STRUCTURE AND PROPERTIES OF WELDED JOINTS OF STEEL S390 (S355 J2)

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The influence of thermal cycles of welding on the change of structure and mechanical properties of HAZ metal of welded joints of steel S390 (S355 J2) was studied. The range of admissible rates of cooling of HAZ metal in the temperature range of 600–500 °C was established, and welding consumables were selected ensuring welded joint properties on the level of requirements to the base metal, as well as their resistance to cold cracking.

Keywords: *arc welding, high-strength steel, building metal structures, thermal welding cycle, structure, mechanical properties, cooling rate, cold cracks, diffusive hydrogen*

In the recent years the high-strength steel S390 (S355 J2) with yield strength of more than 390 MPa finds even more wider application in manufacture of construction welded metal structures. The domestic metallurgy industrial complexes mastered the production of rolled metal of this steel in the sheets of 16–100 mm thickness. According to the standard EN 10025-2:2004 it can be supplied both in as-normalized state as well as after controllable rolling. The steel has the following chemical composition, wt.%: 0.14–0.17 C; 1.42–1.45 Mn; 0.18–0.25 Si; 0.06–0.09 Cr; 0.22–0.24 Ni; ≤0.06 Cu; 0.003–0.005 S; 0.013–0.019 P. Mechanical properties of this steel are characterized by the following values: σ_y = 370–420 MPa; σ_t = 530–570 MPa; δ_5 = = 28–32 %; ψ = 52–68 %; KCV_{-20} = 110–210 J/cm^2.

In the domestic literature there are no information about formation of structure and properties of welded joints of steel S390 under conditions of arc welding that, therefore, became the object of investigations described in this paper.

The influence of welding thermal cycles (WTC) on the structure and properties of HAZ metal of welded joints of steel S390 was studied, the evaluation of their resistance to cold cracks formation depending on rigidity of fixation and content of diffusive hydrogen in deposited metal was performed, the mechanical properties of joints produced using arc manual and mechanized welding in shielding gas were determined.

To evaluate the WTC influence on change of microstructure and impact toughness of HAZ metal of welded joints, the method of bead-on-plate samples was used. The beads deposition on the plates of 600 × 400 × 20 mm size was carried out using automatic welding under the flux AN-60 and wire Sv-10NMA under conditions providing energy input Q_w = 16–54 kJ/cm. The cooling rate of HAZ metal in the temperature range of 600–500 °C ($w_{6/5}$) was changed from 3 to 50 °C/s. The specimens for structure analysis, measurement of hardness and tests on impact bending of HAZ metal with sharp (V-shaped) notch were cut out in the transverse direction relatively to the deposition axis. According to the GOST 13585–68 the notches were arranged in a way that their apexes were on the fusion boundary in the area of the HAZ metal overheating and at the distance of 1.5 mm from the fusion boundary (area of incomplete recrystallization).

The data on WTC influence on strength and ductility of HAZ metal of steel S390 were obtained from the results of mechanical tests on static tension of standard specimens (type II according to the GOST 6996–66). They were manufactured of model specimens of 150 × 13 × 13 mm sizes, which according to WTC were subjected to heating up to the temperature of 1250 °C (heating rate is 150 °C/s) and then cooling at different rates. The conditions of cooling of model specimens were selected in a way that in the temperature range of 600–500 °C the rate of their cooling in the range from 20 to 3 °C/s was provided.

In the course of metallographic examinations it was established that in the initial state the steel is characterized by fine-dispersed line ferrite-pearlite structure, where over the whole volume of austenite grain the precipitations of structure-free ferrite are uniformly distributed (Figure 1, *a*). The analysis of specimens manufactured of samples bead-on-plate showed that depending on the cooling rate of welded joints of steel S355 J2 the structure and hardness of HAZ metal can considerably change. The main com-

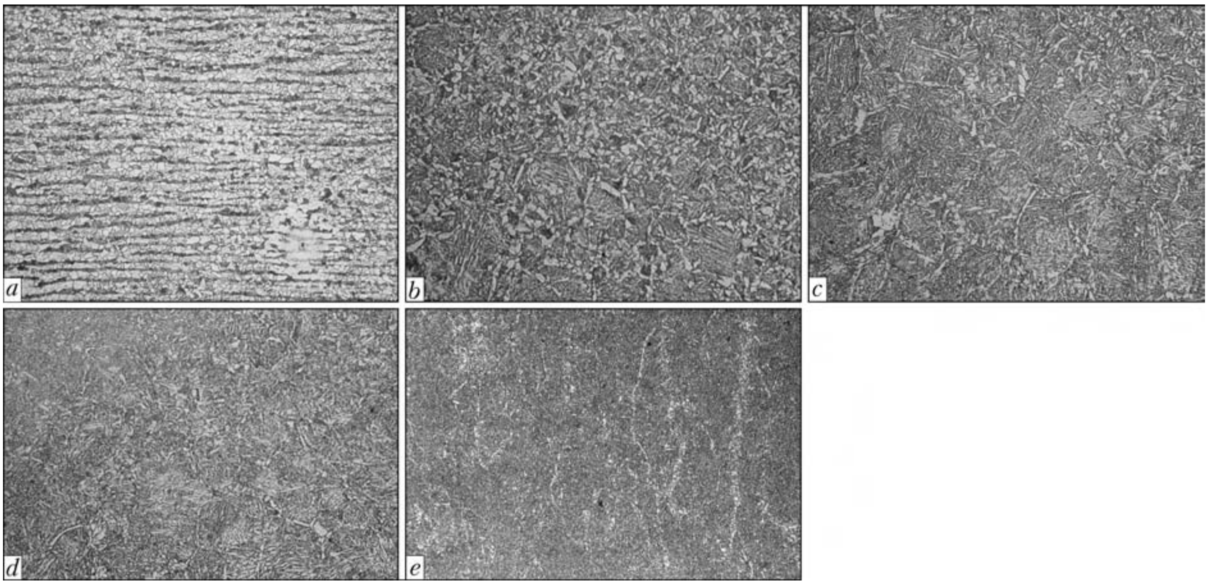

Figure 1. Microstructures (×320) of steel S390 (*a*) and area of overheating of HAZ metal of welded joints at the cooling rate $w_{6/5}$ = 3 (*b*), 10 (*c*), 20 (*d*) and 50 (*e*) °C/s

ponents of structure of metal at the area of overheating of the HAZ metal of joints, which were cooled at the rate of $w_{6/5}$ = 3 °C/s, are pre-eutectoid (along the grain boundaries) and non-equiaxial (inside the grains) ferrite, and also a small amount of bainite of lamellar and globular morphology (Figure 1, *b*). As the cooling rate of welded joints increases from 3 to 50 °C/s, the amount of pre-eutectoid and non-equiaxial ferrite in the structure decreases and fraction of bainite and dispersity of all structural components increases. It is predetermined by increase of hardness of HAZ metal from *HV* 150 to *HV* 220 (Figure 2).

As the results of static rupture tests of specimens showed, the structural changes in HAZ metal, occurred under the effect of WTCs, influence its strength and ductility (Figure 3). As the $w_{6/5}$ increases from 3 to 20 °C/s the yield strength of metal at the area of overheating of the HAZ metal increases as compared to the initial state from 410 to 550 MPa, however the tensile strength increases from 555 to 725 MPa. At the same time the values of its ductility (elongation and reduction in area) decrease from 30 to 24 and 75 to 62 %, respectively.

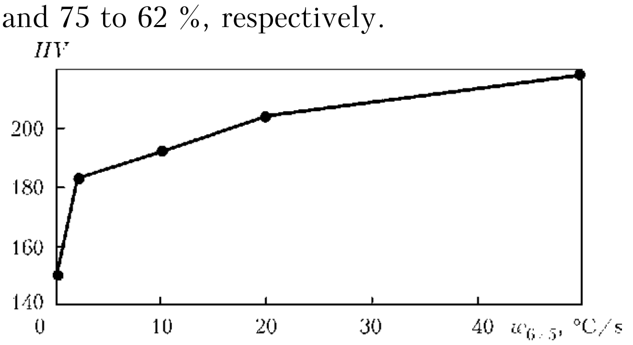

Figure 2. Dependence of HAZ metal hardness on cooling rate of welded joints

Under the influence of WTC the values of impact toughness of HAZ metal change (Figure 4). Their sharp decrease is observed at the area of overheating of the HAZ metal at the temperature of tests at −40 °C (independently of energy input of welding), and at the temperature of tests of 20 and −20 °C in case when cooling

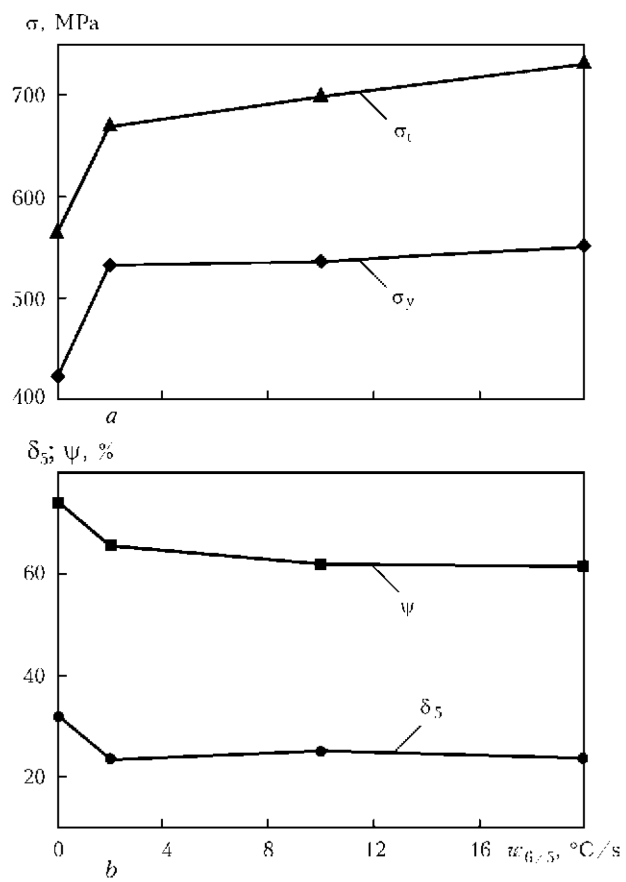

Figure 3. Dependence of values of strength (*a*) and ductility (*b*) at the area of overheating of HAZ metal on cooling rate of model specimens

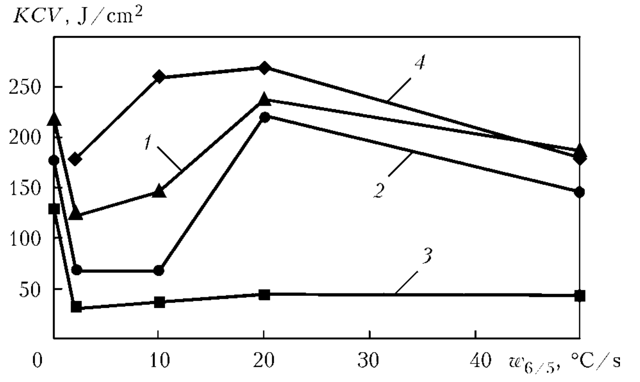

Figure 4. Influence of cooling rate on the impact rate of overheating area (*1–3*) and incomplete recrystallization (*4*) of HAZ metal at the test temperature 20 (*1*), -–20 (*2*, *4*) and –40 (*3*) °C

rate $w_{6/5}$ is below 20 °C/s. However in spite of that, the impact toughness of HAZ metal of welded joints of steel S390 remains at the level of requirements to the base metal ($KCV_{-20} \geq$ ≥ 34 J/cm^2). As the cooling rate increases to 20 °C/s the values of cold resistance of HAZ metal in the given area of welded joints increase and reach the values of impact toughness obtained at the tests of specimens manufactured of the base metal (Figure 4, $w_{6/5} = 0$ °C/s).

The impact toughness of HAZ metal at the area of incomplete recrystallization independently of input energy of welding is preserved at the level of base metal, and in the range of 10–20 °C/s cooling rates it is even higher than those values (Figure 4, curve *4*).

The tendency of steel S390 to delayed fracture depending on diffusive hydrogen content in deposited metal was evaluated using the Implant method [1]. The resistance of welded joints to cold cracks formation was studied from the results of tests of butt joints of width of 100 and 200 mm [2] rigidly fixed on a massive plate and also technological samples «rigid T-joint» [3]. The diffusive hydrogen content $[H]_{diff}$ in deposited metal was determined by the method of pencil samples using mixture of glycerin with distilled water as the blocking liquid.

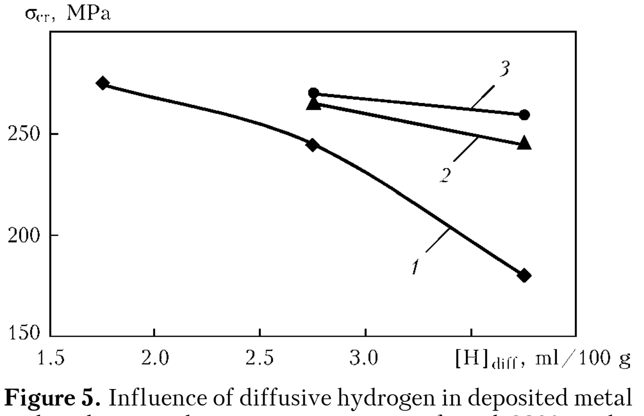

Figure 5. Influence of diffusive hydrogen in deposited metal and preliminary heating on resistance of steel S390 to delayed fracture: *1* — $T_{p.h}$ = 20; *2* — 60; *3* — 90 °C

During test using the Implant method the specimens-inserts of 6 mm diameter, manufactured of steel S390 of 100 mm thickness and cut out along the *Z*-axis with stress concentrator in a form of a screw-type notch, were used. The welding of specimens installed in the holes of basic plate of 20 mm thickness, fixed in test equipment, was performed using electrodes UONI-13/55 under the conditions of $I_w = 160$ A, $U_a = 25$ V, $v_w = 9.5$ m/h. The cooling rate of HAZ metal was varied by change of initial temperature of basic plate (the preliminary heating was used), and also by the adjustment of welding energy input. The concentration of diffusive hydrogen in deposited metal was changed using electrodes with different humidity of coating. The loading of specimens was started at reaching the post-weld temperature of 150–100 °C. As the resistance value of welded joints to formation of cold cracks the critical stress σ_{cr} was taken at which the specimen was not fractured during 24 h.

The technological samples of steel S390 of 20 mm thickness were performed by manual arc welding using electrodes UONI-13/55 of 4 mm diameter and also mechanized CO_2 welding using solid wire Sv-08G2S and flux-cored wire Megafil 821R of 1.2 mm diameter. The welding was performed under the conditions providing energy input of 11.0–12.5 (manual arc welding) and 14–17 kJ/cm (mechanized welding). The temperature of preliminary heating of samples $T_{p.h}$ was varied from 20 to 90 °C, and content of diffusive hydrogen in deposited metal — from 1.0 to 5.3 ml/100 g.

According to the results of tests of Implant specimens (Figure 5) it was established that at small concentrations of diffusive hydrogen ($[H]_{diff}$ = 1.7 ml/100 g) steel S390 has a low tendency to delayed fracture even in welding without preliminary heating ($\sigma_{cr} \approx 275$ MPa $\approx$ $\approx 0.7\sigma_y$ of the steel). The increase of amount of diffusive hydrogen in the deposited metal up to 3.8 ml/100 g under the same welding conditions increases probability of cold cracks formation in HAZ metal of welded joints of the given steel (σ_{cr} of specimens does not exceed 180 MPa $\approx$ $\approx 0.45\sigma_y$ of the steel). To minimize the risk of cracks formation in the specimens at given concentration of hydrogen is possible due to their preliminary heating up to the temperature of 90 °C (Figure 5, curve *3*).

The data obtained from results of tests of the Implant specimens comply well with the results of investigations of technological samples. The

Table 1. Results of tests of technological samples

Joint type	Welding method	Welding material	Q_w, kJ/cm	$T_{p.h}$, °C	$[H]_{diff}$, ml/100 g	Presence of cracks
Rigid T-joint	MAG	Sv-08G2S	14.0	20	1.0	No
		Megafil 821R	17.0	20	3.0	Same
	MMA	UONI-13/55	12.5	20	3.0	»
				20	5.3	Present (100 %)
				60	5.3	No
Rigidly-fixed butt joint, b = 100 mm	MAG	Sv-08G2S	15.0	20	1.0	Same
		Megafil 821R	15.8	20	3.0	»
	MMA	UONI-13/55	14.0	20	3.0	»
				20	5.3	Present (100 %)
				60	5.3	No
Rigidly-fixed butt joint, b = 200 mm		UONI-13/55	11.0	20	5.3	Same

tests of the latter showed that in case when diffusive hydrogen content in deposited metal does not exceed 3 ml/100 g the cold cracks formation in technological tests comes to minimum even in welding without preliminary heating if it is performed at the environmental temperature higher than 10 °C (Table 1).

With the diffusive hydrogen content increase in deposited metal up to 5.3 ml/100 g, the welded joints of steel S390 become prone to cold cracks formation. In welding without preliminary heating the cracks in technological samples «rigid T-joint» are observed visually at the surface of welds after 2.5 h, and in rigidly-fixed butt joints of 100 mm width — in 4 h after formation of the joints. It was established that at given saturation of welds with diffusive hydrogen the increase of stability of welded joints to cold cracks formation is possible due to their preliminary heating to the temperature of 60 °C. Under these welding conditions the cracks were absent both in T-joints as well as in rigidly-fixed butt joints.

It is possible to minimize the risk of cold cracks formation in welded joints of steel S390 due to decrease of rigidity of their fixing which is proved

Table 2. Mechanical properties of weld metal and welded joints of steel S390

Welding method	Welding conditions	Q_w, kJ/cm	Weld metal						
			σ_y, MPa	σ_t, MPa	δ_5, %	ψ, %	KCV, J/cm^2, at T, °C		
							20	−40	−20
MAG	Sv-08G2S, Ar + CO_2, δ = 16 mm	14	–	–	–	–	240	90	–
	Sv-08G2S, Ar + CO_2, δ = 50 mm	14	–	–	–	–	–	60	–
MMA	UONI-13/55, δ = 20 mm	11	497	596	29.0	75.0	166	44	30
MAG	Sv-08G2S, δ = 20 mm	15	522	601	27.3	71.0	105	39	24
	Megafil 821R, Ar + CO_2, δ = 20 mm	16	491	605	27.1	62.6	135	61	35

Table 2 (cont.)

Welding method	Welding conditions	Welded joint						
		σ_t, MPa	α_b, deg	KCU		KCV		
				J/cm^2, at T, °C				
				20	−40	20	−20	−40
MAG	Sv-08G2S, Ar + CO_2, δ = 16 mm	543	81	205	197	208	197	–
	Sv-08G2S, Ar + CO_2, δ = 50 mm	569	65	–	101	–	70	–
MMA	UONI-13/55, δ = 20 mm	–	–	–	–	106	–	70
MAG	Sv-08G2S, δ = 20 mm	–	–	–	–	248	–	166
	Megafil 821R, Ar + CO_2, δ = 20 mm	–	–	–	–	219	–	140

by test results of butt joints of 100 and 200 mm width. They showed that increase of the base of fixing *b*, i.e. the width of joints, and decrease of level of residual stresses in them from 350 to 230 MPa allowed eliminating cold cracks formation in technological samples even in case when content of $[H]_{diff}$ in deposited metal amounted to 5.3 ml/100 g and welding was performed without preliminary heating.

Taking into account the selected welding conditions the butt joints of steel S390 16 and 20 mm thick with V-shaped edge preparation and those with 50 mm thickness and X-shaped edge preparation (S17 and S25 according to the GOST 14771–76) were made. The welding of joints was performed without preliminary heating by the electrodes UONI-13/55 of 4 mm diameter, conventionally applied for this grade of steels, and the wire Sv-08G2S of 1.2 mm diameter in CO_2 and mixture of gasses (Ar + 20 % CO_2) and also flux-cored wire Megafil 821R of 1.2 mm diameter in CO_2. The conditions of welding provided values of energy input given in Table 2. It presents also the results of mechanical tests of specimens of weld metal for static tension, of welded joints for static rupture and bending, and also impact bending. A round and sharp notch was made on the specimens for impact tests along the weld axis and fusion line, and the tests themselves were carried out at the temperatures from 20 to −40 °C.

The results of mechanical tests evidence that values of strength and ductility of weld metal of welded joints of steel S390, performed using mentioned materials, are compatible with similar characteristics of the base metal and correspond to the requirements specified to them. The impact toughness of weld metal of such joints is also at the high level and meets the requirements not only of domestic standards ($KCU_{-40} \geq 29$ J/cm^2), but also European standards ($KV_{-20} \geq 27$ J or $KCV_{-20} \geq 34$ J/cm^2).

CONCLUSIONS

1. In the initial state steel S390 is characterized by fine-dispersed line ferrite-pearlite structure, thus providing the high ductility and impact toughness.

2. Under the influence of WTC at the area of HAZ metal overheating the ferrite-bainite structure is formed. As the cooling rate $w_{6/5}$ increases from 3 to 50 °C/s, the amount of ferrite in the structure decreases and amount of bainite and dispersity of all structural components increases.

3. The strength values of HAZ metal of welded joints of steel S390 increase relatively to the base metal and ductility, and impact toughness decrease but remain at the level of requirements to the rolled metal. The most remarkable decrease of impact toughness values is observed at $w_{6/5} < 20$ °C/s.

4. Welded joints of steel S390 are characterized by high resistance to cold cracks formation at the condition when diffusive hydrogen content in deposited metal does not exceed 3 ml/100 g.

5. The required mechanical properties of welded joints of steel S390 are achieved using materials, conventionally used for welding steels of this grade of strength: UONI-13/55 electrodes and Sv-08G2S wire.

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