ISSN 1028-2335 (Print)
Теорія і практика металургії, 2025, № 2
Theory and Practice of Metallurgy, 2025, No. 2

https://doi.org/10.15802/tpm.2.2025.04

UDC 669.715.018:621.745

Aiupova T.A., Yelagin A.S., Kovzik A.M., Bila O.V., Pohrebna N.E.

Influence of physicochemical melt treatment on structure and properties of AK7ch alloy microalloyed with Sr-Sc and Ti-B-Sr complexes

Аюпова Т.А., Єлагін А.С., Ковзік А.М., Біла А.В., Погребна Н.Е.

Вплив фізико-хімічної обробки розплаву на структуру та властивості силумінуАК7ч при мікролегуванні комплексами Sr-Sc та Ti-B-Sr

Abstract. Purpose. *The aim of research is to determine the features of structure formation and property enhancement in the AK7ch alloy under the influence of microalloying with complex modifiers Sr-Sc and Ti-B-Sr, as well as physicochemical treatment in the liquid state.* ***Methodology.*** *The object of study was the AK7ch alloy of the base composition and micro-alloyed with Sr-Sc and Ti-B-Sr complexes in both the as-cast state and after hydrogen and thermotemporal melt treatments. Structural formation was investigated using metallographic analysis. The ultimate deformability was determined by an improved method for assessing the limiting deformation degree during rolling of wedge-shaped samples. Corrosion resistance, including general and intergranular corrosion susceptibility, was assessed using standard testing methods.* ***Results.*** *It was found that the combined physicochemical effect of microalloying with Sr-Sc and 20-minute hydrogen melt treatment increased the deformability of the AlSi7 alloy by 60%. Ti-B-Sr addition and 30-minute thermotemporal melt treatment increased deformability by 46% compared to the original as-cast alloy. It was also established that microalloying with Ti-Sr-B and isothermal treatment for 30 minutes significantly enhance the corrosion resistance of the AK7ch alloy.* ***Scientific novelty.*** *The study proves the effectiveness of microalloying with Sr-Sc and Ti–B–Sr complexes in combination with hydrogen and thermotemporal melt treatments for improving the deformability of AK7ch alloy compared to the base composition. The positive effect of such treatments on the alloy's general corrosion resistance was also confirmed.* ***Practical significance.*** *The research provides effective methods for enhancing the technological deformability and corrosion resistance of AK7ch aluminum alloy through microalloying with Sr–Sc and Ti–B–Sr complexes in combination with hydrogen or thermotemporal melt treatment. The proposed approaches significantly improve the alloy's structure, which promotes increased corrosion resistance and overall reliability of finished products, especially in critical components used in mechanical engineering, aviation, and transport industries.*

Key words: *silumin, microalloying, hydrogen treatment, thermotemporal treatment, deformability, corrosion properties.*

Анотація. Мета. *Метою дослідження є визначення особливостей формування структури та властивостей в сплаві АК7ч, при дії мікролегування комплексним модифікаторами Sr-Sc і Ti-B-Sr та фізико-хімічної обробки в рідкому стані.* ***Методика.*** *Об'єктом дослідження служив сплав АК7ч вихідного складу та мікролегований комплексними модифікаторами Sr-Sc та Ti-B-Sr в литому стані та після водневої та термочасової обробок в рідкому стані. Дослідження особливостей формування структури проводили за допомогою металографічного, аналізу, граничну деформівність сплавів визначали за вдосконаленою методикою визначення граничного ступеню деформації металів при прокатці клиновидних зразків, корозійні випробування на загальну корозію та схильність до міжкристалітної корозії проводили за стандартними методиками.* ***Результати.*** *Встановлено, що комплексний фізико-хімічний вплив мікролегування комплексом Sr-Sc та 20-хвилинне водневе оброблення розплаву АК7ч підвищує його деформівність на 60%, а додавання комплексу Ti-B-Sr та термочасова обробка розплаву притягом 30 хвилин сприяють підвищенню його деформівності на 46 % порівняно з вихідним литим сплавом. Встановлено, що мікролегування Ti-Sr-B та термочасова обробка розплаву протягом 30 хв. підвищують корозійну стійкість сплаву АК7ч.* ***Наукова новизна.*** *Доведено ефективність мікролегування комплексними модифікаторами Sr-Sc та Ti–B–Sr у поєднанні з водневою та термочасовою обробками розплаву для підвищення деформівності сплаву АК7ч у порівнянні з вихідним складом. Встановлено позитивний вплив мікролегування та термочасової обробки розплаву на підвищення загальної корозійної стійкості сплаву АК7ч.* ***Практична значущість*** *проведеного дослідження полягає в розробці ефективних методів підвищення технологічної деформівності та корозійної стійкості алюмінієвого сплаву типу АК7ч шляхом мікролегування комплексами Sr–Sc та Ti–B–Sr у поєднанні з водневою або термочасовою обробкою розплаву. Запропоновані технологічні підходи забезпечують суттєве покращення структури сплаву, що сприятиме підвищенню корозійної стійкості та загальної надійності готових виробів, особливо у відповідальних конструкціях машинобудування, авіації та транспортного призначення.*

Ключові слова*: силуміни, мікролегування, воднева обробка, термочасова обробка, деформівність, корозійні властивості.*

© Aiupova T.A. - Ukrainian State University of Science and Technologies, Dnipro, Ukraine
Yelagin A.S. - PE "DYVOTSVIT", Dnipro, Ukraine
Kovzik A.M. - Ukrainian State University of Science and Technologies, Dnipro, Ukraine
Bila O.V. - Ukrainian State University of Science and Technologies, Dnipro, Ukraine
Pohrebna N.E. - Ukrainian State University of Science and Technologies, Dnipro, Ukraine

This is an Open Access article under the CC BY 4.0 license https://creativecommons.org/licenses/by/4.0/

Analysis of Literature Data and Problem Statement

Aluminum alloys based on the Al–Si system, particularly alloys of the AK7ch type (analogue of Aluminum Alloy A356 (AlSi7Mg0.3) according to the ASTM classification, and EN AC-42000 (AlSi7Mg0.3) according to the European standard EN 1706), are widely used in mechanical engineering, aviation, and transportation industries due to the combination of such properties as low density, good casting properties, sufficient corrosion resistance, and acceptable mechanical characteristics. However, the as-cast state of alloys of this type is characterized by increased brittleness, limited deformability, and structure heterogeneity, which significantly restrict their application in plastic forming processes such as rolling or drawing [1].

One of the approaches to improving the properties of silumins is microalloying—the addition of small amounts of active elements or their compounds (Sr, Sc, Ti, B, etc.) into the melt, which are capable of modifying the structure by changing the morphology of eutectic silicon and intermetallic inclusions. Recent studies confirm the effectiveness of complex modifiers [2–3], in particular Sr–Sc and Ti–B–Sr, in improving mechanical and performance properties, including deformability, strength, and corrosion resistance [4–6].

In addition, a promising direction is the physico-chemical treatment of the melt—specifically, hydrogen and thermotemporal treatments—which ensures structural homogenization and intermetallics refinement. The combined use of microalloying and liquid-state treatment makes it possible to achieve a synergistic effect of property improvement; however, in the context of AK7ch-type alloys, these aspects remain insufficiently studied [7–10].

It should be noted that in Ukraine, there is a lack of industrial production of primary aluminum and wrought aluminum alloys. The closure of the electrolysis workshop at the Zaporizhzhia Aluminum Plant in 2011 deprived the country of the status of a primary aluminum producer. Existing enterprises, such as the Brovary Aluminum Plant, are mainly engaged in secondary raw material processing and profile production, which does not meet the demand for high-quality wrought alloys for critical industrial sectors.

Thus, the relevance of research aimed at improving the technological properties of the AK7ch alloy through microalloying and physico-chemical treatment is increasing. The results of such work may serve as a foundation for the restoration and development of domestic production of wrought aluminum alloys, which is strategically important for meeting the needs of Ukraine's mechanical engineering and aviation industries.

Purpose and Objectives of the Study

The purpose of this study is to determine the features of structure formation and properties in the AK7ch alloy under the influence of microalloying with complex modifiers Sr–Sc and Ti–B–Sr, as well as physico-chemical treatment in the liquid state.

Materials and Methods of Research

The object of the study was samples of the AK7ch alloy microalloyed with the Sr–Sc complex after melt hydrogen treatment, and with the Ti–B–Sr complex after melt thermotemporal treatment under different regimes (Table 1).

Table 1 – Chemical composition of the experimental alloys

Alloy	Chemical element, %mass.							
	Al	Si	Fe	Mg	Mn	Zn	Cu	Modifier
AK7ch	Base	7,05-7,20	0,4-0,6	0,30-0,35	0,02-0,03	0,09-0,1	0,02-0,04	0,1%Sr 0.5%Sc
AK7ch(Sr,Sc)	Base	7,01-7,18	0,4-0,6	0,29-0,33	0,02-0,03	0,09-0,1	0,02-0,04	0,1%Sr 0.5%Sc
AK7ch (Ti-B-Sr)	Base	7,9-8,1	0,05-0,07	1,03-1,07	0,02-0,03	0,09-0,1	0,02-0,04	0,21-0,25%Ti 0,004-0,006%Sr 0,01-0,04% B

The alloys were melted under laboratory conditions in an СШОЛ-12.6/12-М3 laboratory furnace. The furnace temperature was measured using a chromel–alumel thermocouple, with a measurement accuracy of ±0.5 °C. Microalloying complexes Sr–Sc and Ti–B–Sr were introduced into the melt at 750–780 °C in the form of Al–5%Sr, Al–2%Sc, and Al–Ti–B–Sr master alloys, respectively. After the master alloy introduction, the melt was held for 30 minutes with active stirring and then poured into sand–clay molds.

Hydrogen treatment of the AK7ch(Sr–Sc) alloy was carried out at the equipment of the Institute of Problems of Materials Science of NAS of Ukraine according to the method developed by Corresponding Member of NASU H.P. Borysov at 760–770 °C for 20, 40, 60, and 90 minutes. The principle of the thermotemporal treatment of the AK7ch (Ti–B–Sr) alloy consisted in superheating the melt in the range of 720–900 °C, stirring the melt, holding it isothermally for 30 minutes, and cooling from the specified temperatures in a sand mold.

The ultimate degree of deformability of the experimental alloys was evaluated by the method [11] during the rolling of wedge-shaped specimens. Rolling was performed at a speed of 0.3 m/s on a laboratory duo - 180 mill. The dimensions of the initial specimens according to [11] were: h_{01} = 3 mm, h_{02} = 11 mm, b_0 = 10 mm, l_0 = 46 mm. Each experiment was repeated three times.

The microstructure of the studied alloys was examined using a NEOPHOT-21 optical microscope.

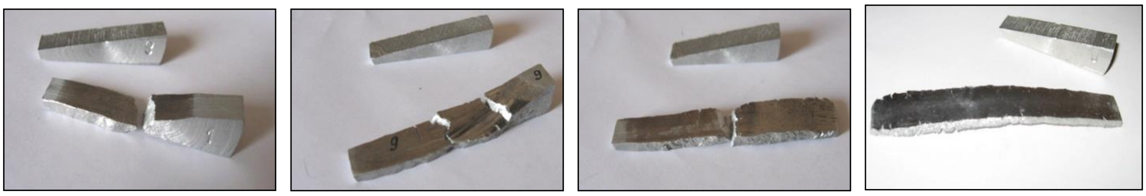
Tests for general corrosion were carried out on flat specimens 50×50×3 mm (three specimens). The tests were conducted in a Г-4 humidity chamber according to a two-stage cycle: stage 1 – relative humidity ~98%, t = 40 ± 2 °C, 8 hours; stage 2 – relative humidity ~98%, t = 18–20 °C, 16 hours. A total of 30 cycles were performed.

Tests for susceptibility to intergranular corrosion were performed on three specimens per variant. Specimens of 20×10×3 mm were prepared for testing. The tests were carried out by immersion in solution (1): 30 g/L NaCl + 10 mL/L HCl (d = 1.19 g/cm³), at a solution temperature of 18–20 °C. The duration of the tests was 24 hours. For testing, the electrochemical method of accelerated corrosion tests was used by recording the anodic polarization curve, which reflects the corrosion resistance of alloys in a medium containing Cl^- ions.

Polarization curves were obtained on an installation including a ПІ-50-1 potentiostat with a ПР-8 programmer in potentiostatic mode, holding the metal potential until the anodic current stabilized. A silver–chloride electrode was used as the reference electrode, and a platinum electrode as the auxiliary one. Potential values were given relative to the normal hydrogen scale.

Results and Discussion

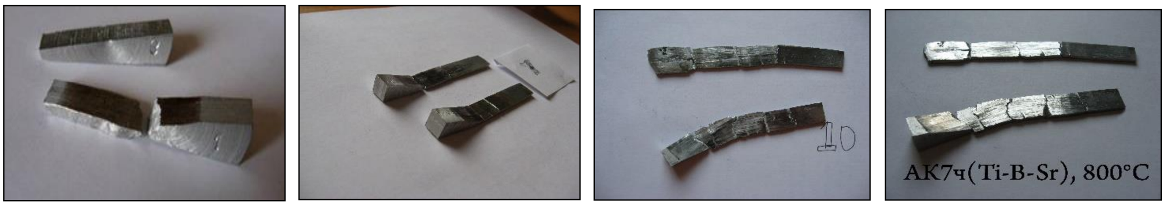
The appearance of characteristic specimens before and after rolling is presented in Figures 1–2.



a b c d

a, b – AK7ch of the initial composition; c, d – AK7ch(Sr-Sc); a, c – cast state; b, d – after hydrogen treatment of the melt for 20 min.

Figure 1 – Samples of AK7ch and AK7ch(Sr-Sc) alloys in the initial state and after technological deformability tests



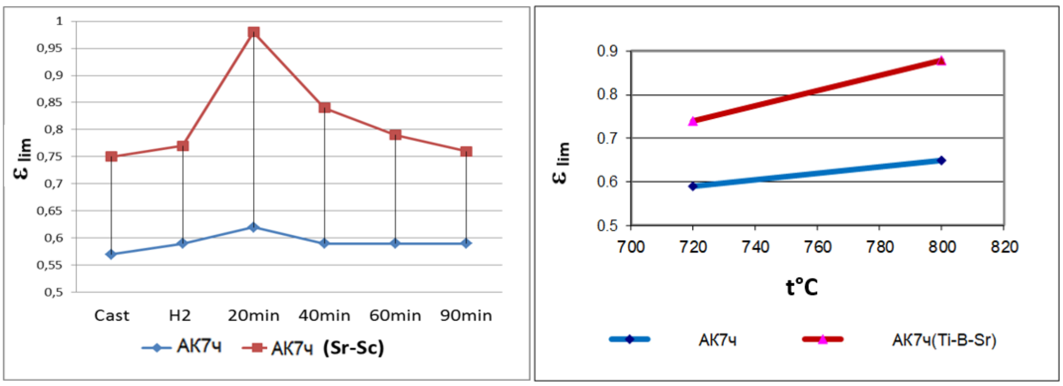
a b c d

a, b – AK7ch alloy of the initial composition; c, d – AK7ch(Ti-B-Sr) alloy; a, c – casting from 720°C; b, d – thermotemporal treatment (T=800°C, t=30 min)

Figure 2 – Samples of AK7ch and AK7ch(Ti-B-Sr) alloys before and after technological deformability tests

The results of the deformability limiting degree calculations of the investigated samples are presented in Figure 3.

Hydrogen melt treatment by 9% increases the deformability of the AK7ch alloy of the initial composition. The maximum effect is produced by complex physicochemical melt treatment– microalloying with the “Sr-Sc” complex and hydrogen treatment for 20 minutes. In this case, the deformability of the alloy increases by 60% compared with the as-cast alloy of the initial composition (Figure 3a).



a b

a – AK7ch and AK7ch(Sr-Sc) after hydrogen melt treatment

b – AK7ch and AK7ch(Ti-B-Sr) after thermotemporal melt treatment

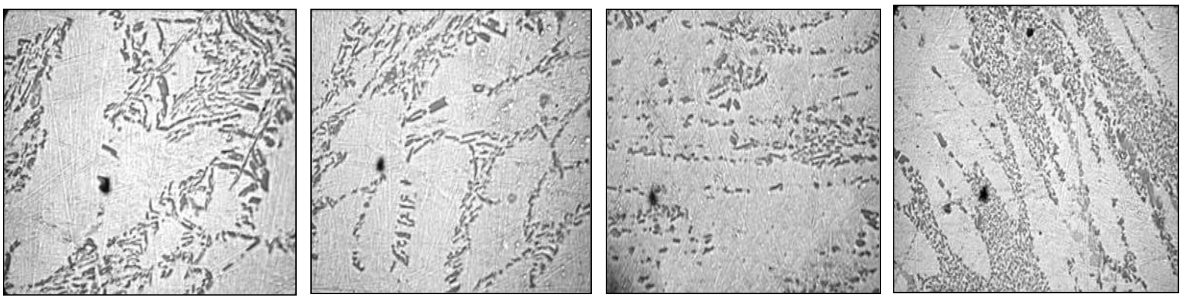
Figure 3 – Dependences of technological deformability of the experimental alloys

During thermotemporal treatment of the AK7ch alloy of the initial composition, an increase in the ultimate degree of deformability by 10% is observed; comparison of deformability data of the AK7ch alloy of the initial composition and the AK7ch(Ti-B-Sr) alloy confirms the fact of increased plasticity in the as-cast state when introducing the (Ti-B-Sr) complex by 25%; the maximum increase in deformability is obtained with complex treatment, which includes microalloying (Ti-B-Sr) – thermotemporal treatment (T=800°C, t=30 min); the deformability of the alloy increases by 46% compared with the as-cast alloy of the initial composition.

Microstructures of AK7ch-type alloys – of the initial composition, and AK7ch(Sr–Sc) in the as-cast state and after hydrogen treatment are presented in Figure 4, and of the AK7ch and AK7ch(Ti-B-Sr) alloys after thermotemporal treatment – in Figure 5.

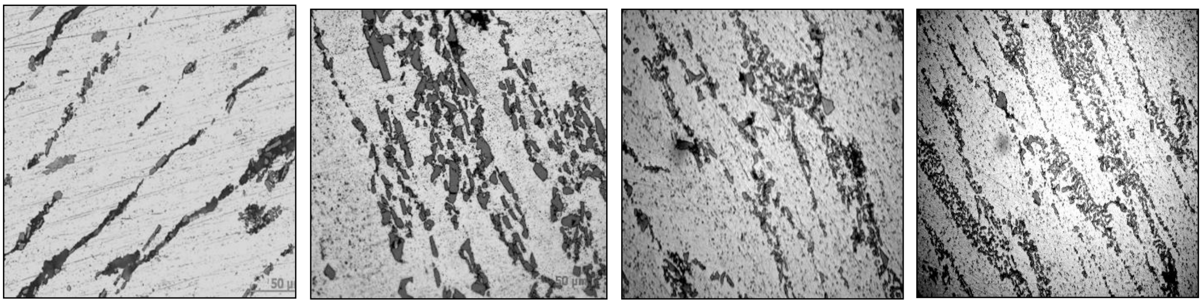
The Figures 4 and 5 demonstrate the α-Al grains geometric orientation along the main deformation axis and eutectic silicon and intermetallics partial refinement.

To establish the regularities of the melt treatment influence (Ti-Sr-B complex microalloying and thermotemporal melt treatment) on the AK7ch alloy corrosion properties, comparative corrosion tests were carried out in a humid atmosphere. The corrosion rate data are presented in Figure 6.



a b c d

a, b – AK7ch, c, d – AK7ch(Sr–Sc)
a, c – without treatment, b, d – hydrogen treatment for 20 min
Figure 4 – Structure of AK7ch and AK7ch(Sr–Sc) alloys, ×500



a b c d

a, b – AK7ch, c, d – AK7ch(Ti-B-Sr)
a, c – casting at 720°C; b, d – casting at 800°C
Figure 5 – Structure of AK7ch and AK7ch(Ti-B-Sr) alloys, ×500

The most intensive and fastest corrosion occurs in the AK7ch alloy crystallized from 720°C, both in the as-cast and heat-treated states. A significant reduction in the corrosion rate is achieved with TTO (thermotemporal treatment) at 800°C – by 84.3% in the as-cast state and by 91.5% in the heat-treated state. A similar decrease in the corrosion rate is observed during modification with the Ti-B-Sr complex. In this case, solidification from 800°C shows good results.

The highest corrosion resistance is demonstrated by the modified alloy in the as-cast state. Analysis of polarization curves (Figure 7) indicates that maximum resistance, similar to samples after heat treatment at 720°C, is exhibited by modified alloy samples after heat treatment at 800°C. The most corrosion-resistant alloy is AK7ch(Ti-B-Sr), which underwent additional solid-state heat treatment under the T6 regime. Slightly lower resistance was observed in the modified alloy in the as-cast state. In contrast, the initial (unmodified) alloy showed noticeably poorer anticorrosion properties, particularly in the heat-treated state, where its resistance was the lowest among the tested samples.

Analysis of the influence of thermotemporal treatment (TTO) on the corrosion resistance of the experimental alloys shows that, according to the position of the polarization curves, samples treated at 800°C have higher corrosion resistance compared with samples after TTO at 720°C. The application of solid-state heat treatment under the T6 regime further improves the anticorrosion properties of silumins.

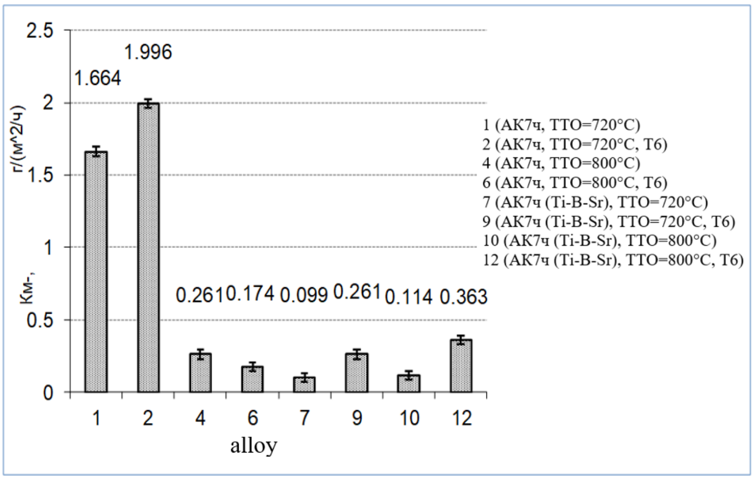
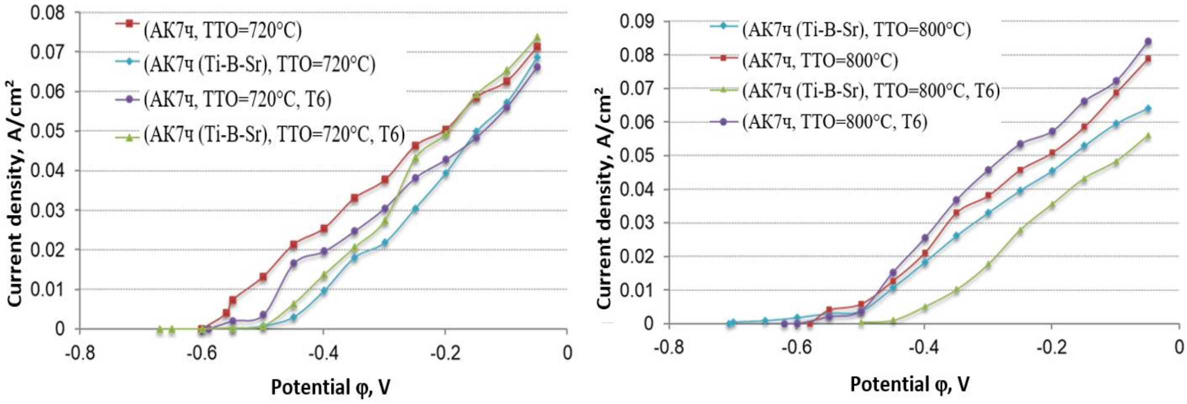


Figure 6 – Corrosion rate of the AK7ch alloy of the initial composition and AK7ch(Ti-Sr-B) depending on treatment regimes

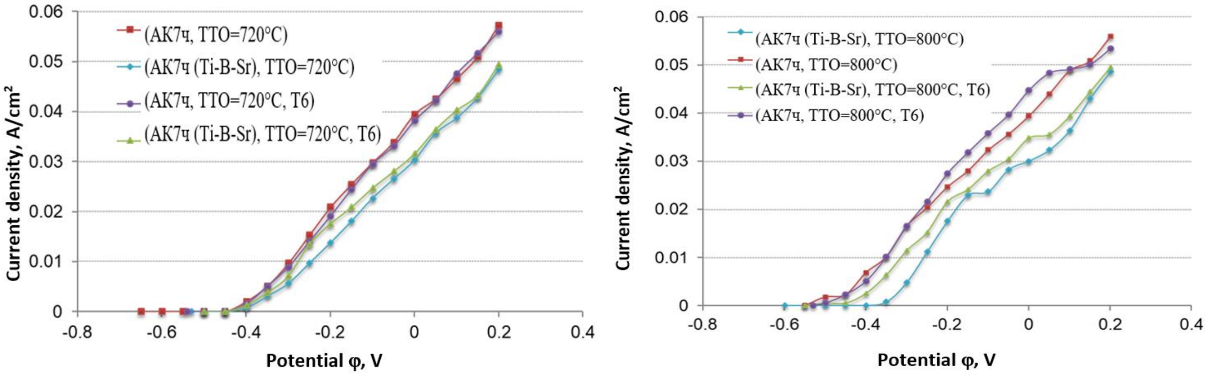


a b

a –TTO at 720°C, b –TTO at 800°C

Figure 7 – Polarization curves of AK7ch and AK7ch(Ti-Sr-B) alloys in the additionally heat-treated state after testing in 0.1 M NaCl solution

The results of tests in an acidic environment (Figure 8) confirm this trend. In particular, AK7ch(Ti-Sr-B) alloys treated at 720°C exhibited higher corrosion resistance than the unmodified AK7ch alloy.



a b

a –TTO at 720°C, b –TTO at 800°C

Figure 8 – Polarization curves of AK7ch and AK7ch(Ti-Sr-B) alloys in the additionally heat-treated state after testing in an aqueous solution of 3% NaCl + 1% HCl

The lowest corrosion resistance, according to polarization characteristics, is demonstrated by the AK7ch sample in the as-cast state. Application of T6 heat treatment slightly improves its anticorrosion properties. The highest corrosion resistance was shown by the sample subjected to TTO at 800°C in the as-cast state, while the AK7ch(Ti-Sr-B) sample after T6 treatment showed slightly lower resistance.

The data on general corrosion studies indicate that both microalloying of the AK7ch alloy with the Ti-Sr-B complex and thermotemporal treatment (T=800°C, t=30 min) increase overall corrosion resistance.

Conclusions

Using the improved methodology for determining the limiting degree of metals deformation during wedge-shaped samples rolling, the dependences of technological deformability of AK7ch and AK7ch(Sr–Sc) alloys on hydrogen melt treatment regimes were obtained, indicating a 60% increase in deformability compared with the as-cast alloy of the initial composition. The dependences of technological deformability of AK7ch and AK7ch(Ti-Sr-B) alloys on thermotemporal melt treatment regimes were obtained, showing that deformability increases by 46% with microalloying by the Ti-Sr-B complex and thermotemporal treatment (T=800°C, t=30 min) compared with the as-cast alloy of the initial composition.

The structures of AK7ch and AK7ch(Sr–Sc) alloys in the as-cast state and after hydrogen treatment (20 min), as well as AK7ch and AK7ch(Ti-Sr-B) alloys in the as-cast state and after thermotemporal treatment (T=800°C, t=30 min) after rolling to the limiting degree of deformation, were studied. In all investigated samples, a pronounced geometric orientation of α-Al solid-solution grains along the main deformation axis was observed. Partial fragmentation of eutectic silicon and intermetallic phases was also recorded, which potentially improves the performance properties of the alloys.

The application of thermotemporal treatment at 800°C and the Ti–Sr–B complex microalloying of the AK7ch alloy significantly increases its corrosion resistance. The lowest resistance is exhibited by the initial alloy in the as-cast and heat-treated states after crystallization from 720°C. A significant decrease in the corrosion rate — up to 91.5% — was determined as a result of complex treatment.

References

1. Kutsova, V. Z., Pohrebna, N. E., & Khokhlova, T. S. (2004). *Aliuminii ta splavy na yoho osnovi. Aluminum and alloys based on it*. Porohy.
2. Chen, G. Q., Fu, G. S ., Yang, K. H., & Lin, C. S., (2020). Study on the Modification Effect of Al-Sr Master Alloy on A356 Aluminum Alloy. *MSF,* 998, 3-8.
3. Ishchenko, A. Y. (1999). *Svaryvaemye aiumynyevye splavy so skandyem. Weldable aluminum alloys with scandium.* Kvits.
4. Kutsova, V. Z., Aiupova, T. A., & Ambrazhei, M. Iu. (2007). Vlyianye mykrolehyrovanyia Sr y Sc na fazovyi sostav y svoistva AK7ch. Influence of Sr and Sc microalloying on the phase composition and properties of AK7ch. *Stroytelstvo, materyalovedenye, mashynostroenye*. *Sb. nauchn. tr*, 41(1),18-30.
5. Hengcheng, Liao, Min, Zhang, Qichang, Wu, Huipin, Wang, & Guoxiong, Sun (2007). Refinement of eutectic grains by combined addition of strontium and boron in near-eutectic Al–Si alloys. *Scripta Materialia*, (57).
6. Kutsova, V. Z. (2011). Struktura y svoistva doevtektycheskykh sylumynov, modyfytsyrovannykh kompleksom Ti-B-Sr. Structure and properties of pre-eutectic silumins modified by the Ti-B-Sr complex. *Metaloznavstvo ta termichna obrobka metaliv: Naukov. Ta inform. Zhurnal*, 1-2(52-53), 310-318.
7. Kotliarskyi, F. M., Borysov, H. P., & Bielik. V. I. (2008). Vodneve rafinuvannia aliuminiievykh splaviv vid tverdykh nemetalevykh vkliuchen. Hydrogen refining of aluminum alloys from solid non-metallic inclusions. *Protsesy lyttia*, 4. 48-55.
8. Mazur, V. Y. (2012). Upravlenye kachestvom sylumynovoho lytia s pomoshchiu termovremennoi obrabotky rasplava. Quality control of silumin casting using thermal treatment of the melt. *Novi materialy i tekhnolohii v metalurhii ta mashynobuduvanni*, (2), 47-49.
9. Kutsova, V. Z. (2008). Vlyianye vodorodnoi obrabotky rasplava na strukturu y svoistva splava typa AK7ch. The effect of hydrogen treatment of the melt on the structure and properties of the AK7ch type alloy. *MTOM*, 4. 50-61.
10. Kutsova, V. Z. (2012). Vlyianye kompleksnoho modyfytsyrovanyia, termycheskoi obrabotky v zhydkom sostoianyy na strukturu y svoistva splava AK7ch, Effect of complex modification, heat treatment in the liquid state on the structure and properties of the AK7ch alloy. *Novyny nauky Prydniprovia,* 2, 13-16.
11. Dolzhansky,i A. M., Kutsova, V. Z., Ayupova, T. A., Storozhko, K. D., & Rybkin. O. P. (2020). Foundry aluminum alloys cold rolling. *Metaloznavstvo ta termichna obrobka metaliv.* 1, 55-61.

Надіслано до редакції / Received: 12.02.2025
Прийнято до друку / Accepted: 30.05.2025