PECULIARITIES OF ALLOYING OF WELD METAL OF HIGH-STRENGTH ALUMINIUM ALLOY WELDED JOINTS WITH SCANDIUM

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The problem of effect of solidification rate on structure of weld metal of scandium-containing aluminium alloys is considered. Peculiarities of scandium precipitation from melt in solidification of aluminium alloys under non-equilibrium conditions, simulating fusion welding, are investigated. Procedure of investigations has been developed and confirmed experimentally. Advantage of offered procedure over the existing ones consists in the fact that it allows simulate almost all the methods of fusion, from argon arc non-consumable electrode welding to electron beam welding. It is shown that the procedure satisfies the put aims completely. Microstructural investigations of ingots in height showed that within the interval of solidification rates from $10^{3.3}$ to $10^{2.5}$ °C/s the change of form of solidification occurs from dendritic to subdendritic ones. It was found that at rates of solidification, commensurable with solidification of weld metal, up to 0.41 % Sc can be contained in solid solution of alloys. When applying the highly concentrated power sources, such as electron beam, it is possible to reach the similar value also in welds. In arc methods of welding approximately 0.3 % Sc can be assimilated in solid solution of weld metal. It was found that it is necessary to provide its content in weld metal at the level of 0.35–0.40 wt.% to maximization of effect from alloying of welds with scandium. In this case the increase in mechanical properties of weld metal is provided both by refining of its crystalline structure, and also by hardening the solid solution by scandium. 7 Ref., 3 Tables, 4 Figures.

Keywords: *high-strength aluminium alloys, scandium, alloying, weld metal, modifying of cast structure*

During development of new alloys the investigations have been always carried out directed to optimization of amount of modifying additions to the alloy. These investigations are especially urgent in use of scandium, as its adding into aluminium alloys increases their cost by 5–10 times [1–3]. However, these investigations are carried out for conditions of industrial production of aluminium alloys, where the rate of solidification (v_{sol}) of ingots are low, and further they are subjected to pressure treatment (pressing, extrusion, rolling). In case of weld metal the situation is somewhat different. The weld has a cast structure, which is not further subjected to pressure treatment, and the rate of solidification is by 1–2 orders higher than that in industrial production of alloys [4].

The aim of this work is the development of method of producing ingots at the solidification rate corresponding to the solidification of weld metal in fusion welding and defining the peculiarities of weld metal alloying with scandium in welding of high-strength aluminium alloys.

The investigations were carried out on ingots of model alloys of the following composition, %: 99.95Al, Al–0.8Sc, Al–0.6Sc, Al–6.3Cu–0.8Sc, Al– 8.5Zn–2.3Mg–1.9Cu–0.2Zr–0.45Sc. To produce the homogeneous chemical composition in all the points being investigated, the alloys were preliminary melted in resistance furnaces with next solidification at v_{sol} = 10–30 °C/s. After this, they were crushed and a charge was prepared for further experiments. Metal was poured into a specially designed wedge-type water-cooled mould, which allows providing the different rates of melt solidification in ingot height. In narrow part the ingot had 0.5 mm thickness, 15 mm width and 95 mm height. Cooling rate in different regions of the wedge-type ingot was calculated by a dendritic parameter of crystallites on the basis of procedure, suggested by Dobatkin [5].

Experiment procedure. Before casting the melt was overheated to 1000 °C up to complete dissolving of all the intermetallics, then it was cooled in crucible at continuous stirring up to casting temperature and solidified into the mould. Rate of solidification of metal was determined by structure of ingot of pure aluminium (99.95 %).

Analysis of the ingot microstructure showed that it is dendritic across the entire section. Size of dendrites is varied from 700 up to 3000 μm in

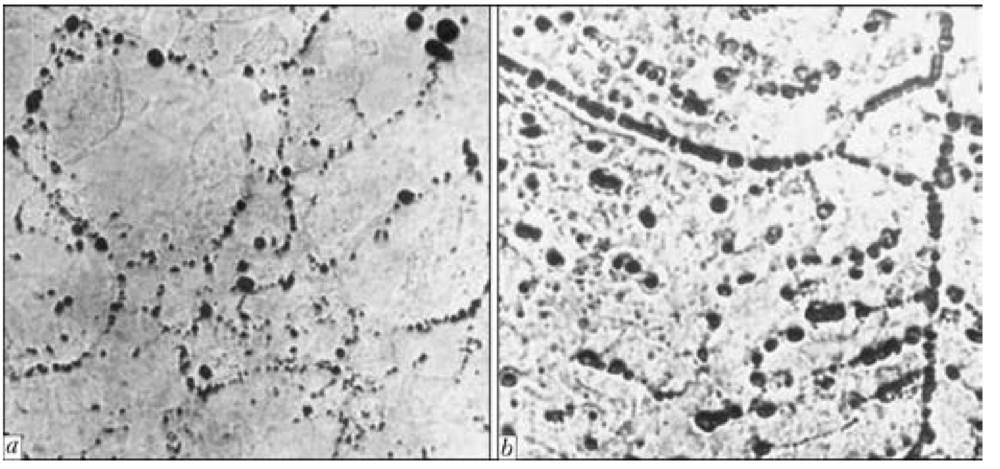

Figure 1. Microstructure (×500) of cast metal of alloy Al–08 % Sc produced by the method of rapid solidification of melt from 800 °C at v_{sol} = 10^2 (*a*) and 10^5 (*b*) °C/s

the zone of maximum and minimum rates of solidification, respectively. Measurement of dendritic parameter showed that in narrow part of the ingot it is 2.7–3.0 μm, that corresponds to v_{sol} ~ $10^{4.5}$–10^5 °C/s [5]. At transition from the ingot narrow part to the wide one the size of dendrites and dendritic parameter are gradually increased. In the ingot middle part the structure corresponds to that for welds in EBW (v_{sol} = = 10^3 °C/s). In the ingot wide part the dendritic parameter is 25–27 μm, that corresponds to v_{sol} = = 10^2 °C/s, typical of TIG welding of aluminium alloys.

Adding of scandium into aluminium changes the nature of solidification of ingots. Thus, for alloy with 0.8 % Sc the dendritic structure is formed in the narrow part, where the maximum rate of solidification is observed (Figure 1). The subdendritic structure is formed in the wide part of the ingot at v_{sol} = 10^2 °C/s.

X-ray and X-ray spectral microanalysis of alloy Al–0.8Sc showed that in the ingot narrow part (v_{sol} = 10^5 °C/s) all the scandium is located in aluminium solid solution (Tables 1 and 2). This fact can be confirmed by investigation of microhardness of solid solution of ingots. Thus, for alloy Al–0.8Sc the mean microhardness of ingot directly after casting is 483 MPa, and after artificial ageing at 330 °C during 1000 s it is 1281 MPa. This increase in hardness in Al–Sc system can be obtained only at scandium precipitation from solid solution and formation of dispersed intermetallic particles (Figure 2). Precisely the same nature of change in microhardness is observed also in ingots of alloy Al–0.6Sc, however, the decrease in scandium content leads to decrease in microhardness of ingots before and after artificial ageing.

Analysis of microstructure in height of ingots showed that within the interval of solidification rates from $10^{3.3}$ up to $10^{2.5}$ °C/s, the structure of ingots is mixed (dendritic-subdendritic), i.e. at these rates the change of form of solidification from dendritic to subdendritic is occurred. Microhardness of ingots is decreased due to precipitation of a part of scandium into primary intermetallics and, respectively, depletion of solid solution of scandium in aluminium.

Table 1. Scandium content in different zones of ingots of alloy Al–0.8 % Sc

v_{sol}, °C/s	Structural constituent	Sc, wt.%
10^2	Base (solid solution)	0.427
	Intermetallic	18.551
10^5	Base (solid solution)	0.812
	Intermetallic	–

Table 2. Results of X-ray phase analysis of alloys investigated

Alloy	T_{cast}, °C	v_{sol}, °C/s	Presence of intermetallics Al_3Sc
Al–0.8 % Sc	670	10^2	+
		10^5	+
	720	10^2	+
		10^5	–
	800	10^2	+
		10^5	–
	900	10^2	+
		10^5	–
Al–6 % Cu–0.8 % Sc	720	10^2	+
		10^5	–
	800	10^2	+
		10^5	–
	900	10^2	+
		10^5	–

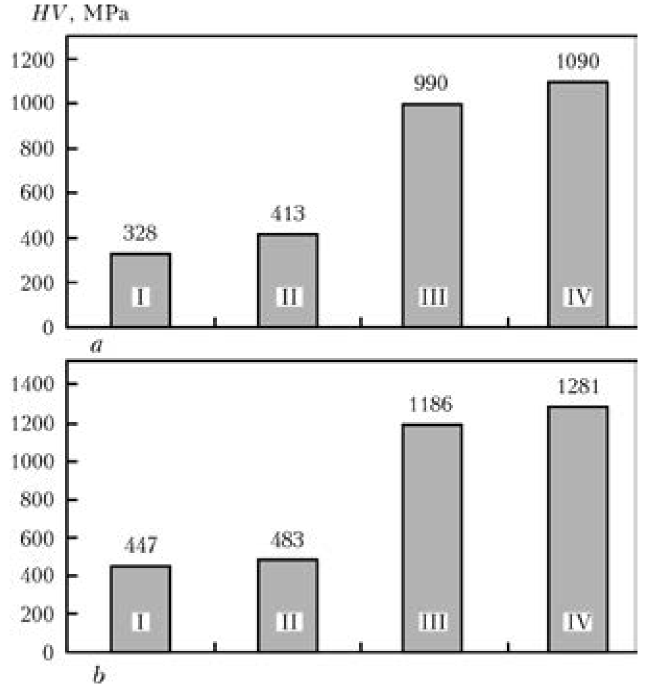

Figure 2. Microhardness of cast metal of alloys Al–0.6 % Sc and Al–0.8 % Sc at different solidification rate: *a* — 10^2; *b* — 10^5 °C/s; I, III (0.6 % Sc) — directly after casting; II, IV (0.8 % Sc) — after additional artificial ageing

At $v_{sol} = 10^2$ °C/s, the structure of ingot Al–0.8Sc is subdendritic. Maximum size of subdendrites is 75 μm, minimum — 20 μm. Scandium content in solid solution is decreased to 0.41 % (see Table 1). Mean size of primary scandium intermetallics is 10–12 μm. Scandium content in them is changed from 14.3 to 20.6 %. A part of scandium is included into composition of eutectic precipitations along the boundaries of subdendrites. The length of these colonies can reach 45 μm.

It can be concluded from the given data that during melt heating above 800 °C the complete dissolution of scandium intermetallics, inherited from charge materials, is occurred. At $v_{sol} = 10^5$ °C/s, the state of melt at the moment of alloy casting can be judged by solid solution of ingots. At $v_{sol} = 10^2$ °C/s, the structure of metal of welds of real welded joints can be predicted by the structure of ingots.

Investigation of peculiarities of solidification of model alloys. For all the alloys, which were overheated above 720 °C before the solidification and solidified with rate of 10^5 °C/s, it was not managed to identify the particles of intermetallics Al_3Sc by the methods of optic and scanning electron microscopy. X-ray phase analysis showed that at $v_{sol} = 10^5$ °C/s, these particles are observed only in the sample, solidified from 670 °C (see Table 2). It was found by the method of differential thermal analysis that intermetal-

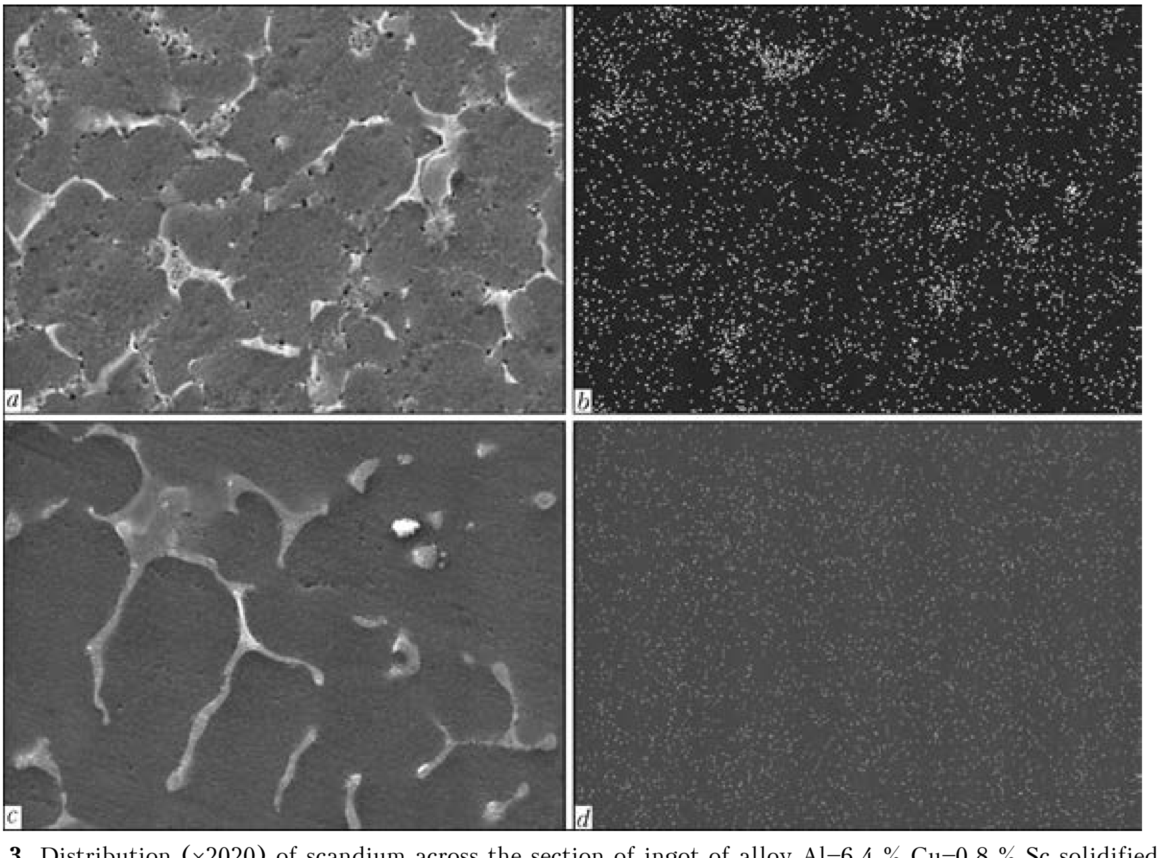

Figure 3. Distribution (×2020) of scandium across the section of ingot of alloy Al–6.4 % Cu–0.8 % Sc solidified from 670 (*a*, *b*) and 900 °C (*c*, *d*) at $v_{sol} = 10^2$ °C/s

Table 3. Chemical composition (wt.%) of structural constituents of ingots of alloy Al–8.5 % Zn–2.3 % Mg–1.9 % Cu–0.2 % Zr–0.45 % Sc

T_{cast}, °C	v_{sol}, °C/s	Phase	Sc	Zn	Mg	Cu	Zr
670	10^2	Solid solution	0.18	4.88	1.06	0.56	0.08
		Eutectics	1	17.19	5.26	7.43	0.55
		Intermetallic	16.94	3.41	0.22	0.22	29
	10^5	Solid solution	0.24	5.58	1.30	0.84	0.20
		Eutectics	0.29	10.21	2.99	3.14	–
		Intermetallic	16.13	3.01	–	0.46	16.76
800	10^2	Solid solution	0.21	5.70	1.24	0.71	–
		Eutectics	0.96	12.20	3.63	4.68	1.70
		Intermetallic	11.11	7.90	1.80	2.64	16
	10^5	Solid solution	0.46	6.08	1.49	1.03	–
		Eutectics	0.30	16.83	5.20	7.44	–
		Intermetallic	6.83	10.36	2.50	4.61	6.88

lics Al_3Sc in alloy Al–0.8Sc are beginning to precipitate at 730 °C. In alloy Al–6Cu–0.8Sc the temperature of precipitation of intermetallics is decreased by 15 °C and it is 715 °C.

Figure 3 gives the distribution of scandium across the section of ingots at $v_{sol} = 10^2$ °C/s. It is seen that at 670 °C temperature of casting the regions with increased content of scandium are observed. With increase in casting temperature up to 900 °C the distribution of scandium is leveled across the section of ingots. It can be stated that non-uniform distribution of scandium, observed in real welds of joints, is predetermined by the metallurgical heredity of metal being welded and non-equilibrium conditions, at which the weld is formed [4, 6].

Ingots of alloy Al–8.5Zn–2.3Mg–1.9Cu–0.2Zr–0.45Sc were solidified from three temperatures: 800, 730 and 670 °C without preliminary overheating, i.e. the ingots were heated to casting temperature and solidified at once into copper wedge-type mould. According to data of equilibrium diagram for Al–Sc system at 800 °C, scandium was completely dissolved in melt, 730 °C is the temperature of beginning of formation of intermetallic particles Al_3Sc in melt, and 670 °C is the approximate temperature of casting of alloys under industrial conditions. Microstructure of produced ingots is given in Figure 4.

At high solidification rate (>10^3 °C/s) of alloy Al–8.5Zn–2.3Mg–1.9Cu–0.2Zr–0.45Sc a mixed dendritic-subdendritic structure is formed. In this case the subdendritic structure is observed in the form of small regions in the central part of ingots. The mean size of dendrites is 90, 70 and 60 μm at solidification temperature of 670, 730 and 800 °C, respectively, and size of subdendrites is 5–18 μm. Along the boundaries of dendrites and subdendrites the eutectic precipitations, containing zinc, magnesium, copper and zirconium, are observed, while in the centre of solidification the precipitations of fine scandium intermetallics are present. X-ray spectral microanalysis showed that except scandium they also contain main alloying elements: zinc, magnesium, copper (Table 3). During overheating of melt up to 900 °C and higher, and also next cooling to casting temperature, these intermetalliucs are not observed. During solidification from 670 °C at $v_{sol} = 10^5$ °C/s, the solid solution of alloy Al–8.5Zn–2.3Mg–1.9Cu–0.2Zr–0.45Sc contains 0.21–0.28 % Sc, while during solidification from 800 °C at the same rate it contains 0.45 % Sc. Mean size of intermetallics Al_3(Sc, Zr) at casting temperatures of 730 and 800 °C is 1–3 μm, maximum size is 10–12 μm, at 670 °C the maximum size of intermetallics is 30 μm.

With decrease in rate of solidification the gradual change in solidification is occurred from mixed subdendritic-dendritic to subdendritic ones. Thus, in casting from 800 °C this process takes place within the interval of rates 10^4–$10^{3.5}$ °C/s, at casting from 800 °C into mould, heated up to 300 °C, and casting from 730 °C into cold mould it takes place within the interval of $10^{3.5}$–$10^{2.5}$ °C/s, i.e. with decrease of degree of melt overcooling the change in solidification form is occurred at its lower rates. Mean size of subdendrites at minimum rate is 18 μm and that of intermetallics Al_3(Sc, Zr) is 3–6 μm. At 670 °C

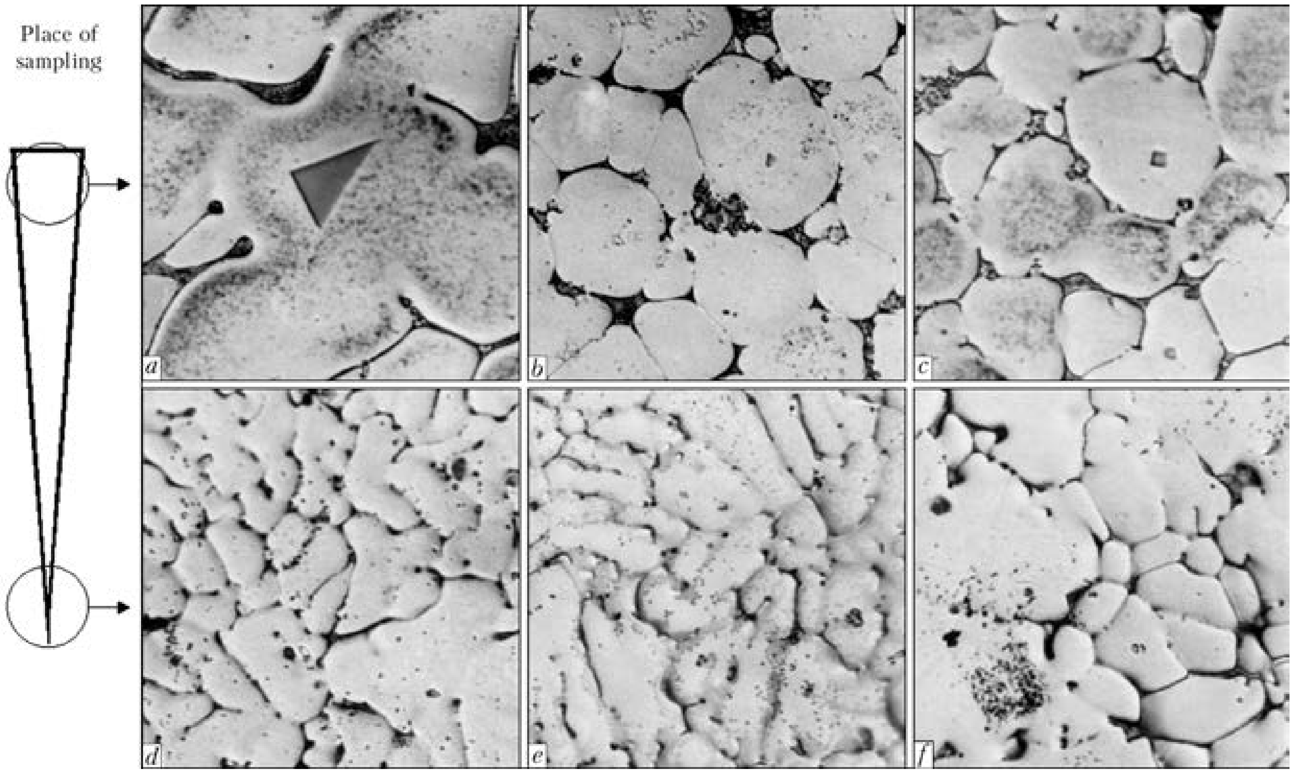

Figure 4. Microstructure (×800) of cast metal of alloy Al–8.5 % Zn–2.3 % Mg–1.9 % Cu–0.2 % Zr–0.45 % Sc at v_{sol} = 10^2 (*a*–*c*) and 10^5 (*d*–*f*) °C/s: *a*, *d* — T_{cast} = 670; *b*–*e* — 730; *c*, *f* — 800 °C

the form of solidification across the section of ingots remains unchanged, i.e. subdendritic-dendritic, however, here the sizes of dendrites are increased from 90 up to 180 μm, those of subdendrites — from 5 up to 18 μm. Maximum size of primary intermetallics, which are precipitated within the whole volume of ingot, is 30 μm. Content of scandium in solid solution is 0.18–0.22 %.

Thus, at rates of solidification, commensurable with solidification of weld metal, the solid solution of alloys can contain up to 0.41 % Sc. When applying highly concentrated power sources, such as electron beam, it is possible to obtain this value also in real welds. In case of application of arc methods of welding 0.3 % Sc can be assimilated in solid solution of weld metal. Coming from the above-mentioned, the conclusion can be made that the weld metal should contain scandium at the level of 0.35–0.40 %. Basing on the earlier investigations of real welds, carried out at the E.O. Paton Electric Welding Institute [7], it is necessary to add 0.3 % Sc into metal being welded and 0.5 % Sc into filler wires to provide this concentration. In this case the increase of mechanical properties of metal of welds will be provided by refining of grain and solid-solution hardening of cast metal.

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