FORMATION OF COLD CRACKS IN WELDED JOINTS FROM HIGH-STRENGTH STEELS WITH 350–850 MPa YIELD STRENGTH

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The main problems in welding of high-strength steels are connected with their susceptibility to cold crack formation. As a rule such cracks are nucleated in HAZ of welded joints under the effect of tensile stresses. Diffusible hydrogen and presence of hardening structures in metal accelerate this process. Given paper presents a comparative analysis of effect of structure, diffusible hydrogen and residual stresses on cold crack resistance of welded joints from high-strength structural steels differ in chemical composition and level of static strength. Experiment-calculation methods of investigation were used for study of microstructural changes and formation of stress-strain state in rigidly fixed welded joints. Resistance of welded joints to cold crack formation was evaluated based on results of testing of technological samples and specimens on Implant method. It was determined as a result of performed investigations that probability of formation of longitudinal cold cracks in rigidly fixed welded joints from high-strength steel changes in wide ranges. However, there are specific regularities related with effect of the residual welding stresses on this processes. Increase of diffusible hydrogen content in deposited metal, steel carbon equivalent, cooling rate and stress-strain state of welded joints reduce their cold crack resistance. Results of performed investigations can be used in development of technological processes of welding of high-strength steels with yield strength from 350 to 850 MPa and carbon equivalent from 0.35 to 0.70 %. 11 Ref., 4 Tables, 6 Figures.

Keywords: *high strength low-alloy steels, welded joints, cold cracks, residual welding stresses, diffusible hydrogen, metal structure, preheating, heat-affected zone*

The main problems in welding of high-strength steels are connected with their susceptibility to formation of cold cracks [1–5]. It is well known fact that presence of hardening structures, diffusible hydrogen $[H]_{dif}$ and tensile stresses [1, 3, 6, 7] in the place of crack potential nucleation are necessary conditions for formation and development of cold crack in welded joints.

Mostly, effect of indicated factors on cold crack resistance of welded joints is evaluated on results of indirect investigations. For this, relation between technological parameters of welding and structure of weld metal and HAZ of welded joints, conditions of saturation of deposited metal by $[H]_{dif}$, capability of metal to resist continuous external tensile stress without failure is investigated. However, the question to what extent conditions of such tests correspond to processes taking place in the welded joints is not enough studied. Meanwhile, development of experimental as well as calculation methods for determination of distribution of parameters of indicated characteristics in welding of different combinations of structural steels allows more accurate selection of technological procedures directed on prevention of risks of cold crack formation in welded joints.

In this connection, aim of the present paper lied in evaluation of effect of hardening structures, $[H]_{dif}$ and residual stresses on cold crack resistance of welded joints from high-strength structural steels using modern experiment-calculation methods of investigation as well as results of testing of specimens on Implant method.

Mathematical modelling of processes of microstructural changes and formation of stress-strain state in rigidly fixed welded joints makes a basis of the experiment-calculation method.

Well approved algorithm [8], according to which weight fraction of ausenite V_a, bainite V_b and martensite V_m in total always equals one was used for mathematical description of microstructural changes, increment of free deformations and change of yield strength of the metal depending on calculation data with respect to temperatures in arbitrary point (x, y, z) in moment of time t.

Residual content of martensite, bainite and austenite was determined on time of staying of (x, y, z) point in 800–500 °C ($\Delta t_{8/5}$) temperature range in accordance with dependences, given in work [9].

Level of residual stresses in discrete points of welded joint was determined by finite element

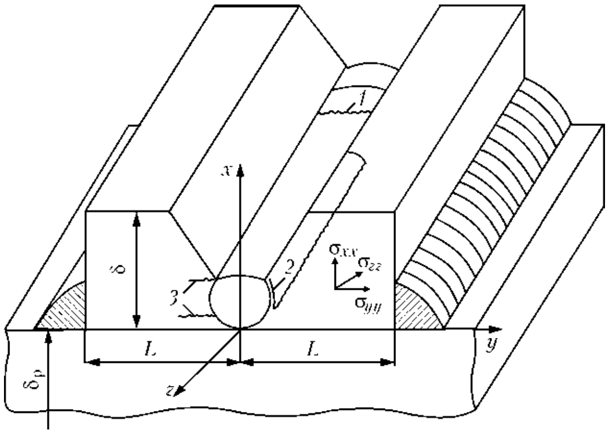

Figure 1. Scheme of technological sample of δ thickness and $2L$ width, fixed by flange welds to plate of $\delta_p >> \delta$ thickness with transverse (*1*) and longitudinal (*2*, *3*) cracks in root weld

method based on corresponding mathematical models, developed by Vladimir I. Makhnenko at the E.O. Paton Electric Welding Institute [10].

Probability of nucleation of cracks in welded joints from steel depending on content of $[H]_{dif}$ in deposited metal (regulated by conditions of electrode baking), residual stresses (regulated by change of specimen fixing basis) and structural change of HAZ metal (regulated by rate of specimen cooling due to change of initial temperature of the plate T_0 = 11, 60 and 80 °C) was evaluated on results of testing of technological samples (Figure 1). 10 single-type specimens were tested at each specific welding conditions.

Tests on Implant method were carried out in accordance with procedure described in [1]. Cylinder specimen-inserts of 6 mm diameter with notch in a form of spiral grove (step 1.25 mm, radius near the top 0.1 mm) were used.

Conditions of formation of cold cracks in manual metal arc (MMA) welding of root weld of rigidly fixed butt joints of the technological samples with fixing basis L = 50, 70 and 100 mm from steel 14KhG2SAFD of δ = 18 mm are considered taking into account mentioned general provisions. MMA welding of specimens was carried out using ANP-10 electrodes of 4 mm diameter. Parameters of welding mode are the following: direct current I_w = 140–150 A; arc voltage U_a = 24 V; v_w = 7.2–7.5 m/h. Table 1 shows chemical composition of the base and filler materials.

Figure 2 shows dependences characterizing changes of V_m in sections of welded joint located at x = 0.25 and 5 mm height from root surface of the weld at different initial temperatures of metal.

As follows from Figure 2, cooling rate of welded joint at T_0 = 11 °C makes $w_{6/5} \approx$ 25–30 °C/s. Quantity of martensite is around 90 % in zone of potential crack formation (area of HAZ metal overheating in Figure) or in point with x = 0.25 mm, y = 2.5 mm (Figure 2, *a*) coordinates. Heating to 70, 90 and 120 °C provides 72, 65 and 50 % decrease in V_m due to reduction of

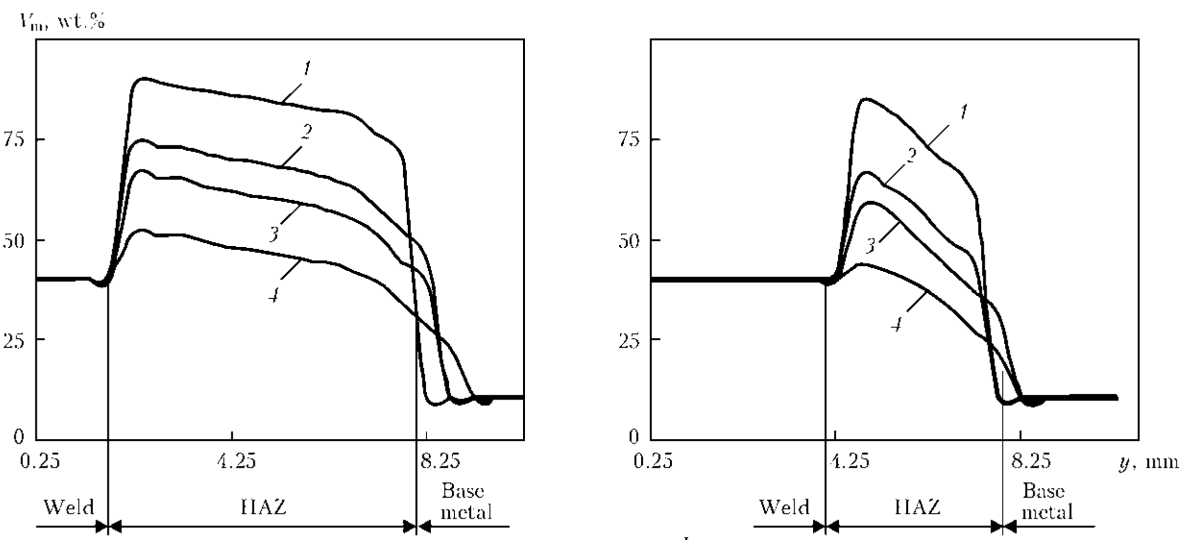

Figure 2. Calculation V_m values in cross section of root weld of studied sample at x = 0.25 and 5 mm height (*a* and *b*, respectively) with L = 50 mm and T_0 = 11 (*1*), 70 (*2*), 90 (*3*) and 120 (*4*) °C

Table 1. Chemical composition of base and filler materials, wt.%

Material	C	Si	Mn	Cr	Cu	V	Ab	P	S	P_{cm}
Steel 14KhG2SAFD	0.13	0.57	1.42	0.44	0.39	0.08	0.08	0.019	0.015	0.27
Electrode ANP-10	0.09	0.43	1.90	–	–	0.01	–	0.020	0.020	0.20

$w_{6/5}$ up to 10 °C/s. Thus, presence of specific quantity of hydrogen in metal and stresses in given point of welded joint develop all the conditions for formation of cold cracks.

Figure 4 represents the data on distribution of longitudinal σ_{zz} and transverse σ_{yy} stresses in zone of cold crack formation of studied welded joints depending on specimen fixing basis. They indicate that level of residual stresses in welded joints of the technological samples changes in wide ranges, approximately from 400 to 120 MPa in the weld metal and from 590 up to 390 MPa in HAZ with increase of L from 50 up to 100 mm.

Table 2 shows the results of testing of technological samples from steel 14KhG2SAFD. They indicate that longitudinal cold cracks will be formed with probability P around 1.0 in welding of root weld of the technological samples with L = 50 mm and at T_0 = 10 °C, when $[H]_{dif}$ content in the deposited metal is on the level of 7 ml/100 g and above. Reduction of $[H]_{dif}$ up to 5.5 ml/100 g decreases P to 0.7, and P = 0 at $[H]_{dif}$ = 40 ml/100 g. Probability of crack formation in studied samples also reduces with increase of welded joints L, namely at L = 70 mm up to P = 0.5, and to P = 0 at L = 100 mm.

As can be seen from Figure 2, content of martensite in metal near the fusion zone in area of HAZ metal overheating reduces from V_m = = 90 % at T_0 = 11 °C to V_m = 50 % at T_0 = 120 °C with T_0 increase. However, it is difficult to evaluate a real effect of T_0 on probability of cold crack appearance in the root layer of welded joints from 14KhG2SAFD steel based on these data. Additionally, data on principal σ_{zz} and transverse stresses σ_{yy} should be analyzed for this.

Calculations show that maximum values of σ_{zz} and σ_{yy} reduce, approximately, from 590 MPa at T_0 = 11 °C up to 500 MPa at T_0 = 120 °C in HAZ area with T_0 rise at L = 50 mm. It is also characteristic that this effect, that is partially caused by reduction of maximum stress values and partly by decrease of quantity of points (volume) with high σ_{zz} and σ_{yy} values, determines lowering of probability of cold crack formation with T_0 rise.

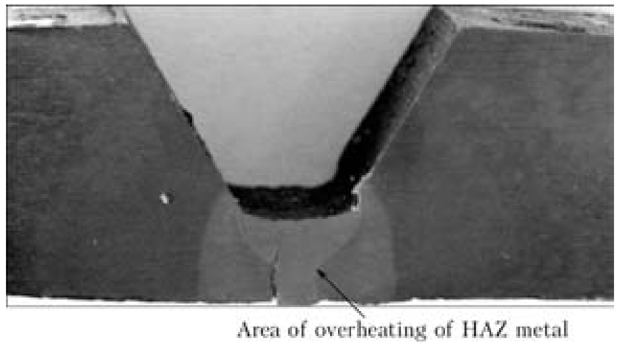

Figure 3. Cross microsection of root weld in studied sample at L = 50 mm, T_0 = 11 °C and $[H]_{dif}$ > 7 ml/100 g

Generalized data concerning effect of $[H]_{dif}$ content in the deposited metal and level of residual stresses σ_{yy} on cold crack resistance of butt joints of technological samples from 14KhG2SAFD steel at V_m ≈ 90 % are given in Figure 5 (curve *1*). This Figure also shows for comparison the results of specimen testing on Implant method (curve *2*), welding of which was carried out using the same modes as for root weld of the technological sample. Due to this cooling rate of specimen-insert was correlated with cooling rate of HAZ metal of the welded joint ($w_{6/5}$ = 25 °C/s) and structure consisting of martensite and bainite (90 and 10 %, respectively) was formed in it under the effect of welding thermal cycle.

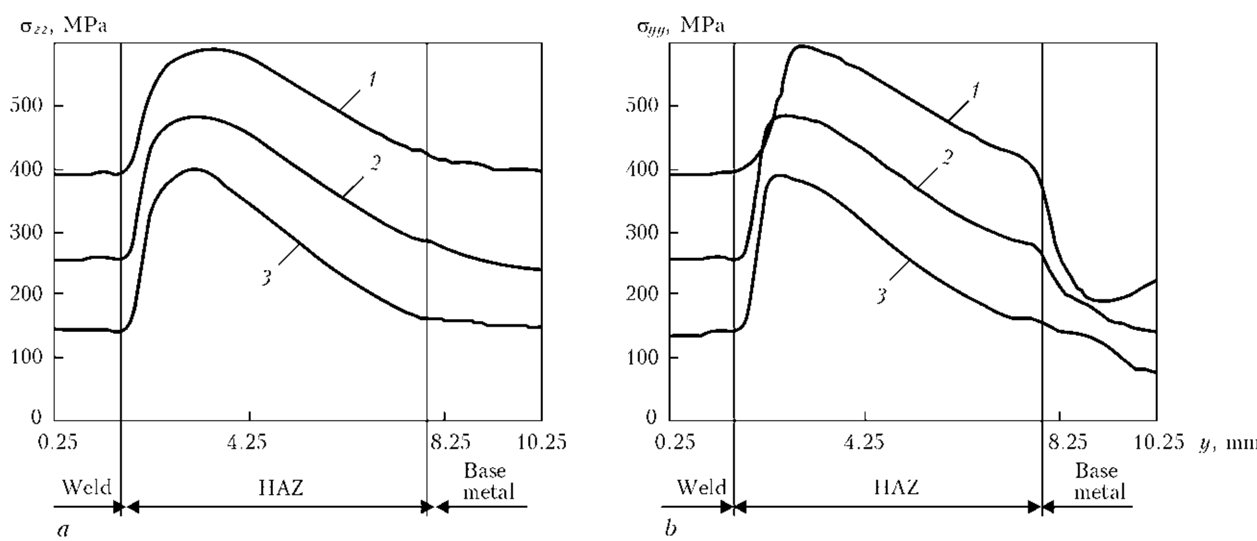

Figure 4. Calculation values of σ_{zz} (*a*) and σ_{yy} (*b*) in cross section of root weld at T_0 = 11 °C, x = 0.25 mm and L = 50 (*1*), 70 (*2*) and 100 (*3*) mm

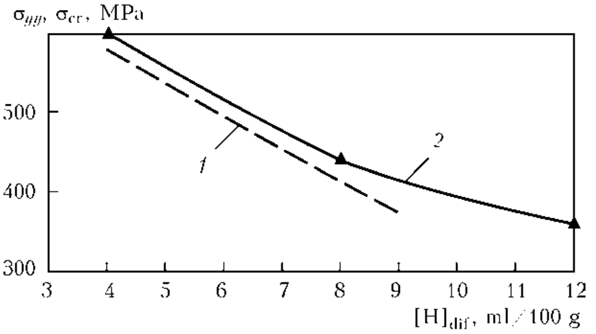

Figure 5. Cold crack resistance of HAZ metal of welded joints of 14KhG2SAFD steel based on results of technological samples (*1*) and specimens on Implant method (*2*)

Thus, investigations, performed as applied to MMA welding of root weld of rigidly fixed welded joints from 14KhG2SAFD steel 18 mm thick, showed that probability of formation of longitudinal cold crack in them changes in wide ranges at selected welding mode and varying T_0 from 11 up to 120 °C, content of $[H]_{dif}$ from 4.0 to 8.6 ml/100 g and L from 50 to 100 mm. However, there are dependences related with effect of residual welding stresses on this process. Similar dependences were detected in testing of specimens on Implant method.

Considering that the results of testing of rigid technological samples and specimens, investigated on Implant method, showed good comparability, further investigations, directed on comparison of susceptibility to cold crack formation of series of domestic high-strength steels with different chemical compositions and indices of static strength, were performed using the same method.

Chemical compositions of studied steels are given in Table 3.

Relative value $\sigma_{cr}/\sigma_{0.2}$ was accepted as a criterion providing more specific comparison of susceptibility to cold crack formation of specified steels taking into account that strength indices in the studied steels are significantly differ between each other. Index σ_{cr} was determined based

Table 2. Results of investigations of technological samples from steel 14KhG2SAFD 18 mm thick made by MMA welding using ANP-10 electrodes

Content of $[H]_{dif}$ in deposited metal, ml/100 g	T_0, °C	L, mm											
		50	70	100	50	70	100	50	70	100	50	70	100
		Quantity of specimens with cracks the length of which correspond to specimen length, pcs			Quantity of partially fractured specimens, pcs			Quantity of specimens without cracks, pcs			Probability of formation of cracks P		
4.0	11	0	0	0	0	0	0	10	10	10	0	0	0
5.5		3	0	0	4*	0	0	3	10	10	0.7	0	0
7.0		10	0	0	0	0	0	0	10	10	1	0	0
8.6		10	4	0	0	2**	0	0	4	10	1	0.6	0
8.6	60	5	0	0	1***	0	0	4	10	10	0.6	0	0
8.6	80	0	0	0	0	0	0	10	10	10	0	0	0

*Length of crack in relation to specimen length made 80, 55, 40 and 35 %. **The same, but 30 and 70 %. ***The same, but 60 %.

Table 3. Chemical composition (wt.%) and carbon equivalent C_{eq} of studied steels

Steel	C	Si	Mn	Cr	Ni	Mo	Cu	V	Nb	Al	S	P	C_{eq}, %
10KhSND	0.09	0.98	0.70	0.77	0.80	–	0.37	–	–	–	0.018	0.020	0.46
09G2SYuch	0.01	0.36	1.90	–	–	–	0.39	–	–	0.06	0.010	0.015	0.44
06G2B	0.08	0.27	1.50	–	–	0.19	0.23	–	0.05	0.04	0.006	0.011	0.37
14G2GMR	0.15	0.28	1.10	1.30	–	0.43	0.20	–	0.02	0.05	0.023	0.024	0.63
12GN2MFAYu	0.15	0.41	1.14	0.38	1.56	0.22	0.19	0.07	–	0.06	0.032	0.014	0.50
14KhGN2MDAFB	0.14	0.25	1.30	1.15	1.94	0.24	0.42	0.14	0.04	0.05	0.008	0.014	0.70
12GN3MFAYuDR	0.13	0.23	1.36	–	3.08	0.33	0.40	0.05	–	0.02	0.004	0.020	0.48

Table 4. Mechanical properties of metal of simulated HAZ of studied steels

Steel	$w_{6/5}$, °C/s								
	5			10			25		
	$\sigma_{0.2}$, MPa	σ_t, MPa	δ_5, %	$\sigma_{0.2}$, MPa	σ_t, MPa	δ_5, %	$\sigma_{0.2}$, MPa	σ_t, MPa	δ_5, %
06G2B (465, 530, 30)	440	620	28	445	640	28	490	645	26
9G2SYuch (460, 590, 31)	420	630	30	430	640	28	470	650	26
10KhSND (470, 610, 31)	480	720	26	510	740	24	560	790	22
12GN2MFAYu (625, 720, 20)	780	890	18	810	950	16	890	1050	16
14KhG2GMR (680, 780, 18)	900	1040	17	1000	1180	16	1050	1180	14
14KhGN2MDAFB (860, 920, 17)	1100	1150	12	1050	1300	12	1100	1350	12
12GN3MFAYuDR (821, 887, 19)	800	960	16	920	1050	14	1050	1210	13

Note. Values of $\sigma_{0.2}$, σ_t (MPa) and δ_5 (%) respectively for studied steels in initial condition.

on results of Implant method and $\sigma_{0.2}$ values (conditional yield strength of HAZ metal) was obtained during static tension tests of specimens of II type on GOST 6996, manufactured from metal billets and treated using specific thermal welding cycle on MSR-75 machine [6]. Table 4 shows the results of these investigations.

Given results verify that steels of different chemical composition have different reaction on effect of thermal cycle. Low-alloy steels of 06G2B, 09G2SYuch and 10KhSND grade have the lowest susceptibility to hardening. Insignificant weakening can be observed in HAZ metal of such steels at low cooling rates ($w_{6/5} \leq 10$ °C/s). As for high-strength alloy steels, they have typical increase of strength indices in HAZ metal even at low cooling rates. In particular, this refers to steels containing chromium (10KhSND, 14Kh2GMR and 14KhGN2MDAFB) which, as everybody knows, increases steel susceptibility to hardening.

Figure 6 shows the dependencies characterizing susceptibility of high-strength steels of different strength grades to cold crack formation.

It is determined that welded joints from 06G2B steel have the highest delayed fracture resistance independent on cooling conditions. Even if hydrogen concentration reaches the limit, HAZ metal of such steels shows no susceptibility to cold crack formation. Such a high resistance of specified steel to cold crack formation can be explained by very low values of C_{eq}, around 0.37 %.

Low-alloy steels 09G2SYuch and 10KhSND ($C_{eq} \approx 0.44$ and 0.46 %, respectively) also have high cold crack resistance. However, in contrast to 06G2B steel, they are more sensitive to hydrogen embrittlement and require either more rigid limitations on $[H]_{dif}$ saturation of welds or $w_{6/5}$ delay due to preheating application.

HAZ metal of welded joints from high-strength steels of 12GN2MFAYu and 12GN3MFAYuDR type has cold crack resistance comparable with low-alloy steels 09G2SYuch and 10KhSND at limited content of $[H]_{dif}$ and delayed cooling. But, since their carbon equivalent is higher ($C_{eq} \approx 0.50$ %), then increase of metal cooling intensity results in rise of portion of martensite constituent in it and significant promotion of its susceptibility to cold crack formation.

Additional chromium alloying of high-strength steels, such as for example, 14Kh2GMR

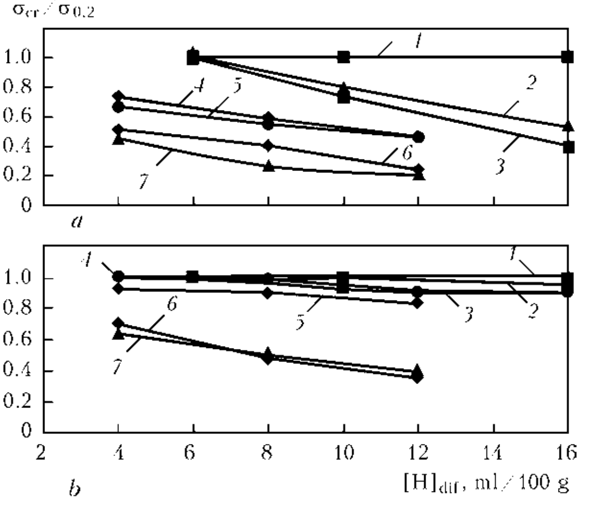

Figure 6. Susceptibility of 06G2B (*1*), 09G2SYuch (*2*), 10KhSND (*3*), 12GN2MFAYu (*4*), 12GN3MFAYuDR (*5*), 14Kh2GMR (*6*) and 14KhGN2MDAFB (*7*) to cold crack formation depending on weld saturation by hydrogen and conditions of cooling of welded joints at $w_{6/5}$ = 25 (*a*) and 10 (*b*) °C/s

and 14KhGN2MDAFB, promotes increase of C_{eq} in them up to 0.70 %, that has negative effect on delayed fracture of HAZ metal. Therefore, their welding requires simultaneous reduction of level of weld saturation by $[H]_{dif}$ and delay of $w_{6/5}$.

Conclusions

1. Probability of formation of longitudinal cold cracks in rigidly fixed welded joints from high-strength steels changes in wide ranges, however, they have specific dependencies related with effect of welding residual stresses on this process.

2. Probability of formation of cold cracks in welded joints from high-strength steels will be reduced to minimum at limitation of rate of their cooling up to $w_{6/5} \leq 10$ °C/s, content of diffusible hydrogen in the deposited metal up to 4 ml/100 g, level of residual stresses for steels with carbon equivalent C_{eq} = 0.35–0.45 % up to $0.9\sigma_{0.2}$, and up to $0.7\sigma_{0.2}$ and $0.5\sigma_{0.2}$ with C_{eq} = = 0.45–0.55 and 0.60–0.70 %, respectively.

3. Increase of cooling rate of welded joint up to 25 °C/s and content of diffusible hydrogen in deposited metal up to 16 ml/100 g promotes the necessity of 1.7–1.9 times reduction of limits of residual stresses at C_{eq} = 0.35–0.55 % and 2.5 times at C_{eq} = 0.60–0.70 %.

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