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EFFECT OF PARAMETERS OF ARC, LASER AND HYBRID METHODS OF WELDING ON STRUCTURE AND PROPERTIES OF BUTT JOINTS OF HIGH-STRENGTH STEEL S460M

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The paper studies the effect of parameters of arc, laser and hybrid laser-arc welding on formation of structure and properties of weld metal and heat-affected zone of butt joints from high-strength low alloy steel S460M with yield point up to 480 MPa. It is shown that increase of rate of gas-shielded arc welding to 50 m/h (13.9 mm/s) allows receiving a quality weld with increased indices of static strength and impact toughness. Laser welding with increased cooling rate provokes reduction of the indices of ductility and impact toughness of weld metal that is related with formation of martensite hardening structure of weld metal and heat-affected zone of the welded joints revealing at higher cooling rate. Application of hybrid laser-arc welding method of steel S460M allows decreasing cooling rate of weld metal and heat-affected zone in comparison with laser welding method. This provides high level of mechanical properties and impact toughness of metal of these zones. 16 Ref., 1 Table, 5 Figures.

Keywords: *butt joints, high-strength steel, arc welding, laser welding, hybrid laser-arc welding, thermal cycle, structure peculiarities, mechanical properties*

Mechanized and automatic arc welding in active shielding gases medium as well as in their mixtures with inert gas (Ar + CO_2, Ar + CO_2 + O_2) [2] using solid wire as well as flux-cored wire [3] are widely applied in manufacture of metallic structures of high-strength steels [1] of up to 10 mm thickness. Preferable, from point of view of receiving of quality welded joints are such modes of arc welding, at which weld metal and metal of heat-affected zone (HAZ) preserve the strength, ductility and cold resistance at the level of base metal and have high resistance to cold crack formation [4].

Laser [5, 6] and hybrid laser-arc welding [7–16] are implemented in production in the recent years in order to decrease deformation and increase of quality of welded thin-wall (thickness up to 10 mm) metallic structures of ferrite-pearlite class low-alloy steels. The advantages of these types of welding are [5–16]: increase of productivity due to several times rise of welding rate [7]; significant decrease of heat input [8, 9]; obtaining the balanced fine-grain microstructures in weld metal and HAZ [10–12], which exceed joint strength, reduce level of residual stresses and susceptibility to cold crack formation [13–15].

In this connection the relevant are the investigations of effect of technological processes parameters in laser, arc and hybrid laser-arc welding on structure and properties of butt welded joints from low-alloy steels of C440–C460 strength class.

Present work has studied the effect of parameters of arc, laser and hybrid laser-arc welding on formation of structure as well as properties of weld metal and HAZ of joints of high-strength alloy steel S460M with yield point σ_y = 480 MPa and following composition, wt.%: 0.15 C; 0.23 Si; 1.3 Mn; 0.09 Cr; 0.02 Ni; 0.23 Mo; 0.1 V; 0.6 Cu; 0.013 S; 0.017 P.

An initial stage of work was dedicated to investigation of effect of mode parameters of mentioned above welding methods on heating and cooling conditions of butt welded joints of 8 mm thickness.

Automatic arc welding of such joints is carried out by flux-cored wire Megafil 821R of 1.2 mm diameter in gas mixture (82 % Ar + 18 % CO_2) at the following modes, i.e. welding current I_w = 220–240 A; arc voltage U_a = 30–32 V; welding rate v_w = 30; 40; 50 m/h (8.3, 11.1 and 13.9 mm/s, respectively). Further increase of welding rate appeared to be unreasonable, since selected welding modes did not allow getting quality joints. Weld formation was deteriorated, lack of penetration and spattering of electrode metal appeared.

In laser process the welding rate lied in the limits from 40 m/h (11.1 mm/s) to 50 m/h (13.9 mm/s) ($w_{6/5}$ = 65–103 °C/s). The parameters of laser radia-

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tion were 4.4 kW power of Nd:YAG laser, focus penetration $\Delta F = -1.5$ mm.

In hybrid laser-arc welding the modes of laser constituent were 4.4 kW power of Nd:YAG laser, focus penetration $\Delta F = -1.5$ mm. The parameters of arc constituent of hybrid welding process at constant consumption of shielding gas mixture 82 % Ar + 18 CO_2 Q_{shield} = 14–16 l/min varied depending on welding rate. At rate of hybrid laser-arc welding v_w = 72 m/h (20.0 mm/s) current and arc voltage made I_w = 120 A and U_a = 22 V; at that I_w = 170 A and U_a = 24 V at welding rate v_w = 90 m/h (25 mm/s) and I_w = 200 A at v_w = 110 m/h (30.5 mm/s).

Record of thermal welding cycles was carried out using chromel-alumel thermal couples of 0.5 mm diameter, connected through USB-converter of electric signals to PC. Their joint was located in the place of HAZ metal overheating. Cooling rate of HAZ metal in a 600–500 °C ($w_{6/5}$) temperature range was taken as a parameter of thermal cycle, which further was used as criterion for evaluation of its effect on structure and mechanical properties of weld metal and HAZ of welded joints.

Analysis of thermal cycles of automatic arc welding of S460M steel butt joints showed that a heating rate of such joints virtually does not depend on rate of heat source — welding arc displacement and makes 180–200 °C/s. Intensity of HAZ metal cooling (Figure 1) has significant effect on welding rate. Increase of v_w promotes rise of cooling rate of welded joints. Thus, cooling of metal of HAZ overheating area in the 600–500 °C temperature range at welding rate v_w = = 30 m/h (8.3 mm/s) takes place with $w_{6/5}$ = 24 °C/s rate, at v_w = 40 m/h (11.1 m/s) $w_{6/5}$ = 27 °C/s and at arc welding rate v_w = 50 mm/h (13.9 mm/s) HAZ metal is cooled with $w_{6/5}$ = 36 °C/s rate.

Analysis of thermal cycles of laser and hybrid laser-arc welding of butt joints of S460M steel showed that the values of heating rates of HAZ metal to 1100–1300 °C temperatures and cooling rates of the overheating areas in 600–500 °C temperature range are identical to the values received for steel 14KhGN2MDAFB [13].

From point of view of structure formation laser welding process is characterized by «rigid» thermal cycle with sufficiently high (up to $w_{6/5}$ = 103 °C/s) cooling rates in HAZ metal of S460 steel welded joints that can result in formation in it of hardening structures of high hardness. It is shown by the results of investigations of structural transformations in HAZ metal of S460M steel in heating-cooling process, obtained with the help of dilatometry [16]. For «softening» of such thermal cycle it is reasonable to use hybrid laser-arc welding, which allows providing cooling of HAZ metal of welded joints with $w_{6/5}$ = 58–62 °C/s rate at productivity preserving.

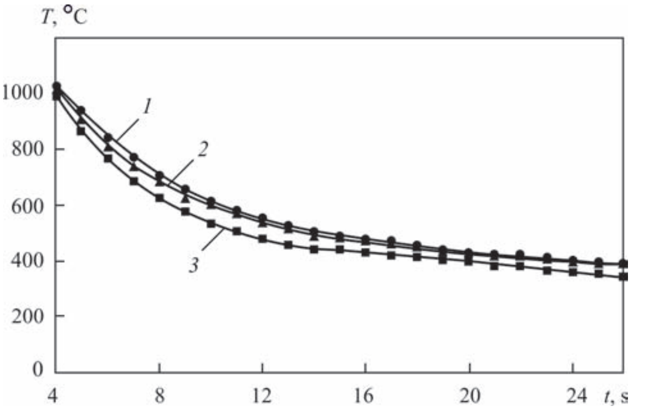

Figure 1. Thermal cycles in automatic arc welding of S460M steel: *1* — v_w = 30 m/h ($w_{6/5}$ = 24 °C/s); *2* — 40 m/h (27 °C/s); *3* — 50 m/h (36 °C/s)

Differences in cooling conditions in arc, laser and hybrid laser-arc welding cause formation of different structure that, in turn, results in change of mechanical properties of weld metal and HAZ of welded joints. It is indicated by the results of investigations carried below.

Based on data of metallographic analysis it is determined that microstructure of HAZ metal of specimens of steel S460M performed by arc welding can vary from ferrite to bainite. Increase of cooling rate from $w_{6/5}$ = 24 °C/ s (v_w = 30 m/h, Figure 2, *a*) to $w_{6/5}$ = = 27 °C/ s (v_w = 40 m/h, Figure 2, *b*) and $w_{6/5}$ = 36 °C/s (v_w = 50 m/h, Figure 2, *c*) promotes structure transformation from acicular ferrite into bainite and it consists of different-oriented packages of bainite containing residual austenite. At that value of integral microhardness in HAZ metal of S460M specimens rises (from *HV*0.1-2490–2730 MPa at v_w = 30 m/h to *HV*0.1-3530–3650 MPa at v_w = 50 m/h, respectively).

Transformation of the structure from bainite to martensite (Figure 3) is observed for specimens cooling rate $w_{6/5}$ around 60 °C/s, typical for hybrid laser-arc welding, in HAZ metal of welded joints of S460M steel. This cooling rate is characterized with acicular martensite structure with different-oriented needles of 60 and 120 ° angle. HAZ metal structure contains dark and light etching martensite. In this case microhardness of dark etching martensite makes *HV*0.1-3600–3760 MPa, and that for light etching is *HV*0.1-3860–4260 MPa.

Increase of cooling rate for more than 100 °C/s (typical for laser welding with v_w = 50 m/h) also promotes formation of martensite in HAZ metal of S460M steel welded joints. But under such conditions of cooling the martensite structure consists of more close-packed packages that results in further growth of microhardness values *HV*0.1-4100–4630 MPa.

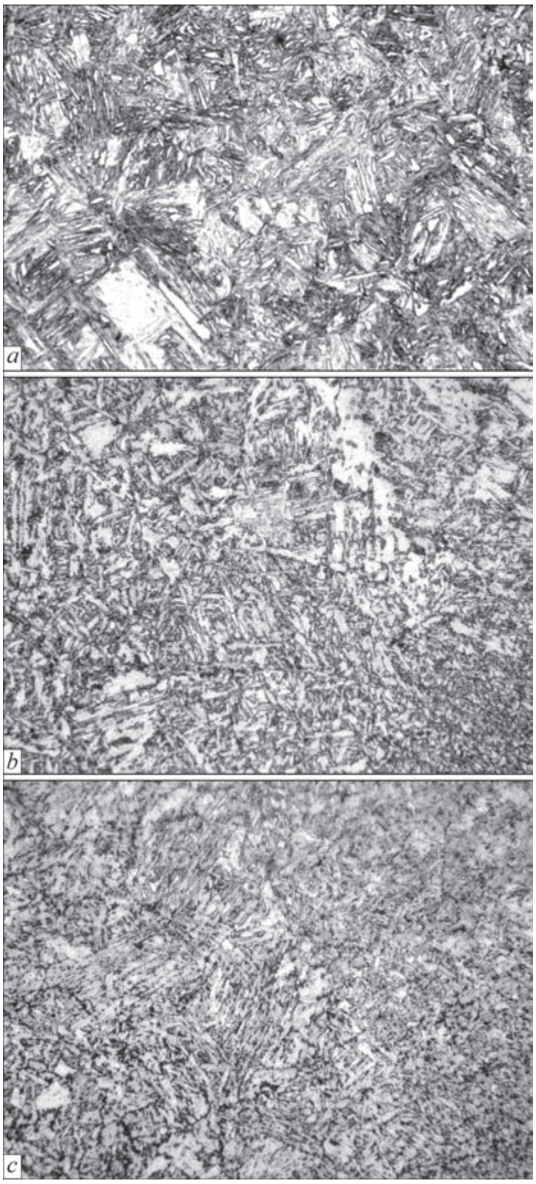

Figure 2. Microstructure (×500) of HAZ metal of steel S460M welded joints produced at different rate of arc welding: *a* — v_w = = 30 m/h (8.3 mm/s) ($w_{6/5}$ = 24 °C/s); *b* — 40 m/h (11.1 mm/s) ($w_{6/5}$ = 27 °C/s); *c* — 50 m/h (13.9 mm/s) ($w_{6/5}$ = 36 °C/s)

The specimens for static tension tests (type I) and V-notch impact bend tests (type X) on weld metal as well as HAZ were made from welded joints according to GOST 6996–66 for evaluation of mechanical properties. The tensile specimens were tested at room temperature and the impact bend ones at temperatures from 20 to –40 °C.

The results of investigation of mechanical properties of welded joints, performed using arc, laser and hybrid laser-arc welding are given in the Table.

It is determined that in increase of arc welding rate from 30 m/h ($w_{6/5}$ = 24 °C/ s) to 50 m/h ($w_{6/5}$ = = 36 °C/s) the values of yield point and ultimate strength rise from 582 to 607 MPa and from 625 to 657 MPa, respectively. Impact toughness of weld metal and HAZ of welded joints at that also increases. The

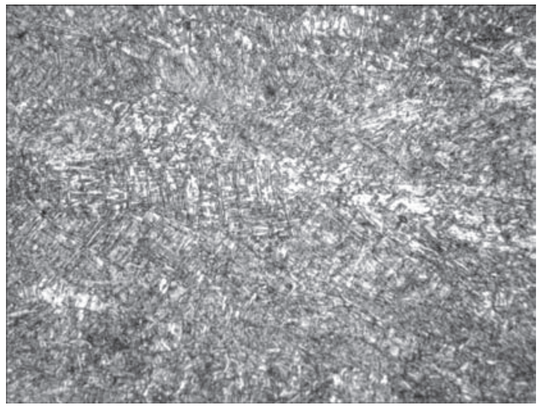

Figure 3. Microstructure (×500) of HAZ metal in hybrid laser-arc welding of S460M steel (v_w approximately 90 m/h (25.0 mm/s))

most significant increase of *KCV* indices is observed in the specimens which were tested at –40 °C temperature. In particular, rise of $w_{6/5}$ from 24 (v_w = 30 m/h) to 36 °C/ s (v_w = 50 m/h) increases the values of weld metal KVC_{-40} from 70–83 to 137–161 J/cm^2 and HAZ from 80–110 to 115–120 J/cm^2. Weld metal ductility of such joints, independent on selected welding conditions, virtually does not change and remains at high level (elongation 21–23 % and reduction in area 68–70 %).

The results of mechanical tensile tests of the cylinder specimens showed that yield point and tensile strength of weld metal of S460M welded joints, produced using laser process, rises two times in comparison with welded joints, produced by arc welding. However, its ductility is significantly reduced at that, namely two times at welding rate 40 m/h and virtually four times at v_w = 50 m/h. Impact toughness of weld metal of such joints completely satisfies the requirements set for welded joints of steels with $\sigma_{0.2} \geq$ $\geq$ 390 MPa ($KVC_{-40} \geq$ 34 J/cm^2). At the same time, it is noted that increase of rate of laser welding reduces the indices of impact toughness of weld metal of S460M steel welded joints at positive as well as at negative temperatures. Impact toughness of HAZ metal of such welded joints lies at high level (KCV_{40} = = 120–150 J/cm^2), and its values in the investigated range of welding rates virtually do not change. Hybrid laser-arc welding of S460M steel demonstrates the same tendency of change of mechanical properties of weld metal as in laser welding. Static strength of weld metal of S460M steel welded joints rises in comparison with arc welding per 65–70 %, however, its ductility reduces virtually two times.

Increase of rate of hybrid laser-arc welding to 110 m/h ($w_{6/5}$ = 58–63 °C/s) results in reduction of the strength indices by 100 MPa and insignificant (by 15 %) rise of the ductility indices (Table). Increase of rate of hybrid laser-arc welding from 72 (20.0 mm/s) to 110 m/h (30.5 mm/s) ($w_{6/5}$ = 58–63 °C/s) promotes decrease of

Mechanical properties of S460M steel welded joints in arc, laser and hybrid laser-arc welding

Variant of welding	$\sigma_{0.2}$, MPa	σ_t, MPa	δ_5, %	ψ, %	*KCV*, J/cm² at *T*, °C					
					Weld			HAZ		
					20	–20	–40	20	–20	–40
Base material	490	600	24	59	110*	–	–	–	–	–
Arc v_w = 30 m/h (8.3 mm/s)	576.3 587.3	623.6 626.3	22.3 23.3	69.7 68.0	186.0 172.1	121.7 153.7	69.8 83.4 80.9	–	–	83.3 109.4 90.7
Arc v_w = 40 m/h (11.1 mm/s)	586 608.9	629.6 637.7	21.7 23.3	69.8 69.9	176.2 173.9	158.3 134.8	93.3 80.1 113.9	–	–	107.1 73.6 88.6
Arc v_w = 50 m/h (13.9 mm/s)	606.4 608.3	658.1 656.7	21.0 23.0	68.0 69.9	174.8 185.7	149.0 167.9	161.1 145.2 136.9	–	–	120.8 120.2 115.2
Laser v_w = 40 m/h (11.1 mm/s)	998.8 996.0 997.4	1172.2 1151.4 1161.8	10.0 11.3	24.9 41.2	175.1 202.3	163.7 232.1 112.3	109.4 113.2 132.7	100.8 207.0	–	130.5 116.9 148.6
Laser v_w = 50 m/h (13.9 mm/s)	964.6 923.3 907.7	1123.1 1130.0 1068.3	5.3 6.7 4.0	19.5 19.5 18.5	154.2 87.6	57.2 85.2 54.2	46.0 102.5 42.3	150.0	–	167.5 132.1 157.2
Hybrid v_w = 72 m/h (20.0 mm/s)	861.3 795.1	1047.3 971.5	11.3 8.0	34.0 36.4	116.5 103.2	123.1 103.4 103.4	67.6 101.5 96.5	33.8 106.6 58.3	–	45.0 42.1 40.8
Hybrid v_w = 90 m/h (25.0 mm/s)	826.8 800.9	1033.5 1019.9	12.0 9.4	41.6 41.8	109.5 125.7	92.4 71.0 111.2	79.3 76.8 60.5	92.5 119.9 136.3	–	67.5 85.7 96.8
Hybrid v_w = 110 m/h (30.5 mm/s)	745.1 638.1	941.9 894.7	13.3 12.9	46.2 46.4	58.9 77.4	39.7 58.4 55.7	57.3 44.4 60.8	114.9 128.2 121.5	123.9 125.7 124.8	46.9 59.1 101.6

*Data of base metal across rolled stock.

impact toughness of weld metal at all test temperatures (KCV_{20} from 189 to 102 J/cm², KCV_{-20} from 170 to 75 J/cm² and KCV_{-40} from 118 to 63 J/cm²).

Resistance to cold crack formation in S460M steel welded joint, performed using arc, laser and hybrid laser-arc welding processes, were evaluated using technological test «rigid boxing» [13]. A reference welded joint was of *B* = 100 mm width that corresponded to the highest rigidity of the planes fixed on a plate. It is determined as a result of such investigations that S460M steel welded joints performed using arc, laser and laser-arc processes are not susceptible to formation of cold cracks. This conclusion was made based on the results of analysis of the macrosections made of technological tests of Figure 4, *a*–*c*. It showed that there are no cold cracks in the joints even in welding without preheating.

In addition to cold cracks a welded joint can have other defects such as lacks of penetration, pores, undercuts, slag inclusions etc. At static and cyclic loading they can play a role of nucleus of initiation and propagation of cracks, which during operation (in particular at negative temperatures) can result in brittle fracture of metal. Therefore, further work was directed on evaluation of resistance of weld metal and HAZ of S460M steel welded joints to brittle fracture. These investigations were carried out using criteria of fracture mechanics. The double-sided single-pass joints of S640M steel of 10 mm thickness with groove preparation were made for these purposes using arc welding process and that without groove preparation was made by hybrid laser-arc welding. Arc welding of such joints was performed at 30 m/h rate and hybrid laser-arc welding at 72 m/h rate. The rest of technological parameters of welding modes are indicated above. The indicated welded joints were used to make the specimens of 20×10 mm section for three point bend tests. A chevron notch on the specimens was done in such a way that a mouth of crack grown from its tip was in a weld metal (part of specimens) and in joint fusion line (other part of the specimens). The specimens were tested at –40, –20 and 20 °C temperatures. The results of tests were used for determination of critical coefficient of stress intensity K_{1C} and critical crack opening δ_C.

Analysis of the results of carried investigations allowed determining the following. Steel S460M welded joints made by arc welding differ by higher brittle crack resistance. At test temperatures –40, –20 and 20 °C the average K_{1C} values of weld metal of such

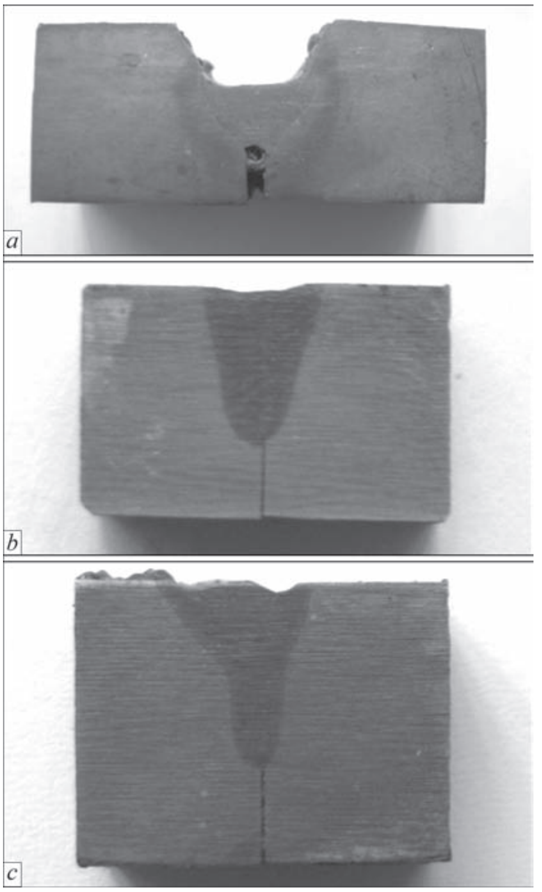

Figure 4. Macrosections of rigid butt technological probes of S460M steel of 8 mm thickness (B — 100 mm): *a* — in automatic arc welding in Ar + 18 % CO_2 gas mixture with flux-cored wire Megafil 821R (v_w = 30 m/h (8.3 mm/s)); *b* — laser welding without filler material (v_w = 40 m/h (11.1 mm/s)); *c* — in hybrid laser-arc welding with indicated above flux-cored wire (v_w = 72 m/h (20.0 mm/s))

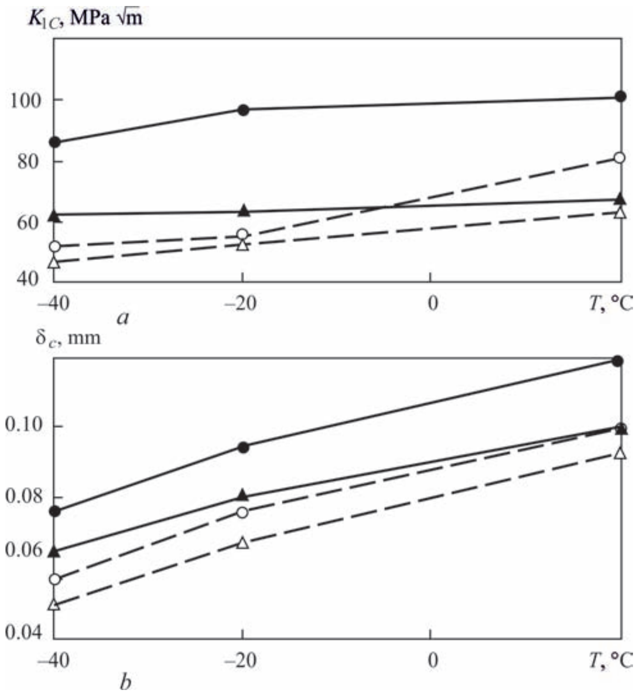

Figure 5. Dependence of values of critical coefficient of stress intensity K_{1C} (*a*) and critical crack opening δ_C (*b*) on tests temperature for weld metal (●, ○) and HAZ metal (▲, Δ) of δ = 8 mm S460M steel welded joints in automatic arc (●, ▲) and hybrid laser-arc welding (○, Δ)

joints make 86.3; 96.8 and 101 MPa√m, respectively (Figure 5, *a*). Increase of test temperatures promote also rise of δ_C indices of weld metal from 0.08 and 0.09 mm at –40 and –20 °C temperatures, respectively, to 0.12 mm at 20 °C test temperature (Figure 5, *b*).

High, but significantly lower in comparison with the weld, produced by arc welding, K_{1C} indices are typical for the welded joints, made using hybrid laser-arc welding. Average K_{1C} indices rise from 52.2 MPa√m (test temperature –40 °C) to 55.4 and 81.2 MPa√m at test temperatures –20 and 20 °C, respectively, (Figure 5, *a*) with rise of test temperature of specimens, produced from such joints. δ_C indices of weld metal are changed in the same way from 0.067 mm to 0.076 mm at –40, and –20 °C temperatures, respectively, and to 0.1 mm at test temperature 20 °C (Figure 5, *b*).

The following can be noted in relation to HAZ metal of welded joints from investigated steel. At test temperature 20 °C the values of K_{1C} and δ_C indices of HAZ metal of welded joints made by arc as well as hybrid laser-arc welding are close and, correspondingly make 65.6 MPa√m and 0.095 mm. Under conditions of testing at negative temperatures the values of K_{1C} and δ_C of HAZ metal of welded joints, produced using hybrid laser-arc welding, are 22–32 % lower than in the welded joints made using arc welding. Thus, at –20 ° C test temperature the K_{1C} and δ_C indices of HAZ metal of welded joints, performed by hybrid laser-arc welding, make 52.6 MPa√m and 0.057 mm, and that for arc welding is 63.3 MPa√m and 0.076 mm. At specimen test temperature –40 °C K_{1C} and δ_C indices of HAZ metal of joins are K_{1C} = 46.7 MPa√m and δ_C = 0.05 mm in welded joints produced by hybrid laser-arc welding and 62.1 MPa√m, δ_C = 0.065 mm, made by arc welding (Figure 5, *a*, *b*).

S460M steel welded joints, performed using arc and hybrid laser-arc welding, differ on resistance to fatigue crack formation. It is shown by the results of cyclic cantilever bend tests of specimens. Such tests were carried out applicable to the specimens of 400×120×10 mm size, produced of butt joints, arc and hybrid welding of which was carried out in shielding gas mixture 82 % Ar + 18 % CO_2 using Megafil 821R wire of 1 mm diameter at modes similar to modes for brittle fracture test joints. The tests of specimens at symmetric cyclic loading were carried out with 14 Hz cycle frequency. Cycle stress varied from 40 to 80 MPa with 20 MPa step. The results of carried investigations showed that the arc welded joints have higher resistance to formation of fatigue cracks.

Under indicated conditions of loading, formation of fatigue cracks in the arc welded joints were not observed after $N = 2\cdot10^6$ cycles of loading. The fatigue cracks of 3 mm depth were detected only in the welded joints performed by hybrid laser-arc process at cycle stresses 60 and 80 MPa. Thus, in the specimens, which were tested at 60 MPa cycle stress, they started to be formed after 1540400 cycles of loading, and at σ = 80 MPa after N = 1300680 loading cycles.

Conclusions

Increase of welding rate of gas-shielded arc welding up to v_w = 50 m/h (13.9 mm/s) ($w_{6/5}$ = 36 °C/s) allows receiving quality weld in welded joints of high-alloy S460M steel with yield point σ_y = 480 MPa and increased indices of static strength and impact toughness.

In laser welding rise of cooling rate $w_{6/5}$ of S460M steel welded joints promotes decrease of indices of ductility and impact toughness of weld metal. It is related with formation of martensite hardening structure in weld metal and HAZ of welded joints, which is formed as a result of typical for laser welding intensive cooling of metal in 600–500 °C temperature range ($w_{6/5}$ = 65–103 °C/s).

Application of hybrid laser-arc welding of S460M steel allows significantly rising linear welding rate in comparison with arc and laser processes. At that decrease of cooling rate of weld metal and HAZ is provided in comparison with laser welding method. All together it allows significantly rising productivity of welding process and preserving at that indices of mechanical properties and impact toughness of weld metal and HAZ of the welded joints at the level of the requirements made to welded structures produced of steels of C440–C490 strength class.

It is determined that S460M steel welded joints produced using arc, laser and hybrid laser-arc processes, are not susceptible to cold crack formation.

The indices of fracture toughness of joints in hybrid laser-arc welding can be increase due to formation in HAZ metal of lower bainite structure that is reached at welding rate 72 m/h.

It is shown that butt joints of S460M steel, produced by arc welding method, have higher service life. In hybrid laser-arc welding fatigue fracture resistance can be increases under condition of performance of groove preparation in the joints with small opening angle up to 10°.

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