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PREVENTION OF COLD CRACKING IN ARMOUR STEEL WELDING

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ABSTRACT

The work presents the results of investigations of cold cracking susceptibility of welded joints on modern high hardness armour steels and gives recommendations on their prevention. Investigations were performed using a calculation method according to EN 1011-2:2001 — the Implant method to determine the delayed fracture resistance of the HAZ metal and rigid technological test in welding multilayer joints. It is found that in arc welding the joints of high hardness armour steels have a higher susceptibility to cold cracking in the HAZ metal. In welding with low-alloyed consumable of Sv-10GSMT type application of preheating allows avoiding them. The preheating temperature can be calculated by CET and PT indices in keeping with the armour steel composition. In the presence of steel raisers in the welded joints the calculated preheating temperature should be increased by 50–70 °C. The welded joints made with high-alloyed consumable of Sv-08Kh20N9G7T type have higher delayed fracture and cold cracking resistance. In manufacture of light armoured vehicles, it is recommended to select armour steel with carbon content of not more than 0.26 %. In welding such armour steel by low-alloyed consumables sufficiently high cold cracking resistance of welded joints is ensured, even in the presence of stress raisers, due to preheating up to the temperature of 150 °C, as well as in welding without preheating at application of high-alloyed consumables.

KEYWORDS: armour steel, high hardness steel, arc welding, welded joints, HAZ metal, cold cracks

INTRODUCTION

In selection of high-strength alloyed steel for welded structure fabrication one of the important factors is its weldability, alongside a complex of mechanical and special properties. Weldability is understood as the possibility of producing high-quality joints, which satisfy the requirements to technological and service properties of the structure. Therefore, at development of technologies of welding such structures, it is first of all necessary to have sufficient information on the weldability of the steel, which determines the respective selection of the welding consumables and welding technology parameters. It is also known that the main problem in welding high-strength alloyed steels is prevention of cold cracking in the welded joints [1–4].

Formation and development of cold cracks in the welded joints depends on the structural-phase composition of metal in the HAZ and in the weld, content of diffusion-mobile hydrogen in the deposited metal and stress level in the welded joints. Here, the cracking susceptibility of the welded joints becomes higher with increase of the content of carbon and such alloying elements as nickel, chromium, manganese, molybdenum and vanadium in steel. The mechanism of cold crack initiation and development in the welded joints is of a delayed nature. It is usually explained by Zener–Stroh classical model, according to which microcrack initiation in a metal hardened structure takes place along the grain boundaries in the areas of dislocation accumulation. Further crack propagation, depending on the state of the metal structure and stress level, occurs both along the boundaries and through the body of the grains. Hydrogen, with which the HAZ metal is saturated during welding, promotes an increase in the level of the structure brittleness, and the destruction process runs more intensively [5–7].

Modern high hardness armour steels ($HB \geq 5000$ MPa), which are used in manufacture of lightly armoured vehicles, belong to high-strength medium-carbon alloyed steels by the content of carbon and alloying elements (Table 1). It is known that the welded joints of this class of steels have an increased cold cracking susceptibility exactly in the HAZ metal. In welding such steels by low-alloyed consumables to prevent cold cracking, preheating with the temperature of up to 250 °C and thermal tempering of the welded joints after welding are usually performed. In welding by high-alloyed consumables no preheating is required. Here, selection of the technological solutions depends on a specific type of the welded structure and its purpose.

The objective of this work was a comprehensive comparative evaluation of the susceptibility of modern high hardness armour steels to cold cracking and issuing recommendations on their prevention.

MATERIALS AND METHODS OF INVESTIGATION

High hardness armour steels of local and foreign production were used in investigations. Their chemical composition is given in Table 2.

Table 1. Chemical composition of modern high hardness armour steels

Armour steel	Weight fraction of elements, %												
	C	Si	Mn	Cr	Ni	Mo	Cu	V	Al	Ti	S	P	B
Grade 71 (Ukraine)	0.29–0.36	1.20–1.50	0.60–1.0	1.50–2.0	2.0–2.40	0.45–0.55	≤0.30	0.18–0.25	0.015–0.050	0.005–0.025	≤0.003	≤0.012	–
Foreign steels	Specified maximum element content, %												
ARMSTAL 500 (Poland)	0.32	0.50	1.20	0.90	1.10	0.30	0.090	–	–	–	–	–	–
HB 500 MOD (Belgium)	0.30	0.80	1.60	1.0	1.0	0.50	0.023	–	–	–	0.010	0.025	0.005
Protection 500 (Finland)	0.30	0.70	1.70	1.5	0.80	0.50	0.026	0.020	–	–	0.015	0.030	0.004
ARMOX 500 (Sweden)	0.32	0.40	1.20	1.0	1.80	0.70	–	–	–	–	0.003	0.010	0.005
RAMOR 500 (Finland)	0.35	0.70	1.50	1.0	2.0	0.70	–	–	–	–	0.010	0.015	0.005

Weldability of steels was first evaluated by calculation methods by P_{CM} and CET values. In keeping with the recommendations of [1, 8] these values were calculated as follows:

$$P_{CM} = C + Si/30 + (Mn + Cr + Cu)/20 + Ni/60 + Mo/15 + V/10 + 5B, \% \ [1];$$

$$CET = C + (Mn + Mo)/10 + (Cr + Cu)/20 + Ni/40, \% \ [8].$$

Further on CET value and quantity of diffusible hydrogen in the weld metal were used to determine the preheating temperature, at which no cracks form in the welded joints:

$$PT = 697 \times CET + 160 \times \tanh(d/35) + 62 \times HD \times 0.35 + (53 \times CET - 32) \times Q - 328, °C \ [8],$$

where d is the metal thickness, mm; HD is the quantity of diffusible hydrogen in the deposited metal (determined by chromatographic method), $cm^3/100$ g; Q is the welding heat input, kJ/mm.

For quantitative evaluation of cold crack formation in the welded joints of armour steels, a recognized Implant method was used at HAZ metal testing for delayed fracture resistance [9, 10]. Samples-inserts from the studied steel of 6.0 mm diameter with and without a screw notch as a stress raiser were tested. Samples were inserted into a technological plate from high-strength steel, on which surfacing was performed. After metal cooling to the temperature of 30–50 °C, the samples were loaded by a constant force at axial tension. The results of these tests were used to determine the critical stresses (σ_{cr}) and preheating temperature, at which sample failure did or did not occur within 24 hours. Maximal critical stresses, at which no delayed fracture occurred anymore under the defined welding conditions, was taken as the quantitative index of the cold cracking susceptibility of the HAZ metal.

Samples for the Implant method were welded by a mechanized process in the atmosphere of a mixture of shielding gases (82 % Ar + 18 % CO_2) by high-alloyed and low-alloyed wires of the respective Sv-08Kh20N9G7T and Sv-10GSMT grades of 1.2 mm diameter. Welding was performed at the heat input of 8.6–9.0 kJ/cm, the welding modes were as follows: welding current of 160–180 A, arc voltage of 26–28 V, welding speed of 12–15 m/h.

For sound detection of cold cracks in welded joints of armour steels, the method of "rigid boxing"

Table 2. Chemical composition of the studied high hardness armour steels

Armour steel	Weight fraction of elements, %												
	C	Si	Mn	Cr	Ni	Mo	Cu	V	Al	Ti	S	P	B
Grade 71	0.31	1.16	0.74	1.66	2.26	0.30	0.080	0.202	0.040	0.024	0.010	0.016	–
ARMSTAL 500	0.29	0.24	0.89	0.74	1.03	0.23	0.090	0.060	0.019	0.037	0.005	0.009	0.002
HB 500 MOD	0.26	0.21	0.78	0.42	0.74	0.27	0.023	0.001	0.033	0.004	0.006	0.012	0.001
Protection 500	0.28	0.49	0.96	0.58	0.37	0.25	0.026	0.002	0.028	0.029	0.011	0.016	0.002
ARMOX 500	0.23	0.25	0.84	0.50	0.97	0.33	0.030	0.001	0.023	0.021	0.003	0.010	0.002
RAMOR 500	0.21	0.45	0.92	0.58	0.38	0.20	0.010	0.002	0.027	0.015	0.005	0.023	0.002

of a technological sample was used [11]. Control joints, which were first mounted on a rigid plate of 50–60 mm thickness and welded around the contour on it, had a stress raiser in the form of a blunting of up to 4 mm to produce a lack-of-penetration. The joints were welded by the same method, welding consumables and in the modes as at sample testing by the Implant method. Acoustic emission method was used for registering the moment of cold crack initiation and propagation during cooling of the control welded joints. After welding the samples were kept for three days, which was followed by cutting templates out of the control joints with their further visual examination to detect cracks.

INVESTIGATION RESULTS AND THEIR DISCUSSION

The calculated estimate of weldability of high hardness armour steels which was determined by the preheating temperature (PT) to eliminate the probability of cold cracking in the joints, was performed on the base of analysis of the data on their chemical composition. Calculations were performed both for the maximal composition, declared in the normative documents (specifications, manufacturer's price-lists), and for the actual chemical composition of armour steels, which were provided for investigations. Results of calculation of P_{CM}, CET and PT values in armour steel welding by ferrite-pearlite materials, at which no cold cracks form in the welded joints, are given in Table 3. Here, it was taken into account that welding of the joints is performed on the thickness of 10 mm at the heat input of Q_w = 10 kJ/cm, which is typical for armoured structures. Diffusible hydrogen content in the deposited metal was specified in the range of $[H]_{dif}$ = 3–5 cm^3/100 g, the presence of which is typical in welding with low-alloyed wires.

Thus, it was previously determined that high hardness armour steels are characterized by poorer weldability. At calculations by the maximal chemical composition, P_{CM} and CET values are higher than 0.50 and 0.54 %, respectively, which results in equally difficult conditions for welding all the steels to eliminate the probability of cold cracking in the welded joints. The temperature of their preheating in welding should be equal from 185 to 310 °C, depending on the steel and diffusible hydrogen content. This value is the highest for steel of grade 71, and the smallest for ARMSTAL 500 steel. It should be taken into account that the heating temperature of 230 °C corresponds to that of low-temperature tempering at armour steel hardening, exceeding which can lead to lowering of its hardness.

The P_{CM}, CET and PT values for actual chemical composition differ from those, which are characteristic for the maximal composition. They are significantly lower, particularly for foreign steels. They remain the highest for steel of grade 71, and the lowest for RAMOR 500 steel. Preheating temperature for steel of grade 71 decreases to 195–210 °C, and for RAMOR 500 steel, it does not exceed 80 °C. An essential lowering of PT values by more than 2 times is also characteristic for *HB* 500 MOD, PROTECTION 500 and ARMOX 500 steels. This is attributable to the fact that the actual chemical composition of armour foreign steels, which were studied, is lower than the declared one, as they are sparsely-alloyed. Here, the steels have sufficiently high hardness (*HB* ≥ 5000 MPa), which is achieved at application of special heat treatment methods. Lowering of the steel alloying level, from the viewpoint of improvement of their weldability is positive leverage. When welding the joints, however, it may lead to a significant lowering of armour steel hardness in the tempering zone of the HAZ metal.

The following stage of investigations was Implant testing of samples, in which the stress raiser was absent. It was established, first of all that in welding without preheating of the studied armour steels

Table 3. Calculated values of preheating temperature in welding of high hardness armour steels 10 mm thick

Armour steel	Steel chemical composition	P_{CM}, %	CET, %	Preheating, PT, °C	
				3 cm^3/100 g	5 cm^3/100 g
Grade 71	Maximal	0.67	0.69	300	310
	Actual	0.55	0.56	195	210
ARMSTAL 500	Maximal	0.50	0.54	185	200
	Actual	0.43	0.47	130	150
HB 500 MOD	Maximal	0.53	0.59	235	255
	Actual	0.36	0.41	85	105
Protection 500	Maximal	0.55	0.61	240	260
	Actual	0.41	0.44	110	125
ARMOX 500	Maximal	0.55	0.61	240	260
	Actual	0.35	0.40	80	100
RAMOR 500	Maximal	0.60	0.65	280	290
	Actual	0.33	0.34	60	80

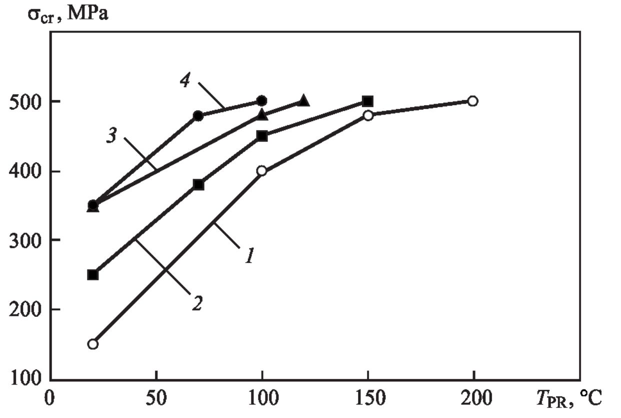

Figure 1. Delayed fracture resistance of armour steel HAZ metal in welding by Sv-10GSM wire (samples without stress raiser): *1* — steel of grade 71; *2* — ARMSTAL 500; *3* — Protection 500; *4* — *HB* 500 MOD

by high-alloyed wire of Sv-08Kh20N9G7T type no delayed fracture of the samples is observed, even at loads with up to 500 MPa stress level. At loads, when the stresses were higher than 500 MPa, the plastic deformation processes in the high-alloyed deposited metal became more active. It resulted in mechanical destruction exclusively through it. The rather high delayed fracture resistance of the HAZ metal in armour steel welding by high-alloyed wire is attributable to formation of predominantly tempering martensite in the hardening area, in which the dislocation density and structural stresses are practically 2 times lower than in welding with low-alloyed consumables [12, 13]. Therefore, at external loading such HAZ metal is more prone to microplastic deformation without microcrack formation.

Considering the obtained data in welding with high-alloyed wire, a stress of 500 MPa level was conditionally taken as the criterion, which should be reached in welding samples by low-alloyed wire due to preheating application. The generalized results of delayed fracture resistance testing of the HAZ metal of armour steel joints in welding with wire of Sv-10GSMT type, in the case of a dependences of critical breaking stresses on preheating temperature (T_{pr}) are presented in Figure 1.

Critical breaking stresses in welding without preheating, which depending on the steel grade are equal to 150–350 MPa, are several times lower than the yield point of armour steel ($\sigma_{0.2} \geq 1250$ MPa). The time of development of the delayed fracture process at sample loading with the stress level of 500 MPa is quite fast and it is equal to not more than 1–3 min. Preheating application promotes increase of delayed fracture resistance of the HAZ metal, which is related to formation of more ductile structures in the HAZ metal. Microcrack initiation and propagation time is significantly increased. So, for instance, in welding steel of grade 71 at preheating at the temperature of 100 °C, the time to fracture of the samples at such a loading level was equal to 1.5–2 h, at 150 °C it was already 4–6 h, and at 200 °C no delayed fracture of the samples was observed for 24 h.

Figure 2 shows typical surfaces of sample fracture through the HAZ metal in the case of armour steel of grade 71. As shown by special fractographic studies of the fracture surfaces, in welding without preheating, sample destruction during microcrack initiation and propagation occurs predominantly in the brittle mode by the boundaries and in the grain body (Figure 2, *a*). The ratio of brittle intergranular and intragranular fractures is equal to approximately 4/1. At application of preheating, the critical stresses are gradually increased. So, at preheating at the temperature of 100 °C the fraction of brittle intergranular fracture decreases to 30 % (Figure 2, *b*). At preheating at the temperature of 150 °C, the fracture can be characterized as a predominantly intragranular one with a small fraction of ductile fracture (Figure 2, *c*).

If we compare the data given in Table 3 and in Figure 1, one can see that the preheating temperature at sample testing, at which the critical stresses are equal to 500 MPa, is close to the calculated values for the mentioned steels at diffusible hydrogen content at the level of 3 cm^3/100 g. Such a level of diffusible hydrogen is ensured in welding in a shielding gas mixture. Comparative studies showed that the preheating tem-

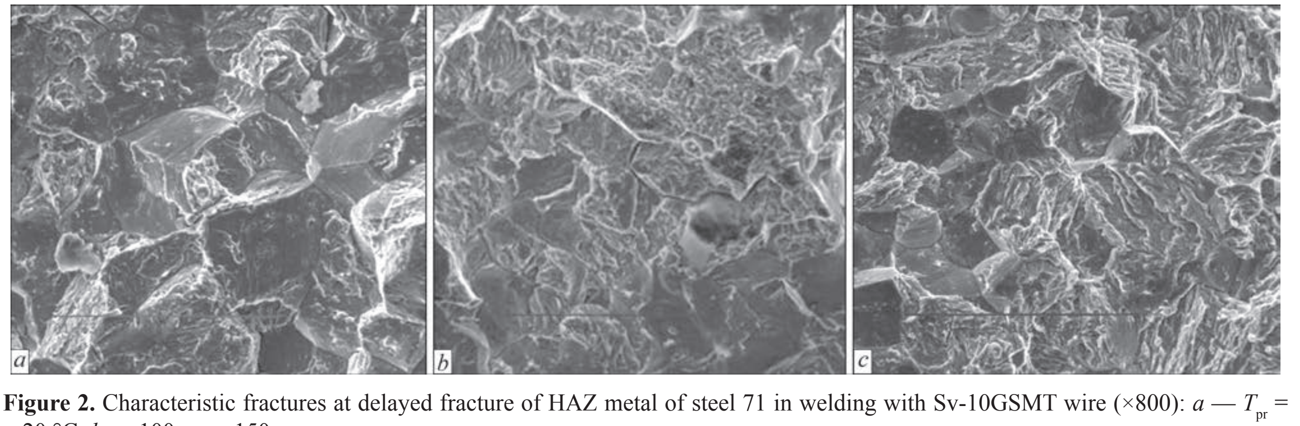

Figure 2. Characteristic fractures at delayed fracture of HAZ metal of steel 71 in welding with Sv-10GSMT wire (×800): *a* — T_{pr} = = 20 °C; *b* — 100; *c* — 150

perature, at which according to calculated data cold cracks are absent in the welded joints, and according to Implant sample tests no delayed fracture takes place in the HAZ metal, for armour steel of grade 71 it is equal to 195 and 200 °C, for SMSTAL 500 steel — to 135 and 150 °C, for PROTECTION 500 — to 110 and 120 °C, for *HB* 500 MOD — to 85 and 100 °C, respectively. Thus, in welding joints of armour steels without any stress raisers, in order to eliminate the probability of cold crack formation in the welded joints, their preheating temperature can be determined by the calculation method by CET and PT indices.

It should be noted, however, that the presence of stress raisers in the welded joint can be incorporated in the design, if the joint is made without full penetration. These, for instance, can be fillet or overlap joints (DSTU EN ISO 9692-1). Stress raisers can also form in full penetration joints at violation of the welding technique or modes, when such individual defects as lack-of-penetration, lack-of-fusion, undercuts, etc. develop, as well as those, which could not be detected and removed promptly after welding. That is why Implant tests of the samples with a geometrical stress raiser were conducted. The generalized results of these tests are shown in Figure 3.

If we compare the data in Figure 1 and Figure 3, one can see that in welding Implant samples of armour steels with a geometrical stress raiser the processes of delayed fracture of the HAZ metal run more actively. In welding without preheating the critical stresses, which lead to delayed fracture, decrease to 50–150 MPa. Here, in order to each critical stresses at 500 MPa level, it is necessary to apply preheating at higher temperatures. So, for steel of grade 71 of the actual chemical composition the preheating temperature should already be not 200, but 250 °C, for steel of grade ARMSTAL 500 — not 150, but 200 °C, for PROTECTION 500 — not 120, but 180 °C, respectively. The same tendency of preheating temperature increase in the presence of a stress raiser is also characteristic for other armour steels. This is related to the fact that the stress raisers in armour steel welded joints significantly accelerate initiation and propagation of cracks in the HAZ metal. Therefore, in case of welding joints without complete penetration the calculated preheating temperature should be increased. As shown by Implant testing the preheating temperature of the welded joints should be increased approximately by 50–70 °C, compared to the calculated one, and the defects present in the welded joins must be detected and removed.

It should be also noted that at testing Implant samples with a geometrical stress raiser, which were welded by high-alloyed Sv-08Kh20N9G7T wire without preheating, a lowering of the level of critical stresses of delayed fracture in the HAZ metal was also observed (Figure 4).

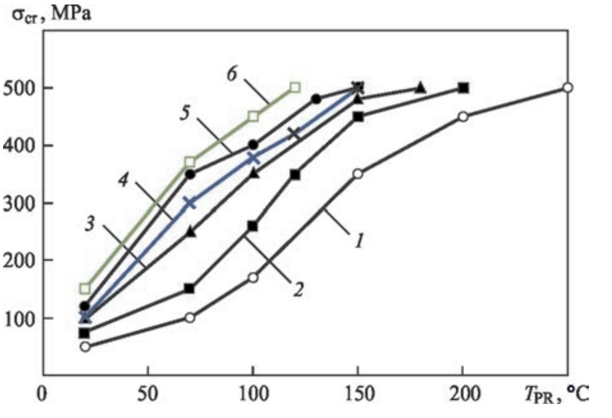

Figure 3. Delayed fracture resistance of armour steel HAZ metal in welding by Sv-10GSM wire (samples with a stress raiser): *1* — steel of grade 71; *2* — ARMSTAL 500; *3* — PROTECTION 500; *4* — *HB* 500 MOD; *5* — ARMOX 500; *6* — RAMOR 500

The above-given data show that the stress raiser has a significant influence on development of delayed fracture processes in the HAZ metal of armour steel joints, even at application of high-alloyed welding consumables. While no delayed fracture took place at testing of samples of all the mentioned steels without a geometrical concentrator, in its presence they already proceed actively. So, critical stresses, at which fracture is absent, for steel 71 decrease to 200 MPa, and for ARMSTAL 500, ARMOX 500 and PROTECTION 500 steels to 300–350 MPa. With this testing variant *HB* 500 MOD and RAMOR 500 steels were also tested. The critical stresses for them were higher and were equal to 400–450 MPa. For foreign armour steels of the specified composition, this is a rather high level of critical stresses, above 300 MPa, which can be sufficient for avoiding cold cracking in the root part of the welded joints in welding multilayer joints. It cannot be stated for steel of grade 71. Therefore, it was nec-

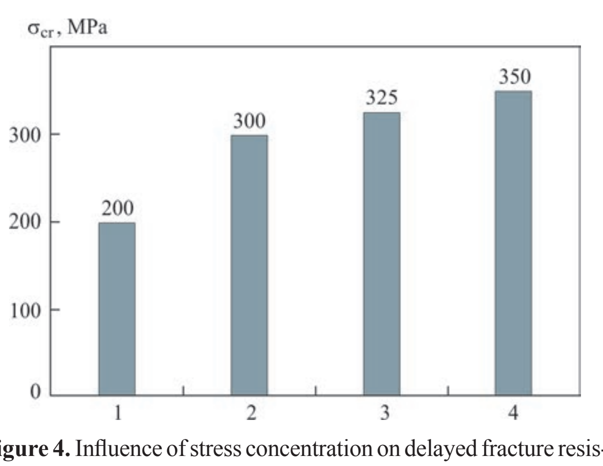

Figure 4. Influence of stress concentration on delayed fracture resistance of armour steel HAZ metal in welding by Sv-08Kh20N9G7T wire without preheating: *1* — steel of grade 71; *2* — ARMSTAL 500; *3* — ARMOX 500; *4* — PROTECTION 500

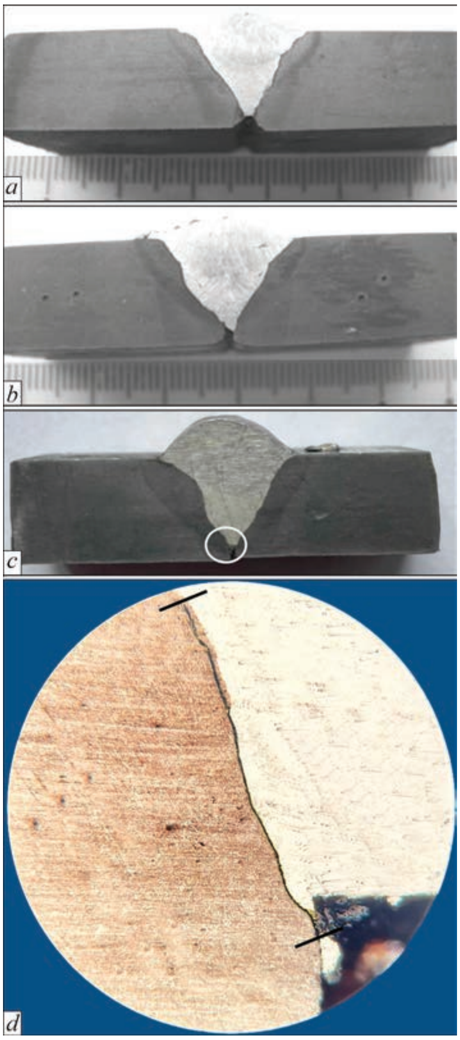

Figure 5. Macrosections of welded joints of “rigid boxing” technological samples of 10–12 mm armour steels made by Sv-08Kh20NG7T wire without preheating: *a* — *HB* 500 MOD; *b* — PROTECTION 500; *c* — grade 71; *d* — microcrack in the HAZ of the joint of grade 71 steel (×100)

essary to conduct additional studies with application of technological samples.

Making of “rigid boxing” technological samples confirms the conclusions based on the results of Implant tests. No cold cracks form in the joints in welding armour steels of the above-mentioned chemical

Table 4. Cold cracks in control joints of 10–12 mm armour steels in welding technological samples by Sv-10GSMT wire

Armour steel	Preheating temperature (T_{pr}), °C				
	20	100	150	200	250
Grade 71	Yes	Yes	Yes	Yes	No
ARMSTAL 500	–»–	–»–	–»–	No	–
HB 500 MOD	–»–	–»–	No	–	–
PROTECTION 500	–»–	–»–	Yes	No	–
ARMOX 500	–»–	–»–	No	–	–
RAMOR 500	–»–	No	–	–	–

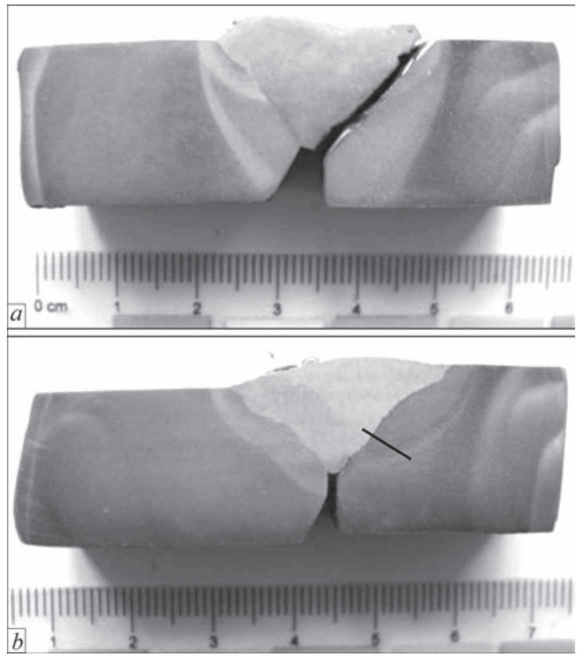

Figure 6. Cold cracks in welded joints of armour steel of grade 71 in welding by Sv-10GSMT wire: *a* — welding without preheating; *b* — T_{pr} = 150 °C

composition of foreign grades without preheating at application of high-alloyed Sv-08Kh20N9G7T wire (Figure 5, *a*, *b*). In welding armour steel of grade 71 no cold cracks were visually observed in the welded joint, either, at regular examination. However, after special etching of some sections and image magnification microcracks of up to 0.5 mm depth were detected. These are so-called “tears”, which formed in the joint HAZ in the stress raiser area (Figure 5, *d*). These cracks did not propagate any further, which is attributable to stress relaxation at crack formation and high enough ductile properties of the metal of the joint HAZ, which formed at application of a high-alloyed welding consumable. This, however, does not exclude the possibility of their development at external loads during the product service. In other cases, no such microcracks were revealed in welding foreign armour steels of the specified chemical composition. Still, however, welding of joints by a high-alloyed consumable without preheating of the local armour steel of grade 71 and foreign armour steels, which are close by carbon content to the composition of steel of grade 71, should be performed with full penetration.

Contrarily, in welding with Sv-10GSMT wire cold cracks actively propagate in the HAZ metal in the welded joints. Cold cracking in welded joints at this welding variant can only be avoided under the conditions, when the preheating temperature is from 100 up to 250 °C, depending on the steel grade. Table 4 gives the general results of welding the technological samples by Sv-10GSMT wire, and Figures 6, 7 show the typical microsections of welded joints.

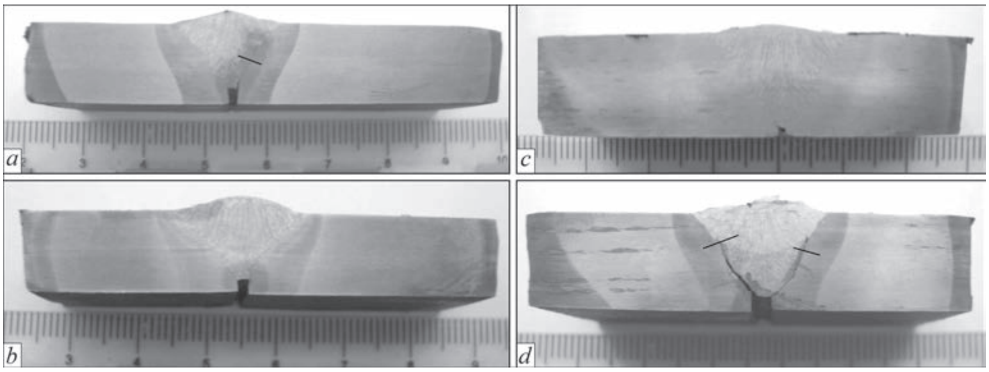

Figure 7. Macrosections of welded joints of foreign armour steels in welding by Sv-10GSMT wire: *a* — *HB* 500 MOD without preheating, cold cracks in the HAZ; *b* — *HB* 500 MOD, T_{pr} = 150 °C; no cracks; *c* — PROTECTION 500, T_{pr} = 200 °C, no cracks; *d* — ARMSTAL 500, T_{pr} = 100 °C, cold cracks in the HAZ

Initiation and propagation of cold cracks can be different, depending on the steel composition, which was determined by the acoustic emission method. So, in welding of armour steels of grades 71 and ARMSTAL 500 without preheating cold cracks intensively form already directly after welding of the first layer of the weld is over. The time of their development is up to one minute. In welding *HB* 500 MOD, PROTECTION 500, ARMOX 500 and RAMOR 500 steels cold cracks propagate slower in the HAZ metal of the joints, during 10 to 30 min. At application of preheating the destruction processes are decelerated, and at the temperature of 150 °C, the time of crack initiation and propagation in the welded joints of steels of grades 71 and ARMSTAL 500 is already equal to approximately one hour. This is attributable to the fact that at preheating the cooling rate decreases and the HAZ metal forms structures with a lower degree of hardening, the metal becomes more ductile and much more time is required for its destruction. It should be noted that obtained values of preheating temperature in welding control joints of "rigid boxing" technological samples, in which a lack-of-penetration was incorporated, and those derived by the results of testing samples with the geometrical stress raiser by the Implant method practically coincide.

One can also see from the results of investigations that the cold cracking susceptibility of welded joints of high hardness armour steels and value of preheating temperature for their prevention essentially depend on the steel chemical composition, namely carbon content. So, among the armour steels of the specified composition, considered by us, the highest carbon content, at the level of 0.28–0.30 % is found in steels of grades ARMSTAL 500, PROTECTION 500 and 71. Therefore, preheating temperature of the joints in their welding with low-alloyed consumables should be equal to 200–250 °C, respectively. In welding joints of steels of grades RAMOR 500, ARMOX 500 and *HB* 500 MOD, in which the carbon content is on the level of 0.21–0.26 %, the preheating temperature is equal to 100–150 °C, respectively. If foreign armour steels are made with maximum admissible carbon content, i.e. increased to 0.30–0.35 %, as it is declared by the manufacturers' specifications, then from the viewpoint of ensuring the cold cracking resistance of the welded joints it will be necessary to increase their preheating temperature to 250 °C, and higher. Here, it should be noted that this preheating temperature is higher than that of low-temperature tempering of the steel during its production, and it will certainly lead to lowering of armour steel hardness in the welded joint area. As a result, it will have a negative impact on the performance of products as a whole, which is inacceptable. Therefore, it is rational to limit the carbon content in armour steels to a level not higher than 0.26 %.

CONCLUSIONS

1. In arc welding by low-alloyed consumables of Sv-10GSMT type, the joints of high hardness armour steels have a higher susceptibility to cold cracking in the HAZ metal. Application of preheating allows preventing them. Preheating temperature, at which no cold cracks initiate in the welded joints, can be calculated by CET and PT values, in keeping with the chemical composition of the armour steel. In the presence of incorporated stress raisers in the welded joints, the calculated preheating temperature should be increased by 50–70 °C.

2. Welded joints of high hardness armour steels of the studied composition were made by high-alloyed consumable of Sv-08Kh20N9G7T type. As a result of formation of more ductile hardening structures in the HAZ metal they have higher delayed fracture and cold cracking resistance. Presence of stress raisers in welding foreign armour steels activates the delayed fracture processes, but critical breaking stresses are rather high, more than 300 MPa. As a result, no microcracks in the HAZ metal or cold cracks in the joints

are formed. That is why, the joints of these steels can be welded without preheating by high-alloyed consumables, even in the presence of stress raisers.

3. In welded joints of local armour steel of grade 71 with carbon content of 0.31 % made by a high-alloyed consumable without preheating, presence of stress raisers significantly accelerates the delayed fracture processes, and microcracks form in the HAZ metal. Furtheron, these microcracks do not develop into a main cold crack. It is attributable to stress relaxation during their formation and sufficiently high ductile properties of the metal to hinder their propagation. This, however, does not exclude the possibility of their propagation at external loads during the product service. Therefore, it is rational to weld joints of armour steel of grade 71 by high-alloyed consumables with full penetration.

4. At selection of high hardness steel in manufacture of lightly-armoured vehicles preference should be given to steel with not more than 0.26 % carbon content. In welding such armour steel by low-alloyed consumables sufficiently high cold cracking resistance of the welded joints is ensured even in the presence of stress raisers, due to preheating up to the temperature of 150 °C, as well as in welding without preheating at application of high-alloyed consumables.

REFERENCES

1. Makarov, E.L. (1981) *Cold cracks in welding of alloyed steels.* Moscow, Mashinostroenie [in Russian].
2. Efimenko, M.G., Radzivilova, N.O. (2003) *Physical metallurgy and heat treatment of welded joints.* Kharkiv, Kharkivska Drukarnya No. 16 [in Ukrainian].
3. Skulsky, V.Yu. (2009) Peculiarities of kinetics of delayed fracture of welded joints of hardening steels. *The Paton Welding J.,* **7**, 12–17.
4. Günen, A., Bayar, S., Karakaş, M.S. (2020) Effect of different arc welding processes on the metallurgical and mechanical properties of Ramor 500 armor steel. *J. of Engineering Materials and Technology*, **142**, 2.
5. Pokhodnya, I.K., Shvachko, I.V. (1997) Physical nature of hydrogen induced cold cracks in welded joints of structural steels. *Avtomatich. Svarka,* **5**, 3–12 [in Russian].
6. Gajvoronsky, A.A. (2013) Influence of diffusible hydrogen on delayed cracking resistance of high-carbon steel welded joints. *The Paton Welding J.,* **5**, 14–20.
7. Magudeeswaran, G., Balasubramanian, V., Reddy, G.M. (2008) Hydrogen induced cold cracking studies on armour grade high strength, quenched and tempered steel weldments. *Int. J. of Hydrogen Energy*, 33(**7**), 1897–1908.
8. EN 1011-2:2001: *Recommendations for welding of metallic materials*.
9. Suzuki, H. (1980) *Cold Cracking and its Prevention in Steel Welding (III)*. DOC IIW IX-1157–80.
10. Magudeeswaran, G., Balasubramanian, V., Madhusudhan Reddy, G. (2008) Effect of welding consumables on hydrogen induced cracking of armour grade quenched and tempered steel welds. *Ironmaking & Steelmaking*, 33(**7**), 549–560.
11. Poznyakov V.D., Shelyagin V.D., Zhdanov S.L. et al. (2015) Laser-arc welding of high-strength steels with yield strength of more than 700 MPa. *The Paton Welding*, **10**, 19–24.
12. Gaivoronskyi O.A., Poznyakov V.D., Berdnikova O.M. et al. (2020) Influence of low-temperature tempering on structure and properties of welded joints of high-strength steel 30Kh2N2MF. *The Paton Welding*, **6**, 20–26. DOI: https://doi.org/10.37434/tpwj2020.06.04
13. Magudeeswaran, G., Balasubramanian, V., Reddy, G.M. (2018) Metallurgical characteristics of armour steel welded joints used for combat vehicle construction. *Defence Technology*, 14(**5**), 590–606.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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