doi: 10.18323/2782-4039-2025-1-71-6

# Effect of erbium and hafnium microalloying on the formation of $Al_3Sc$ particles in aluminium alloy with a high magnesium content

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*Received 07.10.2024* *Revised 27.11.2024* *Accepted 04.02.2025*

***Abstract:*** The paper studies the effect of hafnium and erbium additives on the microstructure formation during heat treatment of aluminium alloys with a high magnesium content additionally alloyed with scandium and zirconium. For the study, ingots of aluminium alloys with a high content of magnesium alloyed with scandium, erbium and hafnium with a content in the ranges of 0.03–0.16 % and 0.05–0.16 %, respectively, were produced by casting in a steel chill mould. After casting, the samples were treated with heat at a temperature of 370 and 440 °C with a holding time of 2 to 96 h. Changes in microhardness depending on the heat treatment were studied. For 1590-3 and 1590-4 alloys in the as-cast condition and after heat treatment at a temperature of 440 °C for 2 and 48 h, the fine microstructure and coarse intermetallic compounds were studied using transmission microscopy. The study found that additions of hafnium and erbium lead to an increase in microhardness due to a decrease in the size and an increase in the number of $Al_3Sc$ nanoparticles. After heat treatment at a temperature of 440 °C for 4 h, $Al_3Sc$ particles of the same size (8 nm) and density precipitate in all the alloys under study. However, with an increase in the holding time in the alloy with a lower hafnium content and a higher erbium content, the particle size increases by 2 times compared to the particles of the alloy where the hafnium content is higher and the erbium content is low.

***Keywords:*** aluminium alloys; microalloying; scandium; hafnium; erbium; formation of $Al_3Sc$ particles; microhardness; microstructure; nanoparticles.

***Acknowledgments:*** The study was supported by the grant of the Russian Science Foundation No. 22-19-00810, https://rscf.ru/project/22-19-00810/.

***For citation:*** Ragazin A.A., Aryshenskiy E.V., Aryshenskiy V.Yu., Rasposienko D.Yu., Konovalov S.V., Bakhtegareev I.D. Effect of erbium and hafnium microalloying on the formation of $Al_3Sc$ particles in aluminium alloy with a high magnesium content. *Frontier Materials & Technologies*, 2025, no. 1, pp. 69–80. DOI: 10.18323/2782-4039-2025-1-71-6.

## INTRODUCTION

Aluminium alloys are in high demand in many advanced industries. Among them, the Al–Mg alloys stand out characterised by lower weight, increased strength and good corrosion resistance [1–3].

To improve the properties, various alloying components are added to the alloys. One of the most effective is scandium, which increases strength due to the formation of reinforcing $Al_3Sc$ nanoparticles with the $L_{12}$ structure, improves weldability, corrosion properties and helps modify the grain structure [4–6]. The efficiency of scandium alloying can be further increased by adding zirconium. Its introduction reduces the scandium concentration required for effective grain refinement during casting, and creates a shell promoting

thermal stabilisation of $Al_3Sc$ nanoparticles [6; 7]. Most often, combined scandium-zirconium microalloying is used in Al–Mg system alloys. This is explained by the fact that due to solid solution strengthening caused by magnesium, these alloys themselves have high strength characteristics [3]. One of such alloys is 1570 alloy with a scandium content of 0.25 %.

However, due to the high cost, reducing the scandium content from 0.25 to 0.15÷0.1 % seems promising [8]. At the same time, reducing the scandium concentration will lead to a decrease in mechanical properties [9]. One way to solve this problem is the additional use of additives such as erbium and hafnium. Erbium helps to increase the number and rate of formation of $Al_3Sc$ particles. This occurs because erbium, having a higher diffusion coefficient than scandium, forms $Al_3Er$ nanoparticles with aluminium with an $L_{12}$ structure, which are also coherent in the aluminium matrix [10; 11]. Due to the solubility of scandium in erbium, these particles serve as a nucleus for $Al_3Sc$, actually being their core [9].

Hafnium partially dissolves in $Al_3Sc$ particles, creating a shell around them and thermally stabilising them due to a lower diffusion coefficient. Moreover, hafnium additives, like zirconium, increase modifications of the cast structure [12], thereby increasing mechanical properties.

However, the combined effect of erbium and hafnium on $Al_3Sc$ particles has not been studied previously. There are only studies of the effect of erbium and hafnium on $Al_3Sc$ separately. As a rule, studies were carried out for pure aluminium and only in some cases for high-magnesium alloys, which have become widespread in industry [13–15]. Moreover, in the case of the effect of hafnium, studies were carried out with a scandium content of 0.2 % [13; 15], while the effect of hafnium may be different with a further decrease in the scandium concentration.

The aim of this work is to study the influence of erbium and hafnium content on the formation of the microstructure, and mechanical properties of high-magnesium aluminium alloys sparingly alloyed with scandium during their thermomechanical processing.

## METHODS

A new aluminium high-magnesium 1590 alloy sparingly doped with scandium, microalloyed both with scandium and zirconium and with erbium and hafnium [16] was selected for the study. The Er and Hf content in this alloy varies in the ranges of 0.03–0.16 wt. % and 0.05–0.16 wt. %, respectively. By changing the content of elements in these ranges, it is possible to study the effect of their concentration on the formation of $Al_3Sc$ particles. Four modifications of the 1590 alloy were selected to study the effect of the content of these elements on the formation of the microstructure. Table 1 presents the chemical composition of these modifications, which differ from each other in the content of erbium and hafnium.

To produce ingots of 1590, 1590-3, 1590-4 and 1599A alloys, UI-25P medium-frequency (1–20 kHz) induction furnace was used. The ingot dimensions were 20×40×400 mm. The ingots were cast in a steel chill mould and then cooled in water. The cast ingot weight was 5 kg. The following materials were used as a charge for the alloy: A85 grade aluminium, MG90 grade magnesium, alloying elements of $Al–Sc_2$, $Al–Zr_5$, $Al–Hf_2$, $Al–Er_5$ grades and Mn90Al10 grade alloying tablets. First, aluminium was loaded and melted. After the aluminium melted and the temperature reached 730 °C, slag was removed from the melt surface. Then the melt was heated to 770–790 °C and the $AlSc_2$, $AlZr_5$, $Al–Hf_2$, $Al–Er_5$ alloying elements were added in portions weighing no more than 300 g, followed by stirring and holding the melt for 5 min. After adding the entire calculated alloying elements, the melt was cooled to 750 °C and alloying components (Mg, Mn) were added according to the calculation results. The melt was stirred for 3 min, followed by heating to 740 °C, and a sample was taken for express analysis of the chemical composition of the melt. The chemical composition of the alloys (Table 1) was determined by the spectral method on an ARL 3460 atomic emission spectrometer (GOST 25086, GOST 7727, GOST 3221, ASTM E 716, ASTM E 1251) using the $Al–Er_5$ alloying element. The Er and Hf content in the ingot was determined by calculation due to the lack of standard samples.

***Table 1.*** *Chemical composition of the 1590, 1590-3, 1590-4, and 1599 alloys*
***Таблица 1.*** *Химический состав сплавов 1590, 1590-3, 1590-4, 1599*

| Alloy | Weight content of elements, % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Si | Fe | Mn | Mg | Zn | Zr | Sc | Er* | Hf* |
| 1590 | 0.04 | 0.07 | 0.41 | 5.57 | 0.21 | 0.1 | 0.14 | 0.1 | 0.05 |
| 1590-3 | 0.05 | 0.08 | 0.41 | 5.58 | 0.2 | 0.1 | 0.14 | 0.03 | 0.16 |
| 1590-4 | 0.05 | 0.08 | 0.41 | 5.53 | 0.21 | 0.1 | 0.14 | 0.1 | 0.1 |
| 1599 | 0.04 | 0.08 | 0.41 | 5.53 | 0.2 | 0.09 | 0.07 | 0.06 | 0.1 |

*Note. * is content of Er, Hf according to calculation.*
*Примечание. * – содержание Er, Hf согласно расчету.*

To study how heat treatment influences the formation of the microstructure and mechanical properties, the ingots were annealed in a muffle electric furnace at 370 and 440 °C with holding for 2, 4, 8, 24, 48, 72, 96 h and subsequent cooling in water to fix the supersaturated solid solution.

Microhardness measurements were carried out on an HV-1000 microhardness tester using the restored indentation method. The calculation was carried out in the Nexsys Image Expert Micro Hardness 2 software package in accordance with GOST 9450-76 "Measuring Microhardness by Indentation of Diamond Tips", a tetrahedral pyramid with a square base was used as a tip. A pre-prepared sample (with a polished surface) was installed using a special device that ensured that the working surface of the sample was parallel to the surface of the table. Then, under a load of 0.025 kgf, the tip dug into the sample surface, and was kept at the specified load for 10 s. To obtain correct microhardness values, ten measurements were taken for each sample, the distance between measurements was more than three diagonals of the indentation, the measurement locations were evenly distributed over the sample surface. Then, for each measurement, the actual microhardness values were calculated. The average was calculated for the obtained values and indicated on the graph with a confidence interval.

To study fine particles, transmission microscopy (hereinafter referred to as TEM) was used for the as-cast state and after annealing at 440 °C for 4 and 48 h. The studies were carried out on a Tecnai G2 30 (FEI Company, Holland, USA) high-resolution scanning transmission electron microscope (SEM), equipped with a GATAN scanning system, a system for mapping images in characteristic X-ray radiation, an EELS electron energy loss spectroscopy system and an EDAX energy-dispersive spectrometer for elemental analysis.

For electron microscopic studies, the samples were mechanically thinned by double-sided grinding on fine-grained grinding paper to a thickness of 40–60 μm. The resulting plates were electrolytically thinned to a thickness suitable for transmission in an electron microscope. After that, disks with a diameter of 3 mm were cut from the samples using the Ultratonic Disk Cutter module. Electropolishing was carried out in a Struers Tenupol electrolytic thinning unit using the standard A2 electrolyte for aluminium alloys recommended by Struers. To clean the foil surface from carbon traces, and if necessary, for final thinning and increasing the viewing fields, a PIPS II ion-polishing device was used.

Identification of the phases precipitated during the decomposition of the supersaturated solid solution, was carried out by calculating their interplanar distances from additional reflections in the electron diffraction patterns and analysing their chemical composition. The calculated interplanar distances were compared with the data given in the international X-ray tables (JCPDS-ICDD). To identify the morphology and distribution pattern of each of the precipitated phases, dark-field images in additional reflections of these phases were analysed.

Considering the fact that TEM is a rather resource- and labor-intensive operation, only two alloys were studied by this method – 1590-3 and 1590-4. The 1590-4 alloy was chosen because it contains the minimum amount of erbium and the maximum amount of hafnium, and the 1590-3 alloy – because it contains the median value of the concentrations of these elements.

## RESULTS

In the as-cast state, the 1590-4 alloy demonstrates the maximum microhardness value (Fig. 1). The lowest microhardness values in the as-cast state were found in the 1590 alloy with a minimum hafnium content.

However, after 2 h of holding at a temperature of 370 °C, a sharp increase in microhardness is observed in 1590, 1590-3 and 1590-4 alloys. In the 1599 alloy, no changes in microhardness are observed; throughout the entire holding time, it varies within the range of 75–80 HV 0.25. In the 1590-3 alloy, after 8 h of holding, a sharp increase in microhardness begins to 109.2 HV 0.25, which after 24 h is replaced by a decrease down to 89 HV 0.25 at 96 h of holding. The 1590-4 alloy shows high microhardness values from 100.2 to 101.1 HV 0.25 during the first 48 h of holding, after which a smooth decrease in its values to 94.7 HV 0.25 occurs. The maximum microhardness value in the case of annealing of alloys at 370 °C is observed in the 1590-3 alloy after 24 h of holding and amounts to 109.2 HV 0.25.

It can be seen (Fig. 2) that in 1590, 1590-3, 1590-4 alloys after 2 h of heat treatment at a temperature of 440 °C there is a sharp increase in microhardness, in contrast to 1599 alloy. After 8 h of holding, the microhardness of the 1590-4 alloy drops. This is not observed in the 1590-3 alloy with a higher hafnium content, which, after 48 h of holding at a temperature of 440 °C, only increases the microhardness values to 97.1 HV 0.25, after which a gentle decline in microhardness occurs. However, in the 1590 alloy with an erbium content of 0.1 % and a hafnium content of 0.05 %, an increase in microhardness is observed compared to the 1590-4 alloy, where the erbium and hafnium content is equal and amounts to 0.1 %. The 1599 alloy shows the lowest microhardness values compared to other alloys. After holding for 24 h, it begins to grow. After 48 h of holding, it reaches its maximum values, after which it decreases.

In the structure of 1590-3 and 1590-4 alloys, the precipitation of $Al_3Sc$ dispersoids was detected already in the as-cast state (Fig. 3). Apparently, they were formed during the decomposition of the supersaturated solid solution during cooling of the materials from the crystallisation temperature to room temperature. In the 1590-3 alloy, the $Al_3Sc$ phase precipitates in the form of equiaxed particles with a diameter of 10–25 nm with a sufficiently high volume fraction and density of spatial distribution (Fig. 3). A comparative analysis of the TEM results for the 1590-3 and 1590-4 alloys in the as-cast state identified an increase in the volume fraction and density of spatial distribution of dispersoids (Fig. 4). It is worth noting that the 1590-4 alloy contains 0.07 % more erbium and 0.06 % less hafnium than the 1590-3 alloy. Thus, this change in the chemical composition affects the amount of nanoparticles.

Annealing for 4 h at a temperature of 440 °C led to an increase in the particle size. After treatment, the diameter of the smallest particles is 15 nm, which is 5 nm more

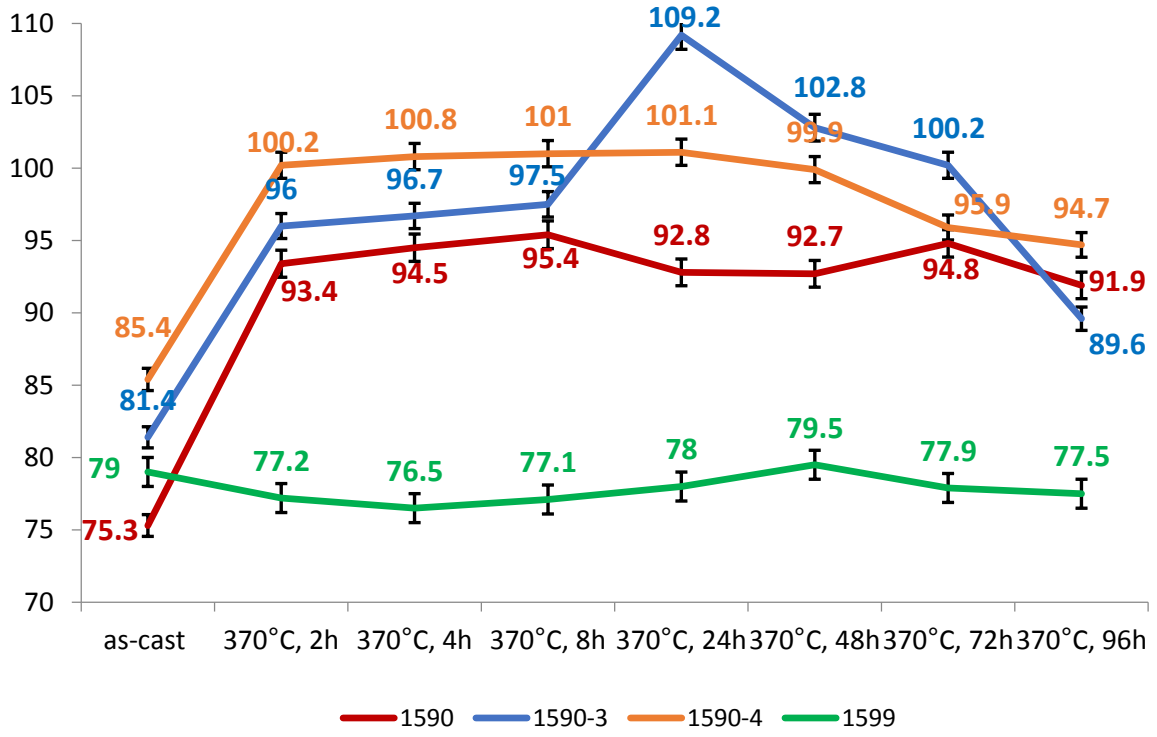



***Fig. 1.*** *Dynamics of changes in microhardness for alloys of 1590, 1590-3, 1590-4, 1599 grades in the as-cast state and after heat treatment at a temperature of 370 °C in the range from 2 to 96 h*

***Рис. 1.*** *Динамика изменения микротвердости сплавов марок 1590, 1590-3, 1590-4, 1599 в литом состоянии и после термической обработки при температуре 370 °С и выдержке от 2 до 96 ч*

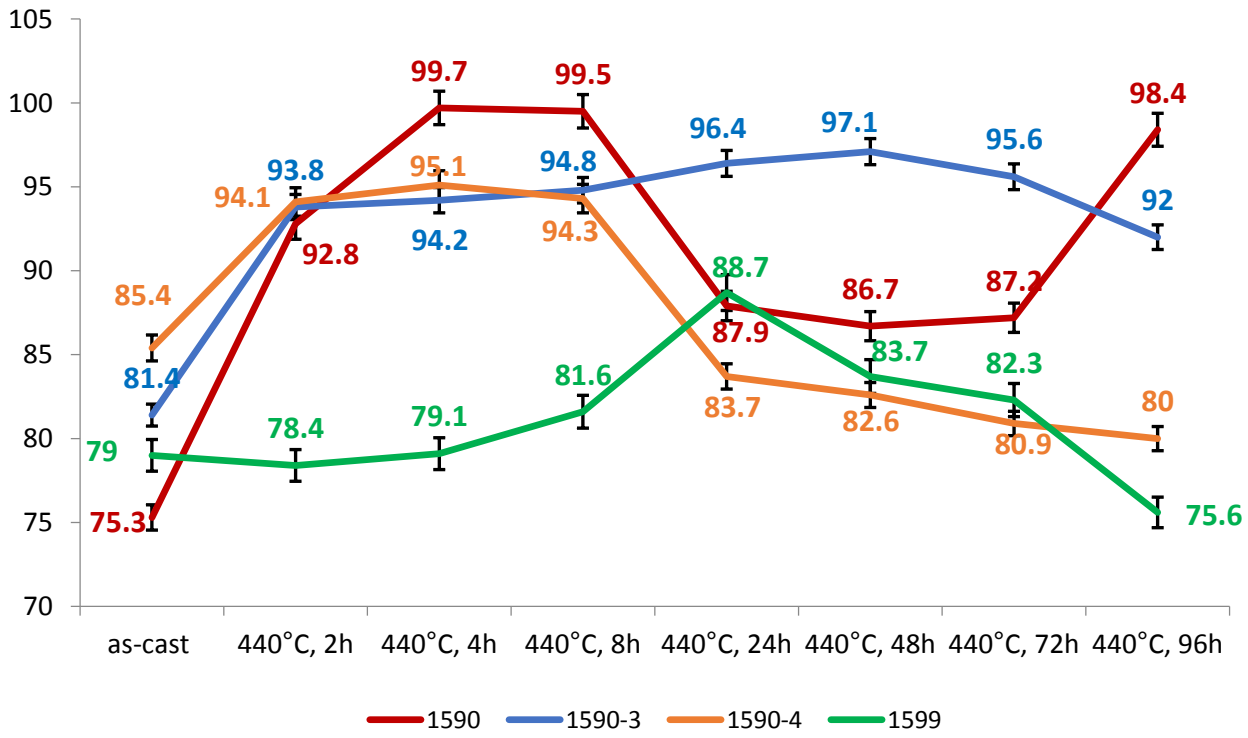
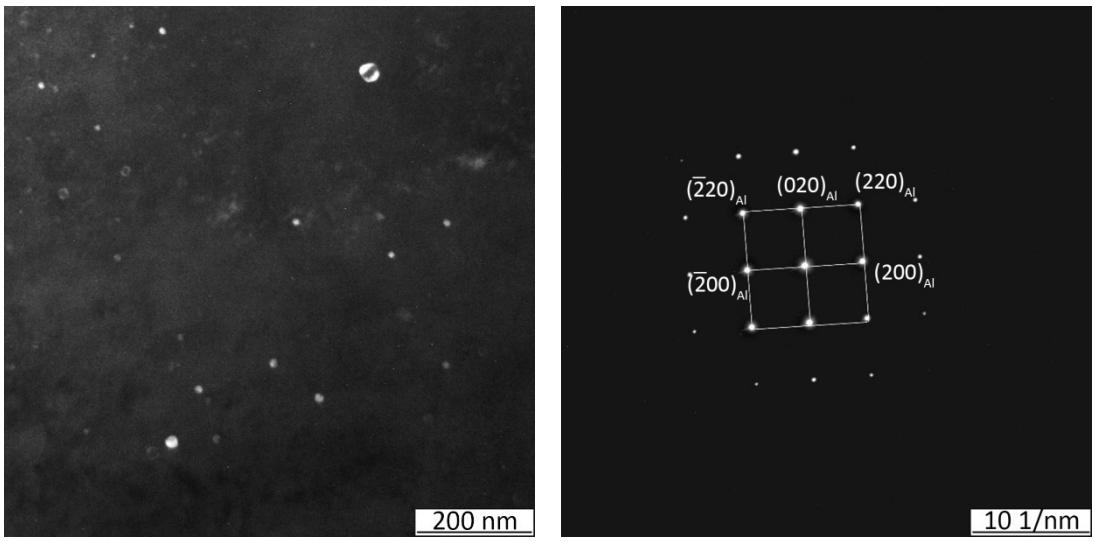



***Fig. 2.*** *Dynamics of changes in microhardness for alloys of 1590, 1590-3, 1590-4, 1599 grades in the as-cast state and after heat treatment at a temperature of 440 °C in the range from 2 to 96 h*

***Рис. 2.*** *Динамика изменения микротвердости сплавов марок 1590, 1590-3, 1590-4, 1599 в литом состоянии и после термической обработки при температуре 440 °С и выдержке от 2 до 96 ч*



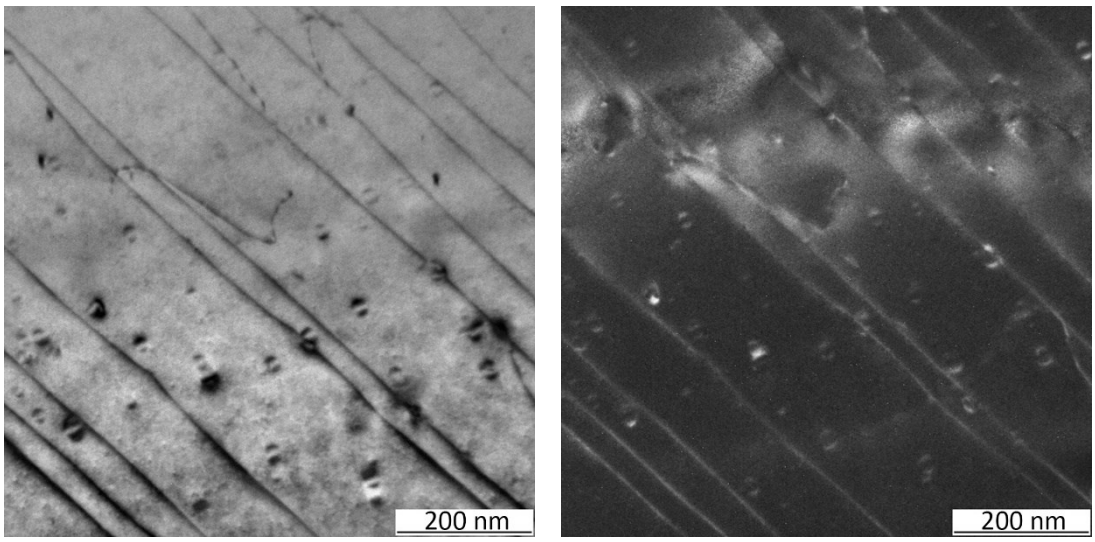

***a*** ***b***

***Fig. 3.*** *Electron microscopic images of the microstructure of the 1590-3 alloy in the as-cast state:*
***a*** *– dark-field image in the* $(110)_{Al3Sc}$ *reflex;*
***b*** *– micro-electron-diffraction pattern,* $[100]_{Al}$ *zone axis*
***Рис. 3.*** *Электронно-микроскопические изображения микроструктуры сплава 1590-3 в литом состоянии:*
***a*** *– темнопольное изображение в рефлексе* $(110)_{Al3Sc}$*;*
***b*** *– микроэлектронограмма, ось зоны* $[100]_{Al}$

than in the as-cast state. At the same time, the diameter of the largest particles did not change and remained equal to 25 nm (Fig. 5).

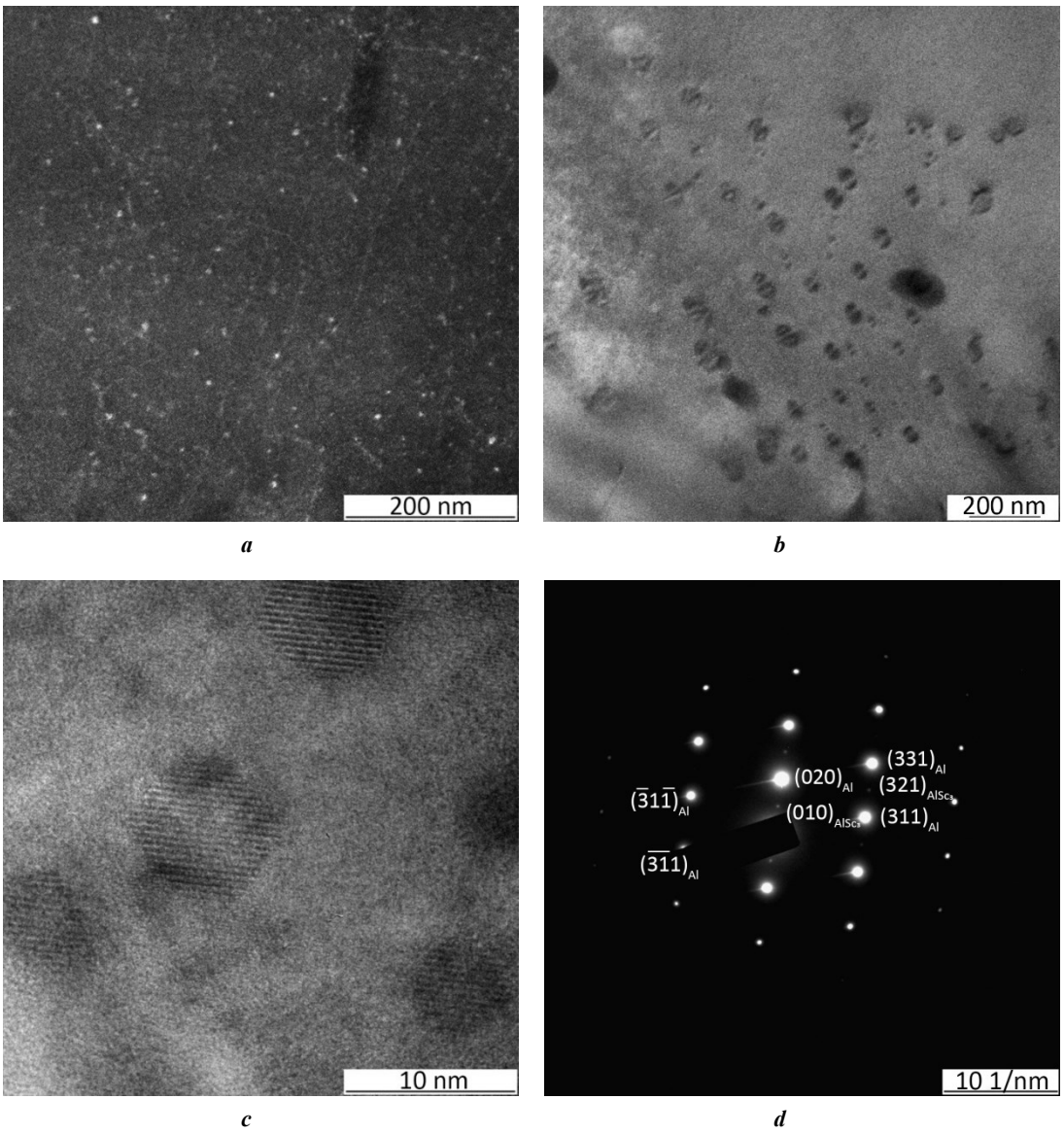
The $Al_3Sc$ particles formed during the heat treatment were characterised by a diameter of 6–8 nm, smaller than that of the dispersoids found in the as-cast state. The reason for the precipitation of more dispersed particles during the heat treatment may be their lower formation temperature and lower saturation of the solid solution with Sc atoms.

Just as in the 1590-3 alloy, in the structure of the 1590-4 alloy sample annealed for 4 h at a temperature of 440 °C, two types of $Al_3Sc$ particles are observed: more dispersed ones with a diameter of about 8 nm (apparently precipitated during annealing) constituting the majority, and rarer large




***a*** ***b***

***Fig. 4.*** *Electron microscopic images of the microstructure of the 1590-4 alloy in the as-cast state:*
***a*** *– light-field image;* ***b*** *– dark-field image in* $(111)_{Al}$ *reflex*
***Рис. 4.*** *Электронно-микроскопические изображения микроструктуры сплава 1590-4 в литом состоянии:*
***a*** *– светлопольное изображение;* ***b*** *– темнопольное изображение в рефлексе* $(111)_{Al}$




*a* *b*

*c* *d*

***Fig. 5.*** *Electron microscopic images of the microstructure of the 1590-3 alloy after annealing at 440 °C, 4 h:*
***a*** *– dark-field image in the* $(110)_{Al3Sc}$ *reflex;* ***b***, ***c*** *– light-field images;*
***d*** *– micro-electron-diffraction pattern,* $[103]_{Al}$ *zone axis*
***Рис. 5.*** *Электронно-микроскопические изображения микроструктуры сплава 1590-3 после отжига при 440 °С в течение 4 ч:*
***a*** *– темнопольное изображение в рефлексе* $(110)_{Al3Sc}$; ***b***, ***c*** *– светлопольные изображения;*
***d*** *– микроэлектронограмма, ось зоны* $[103]_{Al}$

ones, mainly 15–25 nm in size (formed earlier during cooling of the ingot) (Fig. 6).

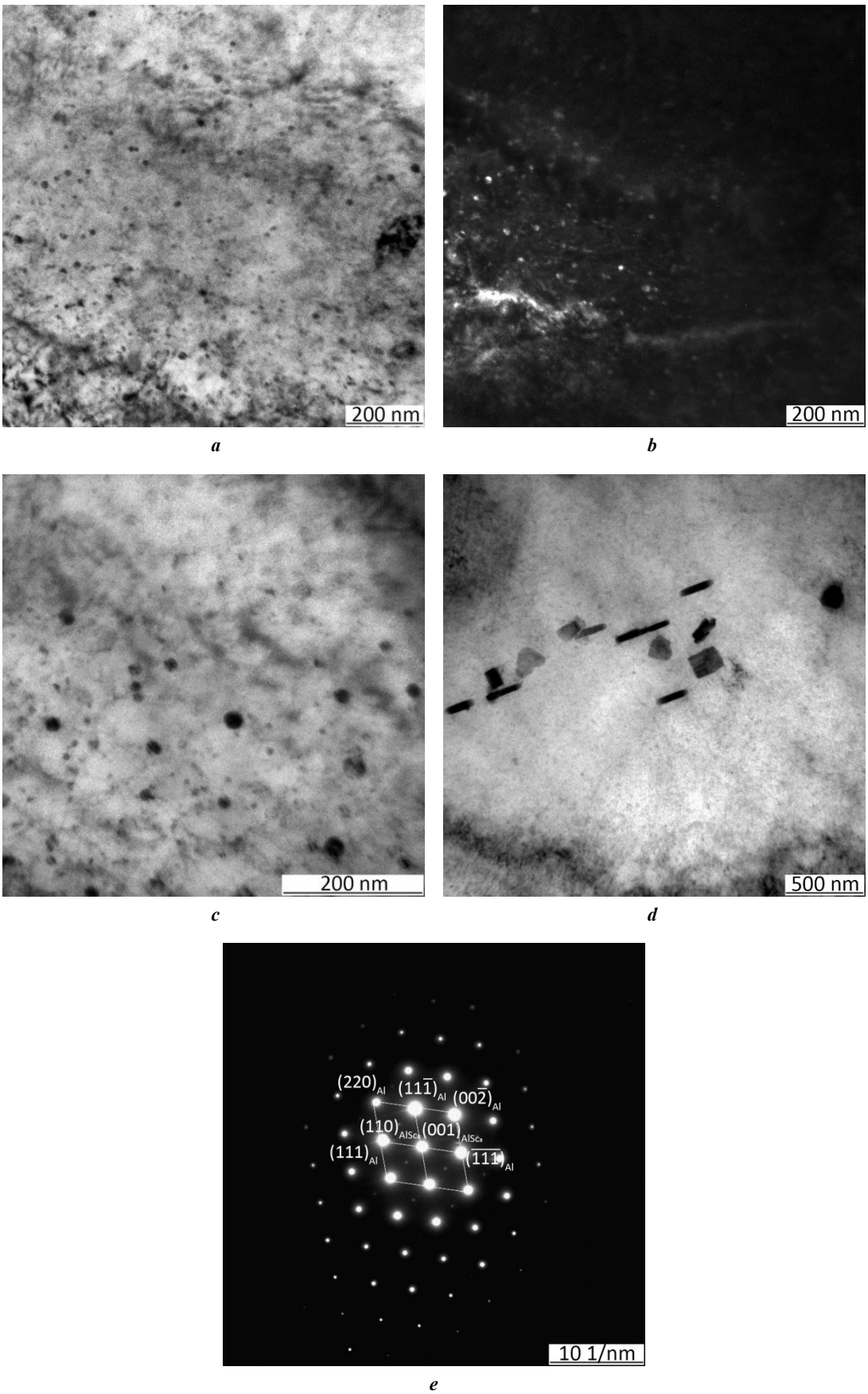
In the bright-field images, $Al_6Mn$ plates up to 250 nm long and 100 nm wide were also identified with their distribution throughout the grain volume being non-uniform: in some areas, their clusters and alignment of particles along certain directions were observed (Fig. 6).

Increasing the duration of annealing at 440 °C to 48 h leads to an increase in the diameter of the most dispersed precipitates. The average size of dispersoids is about 15 nm, with the sizes of the largest particles remaining at the level of 25 nm (Fig. 7).

Particle coagulation contributes to their more uniform size distribution: the range of most of the observed dispersoids is 13–15 nm, and only single particles are characterised by larger or smaller sizes. At the same time, the volume fraction and spatial distribution density of dispersoids remain high.

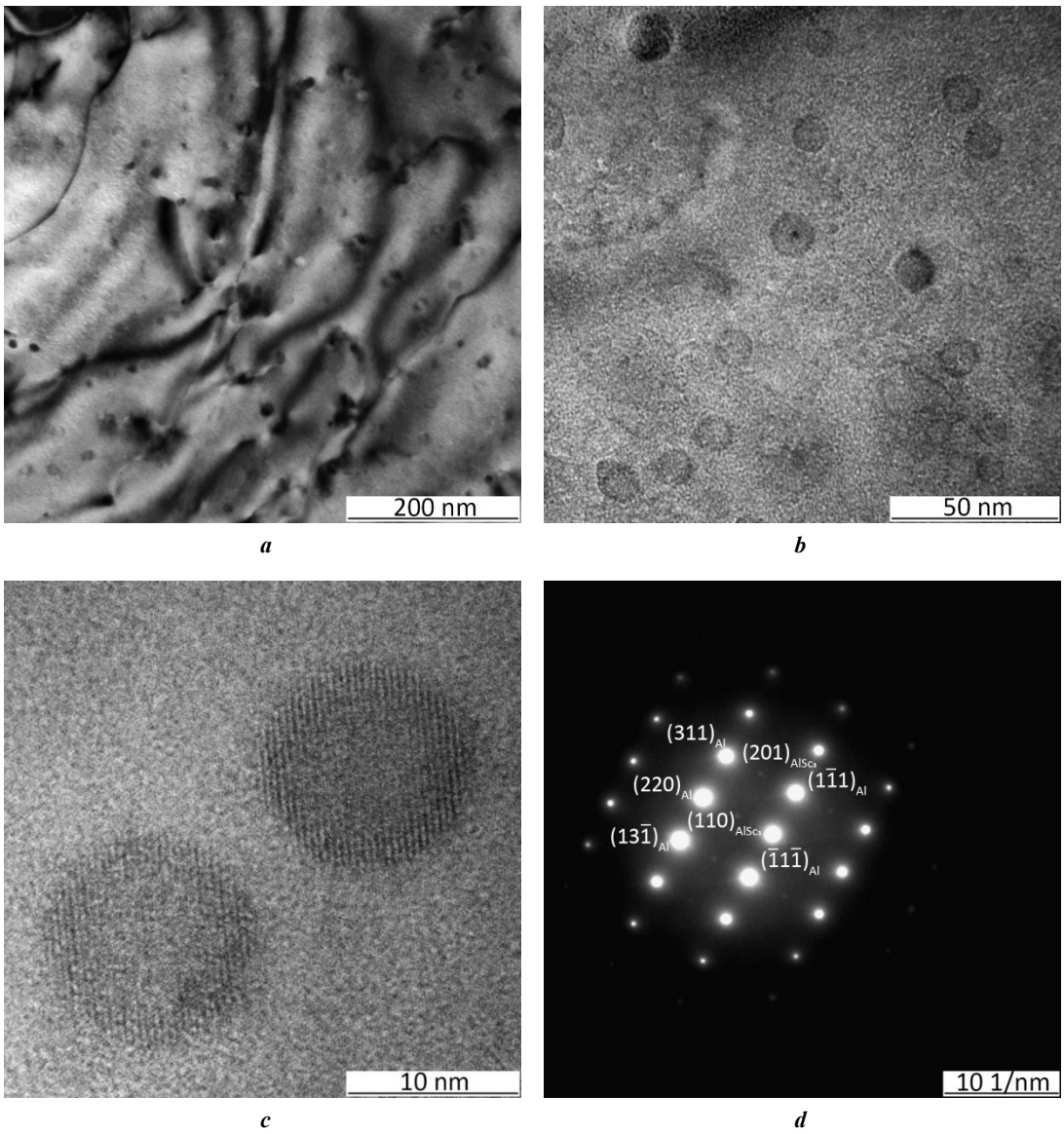
With an increase in the duration of annealing at 440 °C to 48 h, similar changes in the structure also occur in the 1590-4 alloy. After heat treatment in this mode, electron microscopic images show equiaxed dispersoids with sizes from 15 to 30 nm (Fig. 8).

A comparative analysis showed that changes in the chemical composition of the 1590-4 alloy lead to the precipitation of larger particles and a less uniform distribution of their sizes. Most dispersoids are characterised by a diameter in the range of 20–25 nm, however, more dispersed precipitates with sizes of 15 nm and more are also preserved, and particles with a diameter of 30 nm and more are also formed.




***a*** ***b*** ***c*** ***d*** ***e***

***Fig. 6.*** *Electron microscopic images of the microstructure of the 1590-4 alloy after annealing at 440 °C, 4 h:*
***a***, ***c***, ***d*** *– light-field images;* ***b*** *– dark-field images in the* $(110)_{Al3Sc}$ *reflex;* ***e*** *– micro-electron-diffraction pattern,* $[110]_{Al}$ *zone axis*
***Рис. 6.*** *Электронно-микроскопические изображения микроструктуры сплава 1590-4 после отжига при 440 °С в течение 4 ч:*
***a***, ***c***, ***d*** *– светлопольные изображения;* ***b*** *– темнопольное изображение в рефлексе* $(110)_{Al3Sc}$*;*
***e*** *– микроэлектронограмма, ось зоны* $[110]_{Al}$




*a* *b*

*c* *d*

***Fig. 7.*** *Electron microscopic images of the microstructure of the 1590-3 alloy after annealing at 440 °C, 48 h:* ***a***, ***b***, ***c*** *– light-field images;* ***d*** *– micro-electron-diffraction pattern,* $[112]_{Al}$ *zone axis*

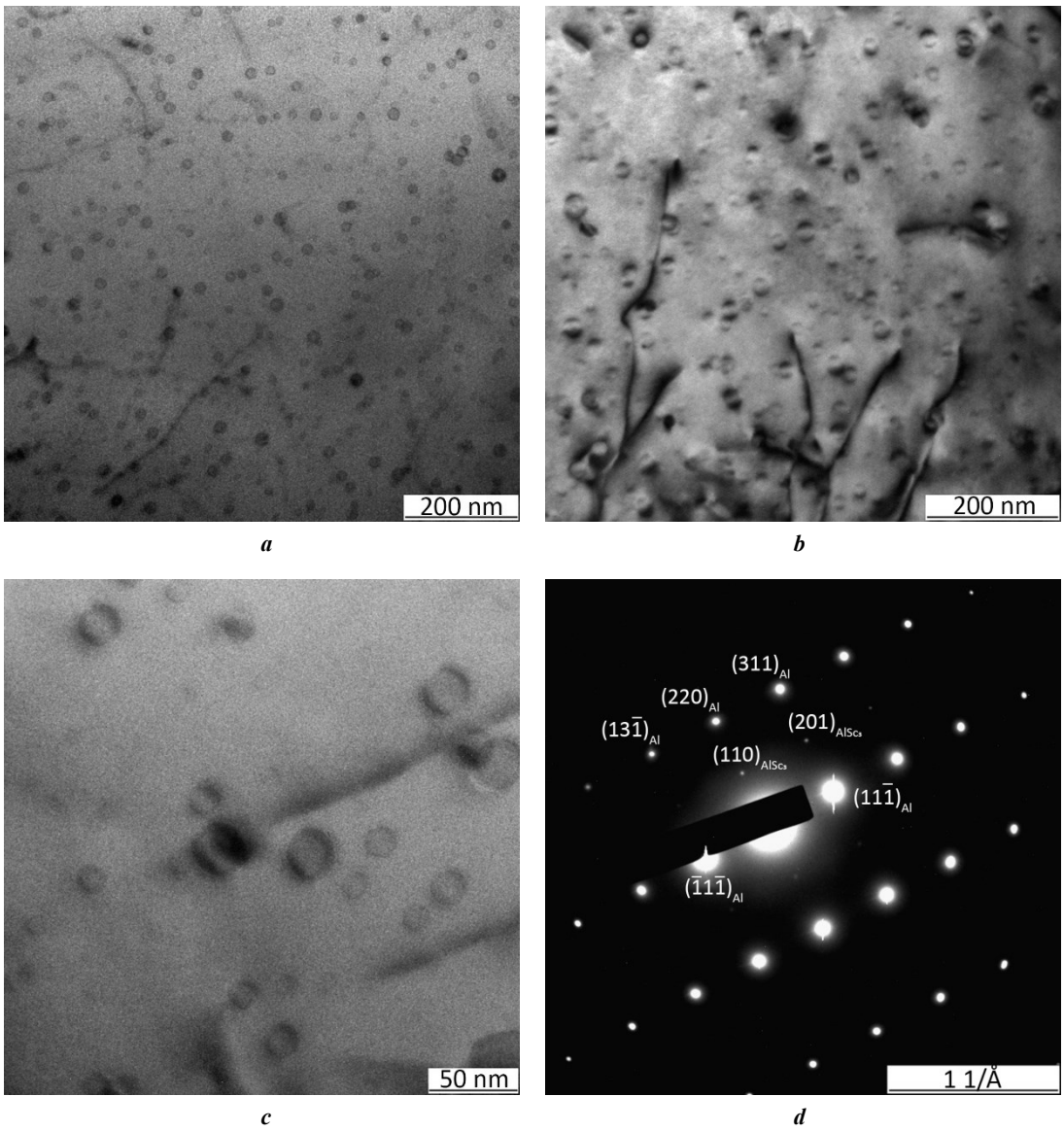
***Рис. 7.*** *Электронно-микроскопические изображения микроструктуры сплава 1590-3 после отжига при 440 °С в течение 48 ч:* ***a***, ***b***, ***c*** *– светлопольные изображения;* ***d*** *– микроэлектронограмма, ось зоны* $[112]_{Al}$

## DISCUSSION

First, it should be noted that in both alloys studied using TEM, discontinuous precipitation of the supersaturated solid solution is observed. Discontinuous precipitation has a negative effect on the mechanical properties, since it leads to a decrease in the amount of scandium in the solid solution, which causes the decrease in the number of finer particles.

The particles formed during discontinuous precipitation can be either equiaxed or elongated. As a rule, they are either completely or partially coherent with the aluminium matrix [17–19]. However, their strengthening effect is not as high as that of particles formed during continuous precipitation [20]. In this case, the cause of discontinuous precipitation could be erbium, which accelerates the formation of $Al_3Sc$ particles. This is also evidenced by the fact that with an increase in the erbium content from 0.03 to 0.10 %, the number and size of $Al_3Sc$ particles increases.

The highest value of microhardness in the as-cast state for the 1590-4 alloy in Fig. 1 is explained by the fact that this alloy is maximally doped with hafnium and erbium with their total content of 0.2 %. Dissolving in the solid solution, hafnium and erbium cause maximum strengthening. The subsequent increase in microhardness observed in 1590, 1590-3 and 1590-4 alloys (Fig. 1) is explained by the fact that in these alloys, a precipitation of $Al_3Sc$ type dispersoids occurs, which significantly increase their strength properties. The main reason that this increase does not occur in the 1599 alloy is the insufficient amount of Sc for the formation of finely dispersed strengthening $Al_3(ScZr)$ particles. The main reason for the sharp increase in microhardness after 8 h of annealing of the 1590-3 alloy (Fig. 1) is the maximum precipitation of finely dispersed $Al_3(ScZrHf)$ particles from the solid supersaturated solution, and the drop in microhardness after 24 h of annealing




***a*** ***b*** ***c*** ***d***

***Fig. 8.*** *Electron microscopic images of the microstructure of the 1590-4 alloy after annealing at 440 °C, 48 h:* ***a***, ***b***, ***c*** *– light-field images;* ***d*** *– micro-electron-diffraction pattern,* $[112]_{Al}$ *zone axis*

***Рис. 8.*** *Электронно-микроскопические изображения микроструктуры сплава 1590-4 после отжига при 440 °С в течение 48 ч:* ***a***, ***b***, ***c*** *– светлопольные изображения;* ***d*** *– микроэлектронограмма, ось зоны* $[112]_{Al}$

indicates the beginning of their coagulation process. The constancy of microhardness values during the first 48 h after holding of the 1590-4 alloy (Fig. 1) indicates the stability of finely dispersed particles in this range. A further decrease in the microhardness of the alloy indicates the beginning of the coagulation processes of these particles.

The differences in the change in microhardness in 1590, 1590-3, 1590-4 and 1599 alloys during the first 2 h of annealing at a temperature of 440 °C are explained by the fact that the first three alloys have a higher Sc content than the last one. Therefore, in 1590, 1590-3, 1590-4 alloys, the formation of $Al_3Sc$ dispersoids occurs faster. The decrease in microhardness observed in the 1599 alloy after 48 h of holding occurs due to the low scandium content.

One should note that according to the microhardness measurement data and the results of the study using transmission microscopy, hafnium has a positive effect on the mechanical properties, especially at a temperature of 440 °C. This is explained by the fact that $Al_3Sc$ particles containing a larger amount of hafnium are more thermally stable. It is worth noting that active diffusion of hafnium begins to occur when heated above 400 °C [20]. This is why the effect of hafnium is more clearly visible at high temperatures. Based on the data on the change in microhardness, it is evident that a hafnium concentration of 0.07 % is insufficient to form $Al_3Sc$ particles. A noticeable change in microhardness occurs only with a longer holding time. Therefore, with the addition of hafnium, the microhardness remains stable for at least the first 8 h at 440 °C. In alloys containing only scandium and zirconium, the microhardness at a temperature of 450 °C begins to decrease after several tens of minutes of holding [5]. One should note that in the present paper, unlike [5], both the thermal stability of nanoparticles and its effect on mechanical pro-

perties were studied. Based on the results of microhardness changes obtained in this study, one can conclude that the hafnium concentration of 0.44 % used in [13] is excessive, since 0.16 % of hafnium is sufficient to stabilise the microhardness for 96 h of holding.

It is worth noting that if the effect of hafnium on the formation of nanoparticles and microhardness is obvious, then the effect of erbium is not so clear. The growth of microhardness in the first 2 h of heating in all the studied alloys occurs with the same intensity, which indicates the absence of differences in the formation of nanoparticles. In this case, erbium affects the formation of nuclei. Such pattern is associated with the fact that the precipitation of $Al_3Er$ nanoparticles occurs at lower temperatures [11]. Perhaps, a two-stage annealing scheme will be effective: with the first stage at 250–300 °C for the formation of $Al_3Er$ particles and the second stage at 400–450 °C for the formation of a shell of Sc, Zr and Hf. Therefore, an obvious direction for further research is to study the effect of erbium on the formation of the microstructure and mechanical properties in this group of alloys during their two-stage annealing.

## CONCLUSIONS

The results of the conducted studies revealed a positive effect of hafnium and erbium on the formation of the microstructure and mechanical properties of alloys sparingly alloyed with scandium. An increase in the erbium content in the alloys leads to an increase in microhardness during heat treatment in the modes of 370 °C, up to 24 h of holding, and 440 °C, up to 8 h of holding. With an increase in the temperature and annealing duration, coagulation of $Al_3Sc$ particles occurs, while the particle sizes in the 1590-4 alloy with an increased erbium content increase by 2 times compared to the particle size in the 1590-3 alloy, where the hafnium content is maximum. It is worth noting that in alloys with a high hafnium content, a significant increase in microhardness occurs at a temperature of 440 °C after 8 h of holding, which is confirmed by the TEM results after heat treatment at 440 °C for 48 h. The main explanation for the smaller size of nanoparticles in the 1590-3 alloy is that hafnium forms a shell around the $Al_3Sc$ particles, which slows down their growth at high heat treatment temperatures and long holding times and has a positive effect on microhardness.

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# Влияние микролегирования эрбием и гафнием на формирование частиц $Al_3Sc$ в алюминиевом сплаве с высоким содержанием магния

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*Поступила в редакцию 07.10.2024* *Пересмотрена 27.11.2024* *Принята к публикации 04.02.2025*

***Аннотация:*** Исследовано влияние добавок гафния и эрбия на формирование микроструктуры при термической обработке алюминиевых сплавов с высоким содержанием магния, дополнительно легированных скандием и цирконием. Для исследования методом литья в стальной кокиль были получены слитки из алюминиевых сплавов с высоким содержанием магния, легированного скандием, эрбием и гафнием с содержанием в диапазонах 0,03–0,16 % и 0,05–0,16 % соответственно. После отливки образцы подвергали термической обработке при температуре 370 и 440 °C с выдержкой от 2 до 96 ч. Были исследованы изменения микротвердости в зависимости от термической обработки. Для сплавов 1590-3 и 1590-4 в литом состоянии и после термической обработки при температуре 440 °C в течение 2 и 48 ч с помощью просвечивающей микроскопии исследовали тонкую микроструктуру и крупные интерметаллиды. Установлено, что добавки гафния и эрбия приводят к повышению микротвердости за счет уменьшения размера и увеличения количества наночастиц $Al_3Sc$. После проведения термической обработки при температуре 440 °C в течение 4 ч во всех исследуемых сплавах происходит выпадение частиц $Al_3Sc$, имеющих одинаковый размер (8 нм) и плотность, однако с увеличением времени выдержки в сплаве с меньшим содержанием гафния и большим содержанием эрбия размер частиц увеличивается в 2 раза по сравнению с частицами сплава, где содержание гафния больше, а содержание эрбия низкое.

***Ключевые слова:*** алюминиевые сплавы; микролегирование; скандий; гафний; эрбий; формирование частиц $Al_3Sc$; микротвердость; микроструктура; наночастицы.

***Благодарности:*** Исследование выполнено за счет гранта Российского научного фонда № 22-19-00810, https://rscf.ru/project/22-19-00810/.

***Для цитирования:*** Рагазин А.А., Арышенский Е.В., Арышенский В.Ю., Распосиенко Д.Ю., Коновалов С.В., Бахтегареев И.Д. Влияние микролегирования эрбием и гафнием на формирование частиц $Al_3Sc$ в алюминиевом сплаве с высоким содержанием магния // Frontier Materials & Technologies. 2025. № 1. С. 69–80. DOI: 10.18323/2782-4039-2025-1-71-6.