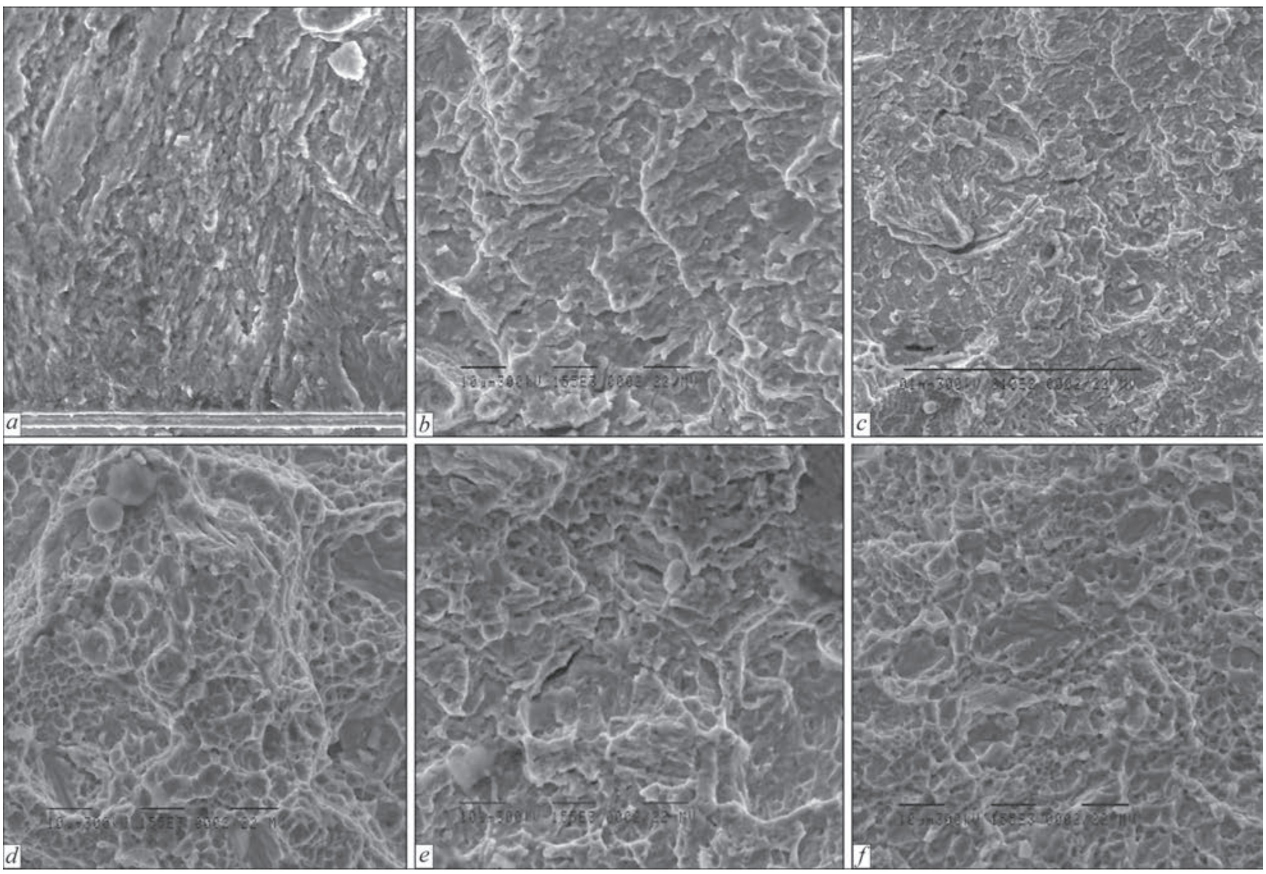

Figure 6. Fracture mode by the zones of armoured steel fracture ($w_{6/5}$ = 21 °C/s): *a*–*c* in fatigue crack zone; *d*, *e* — in the zone of main crack propagation; *f* — in final fracture zone (*a*, *b*, *d*–*f* — ×1550; *a* — ×810)

At $w_{6/5}$ = 21 °C/s, the fatigue crack zone demonstrates a uniform type of quasibrittle fracture with quasicleavage facet size d_f = 3–15 μm and secondary cracks of length L_{cr} = 10–15 μm, their volume fraction being V_{fr} = 2 % (Figure 6, *a*–*c*). At transition into the main crack zone, the fracture mode is predominantly ductile (V_{fr} = 70 %) with pit size d_{pit} = 2–6 μm (Figure 6, *d*, *e*). The main crack zone is characterized by presence of isolated secondary cracks of length L_{cr} = = 8–15 μm (Figure 6, *e*). In the final fracture zone, the fracture mode is also tough with pit size d_{pit} = 2–8 μm (Figure 6, *f*).

Thus, it was found that at $w_{6/5}$ = 3.8–21 °C/s the fracture mode in the fatigue crack zone is quasibrittle. However, in the zone of the main crack development, the fracture mode changes at increase of the cooling rate: volume fraction of the ductile fracture becomes smaller (V_{fr} = 90 to 70 %). In the quasibrittle fracture sections (V_{fr} = 10–30 %) the size of quasicleavage facets becomes larger in the presence of secondary cracks on the fracture surface.

As a result, fractographic studies showed that the optimum structure of armoured steel of 30Kh2N2MF type, from the view point of phase composition, microhardness and minimum parameters of the fracture surface relief elements, at maximum volume fraction of the ductile component is achieved at cooling of the HAZ metal at the rate $w_{6/5}$ = 3.8 °C. This is related to increase of the amount of lower bainite and reduction of the quantity of the martensitic component.

Conclusions

It is found that under the conditions of simulation of thermal cycles of welding ($w_{6/5}$ = 2.5–30 °C/s) of armoured steel of 30Kh2N2MF type with 0.25–0.31 % carbon in shielding gas atmosphere, the transformation of overcooled austenite in the HAZ metal occurs exclusively with formation of the bainite-martensite structure.

Increase of the cooling rate (up to $w_{6/5}$ = 21 °C/s) in welding with armoured steel (0.31 % C) leads to lowering of the fracture toughness coefficient from 110 to 70 MPa·m$^{1/2}$ that is due to increase of the martensitic component (up to 97–98 %) at increase of metal microhardness.

Optimum fine-grained martensite-bainite structure of the metal of armoured steel (0.31 % C), from the view point of phase composition, microhardness, and minimum volume fraction of quasibrittle fracture at mechanical testing for fracture toughness, forms at the metal cooling rate $w_{6/5}$ = 3.8 °C/s, that ensures the metal crack resistance.

1. Otroshchenko, B. (2005) Let armour become stronger and tanks be improved. *Metall Bulleten, Ukraine*, **10** [in Russian].
2. Kashirsky, Yu.V. (2000) Information bank on mechanical engineering materials and modes of treatment. *Tyazholoe Mashinostroenie*, **4**, 12–19 [in Russian].
3. Goldshtejn, M.I., Grachev, S.V., Veksler, Yu.G. (1985) *Special steels*. Moscow, Metallurgiya [in Russian].
4. Kuchuk-Yatsenko, S.I., Grigorenko, G.M., Novikova, D.P et al. (2007) Effect of energy input on ductile properties of flash butt welded joints in steel X70. *The Paton Welding J.*, **6**, 2–6.
5. Gulyaev, A.P. (1960) *Heat treatment of steel*. Moscow, Mashgiz [in Russian].
6. Seo, J.S., Kim, H.J., Ryoo, H.S. (2008) Microstructure parameter controlling weld metal cold cracking. *J. of Achievements in Materials and Manufacturing Eng.*, **27**, 199–202.
7. Sterenbogen, Yu.A. (1986) Some factors determining resistance of HAZ metal of martensitic steels to cold crack formation. *Avtomatich. Svarka*, **6**, 5–8 [in Russian].
8. Skulsky, V.Yu. (2009) Peculiarities of kinetics of delayed fracture of welded joints of hardening steels. *The Paton Welding J.*, **7**, 12–17.
9. Gajvoronsky, A.A., Sarzhevsky, V.A., Gordonny, V.G. (1997) Weldability of medium-carbon alloyed steel 38Kh2MYuA. *Avtomatich. Svarka*, **4**, 20–24 [in Russian].
10. Kostin, V.A., Grigorenko, G.M., Poznyakov, V.D. (2019) Peculiarities of HAZ metal structure formation of welded joints of foreign special steels. *Svarochn. Proizvodstvo*, **12**, 50–56 [in Russian].
11. Grigorenko, G.M., Kostin, V.A., Orlovsky, V.Yu. (2008) Current capabilities of simulation of austenite transformations in low-alloyed steel welds. *The Paton Welding J.*, **3**, 22–24.
12. Cherepin, V.T. (1968) Experimental technique in physical materials science. Kiev, Tekhnika [in Russian].
13. Krimer, B.I., Panchenko, E.V., Shishko, L.A. et al. (1966) *Laboratory practical work on metallography and physical properties of metals and alloys*. Moscow, Metallurgiya [in Russian].

Received 24.02.2020