

UDC 669.715

EFFECT OF SCANDIUM, TRANSITION METALS, AND ADMIXTURES ON STRENGTHENING OF ALUMINUM ALLOYS DUE TO DECOMPOSITION OF THE SOLID SOLUTION

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Translated from *Metallovedenie i Termicheskaya Obrabotka Metallov*, No. 9, pp. 12–19, September, 2007.

Strengthening of aluminum alloys of the Al–Sc system in ingots due to decomposition of the solid solution of scandium in aluminum is studied as a function of the content of scandium (varied from 0.14 to 0.55%), of the presence of Zr, Ti, Hf, V, and Co additives at the same content of scandium (0.2%), of the Sc/Zr proportion at the same total content of Sc + Zr, and as a function of iron and silicon admixtures.

INTRODUCTION

Many publications in the recent years have been devoted to aluminum alloys containing scandium. The focus on scandium as an alloying component of aluminum alloys is explainable by its stable and diverse effect on the structure and properties of these alloys, its strong strengthening influence primarily. A low additive of scandium raises the strength characteristics of deformed semiproducts from aluminum alloys by 100–150 MPa and in some cases by 200 MPa [1]. The growth in the strength characteristics is a result of two factors, i.e., formation of products of decomposition of the solid solution of scandium in aluminum in the form of fine particles of the Al₃Sc phase (precipitation hardening) and preservation of nonrecrystallized structure in deformed semiproducts after their heat treatment (structural hardening). It is problematic to evaluate the contribution of each of the two factors to the strengthening. In each specific case the contributions of precipitation hardening and structural effect vary widely depending on the chemical composition of the alloy, the kind of the semiproduct, and the process of its fabrication.

In the present work we studied the strengthening due to only one of the factors mentioned, i.e., the decomposition of the solid solution of scandium in aluminum. In order to eliminate the effect of structural hardening, we performed experiments using undeformed material in the form of continuously cast ingots. The hardening of the ingots due to decomposition of the solid the solution was primarily determined by the fineness of the products of the decomposition of the solid solution of scandium in aluminum (particles of the

Al₃Sc phase), which is influenced by the chemical composition of the alloy (primarily by the content of scandium) and by the presence of other alloying components and admixtures. We studied the effect of the composition of the cast material on its hardening in the course of decomposition of the solid solution of scandium in aluminum, i.e., the content of scandium, the presence of additives of transition metals (Zr, Ti, Hf, V, and Co), and the content of iron and silicon admixtures. The aim of the work consisted in choosing the optimum combination of scandium additive with other transition metals that would ensure maximum strengthening, and in determining the permissible content of iron and silicon admixtures in commercial aluminum alloys bearing scandium.

METHODS OF STUDY

We used the method of continuous casting to obtain ingots 92 mm in diameter. The temperature and time parameters of melting and casting of the ingots were chosen so as to ensure maximum assimilation of the aluminum–scandium and aluminum–transition metal additives by the melt (full dissolution of the aluminides contained in the alloying additive in the aluminum melt) and then to determine the content of scandium and other transition metals in the solid aluminum solution in casting of the ingots. For this purpose the melt was heated to 780–800°C, held for 1 h, and cooled to 720–730°C. In this temperature range we performed continuous casting of ingots of the experimental alloys. According to our estimates the rate of cooling of the metal in the temperature range of crystallization for casting of ingots 92 mm in diameter was about 50 K/sec. With allowance for the low content of alloying additives in the alloys studied this cool-

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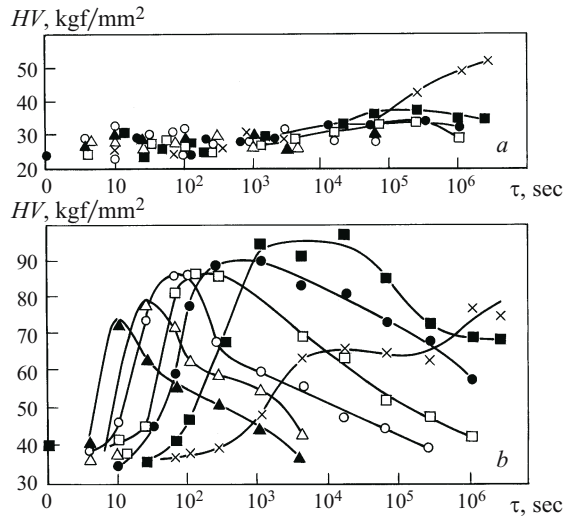


Fig. 1. Dependence of the microhardness of alloys Al – 0.14% Sc (a) and Al – 0.55% Sc (b) on the duration of isothermal hold at various temperatures: ×) 250°C; ■) 300°C; ●) 350°C; □) 400°C; ○) 450°C; △) 500°C; ▲) 550°C.

ing rate ensured (according to the data of microstructure analysis) full fixation of scandium and other transition metals in the solid solution.

We obtained ingots of experimental alloys of the Al – Sc system in which the content of scandium was varied from 0.15 to 0.55%, ingots of Al – Sc system without additive and with additives of Zr, Ti, Hf, V, and Co, alloys with various Sc/Zr proportions, and alloys of the Al – Sc system with different content of Si and Fe admixtures. The alloys were based on aluminum of purity A99.

Ingots in the cast state were cut into pieces for polished sections that were annealed at a temperature of from 250 to 500°C at a step of 50°C with holds from 4 sec to 1 month. Short holds lasting for up to 30 min were performed in a salt-peter bath and longer holds were performed in an air furnace. The hardening of the cast metal due to the decomposition of the solid solution was evaluated by measuring the micro-

hardness. Fifteen to twenty measurements were made for each point. The degree of alloying of the solid solution with scandium and other transition metals was determined by measuring the electric conductivity with the help of an IÉ-1 device.

RESULTS AND DISCUSSION

Effect of Scandium in Binary Alloys of the Al – Sc System on the Hardening Due to Decomposition of the Solid Solution

It has been shown in [2, 3] that in continuous casting of scandium-bearing aluminum alloys scandium is fixed in the supersaturated solid solution that decomposes in subsequent heating operations ensuring strong hardening. For example, the microhardness of an ingot of alloy Al – 0.4% Sc in cast state (scandium is present in the solid solution) amounts to about 33 *HV*. After heating to 300 – 350°C with 1-h hold the microhardness of the ingot increases to 92 – 96 *HV* due to the decomposition of the solid solution and formation of fine particles of Al₃Sc. When the temperature of the isothermal hold is increased, the maximum microhardness attained at each temperature decreases and the time of attainment of the maximum microhardness decreases markedly (Table 1).

The degree of hardening in the decomposition of solid solution of scandium in aluminum should depend primarily on its concentration. We cast ingots of binary alloys of the Al – Sc system with 0.14, 0.23, 0.35, 0.40, and 0.55% scandium [4]. Analysis of the microstructure of the ingots showed the absence of primary Al₃Sc intermetallics. This gives us grounds to assume that the entire scandium introduced into the alloys was concentrated during casting in the solid solution.

Elevation of the concentration of the solid solution of scandium in aluminum from 0.14 to 0.55% increases the microhardness of cast specimens from 26 to 40 *HV*. Heating and subsequent isothermal hold of the ingots change the microhardness of the Al – Sc alloys considerably (Fig. 1). The kinetics of variation of the microhardness depends on the scandium content. Growth of the latter increases the value of maximum of the microhardness, shortens the time of attainment of the maximum, and widens the temperature range in which the hardening occurs (Fig. 1). For example, in an alloy with 0.14% Sc the maximum microhardness and the hardening effect are not high and occur after a long-term hold at 250 – 300°C (Fig. 1a). Growth in the temperature lowers the hardening effect to 25, 8, and 4 *HV* at 250, 300, and 350°C, respectively. At 450°C and higher temperatures the hardening effect in the alloy is absent, though the values of the electric conductivity show that the solution of scandium in aluminum does decompose.

For the Al – 0.55% Sc alloy the growth in the microhardness is considerably higher at all the studied temperatures of isothermal hold, i.e., at 300 – 400°C the increment is 50 – 55 *HV* and is observed after a shorter time (Fig. 1b).

TABLE 1. Maximum Microhardness of Alloy Al – 0.4% Sc in an Ingot and the Time of Its Attainment as a Function of the Temperature of Isothermal Hold

Temperature of isothermal hold, °C	Maximum microhardness <i>HV</i> , kgf/mm ²	Time of attainment of maximum hardness
250	89*	~ 1 month
300	96	5 h
350	92	20 min
400	88	3 min
450	86	40 sec
500	84	~ 25 sec

* Maximum hardness at 250°C has not been attained because of the too short isothermal hold.

To make the comparison of the kinetics of variation of microhardness of alloys in ingots with different contents of scandium convenient we present the curves describing the variation of HV as a function of the duration of isothermal hold at 300°C in one figure (Fig. 2). As the scandium content grows from 0.14 to 0.55%, the maximum of the microhardness increases from 40 to 96 HV , the growth in the microhardness increases from 14 to 60 HV , the time of attainment of the maximum decreases from 300 h to 16 min, and the incubation period decreases from 0.5 h to 0.5 min.

In all the alloys studied (except for Al – 0.14% Sc) maximum microhardness was attained at 300°C and remained unchanged for a long time (the “plateaus” on the curves of Fig. 2). Constant values of microhardness on the curves $HV = f(\tau)$ corresponded to constant or little varying values of electrical conductivity. It seems that the attainment of maximum microhardness corresponds to the stage of metastable equilibrium of the formed segregations and of the solid solution of scandium in aluminum.

Thus, the decomposition of the solid solution of scandium in aluminum produces strong hardening. Maximum hardening attained at a temperature of $300 - 350^\circ\text{C}$ is preserved for several hours. At heating temperatures of $400 - 450^\circ\text{C}$ (a typical temperature range of process heating of aluminum alloys) the hardening is preserved for several minutes and is followed by rapid softening due to intense coagulation of the decomposition products. The hardening effect is almost fully removed.

Effect of Transition Metals on the Hardening of Alloys of the Al – Sc System Due to Decomposition of the Solid Solution

The low stability of the solid solution of scandium in aluminum and the high rate of coagulation of the products of decomposition of the solid solution of scandium in aluminum create difficulties with preservation of the hardening effect in the process of fabrication of deformed semiproducts from scandium-bearing aluminum alloys.

Process heating operations are accompanied by intense decomposition of the solid solution of scandium in aluminum and by coagulation of the decomposition products (particles of Al_3Sc). As a result, the hardening action of scandium is weakened considerably. In order to prevent the process of softening (even a partial one) the temperature and time parameters of the process heating operations are to be controlled quite strictly.

The principal possibility of thermal stabilization of dispersed particles of Al_3Sc due to the introduction of a zirconium additive into alloy Al – 0.4% Sc was first shown in [5]. The rate of softening for an alloy of the Al – Sc – Zr system in the coagulation stage of aging is considerably (by several orders of magnitude) lower than the corresponding rate for a binary Al – Sc alloy. The phenomenon is a result of the fact that zirconium partially dissolves in the Al_3Sc phase due to partial substitution of scandium atoms by zirconium atoms.

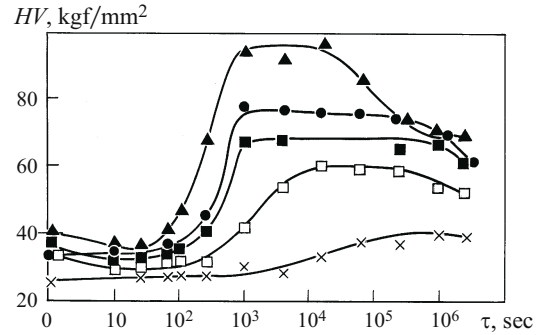


Fig. 2. Dependence of the microhardness of alloys of the Al – Sc system with 0.14 (x), 0.23 (□), 0.35 (■), 0.40 (●), and 0.55% Sc (▲) on the duration of isothermal hold at 300°C .

The forming the $\text{Al}_3(\text{Sc}_{1-x}, \text{Zr}_x)$ phase is close to and simultaneously somewhat different from the Al_3Sc phase in the physical properties due to the lower diffusivity of zirconium with respect to that of scandium. The particles of the $\text{Al}_3(\text{Sc}_{1-x}, \text{Zr}_x)$ phase are characterized by considerably lower susceptibility to coagulation under heating as compared to particles of the Al_3Sc phase.

In the present section we describe the results of a study aimed at determining the possibilities of further stabilization of the particles of Al_3Sc due to the introduction of low additives of transition metals such as Hf, Ti, V, and Co, which would substitute scandium atoms in the Al_3Sc phase like zirconium.

We cast ingots from alloys with the compositions presented in Table 2.

The content of scandium was chosen to be 0.2%, because it was optimum from the standpoint of the efficiency-to-content proportion.

The kinetic curves describing the variation of the microhardness of alloys 1 – 9 are presented in Fig. 3.

All the alloys can be conventionally divided into three groups, namely, zirconium-free alloys with maximum microhardness of 44 – 48 HV , alloys with 0.15% Zr and maximum

TABLE 2. Design Chemical Composition of Alloys of the Al – Sc System with Transition Metals

Alloy	Content of elements, wt. %					
	Sc	Zr	Hf	Ti	V	Co
1	0.2	–	–	–	–	–
2	0.2	0.15	–	–	–	–
3	0.2	–	0.15	–	–	–
4	0.2	0.08	0.08	–	–	–
5	0.2	–	–	0.50	–	–
6	0.2	–	–	–	0.03	–
7	0.2	–	–	0.025	0.015	–
8	0.2	0.15	–	0.03	0.02	–
9	0.2	0.15	–	–	–	0.15

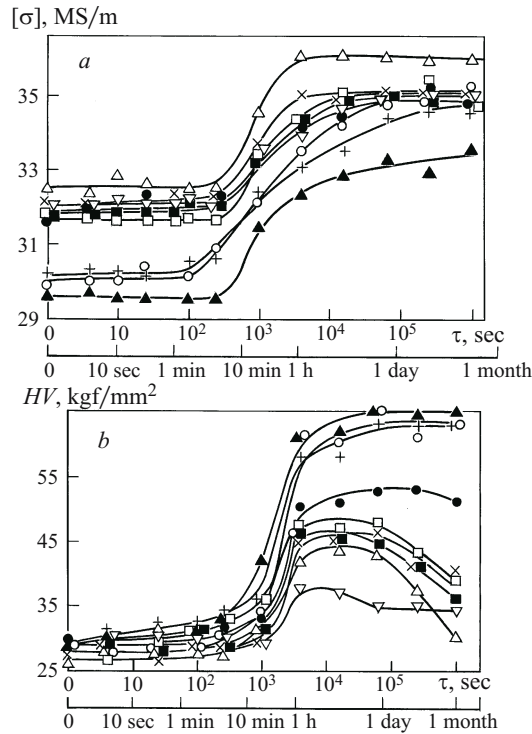


Fig. 3. Dependence of the conductivity $[\sigma]$ (a) and microhardness HV (b) on the time of the hold at 400°C for alloy $\text{Al} - 0.2\% \text{Sc}$ with additives of transition metals: Δ) Sc (1); \circ) Sc + Zr (2); \times) Sc + Hf (3); \bullet) Sc + Zr + Hf (4); \square) Si + Ti (5); ∇) Sc + V (6); \blacksquare) Sc + Ti + V (7); \blacktriangle) Sc + Zr + Ti + V (8); $+$) Sc + Zr + Co (9); the numbers of the alloys in Table 2 are presented in parentheses.

microhardness of 68 – 65 HV , and alloys with 0.08% Zr that occupy an intermediate position. The $\text{Al} - \text{Sc} - \text{V}$ alloy with maximum microhardness of only 38 HV occupies a special

place. The high microhardness of the alloys with 0.15% Zr is preserved at 400°C for quite a long time (up to 277 h), whereas the microhardness of the all the other alloys begins to decrease after a hold of 10 h.

Figure 4 presents dark-background images of the structure of alloys 1–3, 5, and 6 in the reflection of an Al_3Sc -type phase segregated from the supersaturated solid solution after aging in a mode of 450°C , 17.5 h that ensures maximum hardening. In the $\text{Al} - 0.2\% \text{Sc}$ alloy we observe comparatively large rarely-arranged particles; the mean size of the particles is 40 nm and the distance between them is 570 nm. The introduction of 0.15% Zr decreases the mean size of the particles to 10 nm and the distance between them to 160 nm. The alloys of the $\text{Al} - \text{Sc} - \text{Hf}$ and $\text{Al} - \text{Sc} - \text{Zr} - \text{Hf}$ systems have particles of intermediate sizes, i.e., 14 and 16.5 nm, respectively. The distribution of particles in the alloys bearing titanium and vanadium has a bimodal pattern; zones (centers of dendrite cells) with fine particles (≤ 10 nm) are surrounded by regions with coarser particles (about 50 nm).

A study of the variation of the concentration of solid solution over sections of dendrite cells in cast specimens (JXA-733 device) showed that all the additives of transition metals used were susceptible to microsegregation (Fig. 5). Titanium and, especially, vanadium segregated the most strongly. In accordance with the phase diagram of the $\text{Al} - \text{Sc}$ system (of the eutectic type) the concentration of scandium is elevated in the peripheral part of dendrite cells and reduced in the central zones of the cells. Zirconium, titanium, and vanadium, interact with aluminum according to the peritectic diagram and therefore concentrate in the central zones of the cells depleting their periphery. Cobalt resides outside the solid solution.

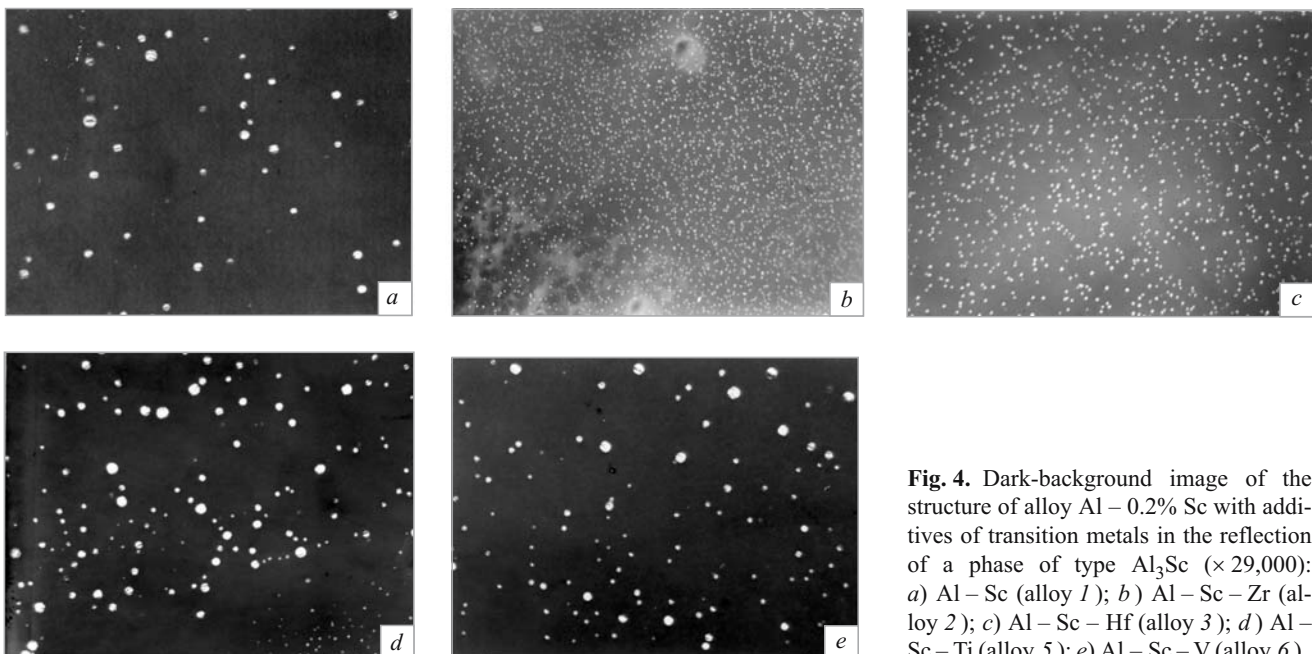


Fig. 4. Dark-background image of the structure of alloy $\text{Al} - 0.2\% \text{Sc}$ with additives of transition metals in the reflection of a phase of type Al_3Sc ($\times 29,000$): a) $\text{Al} - \text{Sc}$ (alloy 1); b) $\text{Al} - \text{Sc} - \text{Zr}$ (alloy 2); c) $\text{Al} - \text{Sc} - \text{Hf}$ (alloy 3); d) $\text{Al} - \text{Sc} - \text{Ti}$ (alloy 5); e) $\text{Al} - \text{Sc} - \text{V}$ (alloy 6).

Analyzing the experimental data obtained we can infer the following.

1. Decomposition of the solid solution of scandium in aluminum in an ingot of alloy Al – 0.2% Sc occurs slower than in alloy Al – 0.4% Sc and ensures inconsiderable hardening (Fig. 6).

2. Introduction of hafnium into alloy Al – 0.2% Sc can theoretically lead to formation of a ternary $Al_3(Sc_{1-x}, Hf_x)$ phase in the process of decomposition of the solid solution. However, the particles of this phase are finer than those of $Al_3(Sc_{1-x}, Zr_x)$. Therefore, the hardening observed in this case is weaker than that due to the introduction of zirconium.

3. Addition of titanium to alloy Al – 0.2% Sc also increases the hardening ensured by decomposition of solid solution in the ingot. In all probability the phase formed in this case is $Al_3(Sc_{1-x}, Ti_x)$ (fine particles in the centers of dendrite cells in Fig. 4).

4. A low additive of vanadium weakens the hardening action of scandium. This effect of vanadium seems to be connected with its very strong microsegregation and the corresponding influence on the morphology of the products of decomposition of the solution.

5. An additive of cobalt to alloy Al – 0.2% Sc – 0.15% Zr produces virtually no effect on the structure and properties of this alloy because cobalt does not enter the solid solution.

6. A joint additive of 0.2% Sc and 0.15% Zr ensures a high level of hardening close to that attained in decomposition of solid solution in the alloys bearing 0.4% Sc (Fig. 6). In contrast to the alloy with 0.4% Sc the hardening is attained after longer holds and at higher temperatures.

Finally, the most important inference following from the analysis of the results of this section is that zirconium is the most effective of all the elements studied; it intensifies and stabilizes the hardening action of scandium. Addition of hafnium and titanium produces a similar effect, but their action is weaker.

Effect of the Sc/Zr Ratio on the Hardening Due to Decomposition of the Solid Solution

It has been shown above that an additive of zirconium intensifies and stabilizes the hardening action of scandium the most effectively. Zirconium dissolves in the Al_3Sc phase, replacing scandium atoms and forming an $Al_3(Sc_{1-x}, Zr_x)$ phase. According to the data of [6] the value of x can reach 0.4. It seems that the properties of the $Al_3(Sc_{1-x}, Zr_x)$ phase are intermediate between those of the Al_3Sc phase and of the metastable Al_3Zr phase. Growth in the content of zirconium in the $Al_3(Sc_{1-x}, Zr_x)$ phase and the corresponding decrease in the content of scandium brings some properties of the Al_3Sc phase closer to those of the metastable Al_3Zr phase.

We cast ingots of alloys of the Al – Sc – Zr system with a constant total content of Sc and Zr equal to 1.5% and different proportions of these components [7]. The figurative points of the alloys chosen are presented on an isothermal section of the equilibrium phase diagram of the Al – Sc – Zr

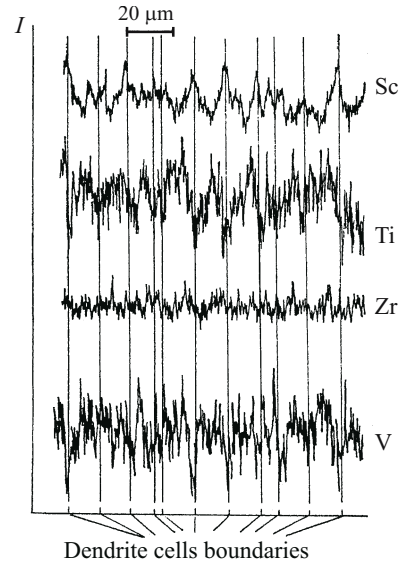


Fig. 5. Variation of the intensity of diffraction lines over cross sections of dendrite cells of the solid solutions of scandium, zirconium, vanadium, and titanium in aluminum in alloy Al – 0.2% Sc – 0.15% Zr – 0.03% Ti – 0.02% V.

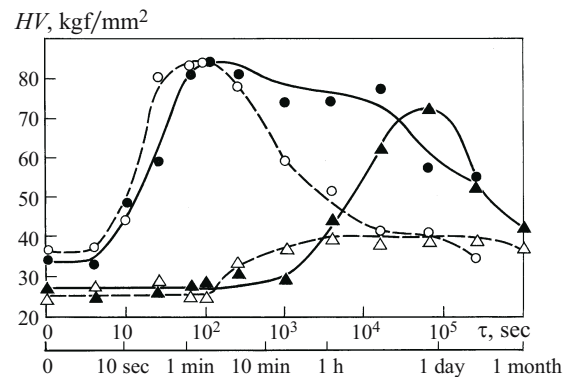


Fig. 6. Dependence of the microhardness of alloys of the Al – Sc and Al – Sc – Zr systems on the duration of isothermal hold at 450°C: ○) alloy Al – 0.4% Sc; ●) Al – 0.4% Sc – 0.15% Zr; △) Al – 0.2% Sc; ▲) Al – 0.2% Sc – 0.15% Zr.

system (Fig. 7). The compositions were chosen so that the alloys were located in different phase regions. In addition to the two alloys with composition $\alpha + Al_3(Sc_{1-x}, Zr_x)$ and different concentrations of zirconium in the $Al_3(Sc_{1-x}, Zr_x)$ phase (alloys 2 and 3 in Fig. 7) we cast ingots of alloys with the phase compositions $\alpha + Al_3Sc$ (alloy 1), $\alpha + Al_3(Sc_{1-x}, Zr_x) + Al_3(Zr_{1-x}, Sc_x)$ (alloy 4), $\alpha + Al_3(Zr_{1-y}, Sc_y)$ (alloy 5), and $\alpha + Al_3Zr$ (alloy 6) for comparison.

The study of the microstructure of the ingots showed the presence of intermetallics of types Al_3Sc and Al_3Zr . This means that not all of the scandium and zirconium introduced into the alloy enter into the supersaturated solid solution. The volume fraction of the intermetallics fluctuated within

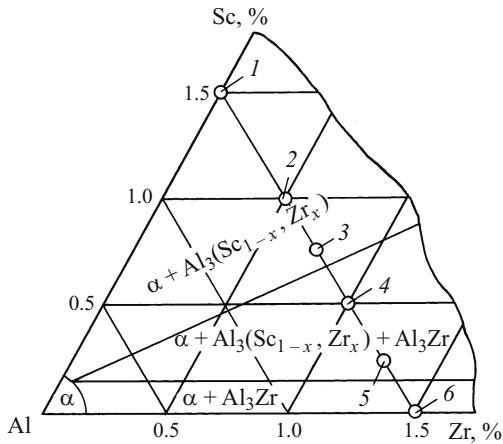


Fig. 7. Figurative points (1–6) of alloys on an isothermal section of the Al–Sc–Zr phase diagram.

2.4–4.5%. The lowest content of intermetallics formed in the ingot of alloy 3 with equal amounts of scandium and zirconium, i.e., 0.75% each (the volume fraction of intermetallics in alloy 3 was 2.4%). Consequently, the solid solution in the ingot of this alloy was saturated to a maximum level. The results of determination of the conductivity confirmed this assumption; alloy 3 with the same contents of scandium and zirconium exhibited the lowest conductivity.

The curves describing the variation of the microhardness of ingots of alloys 1–6 as a function of the duration of isothermal hold at 400°C are presented in Fig. 8. As could have been expected the highest microhardness is attained in alloy 3 with the same contents of scandium and zirconium due to the highest concentration of the solid solution detected in casting of the ingots. With deviation of the scandium-to-zirconium proportion from 1 : 1 the microhardness decreases. The rate of softening of alloy 3 is not high. A high microhardness is preserved in the whole of the studied range of holds.

The alloy with a scandium-to-zirconium ratio of 1 : 1 having the maximum hardness lies in the $\alpha + \text{Al}_3(\text{Sc}_{1-x}, \text{Zr}_x)$ phase region of the ternary Al–Sc–Zr phase diagram and borders the $\alpha + \text{Al}_3(\text{Sc}_{1-x}, \text{Zr}_x) + \text{Al}_3\text{Zr}$ region. Judging by the position of the alloy in the phase diagram the particles of the $\text{Al}_3(\text{Sc}_{1-x}, \text{Zr}_x)$ phase are maximally saturated with zirconium, which possesses a lower diffusivity in aluminum than scandium. This ensures a high thermal stability of dispersed particles (a low rate of coagulation). It is also possible that zirconium dissolving in the Al_3Sc phase lowers the value of the specific surface energy of the interface of the $\text{Al}_3(\text{Sc}_{1-x}, \text{Zr}_x)$ particles with the aluminum matrix. This also promotes a decrease in the susceptibility of the particles to coagulation due to the reduction of the driving force of the coagulation, i.e., the excess surface energy.

Generalizing the results obtained we can infer that the aluminum alloy containing scandium and zirconium in a one-to-one ratio possesses an optimum hardness. The alloy is

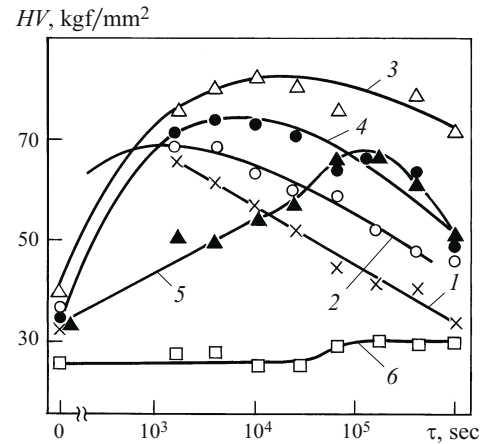


Fig. 8. Dependence of the microhardness of alloys 1–6 of the Al–Sc–Zr system with different amounts of scandium and zirconium on the duration of isothermal hold at 400°C: ×) 1.5% Sc; ○) 1.0% Sc + 0.5% Zr; △) 0.75% Sc + 0.75% Zr; ●) 0.5% Sc + 1.0% Zr; ▲) 0.25% Sc + 1.25% Zr; □) 1.5% Zr.

the most susceptible to supersaturation of the solid solution with scandium and zirconium during casting of ingots by the continuous method, hardens effectively due to the decomposition of the solid solution, and preserves this hardening after high-temperature heating operations imitating process heating. In addition, we can expect that semiproducts from this alloy would have high resistance to recrystallization.

Effect of the Content of Iron and Silicon on the Hardening of Alloy Al–0.4% Sc Due to Decomposition of the Solid Solution

Iron and silicon are inevitable admixtures in commercial aluminum alloys. We studied the effect of the iron and silicon content on the hardening of alloy Al–0.4% Sc in an ingot due to decomposition of the solid solution.

We cast ingots of alloys Al–0.4% Sc of twelve compositions differing from each other in the content of iron and silicon admixtures (Table 3).

In alloys 1–4 bearing the same contents of scandium (0.4%) and silicon (0.1%) the content of iron was varied from 0.02 to 0.7%; in alloys 5–8 bearing the same content of scandium (0.4%) and iron (0.05%) the content of silicon was varied from 0.1 to 0.4%; in alloys 9–12 with the same content of scandium (0.4%) the amounts of iron and silicon were increased.

Analysis of the microstructure of the ingots showed that growth in the content of iron was accompanied by an increase in the number and sizes of the intermetallics containing iron. Scandium was absent in the composition of these intermetallics [8].

Particles of phase *V* appeared upon growth in the content of silicon (Al, Sc, Si) [9].

Growth in the content of iron (alloys 1–4) was accompanied by a decrease in the conductivity and an increase in

TABLE 3. Chemical Composition, Electrical Conductivity [σ], and Microhardness HV of Experimental Alloys in Different States

Alloy	Content of elements, wt. %			$[\sigma]$, MS/m		HV , kgf/mm ²	
	Sc	Fe	Si	cast state	annealed state	cast state	ageing to maximum hardness
1	0.4	0.02	0.1	28.3	35.3	32	80
2	0.4	0.20	0.1	28.0	35.0	36	80
3	0.4	0.45	0.1	27.6	34.5	40	80
4	0.4	0.70	0.1	26.5	33.5	42	80
5	0.4	0.05	0.1	27.0	36.0	34	86
6	0.4	0.05	0.2	27.7	34.6	43	81
7	0.4	0.05	0.3	28.5	34.5	53	80
8	0.4	0.05	0.4	28.5	34.7	53	77
9	0.4	0.05	0.05	30.5	38.9	30	86
10	0.4	0.20	0.1	28.7	35.9	43	76
11	0.4	0.20	0.2	29.5	36.0	47	86
12	0.4	0.40	0.35	29.0	34.5	50	84

the hardness (Table 3) due to the growth in the volume fraction of the particles of iron-bearing intermetallics. Growth in the content of silicon caused a simultaneous increase in the conductivity and microhardness due to the bonding of silicon in the V phase and due to the processes of discontinuous decomposition of the solid solution of scandium in aluminum that occurred during cooling of the ingots from the casting temperature. In the case of simultaneous growth in the content of iron and silicon the influence of silicon was prevailing and the conductivity and microhardness increased.

Increase in the iron content in alloy Al – 0.4% Sc to 0.7% affected little the hardening in the decomposition of the solid solution of scandium in aluminum (Fig. 9a). Only the initial stage of the decomposition changed somewhat.

The effect of silicon on the kinetics of the hardening was considerably stronger (Fig. 9b).

The microhardness in the cast state increased with growth in the silicon content and the maximum microhardness attained due to aging decreased with growth in the content of silicon. The aging effect decreased accordingly. This effect of silicon is explainable by intensification of the discontinuous decomposition of the solid solution of scandium in aluminum, which occurs in cooling of the ingots from the casting temperature and leads to growth in the microhardness in the cast state due to the products of discontinuous decomposition. In addition, the hardening effect due to the isothermal hold decreases as a result of the decrease in the concentration of scandium in the solid solution in the initial state.

In the case of simultaneous growth in the amounts of iron and silicon the action of the latter is prevalent, especially in the initial stages of aging of the Al – Sc alloy (Fig. 9c). Iron neutralizes somewhat the effect of silicon on the kinetics of hardening of the alloy due to binding of silicon in the Al(Fe, Si) phase.

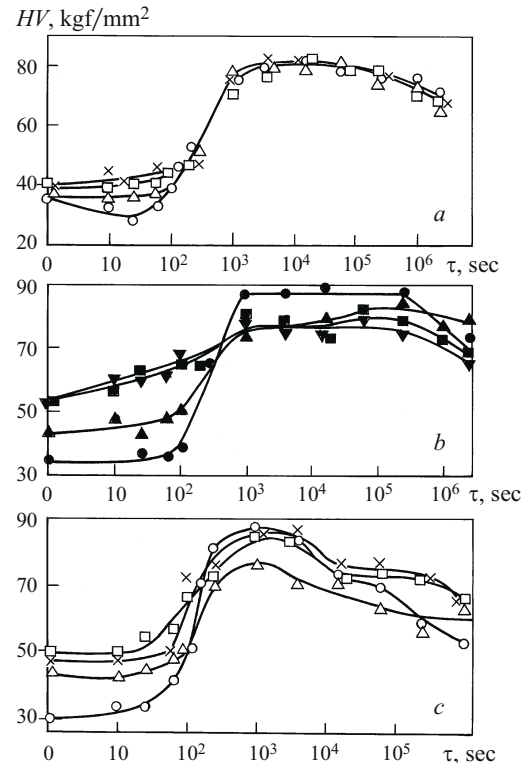


Fig. 9. Dependence of the microhardness of alloy Al – 0.4% Sc with various contents of iron and silicon on the duration of the hold at 300 (a, b) and 350°C (c): a) 0.02 (○), 0.2 (△), 0.45 (□), and 0.7% Fe (×); b) 0.05 (●), 0.15 (▲), 0.3 (■), and 0.4% Si (▼); c) without admixtures of iron and silicon (○), with 0.2% Fe + 0.1% Si (△), with 0.2% Fe + 0.2% Si (×), and with 0.4% Fe + 0.35% Si (□).

Thus, the effect of admixtures of iron and silicon on the structure and properties of aluminum alloys with scandium is reduced to the following. Iron does not interact with scandium and affects little the process of formation of the supersaturated solid solution of scandium in aluminum and the subsequent decomposition of the solid solution of scandium in aluminum (these processes determine the advantages of aluminum alloys with scandium additives). The action of iron on the structure and properties of alloys of the Al – Sc system is similar to its action on aluminum and on traditional aluminum alloys. Therefore, the content of iron in aluminum alloys with scandium additives should be limited for the same considerations as the limitation of the iron content in aluminum alloys without scandium, i.e., it should be reduced to 0.5% in conventional alloys, to 0.3% in pure alloys, and to 0.15% in especially pure ones.

Addition of silicon into alloys of the Al – Sc system produces unfavorable effects, i.e., intensifies the susceptibility of the solution of scandium in aluminum to discontinuous decomposition that occurs in cooling of the ingots from the crystallization temperature and binds scandium into compound V (Al, Sc, Si). These two processes lower the concentration of scandium in the solid solution in the cast state and,

correspondingly, decrease the amount of fine Al_3Sc particles that ensure the hardening.

The content of silicon in aluminum alloys bearing scandium should be limited more strictly than the content of iron, namely, to 0.2% in conventional alloys, to 0.15% in pure alloys, and to 0.08% in especially pure alloys.

CONCLUSIONS

1. Decomposition of the solid solution of scandium in aluminum, which forms due to continuous casting of ingots, causes strong hardening. The intensity of the hardening depends on the concentration of the solid solution of scandium in aluminum.

2. Addition of transition metals to the Al – 0.2% Sc binary alloy affects noticeably the intensity of the hardening. Zirconium additive, which raises the hardening and stabilizes the strengthening in a wider range of aging temperatures, produces the highest effect. Addition of Ti and Hf produces a similar but weaker effect. Vanadium additives lower the hardness of the Al – 0.2% Sc alloy. The presence of zirconium neutralizes the negative effect of vanadium. Cobalt additives do not affect the hardness of the alloy.

3. The strongest hardening due to decomposition of the solid solution in alloys of the Al – Sc – Zr system is attained at equal contents of Sc and Zr. In this case the solid solution is saturated with scandium and zirconium to the highest degree in casting of ingots; subsequent heating is accompanied, judging by the location of the alloy in the phase diagram, by segregation of an $\text{Al}_3(\text{Sc}_{1-x}, \text{Zr}_x)$ phase in which scandium atoms are replaced by zirconium atoms to the maximum possible degree.

4. Iron admixtures do not affect the hardness of alloys of Al – Sc system. Silicon binds scandium into a (Al, Sc, Si) ternary compound and thus lowers the concentration of the solid solution of scandium in aluminum and, correspondingly, the hardness upon the decomposition of the solid solution.

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