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A STUDY OF CONTINUOUSLY CAST INGOTS OF ALUMINUM ALLOY AA2014 WITH INCREASED ULTRASONIC CHARACTERISTICS

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Ingots of aluminum alloy AA2014 obtained in a Wagstaff DC continuous casting machine and meeting the class “A” requirements of ultrasonic control by the method of damping of signal (AMS 2630B) are studied. The yield meeting these requirements is equal to only 20%. The causes of the low yield are determined.

Key words: continuous casting, homogenizing, ultrasonic control, aluminum alloys, degassing.

INTRODUCTION

Aluminum alloys AA2014, AA2219, AA6061, and AA7075 are used widely in various conditions in the form of rolled rings, plates, sheets, forgings, and extruded preforms for automotive and aerospace engineering. Articles from these alloys are aircrafts, which implies high operating stresses and low safety factors. All these kinds of preforms are obtained from continuously cast ingots, which means that the quality of the ingots is very important for the development of critical spacecraft structures. For this reason, all the subsequent production processes require continuously cast ingots classified as “A” in ultrasonic control (according to the AMS 2630B). Control of the composition of the alloy is very important for attaining the required strength and processibility; control of the hydrogen content and inclusions is important for providing the needed endurance characteristics and adaptability of ingots to manufacture [1]. To meet the requirements of the Indian Space Program ingots of such quality and various diameters were produced in continuous casting machines of the Wagstaff DC Company. The casting process included melting of an aluminum alloy in an oil-burning furnace and inoculation (grain refinement) by introducing inoculating bars of alloy Al – 5% Ti – 1% B into the melt. For degassing, the melt was treated in an AlPur Degasser device and filtered with the help of filters with 30 openings per squared inch,[2] after which it was cast into a Wagstaff mold. However, the yield of the metal matching the class “A” requirements of ultrasonic control according to the AMS 2360 for ingots 400 mm in diameter and larger was very low (10 – 15%) [2].

A preliminary study of ingots homogenized at 450°C for 24 h has shown that the rejection was preliminarily caused by a high level of noise in ultrasonic control [3]. The noise in ultrasonic checking is produced by scattering of acoustic waves on gas pores, casting flaws, inclusions, and large-size grains. In order find the parameters determining the low yield in the production of ingots we performed test continuous casting of ingots 400 mm in diameter and studied in detail some cast and homogenized specimens cut from one ingot.

The aim of the work consisted in determining the causes of the low yield and developing recommendations for raising the quality of ingots of aluminum alloy AA2014 with the help of ultrasonic check and study of the microstructure.

METHODS OF STUDY

Continuously cast ingots of AA2014 aluminum alloy 400 mm in diameter and 500 mm long were obtained in a Wagstaff casting machine by the OFAJ producer in Nagpur, India. The blend materials included 20 – 40% secondary alloy (scrap) AA2014, aluminum with purity 99.5 wt.%, an Al – Cu hardener, and pure magnesium. The main parameters of the casting process are presented in Table 1. The casting line included an integral AlPur degasser, an inoculation unit, and a filtering unit with a foam ceramic filter (30 ppi). The ingots were subjected to an ultrasonic check. The chemical composition of the ingots is presented in Table 2. The

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[2] Here and below the notation ppi is used for “openings per squared inch.”

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TABLE 1. Parameters of the Casting Process

Parameter	Used values
Casting speed	40 mm/min
Temperature of mold	705°C
Temperature of furnace	755 – 760°C
Temperature of degasser	736°C
Speed of motion of inoculating bar	20 cm/min
Speed of water flow	1950 liters/min
Temperature of water	29°C
Level of metal in the feeder	117 – 130 mm
Lubricant	2 pulses in every 60 sec

composition matched the standard for alloy AA2014 [4]. Three discs corresponding to classes A, B, and C (lower than B) according to the data of the ultrasonic check were cut from an ingot. The positions of the discs in the ingot are presented in Fig. 1. Disc 052D22C exhibited the highest level of noise and flaws; disc 052D22A exhibited the lowest level of these parameters. The latter disc met the requirements of ultrasonic class A; the quality of the former was worse than class B. The disc marked 052D22B corresponded to ultrasonic class B.

In addition to the ultrasonic check we performed luminescent control on both sides of the discs. The ultrasonic scanning was performed using an S12HB4 sensor at normal incidence of the beam on the whole of the surface of the disc including the periphery.

The specimens cut from the discs were subjected to macro- and microstudies. For the macrostudy we used an etchant from a mixture of acids and studied only one side of a disc. The etched surfaces were investigated by naked eye or using a magnifying lens.

The discs were cut into specimens corresponding to the middle and periphery of the intermediate region for further study and heat treatment, as it is shown in Fig. 2. The homogenized specimens were polished and etched in Keller's reagent. The specimens were studied after polishing (prior to etching) and after etching. After the homogenization we determined the grain sizes. Some specimens were studied using a scanning electron microscope. For determining the chemical composition of the segregations we resorted to energy dispersive spectroscopy.

Specimens cut from discs 052D22A and 052D22C were subjected to homogenization (Fig. 2) in two modes, i.e., 450°C, 24 h and 485°C, 24 h.

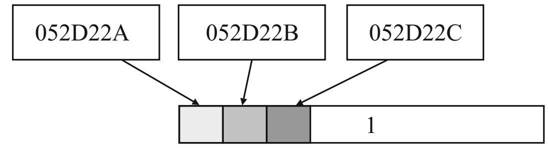

Fig. 1. Scheme of cutting three discs from an ingot.

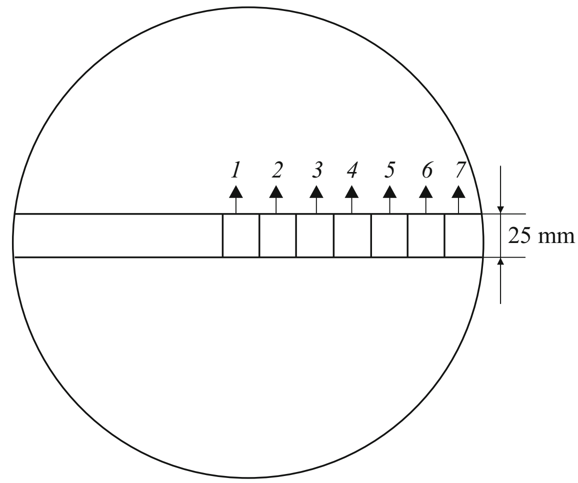

Fig. 2. Scheme of cutting specimens from discs of an ingot 400 mm in diameter: *1*, *2*) for metallography and homogenization of the middle; *4*) for metallography and homogenization of intermediate region; *6*, *7*) for metallography and homogenization of peripheral region; *3*, *5*) for differential scanning calorimetry and determination of hydrogen.

RESULTS AND DISCUSSION

Nondestructive Inspection

We detected fine pores in the middle of the discs subjected to luminescent control. Discs 052D22B and 052D22C had elevated porosity in the peripheral region (see Fig. 3*b* and *c*); in the middle of these discs the concentration of the pores was higher than in disc 052D22A (Fig. 3*a*). The pore size in discs 052D22B and 052D22C was also larger than in disc 052D22A. Quantitative determination of the size of the pores by luminescent inspection is impossible. Figure 3*d* presents the results of a luminescent check of a disc cut from an ingot of ultrasonic class A after the recommended measures. It can be seen that the porosity of the disc is negligibly low both in the middle and at the periphery.

TABLE 2. Chemical Composition of the Ingots

Ingots	Content of elements, wt.%										
	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Na	Ti	Al
TOR	0.5 – 0.9	< 0.5	3.9 – 5	0.4 – 1.2	0.2 – 0.8	< 0.1	< 0.2	< 0.2	< 0.0005	0.2	Other
Disc 052D22	0.58	0.14	4.49	0.49	0.35	0.007	0.007	0.06	0.00005	0.2	Other

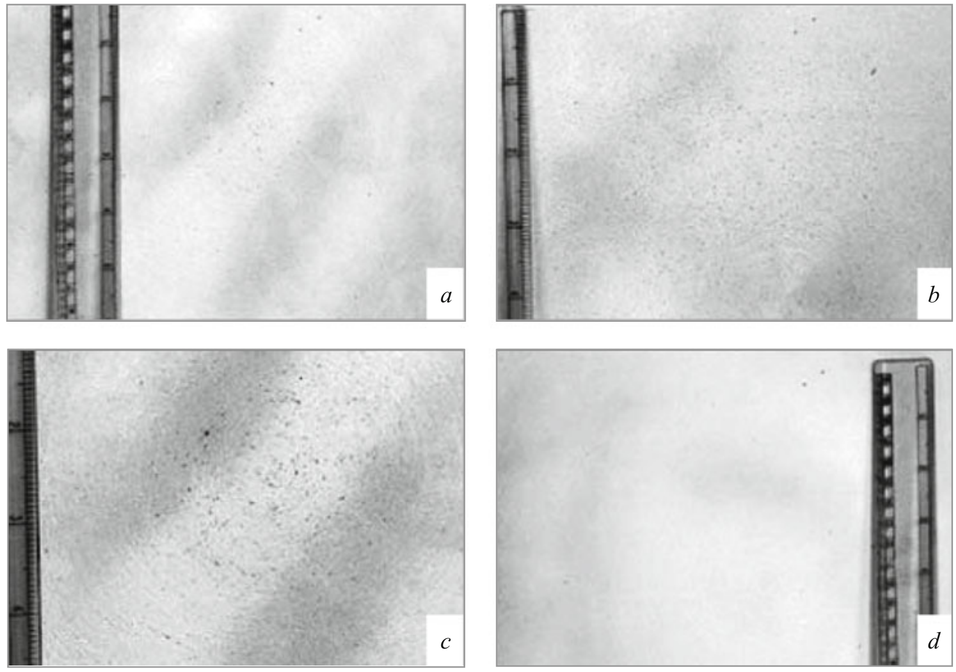

Fig. 3. Photographs of the discs after homogenization at 450°C for 24 h: *a*) 052D22A; *b*) 052D22B; *c*) 052D22C; *d*) disc cut from class "A" ingot produced with allowance for the suggested technological recommendations; the red points mark the result of luminescent inspection; the penetrating dye shows the presence of dot porosity in discs *a*, *b*, and *c*.

Table 3 presents the results of ultrasonic inspection of all of the discs. The results show that such inspection is hard for class "A" of AMS 2630B [5] to the high level of noise. Most cases of rejection of ingots are explainable by the impossibility of the inspection of ingots for ultrasonic class A due to the high level of noise. Most ingots produce strong noise (over 50% of the signal of the digital quantizer DQ) in radial scanning. Axial scanning gives a low level of noise (< 10%), i.e., the factor determining the high level of noise in the radial direction does not act in axial scanning of the whole of the ingot. The low level of noise in the axial direction may also be a result of the lower thickness of the discs (25 – 30 mm) in this direction.

It should also be noted that discs 052D22A, 052D22B and 052D22C were cut from one ingot as it is shown in Fig. 1 and are classifiable as class "A," class "B," and lower than class "B," respectively. This means that some regions of the ingot (discs 051D22B and 052D22C) have a high noise level and do not meet class "A" and some regions (disc 052D22A) have a low noise level and match class "A." This reflects the nonuniform distribution of porosity over the ingot.

The noise level in ultrasonic checking is determined by the scattering of waves, which depends strongly on the grain size. If the grains are smaller than 0.01 wavelength, the scattering is negligibly low [1]. The scattering effects vary approximately in proportion to the cubed grain size; when the grain size attains 0.1 wavelength or exceeds this value, the intense scattering of the acoustic waves may make reliable ultrasonic checking impossible. The grain sizes in the ingots tested are presented in Table 4. These data show that the grain size in the middle of all of the ingots is greater than at the periphery. The difference in the grain sizes amounts to 5 – 30%. The frequency of the acoustic waves is 4 MHz and the speed of sound in aluminum is 220 m/sec, which explains the use of the 55-μm wavelength in our work. Thus, the grain size in the ingots studied is much greater than the 0.1 acoustic wavelength used for the check. However, some regions of the ingot with the same grain size produce a low level of noise, which means that the high level of noise is caused by a factor other than the grain size.

To determine the cause of the high level of noise, the cast discs were homogenized at two temperatures (450 and 485°C) for 24 h. Table 5 presents the results of ultrasonic checking of these discs. It can be seen that homogenization at 450°C raises considerably the level of the noise. It is shown in [7] that homogenization at 450°C does not provide complete dissolution of particles of segregations but coarsens the

TABLE 3. Results of Ultrasonic Check of Discs in Cast Condition (Periphery)

Discs	Results of ultrasonic check
052D22A	No flaw, noise up to 40% FSH
052D22C	Noise 3 dB higher than 1.2 DQ signal
052D22B	Noise 1.5 dB higher than 1.2 DQ signal

TABLE 4. Sizes of Grains and Cells in Different Ingots in Cast Condition

Discs	Grain size, μm		Cell size, μm	
	Core	Periphery	Core	Periphery
052D22A	122.5 ± 31.2	71 ± 16.3	30.6 ± 9.4	28.2 ± 5.6
052D22C	122.6 ± 21.3	65.2 ± 16.2	27 ± 6.5	20.7 ± 5

TABLE 5. Results of Ultrasonic Checking of Discs after Homogenization

Condition	Periphery	Cross-section
Annealing at 450°C, 24 h, disc 052D22A, half cycle	Noise up to 3 dB > DQ	Flaws at two places
Annealing at 485°C, 24 h, disc 052D22B, complete cycle	No flaw, noise up to 2 dB > DQ at individual regions. Total level of noise up to 50% DQ	One flaw, noise up to 8 – 9% FSH
Annealing at 485°C, 24 h, disc 052D22C, half cycle	No flaw, noise up to 1 dB > DQ	No flaw

segregations of CuAl2 and Mg2Si. It seems that the level of the noise increases due to the presence of coarse segregations and remnants of dendritic structure after homogenization at 450°C. Analysis of the microstructure of these specimens shows that the homogenization causes dissolution of grain boundary segregations of CuAl2 due to the accelerated diffusion over grain boundaries. The segregations in the dendrite spacings remain mostly undissolved at the lower homogenization temperature. After homogenization at 485°C the signal/noise ratio improves as compared to the homogenization at 450°C. The mode of homogenization at 485°C has been chosen on the basis of data on grain sizes and eutectic melting [6]. It has been shown that the noise level in the axial direction decreases and so does the correction factor. The latter fact implies that the quality of an ingot improves if the homogenization mode is chosen appropriately.

Microstructure

Figure 4 presents the microstructure of polished specimens cut from different discs. We can observe considerable porosity. Most of the pores have a round shape and this allows us to assume that the pores have a hydrogen origin. In individual places of some ingots we detect pores in the dendrite spacing. In an acoustic check the size and the distribution of the pores manifest themselves so that the growth in the volume fraction of the porosity corresponds to growth in the noise level. When the mode of homogenization is changed, the microstructure of the ingots of class "A" contains fewer pores (Fig. 4). In some regions of the ingots we can observe particles of inclusions. According to the data of the energy dispersive spectroscopy these inclusions are compound oxides (Fig. 5).

Figure 6 presents the microstructure of cast and homogenized specimens. The microstructure of the cast specimen (Fig. 6*a*) is represented by dendrites of an aluminum solid solution and coarse segregations between the dendrites. After homogenization at 485°C the grain bulk contains no segregation; discontinuous segregations of $CuAl_2$ are observable over grain boundaries (Fig. 6*b*).

The microstructure of the specimens homogenized at 450°C for 24 h (Fig. 6*d* and *e*) reflects incomplete homogenization. Parts of dendrite arms are still present. Homogenization at 485°C for 24 h removes fully the veins and the parti-

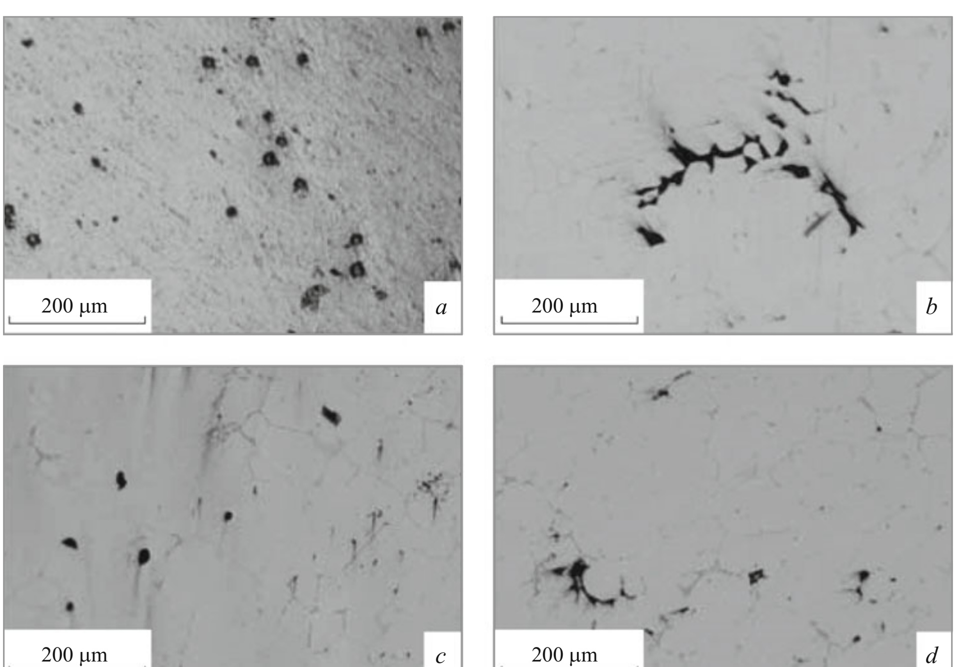

Fig. 4. Micrographs of cast specimens of alloy AA2014 in unetched condition: *a*, *b*) disc 052D22C, core; *c*, *d*) disc 052B22A, core.

cles containing copper (Fig. 6*c*), which means that the copper has passed fully into the solid solution. We may state that this mode of treatment provides complete homogenization and lowers the noise level in ultrasonic checking of the ingots.

Control of Hydrogen Content

The permissible content of hydrogen in aluminum is 0.15 cm^3 per 100 g metal (1.5×10^{-5}%). It is reported in [4] that none of the methods of degassing can reduce the hydrogen content in aluminum below 5×10^{-6}% (0.05 cm^3/100 g) [4, 8]. Since the available degassing unit can reduce the hydrogen content by only 40 – 65%, it is necessary to control the accumulation of hydrogen in the melt after it leaves the furnace. In our work we observed strong gas porosity in the ingots despite the use of dry blend materials and degassing. This is explainable by the high temperature of the melt, which causes saturation with atmospheric hydrogen, as it has been observed in [9]. In order to lower the absorption of hydrogen, we decreased the temperature of the melt from 770 to 740°C. In the degassing unit the temperature was reduced to 720°C (from 760°C); in the casting unit it was reduced to 680°C (from 700°C). Near the casting unit the moisture content was 85% RH,[3] whereas near the furnace it was below 50% RH. We established that control of the temperature of the melt can lower considerably the absorption of hydrogen by the metal.

Control of Inclusions

We controlled the content of inclusions in the melt using a foam ceramic 30ppi filter in accordance with the accepted process. The production line included a cloth 10ppi filter based on silicon dioxide, and the foam ceramic filter was replaced by a ceramic 40ppi filter. This improved the results of the ultrasonic check.

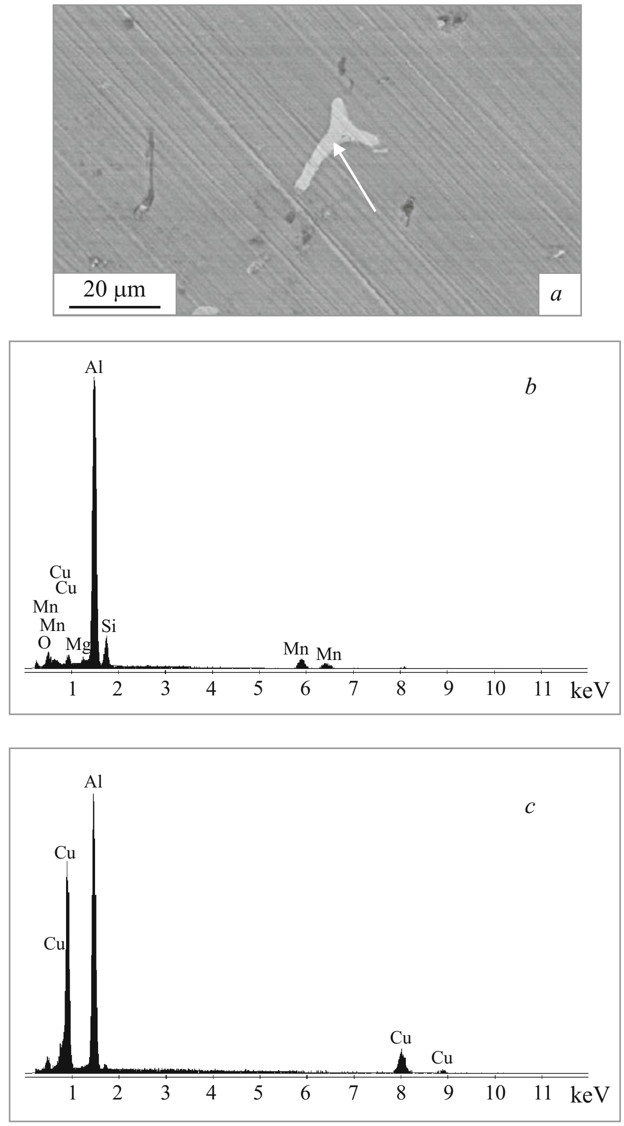

Fig. 5. Image of an inclusion under scanning electron microscope (*a*), energy dispersive spectroscopy of the inclusion (*b*), and energy dispersive spectroscopy of the discontinuous segregation observable at grain boundary in Fig. 6*b* (*c*).

CONCLUSIONS

1. According to the data of a chemical analysis the ingots of aluminum alloy AA2014 meet the performance specification on the whole. However, the presence of compound inclusions bearing Mn, Fe, O, and Si shows that it is necessary to use purer blend materials (≥ 98.5%).

2. The main source of the high level of noise in ultrasonic checking of ingots is porosity. Degassing of the alloy with the help of argon and lowering of the temperature of casting to 680 ± 5°C decrease the hydrogen content in the metal and the size and the number of pores.

3. Homogenization of ingots at 485°C does not change the noise level; homogenization at 450°C increases the latter.

4. Installation of filtration through an aluminum oxide cloth into the production line in addition to a foam ceramic 30ppi-filter lowers the content of inclusions.

5. The class "A" yield due to ultrasonic checking of ingots of alloy AA2014 with a diameter of 400 mm and larger according AMS 2630B has increased from 20 to 100%.

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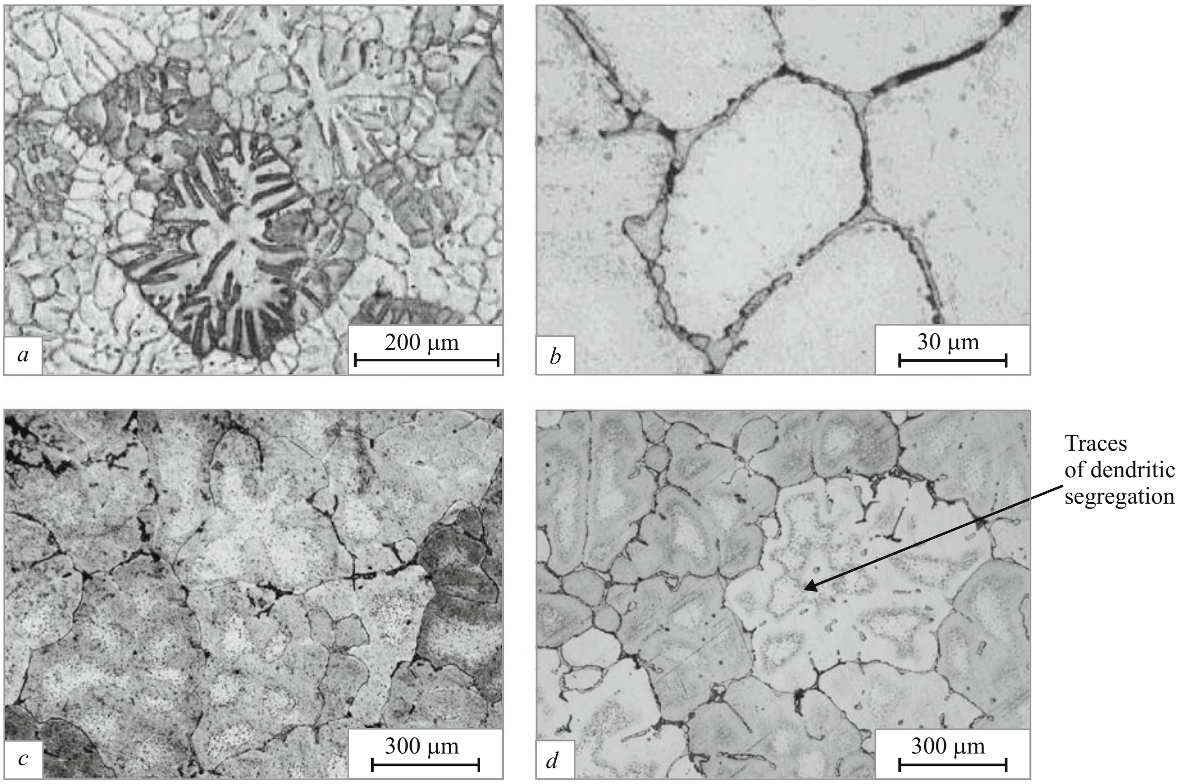
[3] RH is the relative moisture content determined as the ratio of the partial pressure of water vapor to the saturation pressure (partial pressure of water vapor above pure water at the gas temperature). *Ed. note.*



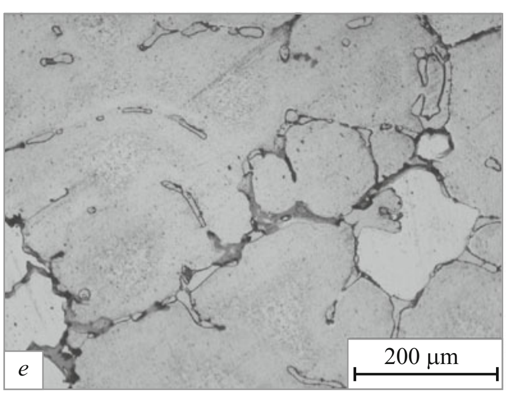


Fig. 6. Microstructure of specimens of alloy AA2014 in cast (*a*) and homogenized (*b* – *e*) conditions: *b*, *c*) homogenization at 485°C, 24 h; *d*, *e*) homogenization at 450°C, 24 h.

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