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PECULIARITIES OF FORMATION OF STRUCTURE IN WELDED JOINTS OF MICROALLOYED STRUCTURAL STEEL S460M

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Structural steels of C440 strength class and higher have found a wide application in high-rise construction, bridge construction and freight rail transport. Application of steel roll stock with yield limit of 440 MPa allows reducing specific amount of metal per structure by 39 % in comparison with steel of St3sp (killed) (C275) grade and by 26 % in comparison with 09G2S (C345) steel grade. Present work examines the peculiarities of formation of structure in the welded joints of structural steel S460M. A CCT diagram of austenite decay in steel S460M was plotted. Effect of cooling rate of HAZ metal sample simulator on structure and strength properties was determined. It is shown that heat treatment of welded joints of steel S460M (thermal cycling, i.e. heating to 1200 °C with 25 °C/s rate plus annealing at 950 °C during 1 h plus air cooling) provides formation in HAZ metal of a favorable complex of ferrite-bainite structures due to decrease of banded structures, reduction of portion of Widmanstatten ferrite and pearlite. 8 Ref. 2 Tables, 7 Figures.

Keywords: *high-strength steel, welding thermal cycle, microstructure, acicular ferrite, cooling rate, CCT diagram of austenite decay*

Today the key Ukrainian commercial production industries have faced with the urgent problem of increase of resource and energy saving, reduction of specific amount of metal in wide designation structures and rise of their reliability [1, 2]. Such a complex of requirements can be received by means of application of new high-strength steels having yield strength of 440 MPa and higher.

Structural steels of C440 strength class and higher have found application in high-rise construction, bridge construction and freight rail transport. Replacement of ordinary structural steels of C245, C345 grades by steels of C440 strength class allows almost 1.5 times decrease of specific amount of metal of building structures due to decrease of wall thickness under similar indices of compression strength. Application of rolled metal of steel with 440 MPa yield limit allows reducing specific amount of metal per structure by 39 % in comparison with steel of St3sp (killed) grade (C275) and by 26 % in comparison with steel of 09G2S (C345) grade [3].

Analysis of new modern structural steels showed that new S460M grade structural microalloyed steel of C440 strength class is characterized by good perspectives in scope of practical application. This steel is produced using a technology of thermomechanical controlled rolling with further heat treatment according to DSTU EN 10025-4:2007 at Mariupol Metallurgical Plant named after Illich (Illich Iron & Steel Works) (Ukraine).

This steel based on data of EN 10025-4 [4] standard has the following mechanical properties, namely yield limit $\sigma_y > 460$ MPa, ultimate strength $\sigma_t = 540$–720 MPa, relative elongation $\delta_5 > 18$ %, impact toughness $KCV_{-40} > 27$ J/cm^2. High mechanical properties of steel S460M are provided due to application of mechanism of dispersion strengthening using niobium and vanadium carbonitrides. Application of the technology of thermomechanical controlled rolling guarantees formation of a fine grain structure in steel with low value of carbon equivalent (0.45–0.48) that provides its good weldability, forming in cold state, stability to brittle fracture at operation temperatures up to –50 °C and high values of impact toughness.

It is known fact [5, 6] that the most problem area of welded joint from point of view of brittle fracture resistance is metal of heat-affected zone (HAZ), in which structure and, therefore, mechanical properties of metal undergo significant changes in effect of welding thermal-deformation cycle (WTC). It is related with grain growth in heating as well as formation in cooling of intermediate and quenching structures, promoting decrease of metal resistance to brittle fracture.

In this connection, the aim of present work lied in study of kinetics of austenite transformation, peculiarities of formation of HAZ metal structure and determination of its effect on mechanical properties in mechanized welding of S460M steel.

Investigation procedure. Structural steel S460M of 16 mm thickness with the following composition, wt.%: 0,15 C; 0,23 Si; 1,3 Mn; 0,09 Cr; 0,019 Ni; 0,01 V; 0,05 Nb; 0,025 Al; 0,007 N; 0,013 S; 0,017 P was taken for investigations. Mechanical properties of investigated steel S460M in as-delivered condition are σ_y = 480 MPa; σ_t = 600 MPa; δ_5 = 27 %; ψ = 58 %.

A nature of structural transformations in metal of the investigated welds was studied by the method for simulation WTC using Gleeble 3800 complex equipped with high-speed dilatometer [7]. The investigations were carried out employing cylinder samples of 6.0 mm diameter and 80 mm length produced of sheet products of 20 mm thickness. In accordance with the procedure developed at the E.O. Paton Electric Welding Institute and using set computer program the samples were heated in a vacuum chamber to 1250 °C temperature and then cooled at cooling rates corresponding to different welding thermal cycles. The cooling curves were set by Newton–Richmann's dependence and corresponded to cooling rates in 5–126 °C /s range at 500–600 °C temperature region (Table 1). At that, it was sufficiently accurate reproduction of real cooling parameters (heat and time) of metal of the welded joints. Used range of cooling rates conformed virtually to all types of welding (automatic submerged arc welding, gas-shielded mechanized welding, manual arc welding with coated electrodes), which are applied in manufacture of metal structures.

The samples for metallographic investigations were made on standard procedure using diamond pastes of different dispersion on high-speed disks. Microstructures of the samples were revealed by chemical etching in 4 % alcoholic solution of nitric acid.

Metallographic exanimations were carried out employing light microscope Neophot-32 at different magnifications (×200, ×500). A non-metallic impurity level was determined by means of visual comparison with scale references (GOST 1778–70). A banding level was determined by visual comparison with standard scales of GOST 5640–68. Microhardness of separate structural constituents was measured on hardness gage M-400 of LECO Company at 100 g (*HV*0.1) loading and that of integral hardness (*HV*1) at 1 kg loading. A digital image was registered by Olympus digital camera (40×40).

Table 1. Modes of welding simulation for S460M steel samples on Gleeble 3800

Sample number	Cooling rate, °C/s	Holding time, *t*, s	Structure type	Microhardness *HV*1, MPa
1	5	10	F	2300
2	10	10	F	2640
3	30*	30	B	3450
4	30	10	B	3600
5	35	10	B + M	3650
6	60	10	M + B	4010
7	126	10	M + B	4260

Note. F — ferrite, B — bainite, M — martensite; heating temperature T_{max} = 1250 °C.

Content of non-metallic inclusions in the initial state meets level 2 of «Spotted nitrides» Table. Single dispersed oxides SiO_2 and sulfides were detected in steel S460M in the initial state. Impurity level with spotted oxides and sulfides does not exceed the 1st level of «Spotted oxides» and «Sulfides» Table.

Obtained results and discussion. The changes of HAZ metal structure (Figure 1) were studied after simulation of typical welding modes and plotting an austenite decay CCT-diagram.

The initial metal structure of steel S460M consists of mixture of ferrite (80–85 %) and pearlite (20–15 %) constituents. An expressed rolling texture (Figure 2, *a*) is formed in the metal as a result of thermal-mechanical controlled rolling. The banding level of the

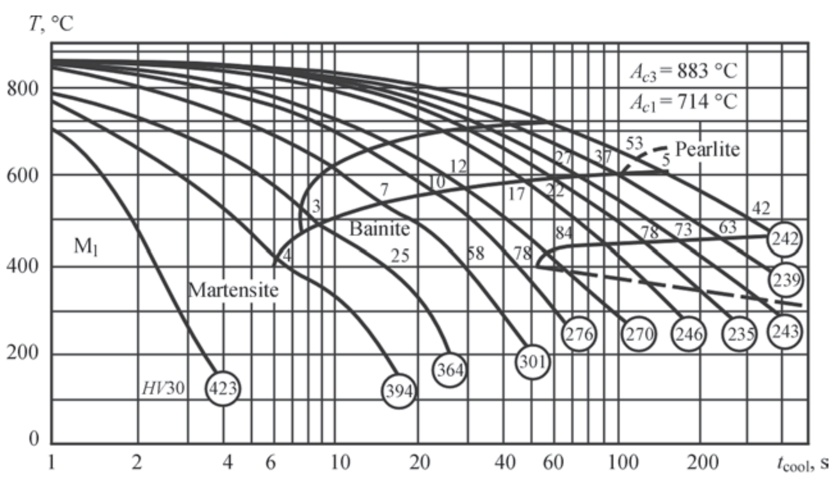

Figure 1. CCT diagram of austenite decay of steel S460M (numbers in circles — Vickers's hardness; numbers on diagrams — phase portion)

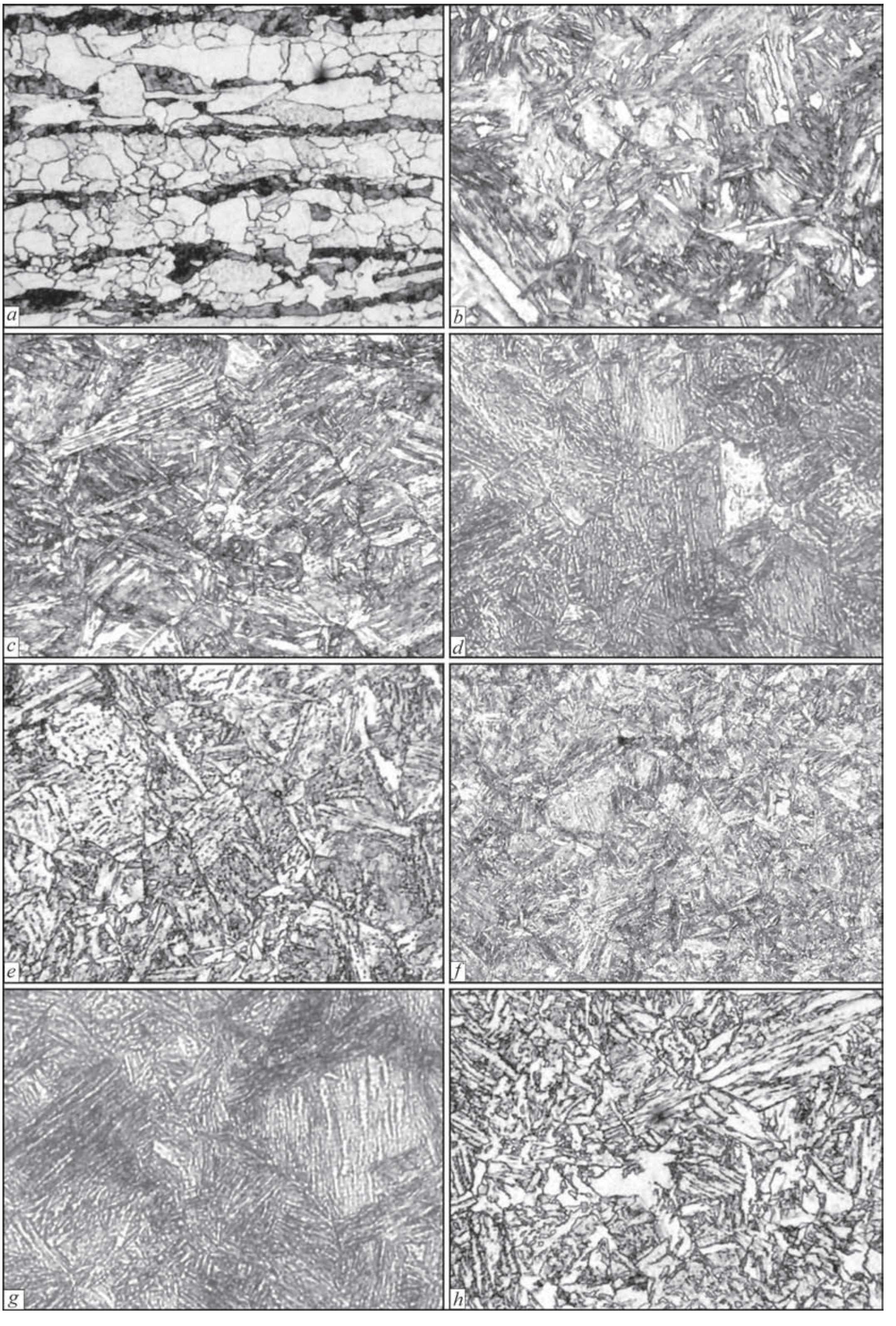

Figure 2. Microstructure (×500) of base metal and sample simulators of HAZ metal of steel S460M at different cooling rates $w_{6/5}$: *a* — base metal; *b* — 5; *c* — 10; *d* — 30 (10 s); *e* — 30 (30 s); *f* — 35; *g* — 60; *h* — 126 °C/s

structure corresponds to level 5 of series B on scale No.3 «Banding of ferrite-pearlite structure (×100)». Microhardness (*HV*0.1) of ferrite makes 1930–1990, that of pearlite 2300–2360 MPa.

A structure of sample simulator of steel S460M HAZ metal cooled at $w_{6/5}$ = 5 °C/s rate consists of different morphological forms of ferrite, i.e. acicular ferrite, polygonal ferrite, ferrite with ordered and disordered secondary phase, free ferrite and pearlite (Figure 2, *b*). Increase of cooling rate of steel S460M sample simulators to $w_{6/5}$ = 10 °C/s results in formation of mainly acicular ferrite (Figure 2, *c*). Further increase of cooling rate of the sample simulators to $w_{6/5}$ = 30 °C/s results in formation in HAZ metal of

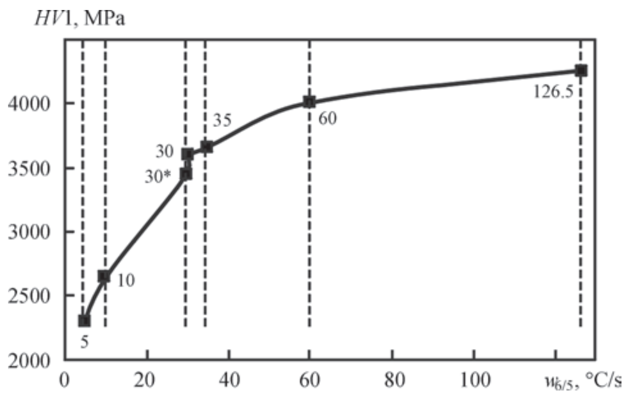

Figure 3. Effect of cooling rate on integral hardness of sample simulators of S460M steel HAZ metal

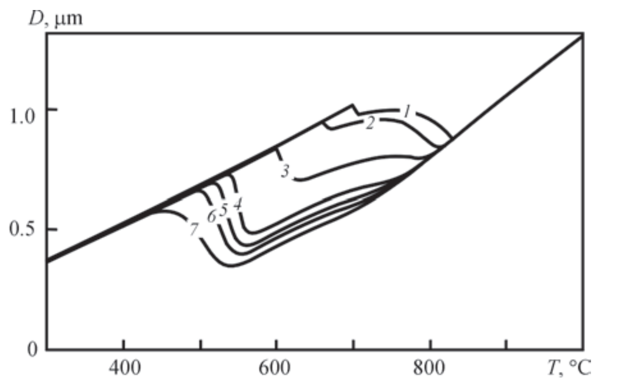

Figure 4. Dilatometric curves of S460M steel cooling: *1* — 0.01; *2* — 0.1; *3* — 1; *4* — 10; *5* — 20; *6* — 30; *7* — 50 °C/s (*D* is the measurement of sample dimensions (metal volume) in heating as a result of dilatometric investigations, μm)

bainite packages of different orientation with registration of insignificant amount of (smooth light) areas of residual austenite (Figure 2, *d*). Microstructure of the sample simulator of HAZ metal of steel S460M, cooled at the same rate $w_{6/5}$ = 30 °C/s, but with increased time of holding to 30 s (in comparison with 10 s) at the maximum heating temperature, consists of the dispersed bainite needles in form of rosettes and areas of residual austenite (Figure 2, *e*).

Further increase of cooling rate of steel S460M to $w_{6/5}$ = 35 °C/s (normalizing mode, free cooling on air) (Figure 2, *f*) results in formation of bainite of different morphology (upper and/or lower), residual austenite and minor amount (up to 3–5 %) of martensite. Microhardness *HV*0.1 of structural constituents is 3300–3360 for upper bainite and 3630–37500 MPa for lower bainite. Martensite acicular type structure is typical for S460M sample cooled with $w_{6/5}$ = 60 °C/s rate (Figure 2, *g*). Martensite areas of two types differed on carbon content are formed. Microhardness (*HV*0.1) of areas of dark etching martensite makes 3600–3760 MPa and that for bright etching martensite is somewhat above up to 3860–4260 MPa. Microstructure of sample simulator of S460M steel HAZ metal cooled with the highest rate $w_{6/5}$ = 126 °C/s (Figure 2, *i*) consists of the weak etching close-packed packages of martensite with 4100–4630 MPa microhardness.

Analysis of a structural state of S460M steel HAZ metal of sample simulators showed that increase of cooling rate from 1 to 35–40 °C/ s provokes change of structure from ferrite-pearlite to ferrite-bainite with primary formation of acicular ferrite, which, as it is known [8], provides optimum combination of strength, ductility and impact toughness to welded joints of microalloyed steels. Further rise of cooling rate for more than 40 °C/s is accompanied by growth of martensite constituent that increases the risk of cold crack formation in S460M steel HAZ metal.

A type of phase transformations, which is realized in process of continuous cooling and structural changes taking place in HAZ metal volume results in the fact that properties of HAZ metal significantly depend on its cooling rates.

A quantitative assessment of the structure-phase content of S460M steel HAZ metal was realized based on a complex analysis of the microstructure, testing of a set of hardness samples and analysis of dilatometric curves.

Effect of cooling rate of sample simulators of S460M steel HAZ metal on integral Widmanstatten hardness *HV*1 is presented on Figure 3 and that for nature of change of dilatometric curves is on Figure 4 and portion of structural constituents is on Figure 5.

Analysis of the dilatometric curves of cooling of steel S460M sample simulators allowed determining temperature of start and end of phases' formation, i.e. ferrite, bainite and martensite.

Analysis of the experimental diagrams showed that the temperature of start of ferrite transformation for given steel make 720 °C and that for bainite is 580 °C. Temperature A_{c3} makes 855 °C and A_{c1} temperature is 723 °C. Typical temperatures of martensite transformation make 400 °C for the beginning, 342 °C is temperature of formation of 50 % of martensite and

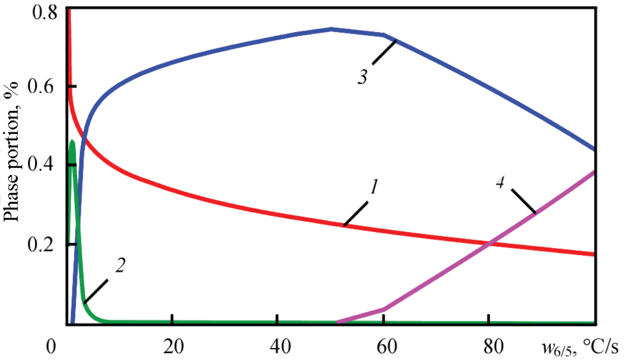

Figure 5. Effect of cooling rate of S460M steel HAZ metal on portion of structural constituents: *1* — ferrite; *2* — pearlite; *3* — bainite; *4* — martensite

Table 2. Mode of deposition of «bead probes» of steel S460M

Number	I_w, A	U_a, V	v_w, m/h	Q_w, kJ/cm	$w_{8/5}$, °C/s
1	540–550	30	13.2	40.4	3
2	540–550	30	24.0	22.1	10
3	540–550	30	35.5	14.8	20
4	500–510	21	37.8	9.0	50

272 °C is temperature of formation of 90 % of martensite. A critical cooling rate, at which completely martensite structure is formed in welding of S460M steel, makes 300 °C/s.

As it was mentioned above, the changes of structure in HAZ metal of welded joints take place under effect of welding thermal cycles. However, investigations carried on the reference samples can not provide full presentation of structure formation in different areas of HAZ metal under effect of WTC due to their small size. Therefore, further investigations were carried out on the samples, size of which allows reconstruct conditions of thermal as well as deformation processes taking place in the welded joints during their heating/cooling.

The investigations were performed using «bead probes» method following GOST 13585–68. Effect of welding heat input on formation of a structure of welded joints of thermal-mechanical strengthened steel S460M was researched. The beads were deposited on modes providing variation of cooling rate in area of HAZ metal overheating in 3–5 °C/s interval. Bead deposition was done by Sv-10NMA wire of 4 mm diameter under AN 60 flux with reverse polarity DC at 20 °C temperature without preheating.

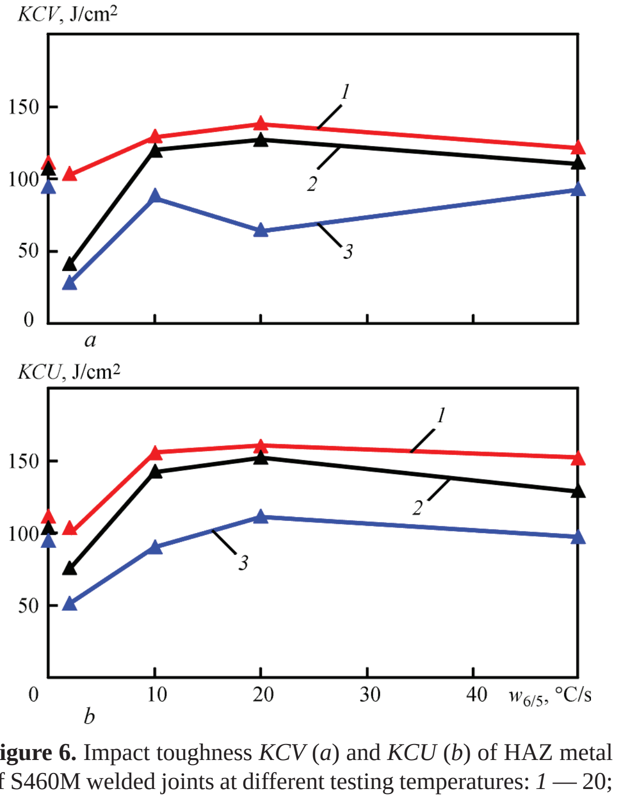

Figure 6. Impact toughness *KCV* (*a*) and *KCU* (*b*) of HAZ metal of S460M welded joints at different testing temperatures: *1* — 20; *2* — –20; *3* — –40 °C

Parameters of the welding modes and corresponding to them cooling rates of «bead probes» HAZ metal are given in Table 2.

Figure 6 shows the dependencies of effect of a welding heat input on impact toughness of HAZ metal of S460M steel welded joints. It is determined that effect of the welding heat input on impact toughness of HAZ metal of S460M steel welded joints is ambiguous.

The lowest indices of impact toughness at V- and U-notch tests, which are 2 times lower than the indices of base metal, are observed in testing at –20 and –40 °C temperatures in the case when welding was carried out with 40 kJ/cm heat input, that corresponded to 3 °C/s cooling rate of HAZ metal.

At increase of cooling rate to 10–30 °C/s range ($9 \leq Q_w \leq 22$ kJ/cm) the indices of impact toughness are at the level of base metal properties in as-delivered condition and even exceed them at all testing temperatures. Decrease of impact toughness indices at cooling rates below 10 °C/s is, apparently, related with formation in HAZ metal of the low-ductility structures, i.e. ferrite with ordered secondary phase and pearlite (Figure 2, *b*). Reduction of the impact toughness indices at cooling rates above 30 °C/s, to the larger extent, is related with growth of part of martensite constituent in HAZ metal of steel S460M.

The lowest indices of impact toughness of HAZ metal on the sharp notch samples at –40 °C testing temperature were observed in the case of cooling at less than 20 °C/s rate (i.e. heat input above Q_w = = 14.8 kJ/cm). At the same time in this situation the indices of impact toughness of HAZ metal of steel S460M exceed the standard values of $KCV_{-40} \geq 34$ J/cm^2 and make KCV_{-40} = 62–68 J/cm^2.

Due to the fact that steel S460M is microalloyed with vanadium and niobium and after controlled rolling is subjected to special heat treatment mode, it was necessary to analyze the effect of different modes of heat treatment on structure and properties of steel S460M welded joints.

Several modes of heat treatment were proposed. Their simulation was done on Gleeble 3800 unit. The initial sample for comparison was sample simulator of steel S460M, produced with 25 °C/s cooling rate (sample No.5). Sample No.6 was heat treated on the following mode, namely annealing at 950 °C temperature during 1 h and then cooling down on air. Sample No.7 was subjected to thermal cycling at 1200 °C temperature with 25 °C/s rate + annealing at 950 °C temperature during 1 h, then cooling on air.

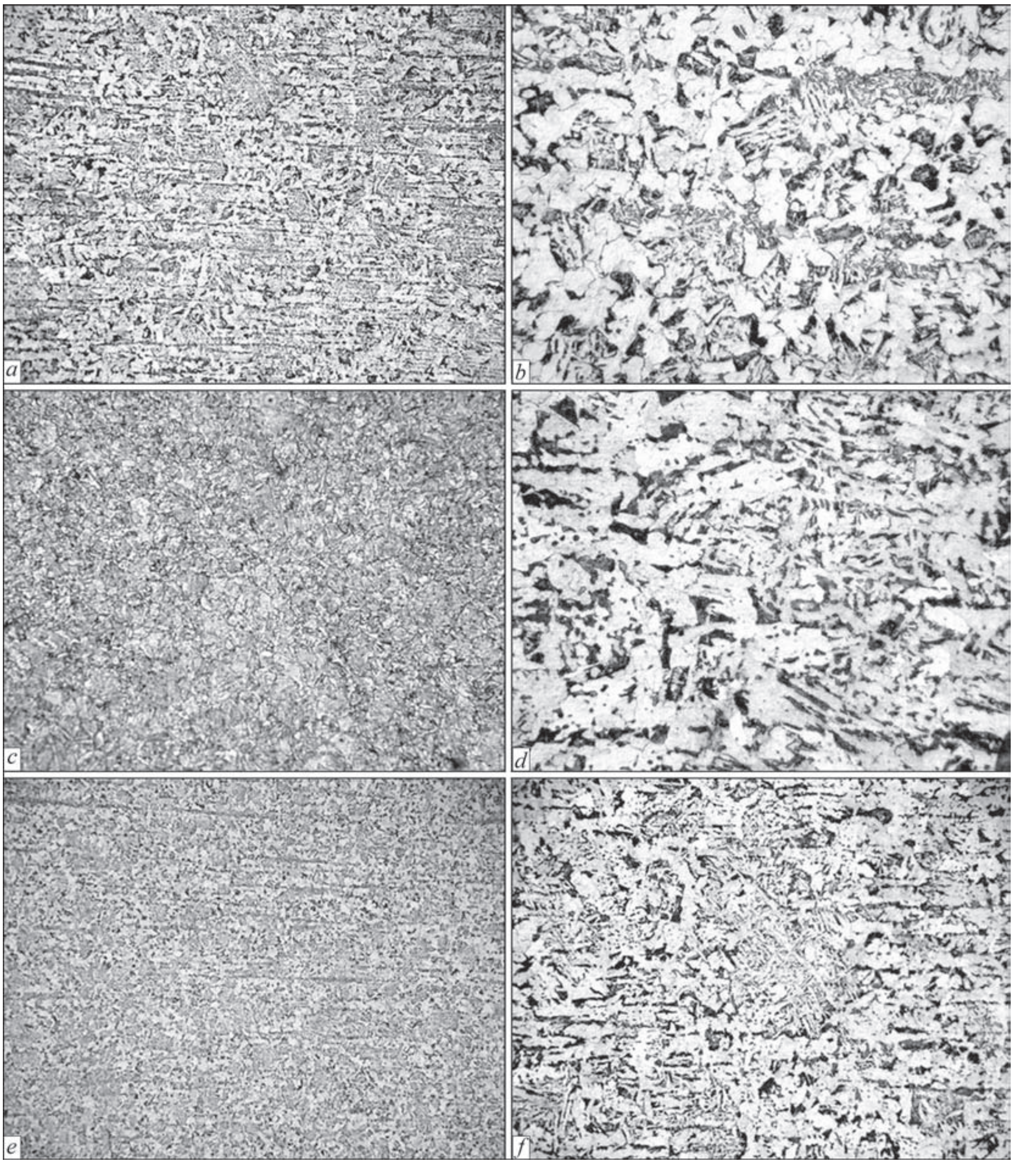

Figure 7. Microstructure of sample simulators of steel S460M after heat-treatment: *a*, *b* — initial; *c*, *d* — at 950 °C during 1 h, cooling on air; *e*, *f* — thermal cycling: heating to 1200 °C with 25 °C/s rate + tempering at 950 °C during 1 h and cooling on air (*a*, *c*, *d* — ×100; *b*, *d*, *f* — ×500)

Figure 7 presents carried metallographic examinations of the initial and heat-treated samples of structural steel S460M.

Microstructure of sample No.6 (annealing at 950 °C during 1 h and cooling on air) is given in Figure 7, *c*, *d*, and presented by ferrite-pearlite structure of band type. The level of structure banding corresponds to No.2b, determined in accordance with standard scale No.3 «Banding of ferrite-pearlite structure». The structure of sample No.6 includes areas of Widmanstatten ferrite and pearlite (Figure 7, *c*, *d*). Vickers' hardness of sample No.6 makes *HV*0.1-1700 MPa. Grain size corresponds to level No.4 on GOST 5639–82.

The microstructure of sample No.7, received on thermal cycling mode at 1200 °C temperature with 25 °C/s rate + annealing at 950°C during 1 h and cooling on air, is ferrite-bainite with the areas of acicular ferrite and Widmanstatten ferrite. Size of ferrite grains is significantly smaller in comparison with grain size of sample No.6. Grain level corresponds to Nos. 6–7 on GOST 5639–82 (Figure 7, *e*, *f*).

Sample No.7 base metal has larger hardness in comparison with base metal of sample No.6 by approximately 300–500 MPa. Lower structure banding is observed in sample No.7 than in sample No.6, namely banding level is No.1 comparing with No.2b for sample No.6. It is determined that heat treatment of the sample simulators in the welded joints of steel S460M (thermal cycling at 1200 °C with 25 °C/s rate + annealing at 950 °C in course of 1 h + cooling on air) provides formation of a favorable complex of ferrite-bainite structures in HAZ metal due to formation of acicular ferrite, decrease of portion of Widmanstatten ferrite and pearlite, decrease of structure banding.

Conclusions

1. A set of ferrite-bainite structures is formed in HAZ metal of structural steel S460M during welding. It provides high characteristics of strength, ductility and impact toughness.

2. The indices of impact toughness of HAZ metal KCU_{-20}, KCU_{-40} and KCV_{-20}, KCV_{-40} are two times lower than the indices of base metal in welding of steel S460M with cooling rate 3 °C/s (heat input 40 kJ/cm). The indices of impact toughness at all testing temperatures at increase of cooling rate to 10–30 °C/s ($9.0 \le Q_w \le 22.1$ kJ/cm) are on the level of initial metal and even exceed them due to formation of lower bainite structure.

3. There is a decrease of the indices of impact toughness in the sharp notch samples to 62–68 J/cm^2 values at cooling rate above 30 °C/s ($Q_w < 90$ kJ/cm) due to formation of mainly martensite structure in HAZ metal.

4. Heat treatment of welded joints of steel S460M on thermal cycling mode (heating to $T = 1200$ °C with $w_{5/6} = 25$ °C/s + annealing at $T = 950$ °C during 1h and cooling on air) provides increase of mechanical properties of the welded joints due to reduction of structure banding, decrease of portion of Widmanstatten ferrite and pearlite.

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