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SCANDIUM EFFECT ON THE PROPERTIES AND STRUCTURE OF ALLOYS OF Al–Zn–Mg–Cu SYSTEM AND THEIR WELDED JOINTS

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The effect of scandium additives on structure and mechanical properties of cast metal, sheet semi-finished products and butt joints made by nonconsumable electrode argon-arc welding of aluminum alloys of Al–Zn–Mg–Cu alloying system was studied. It is shown that scandium-containing alloys, both in the cast metal, and in their sheet semi-finished products, all the structural components have smaller dimensions, than in the alloys without scandium, that ensures the ultimate strength of the sheets on the level of 640–700 MPa, depending on content of main alloying elements in them. It is established that in nonconsumable argon-arc welding of 3 mm sheets from scandium-containing alloys the total length of the softening zone is reduced by 20 % at simultaneous increase of weld metal hardness that provides higher mechanical properties of such joints. Complex addition of scandium to base material and filler wire simultaneously that ensures its content in the weld metal on the level of 0.30–0.35 % allows significantly increasing the resistance of welded joints of Al–Zn–Mg–Cu system to hot solidification cracking. 16 Ref., 3 Tables, 4 Figures.

Keywords: *aluminum alloys, Al–Zn–Mg–Cu alloying system, scandium, microstructure, mechanical properties, hot cracks*

In the recent years there is an intensive investigation of efficiency of scandium application in form of modifier with aluminum alloys of different alloying systems. The main factor explaining the unique effect of scandium on their structure and properties is a dimension-structural affinity of crystalline lattices of aluminum (4.405 Å) and intermetallic phase Al_3Sc (4.407 Å) due to what the particles of the latter act as effective nucleuses of crystallization centers in the ingots and welds [1–3]. It results in refinement of structure of metal being crystallized that has positive effect on its physical-mechanical properties [4]. Thus, in wrought aluminum alloys based on Al–Mg alloying system without heat treatment the scandium additives provide higher indices of ultimate and yield strength of sheet semi-finished products as well as their welded joints and also rises their resistance to formation of solidification cracks in fusion welding [5–7].

It is positive effect of scandium addition into heat hardenable aluminum alloys of Al–Mg–Li alloying system. At that in addition to increase of ultimate strength of their welded joints there are prerequisites for additional strengthening of weld metal due to their heat treatment thanks to precipitation of secondary dispersed aluminum-scandium phases and strengthening particles of the main alloying elements [8–10]. Additives of scandium in aluminum alloys, containing copper as alloying element can reveal in different way. Thus, for 1201 and 1460 alloys the ultimate strength of arc welds is higher using welding wire of Sv1201 type, containing 0.5 % of Sc [11]. At the same time in welding of copper-containing aluminum alloys copper with scandium can form a compound (W-phase) [12]. In the case of their interaction the scandium additives will not participate in alloy strengthening and provide refinement of its structure. And increase of volume fraction of the excess phases will lead to decrease of strength, ductility and fracture toughness of weld metal. A proof of this can be the results obtained in testing D16 (Al–Cu–Mg) alloy additionally containing 0.4 % of Sc [13]. As for high-strength complexly-doped aluminum alloys of Al–Zn–Mg–Cu alloying system then the results obtained at investigation of some alloys indicate that scandium additives can also have positive effect on their physical-mechanical characteristics [14, 15].

Aim of the investigation lied in investigation of effect of Sc additives on structure and mechanical properties of cast metal, sheet semi-finished products and butt joints made by nonconsumable electrode argon-arc welding of aluminum alloys of Al–Zn–Mg–Cu alloying system as well as their resistance to formation of solidification cracks.

Investigation procedure. Four pilot alloys of Al–Zn–Mg–Cu alloying system with different content of Zn, Mg and Sc (Table 1) were produced for investigations. A combined method of pressure treatment was used for manufacture of 3 mm thick sheets of 150 mm

Table 1. Composition of ingots and sheets produced from pilot alloys of Al–Zn–Mg–Cu alloying system

Number of alloy	Content of elements, wt.%				
	Zn	Mg	Cu	Zr	Sc
1	8.0–8.2	1.8–2.1	2.2–2.3	0.10–0.13	–
2	8.0–8.2	1.8–2.1	2.2–2.3	0.10–0.13	0.08–0.14
3	8.3–8.7	2.5–2.8	2.2–2.4	0.15–0.20	–
4	8.3–8.7	2.5–2.8	2.2–2.4	0.15–0.20	0.28–0.32

diameter ingot. The extruded billets of 10×100 mm section were obtained by a hot-pressing method. They were further subjected to hot and cold rolling up to 3 mm thickness. Since rolling of sheets can result in different level of their cold working, then structural peculiarities and mechanical properties of obtained alloys were investigated on the samples cut of the cast billets in cold state (natural aging for 30 days), after annealing (310 °C during 1 h) and after quenching (at 465 °C) with next artificial aging (at 120 °C for 16 h) as well as on the samples cut of ready sheets of 3 mm thickness.

Automated nonconsumable electrode argon-arc welding (NEAAW) of obtained sheets was carried out by alternating current with rectangular wave form MW-450 power supply (Fronius, Austria) using welding torch ACTV-2M. Welding rate made 14 m/h, welding current value was 300 A, rate of feed of filler wire of 1.6 mm diameter — 96 m/h. Alloys without scandium were welded by serial welding wire SvAMg63 (Al–6.3 Mg–0.5 Mn–0,2Zr) and pilot welding wire SvAMg63Sc of the same composition, but additionally containing 0.5% of Sc, and welding of scandium-containing alloys was performed only with pilot wire SvAMg63Sc. Before welding sheet billets were chemically etched by generally accepted technology and then mechanical dressing was used for edges and surfaces of edges to around 0.1 mm depth in order to eliminate defect formation in form of pores and macroinclusions of oxide film. To evaluate the tendency of welded joints to formation of hot solidification cracks a standard procedure with Houldcroft samples in two variants was used, namely welding without filler wire and welding with filler wire. Nonconsumable electrode argon-arc welding of such samples was also carried out on the equipment mentioned above at 12 m/h rate. A value of welding current made 235 A, rate of feed of 1.6 mm filler wire was 92 m/h.

Hardness of metal was measured on transverse macrosections of obtained welded joints. A level of metal softening in welding zone was evaluated on Rockwell device at $P = 600$ N loading. The ultimate strength of welded joints $\sigma_t^{w.j.}$ was determined at static tension on universal servohydraulic complex MTS 318.25 of standard samples with weld reinforcement and removed weld penetration and weld metal ultimate strength $\sigma_t^{w.m}$ on the same samples, but without weld reinforcement. Other mechanical properties of the base metal and welded joints were also performed in accordance with the standard [16]. Evaluation of structural peculiarities of investigated semi-finished products and their welded joints was carried out using optical electron microscope MIM-8.

Investigation results and their discussion. As a result of carried investigations it was determined that addition of Sc in aluminum alloys of Al–Zn–Mg–Cu alloying system has positive effect on structure and mechanical properties of semi-finished products and welded joints. Thus, analysis of microstructure of cast metal showed that noticeable (3–5 times) decrease of grain size (Figure 1) is observed in scandium-containing alloys. In initial state after natural aging, caused by sequence of technological operations of manufacture of pilot alloy ingots and preparation of investigated samples, in weld metal without scandium there is formation of typical cast structure with crystalline particle size in 120–240 μm limits. Microstrucutre of the ingots in initial state is characterized by presence of α-solid solution, $\eta(Mg(CuZn)_2)$, T(ZnMgAlCu) phases and eutectic precipitations on the boundaries of crystals containing Zn (24–26 %), Mg (7.7–8.6 %), Cu (13–15 %) and traces of Zr (0.098 %). Eutectic precipitations in the alloys with scandium also contain traces of scandium (0.028 %) as well as intermetallics $Al_3(Sc, Zr)$ of 3–7 μm size (Figure 1, *a*, *b*). At that in scandium-containing alloys there is formation of finer (30–50 μm) crystalline particles due to presence of primary phase particles $Al_3(Sc, Zr)$ being effective nucleuses of metal crystallization centers.

In process of manufacture in order to get optimum mechanical properties of the cast billets they are subjected to technological operations of heat treatment, which provide performance of high-temperature heating for annealing or quenching with further aging. Performance of such thermal operations for aluminum alloys does not result in significant change of their microstructure, except for appearance of disperse precipitations of secondary phase (Figure 1, *c*–*f*).

Such structural peculiarities of alloys with scandium and without it, affect mechanical properties of obtained cast billets. It is clearly demonstrated by the results of testing of the samples of metal of pilot alloys 1 and 2 (Table 2). After natural aging the cast metal of alloy 2 containing scandium has higher indices of ultimate strength, conventional yield strength and relative elongation than cast metal of alloy 1 without scandium. Annealing of the samples of cast metal of these alloys results in decrease

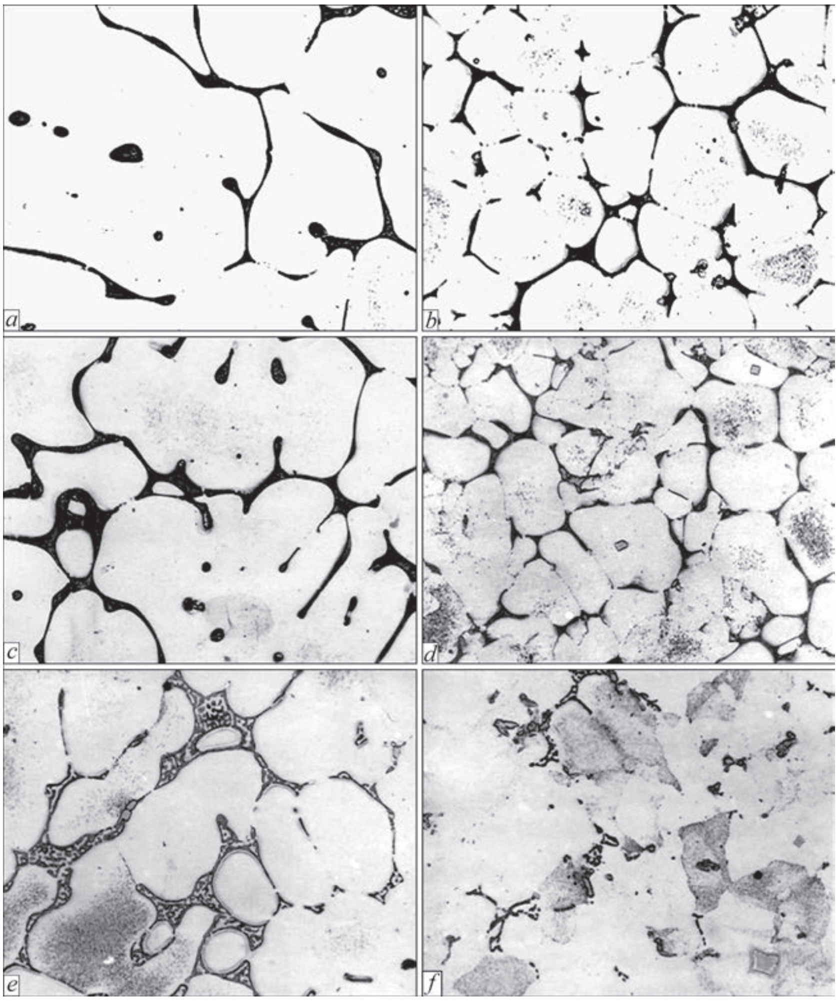

Figure 1. Microstructure (×500) of cast metal of aluminum alloys 1 (*a*, *c*, *e*) and 2 (*b*, *d*, *f*) in initial condition after natural aging during 30 days (*a*, *b*), after annealing at 310 °C for 1 h (*c*, *d*) and after quenching at 465 °C and further artificial aging at 120 °C for 16 h (*e*, *f*)

of their ultimate strength. But if at that in alloy 1 without scandium the ultimate yield limit of cast metal reduces by 50 MPa and relative elongation rises from 2.3 to 3.3 % then presence of scandium in alloy 2 results in rise of conventional yield strength of cast metal by 25 MPa and decrease of relative elongation from 3.7 to 2.3 %. It is related with precipitation of secondary intermetallics based on scandium aluminide, which inhibit dislocation displacement. Quenched and artificially aged samples of cast metal have the maximum ultimate strength.

Investigations of cast billets show that their microstructure was formed as a result of two processes, namely gradual transformation of initial cast structure and formation of new elements of deformation origin — roll texture (Figure 2). Microstructure of such 3 mm thick sheets is characterized by presence of elongated in rolling direction grains of solid solution of main alloying elements in aluminum, elongated and chipped eutectic precipitations as well as large number of small secondary intermetallics uniformly distributed on sheet section and oriented along billet deformation direction. At that virtually all constituents of microstrucutre of sheet billets of alloys with scandium have smaller size than one in which scandium is absent. This ensures their higher mechanical properties. Thus, sheets of alloy 1 have ultimate

Table 2. Mechanical properties of metal of ingots of pilot alloys in initial state and after heat treatment

Number of alloy	State	Mechanical properties		
		σ_t, MPa	σ_y, MPa	δ, %
1	Natural aging: 30 days	326	219	2.3
	Annealing: 310 °C, 1 h	210	169	3.3
	Quenching: 465 °C + artificial aging: 120°C, 16 h	455	–	–
2	Natural aging: 30 days	339	225	3.7
	Annealing: 310 °C, 1 h	251	250	2.3
	Quenching: 465 °C + artificial aging: 120°C, 16 h	525	–	–

Note. Given are average values of the results of testing of 5–7 samples.

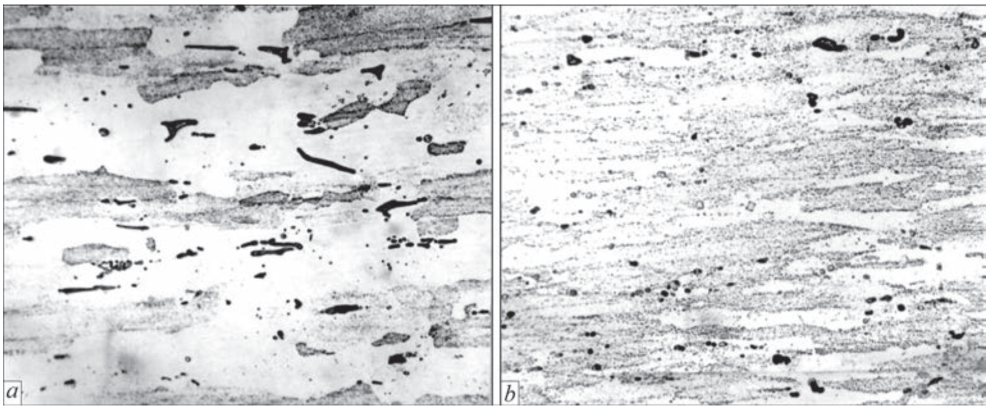

Figure 2. Microstructure (×500) of 3 mm thick sheets of pilot alloys 3 (*a*) and 4 (*b*) after quenching and artificial aging

strength at 600 MPa level and sheets from alloy 3 at 640 MPa level, whereas in corresponding to them scandium-containing alloys 2 and 4 this index makes 630 and 700 MPa. At that conventional yield strength of sheet from alloy 4 makes 645 MPa, of alloy 2 — 580 MPa, of alloy 3 —573 MPa and of alloy 1 — 560 MPa. However, relative elongation in sheets with scandium-containing alloys 2 and 4 is on the level of 6.3 and 5.0 %, respectively, that almost 2 times lower than in sheets without scandium (10.0 %).

Positive effect of scandium in alloys, caused by grain refinement, has an impact on sheet welded joints. Thus, total extension of softening zone in nonconsumable electrode argon-arc welding of 3 mm thick sheets of alloy 4 with scandium makes around 35 mm, and of alloy 3 without scandium it is around 46 mm (Figure 3). At that minimum hardness of weld metal in the first case is on *HRB* 99 level and in the second only *HRB* 94. Base metal hardness in its fusion zone with weld metal for alloy without scandium makes *HRB* 100–102 and for alloy with scandium it is *HRB* 105–107. In the annealing zone there are also different levels of decrease of metal hardness, namely *HRB* 95 in alloy without scandium and *HRB* 101 in alloy with scandium. Such differences in nature of distribution of metal hardness in welded joints with scandium and without it are caused by their structural peculiarities (Figure 4). In weld metal obtained in welding of scandium-containing alloy, there is formation of fine equiaxial crystalline particles with the finest interlayers of eutectic precipitations on the grain boundaries. Whereas in welding of alloy without scandium formation of coarser dendrites takes place and large accumulation of secondary phases in intergranular space is observed. It indicates smaller volume fraction of grain boundaries. However, more noticeable is the difference in sizes of structural constituents in a heat-affected zone adjacent to weld. In alloy 3 without scandium recrystallization of grains results in formation of coarse dendrite metal structure with precipitations on their boundaries of thickened eutectic interlayers. And presence of scandium in alloy 4 allows virtually preventing recrystallization of grains in the heat-affected zone and get fine crystalline metal structure.

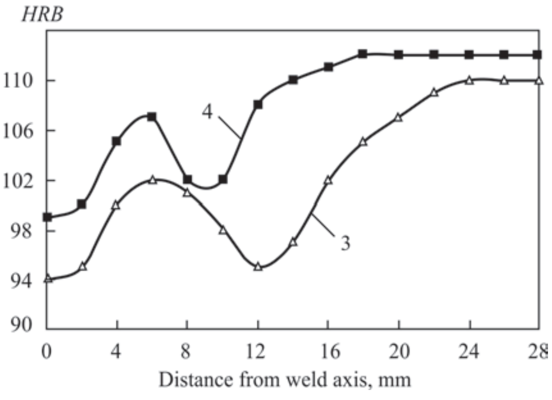

Figure 3. Distribution of hardness in welded joints produced by nonconsumable electrode argon-arc welding of 3 mm thick sheets from pilot alloys 3 and 4 using welding filler wires SvAMg63 and SvAMg63Sc, respectively

Higher levels of metal hardness in typical zones of welded joints of alloys with scandium, caused by formation of fine crystalline metal structure in a zone of formation of permanent joints, can indicate increase of their strength characteristics. The results of mechanical tests of the samples, given in Table 3, prove the efficiency of scandium application in the investigated alloys for rising ultimate strength of their welded joints. Thus, if this index for welded joints of pilot alloys 1 and 3 without scandium is on the level of 309 and 343 MPa, respectively, then for alloys 2 and 4 it is on the level of 329 and 441 MPa using in the latter case filler wire SvAMg63Sc. At that higher value of ultimate strength of weld metal and bending angle α of welded joints can be observed. However, scandium has more substantial effect on increase of ultimate strength of welded joints and weld metal after heat treatment of the samples including quenching at 465 °C and further artificial aging at 120 °C aging during 16 h. Such thermal effect as a result of heating of metal to quenching temperature leads to decay of solid solution of scandium into aluminum and precipitation of secondary intermetallics Al_3Sc having strengthening effect on weld metal. The artificial aging of the sample promotes decay of solid solution of main alloying elements. As a consequence the ultimate strength of welded joints in alloys 2 and 4 with scandi-

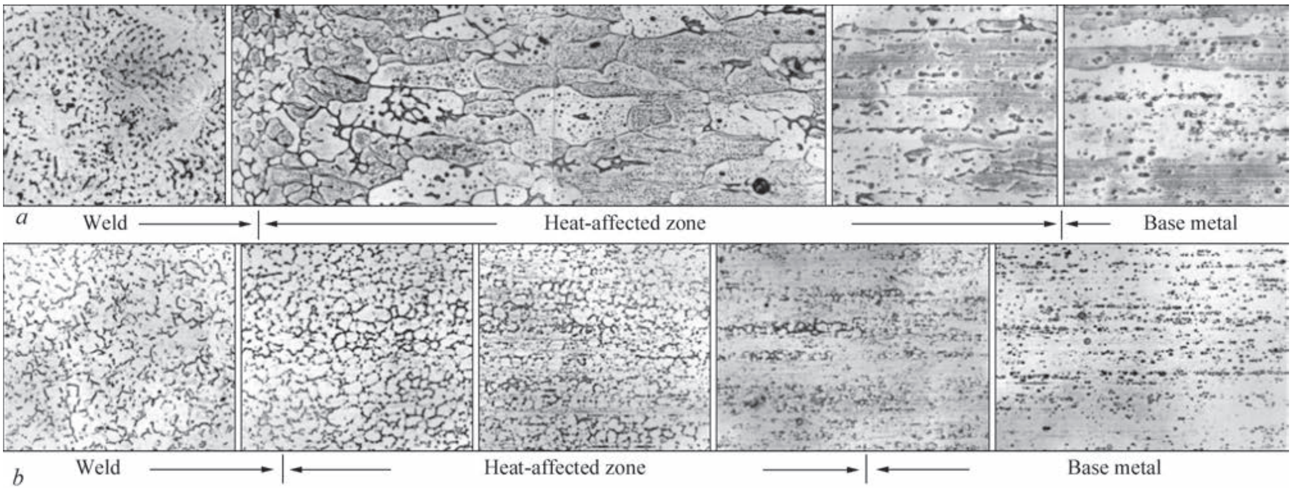

Figure 4. Microstructure (×256) of welded joints produced by nonconsumable electrode argon-arc welding of 3 mm thick sheets from pilot alloys 3 (*a*) and 4 (*b*) using filler wires SvAMg63 and SvAMg63Sc, respectively

um rises to 572 and 660 MPa, respectively, that exceeds this index for alloys 1 and 3 without scandium by 68 and 52 MPa. At that for ultimate strength of weld metal this difference makes 66 and 45 MPa, respectively.

Peculiarities of primary crystallization of weld metal and formation of structural and chemical inhomogeneities in a zone of permanent joint formation in many aspects is determined by resistance of high multicomponent aluminum alloys to formation of hot solidification cracks in welding. They are formed and propagate at the final stage of weld crystallization and have intergranular nature. Therefore, obtaining the fine-crystalline structure of welds with large volume fraction of discrete grain boundaries is one of the effective methods for increase of welded joint resistance to formation of such defects. The results of carried investigations determined that in nonconsumable electrode argon-arc welding of Houldcroft samples without filler wire, propagation of hot solidification cracks takes place in the weld center. Presence of continuous extended eutectic interlayers along the grain boundaries promotes formation of long cracks virtually independently from structure type. Therefore, the indices of hot brittleness *A* reflecting crack length to

Table 3. Mechanical properties of welded joints of sheets of pilot alloys of alloying system

Number of alloy	Σ (Zn+Mg+Cu), %	Filler wire	Mechanical properties after welding		
			$\sigma_t^{w.j}$, MPa	$^{w.m}$, MPa	α, deg
1	12.3	SvAMg63	$\frac{314–305}{309}$	$\frac{336–329}{330}$	$\frac{22–21}{21}$
		SvAMg63Sc	$\frac{321–315}{319}$	$\frac{344–339}{341}$	$\frac{25–23}{24}$
2		SvAMg63Sc	$\frac{333–326}{329}$	$\frac{351–348}{347}$	$\frac{25–23}{24}$
3	13.4	SvAMg63	$\frac{349–340}{343}$	$\frac{408–399}{403}$	$\frac{22–21}{21}$
		СвАМг63Sc	$\frac{361–355}{357}$	$\frac{418–404}{411}$	$\frac{23–22}{22}$
4		SvAMg63Sc	$\frac{445–439}{441}$	$\frac{419–405}{412}$	$\frac{23–22}{22}$
Mechanical properties after heat treatment*					
1	12.3	SvAMg63	$\frac{512–500}{504}$	$\frac{540–529}{536}$	–
2		SvAMg63Sc	$\frac{579–568}{572}$	$\frac{608–600}{602}$	–
3	13.4	SvAMg63	$\frac{616–605}{608}$	$\frac{638–629}{633}$	–
4		SvAMg63Sc	$\frac{665–655}{660}$	$\frac{685–672}{678}$	–

Notes. In nominator there are maximum and minimum, and in denominator are average values of indices on the results of testing of 5–7 samples. *Weld metal ultimate strength after heat treatment (quenching: 465 °C + artificial aging: 120 °C, 16 h) was determined with reduced section in weld central part.

total length of Houldcroft sample in percent relationship as a result of welding of 6–8 such samples for alloys 1 and 3 without scandium are on the level of 59.0 and 53.7 % and for scandium-containing alloys 2 and 4 it is on the level of 50.0 and 45.7 %.

In welding of Houldcroft samples using filler wires cracking of metal does not take place in the weld center, since hot cracks are formed in a zone of its fusion with base metal, where in process of crystallization of molten metal takes place accumulation of fusible eutectic phases in form of intergranular interlayers. Therefore, application of scandium-containing filler wire in welding of alloys without scandium can not have considerable effect on extension of such defects. And only at simultaneous addition of scandium into the base material and filler wire, keeping its level in the weld on the level of 0.30–0.35 %, it is possible to rise significantly the resistance of welded joints of alloys of Al–Zn–Mg–Cu alloying system to formation of hot solidification cracks. Thus, in welding of Houldcroft samples of alloy 2 containing 0.08–0.14 % Sc, with filler wire SvAMg63Sc, which includes in its composition 0.5 % of Sc, the index of hot brittleness *A* reduced to 42.4 % and in welding of such samples of alloy 4, containing 0.28–0.32 % of Sc, with the same filler wire it is up to 39.8 %.

Conclusions

1. Addition of 0.08–0.32 % of Sc in aluminum alloys of Al–Zn–Mg–Cu alloying system due to formation of primary phase particles Al_3(Sc, Zr), being effective nucleuses of metal crystallization centers, provides formation in the ingots of fine (30–50 μm) grains that are 3–5 times less in comparison with typical structural parameters of alloys without scandium.

2. Metal structure refinement reached due to scandium additives is conserved after thermodeformation treatment of ingots and provides higher (by 15–20 %) mechanical properties of obtained semi-finished products in comparison with their scandium-free analogues.

3. Nonconsumable electrode argon-arc welding of 3 mm thick sheet of scandium-containing alloys leads to decrease of total extension of softening zone and reduction of level of softening of metal in the weld on the boundary of its fusion with base material and in zone of annealing, due to what ultimate strength of weld metal and welded joint in whole rises.

4. Simultaneously, scandium addition into the base material and filler wire in order to provide its content in the weld on the level of 0.30–0.35 % allows reducing indices of hot brittleness of the joint by 11–26 % depending on total content of main alloying elements in the alloy.

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