D. LEŚNIAK*, M. BRONICKI*, A. WOŹNICKI*

HIGH-TEMPERATURE HOMOGENIZATION OF ALCUMG ALLOYS FOR EXTRUSION IN T5 TEMPER

WYSOKOTEMPERATUROWA HOMOGENIZACJA STOPÓW ALCUMG PRZEZNACZONYCH DO WYCISKANIA W STANIE T5

Homogenization conditions of the AlCuMg alloys strongly influence the microstructure of ingots for extrusion process. In this work, the homogenization of 2014 and 2024 alloys intended for extrusion with a solution heat treatment on the press (T5 temper) was analyzed. The study describes the dependence of the material microstructure on the alloy chemical composition and the mode of homogenization treatment. The alloys with extreme content of the main additions were taken into consideration and the high-temperature homogenization procedure was proposed. Optical microscopy and SEM/EDS characterisation of the as-cast and as-homogenised samples was applied to reveal the most important microstructural features of the alloys and changes caused by the different heat treatments. Differential Scanning Calorimetry (DSC) analysis was also done to support metallographic observations. The homogenization of AlCuMg alloys at temperatures close to the solidus temperature allows us to obtain the structure without over-melting that could unfavourably affect the extrusions quality. Such homogenization enabled achieving the good uniform microstructure of the alloys with fine particles of intermetallic phases, what can facilitate their dissolution within deformation zone during extrusion process. The improved heat treatment of 2014 and 2024 ingots should make solution heat treatment on the press more effective and thus lead to increased strength properties of extrusions in T5 temper.

Keywords: Homogenization, AlCuMg alloys, billet microstructure, extrusion with solution heat treatment on the press, mechanical properties of extrusions in T5 temper

Warunki homogenizacji stopów AlCuMg bardzo silnie wpływają na strukturę wlewków do wyciskania. W pracy analizowano proces homogenizacji stopów 2014 i 2024 przeznaczonych do wyciskania z przesycaniem na wybiegu prasy (stan T5). Studium opisuje strukturę materiału wlewka, w zależności od składu chemicznego stopu i sposobu homogenizacji. Zaproponowano homogenizację prowadzoną w wysokich temperaturach (bliskich temperatur solidusu) dla stopów o skrajnych zawartościach głównych składników stopowych Cu i Mg. Przeprowadzono badania struktury analizowanych stopów w stanie odlewanym oraz po homogenizacji, z wykorzystaniem mikroskopii optycznej i elektronowej. Badania strukturalne uzupełniono badaniami kalorymetrycznymi. Na podstawie uzyskanych wyników stwierdzono, że poprowadzenie procesu homogenizacji wymienionych wyżej stopów w temperaturach bliskich solidusu pozwala na otrzymanie struktury materiału pozbawionej nadtopień, które mogłyby niekorzystnie wpływać na jakość wyciskanego wyrobu. Wysokotemperaturowa homogenizacja umożliwiła uzyskanie jednorodnej struktury z drobnymi wydzieleniami faz umacniających, dzięki czemu łatwiejsze będzie ich rozpuszczanie w roztworze stałym podczas wyciskania. Proponowana ulepszona obróbka cieplna wlewków ze stopów 2014 i 2024 pozwoli na bardziej skuteczne przesycanie na wybiegu prasy, a w konsekwencji na uzyskanie wyższych własności wytrzymałościowych wyrobów wyciskanych w stanie T5.

1. Introduction

Extrusion with a solution heat treatment on the press (T5 temper) is more and more often applied technology in aluminium extrusion industry. Solution heat treatment of extruded profiles in T6 temper needs an additional heating of a material to solution temperature what increases the time and costs of product manufacturing [1-3]. In addition, this mode of solution heat treatment worsens extrusions quality by unfavourable grain growth and shape distortions [4-5].

In order to achieve required mechanical properties of the profiles in the T5 temper, the ingots for extrusion with solution heat treatment on the press should be characterized by:

– The presence of fine hardening phases particles in their structure, which will fully dissolve during extrusion,

* AGH – UNIVERSITY OF SCIENCE AND TECHNOLOGY, FACULTY OF NON-FERROUS, 30-059 KRAKÓW, 30 MICKIEWICZA AV., POLAND

– The lowest possible flow stress, to increase extrusion speed and reduce time of profile translocation between the die and quenching installation on the press. This is essential for retaining all alloy additions in the solid solution.

The above-mentioned conditions have to be taken into consideration during selection of homogenization parameters. The heating rate to the homogenization temperature should be relatively low. Otherwise, due to slow diffusion rate of copper in aluminium (diffusion coefficient in temperature 500 °C is $5 \cdot 10^{-14}$ m^2/s [6]), increasing local concentrations of alloying additions can cause melting in surroundings of dissolution particles [7].

The temperature of homogenization should exceed the solvus temperature, to provide the full dissolution of hardening phase particles, but should be below the lowest eutectic temperature in the alloy's equilibrium diagram, to avoid melting. It is commonly known, that the higher temperature shortens the time of homogenization. Thus, in the industrial practice, multi-stage homogenization schemes are applied, with exceeding eutectic temperature in the last stages of the process. Dissolution of secondary phases, taking place during homogenization (in the first stages below eutectic temperatures), causes a gradual increment of the alloy solidus temperature (from unequilibrium to equilibrium), and allows the temperature of annealing to rise successively (fig. 1). It is very beneficial in the case of 2xxx alloys, for which homogenization time is usually very long (because of mentioned earlier low diffusion rate of copper in aluminium). The multi-stage homogenization essentially cuts down the costs and improves efficiency of the process.

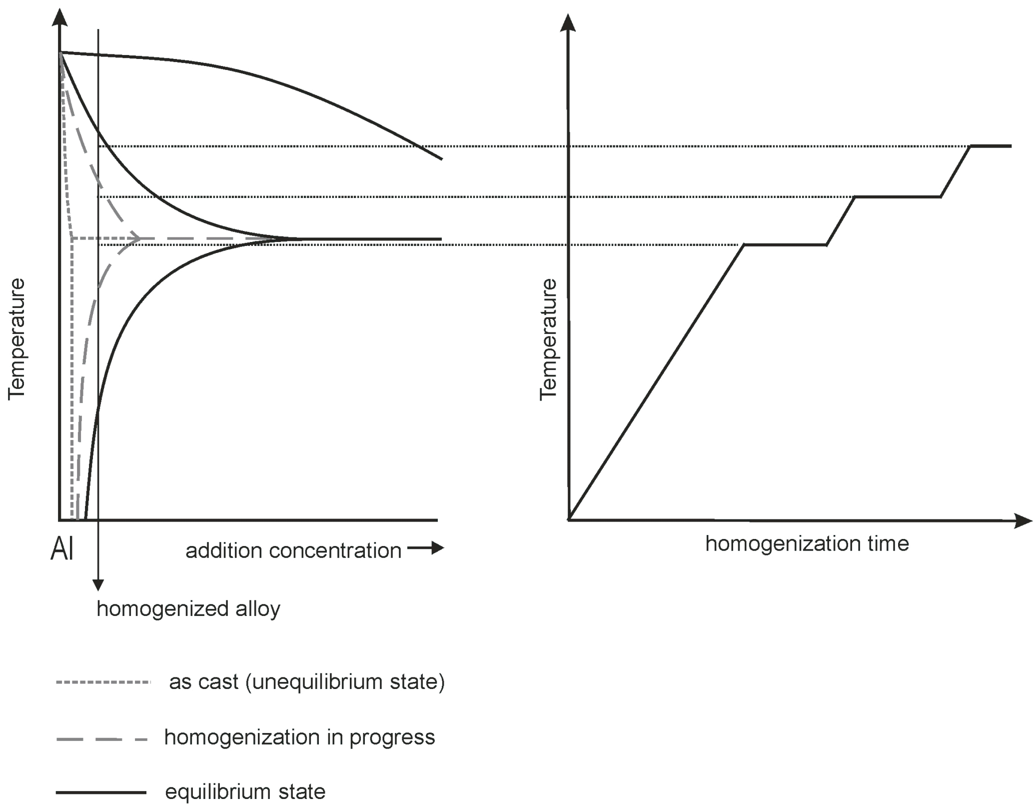


Fig. 1. Temperature-time dependence during homogenization

Cooling rate from homogenization temperature has to be sufficiently high [8-10] to provide precipitation of hardening phases in the form of fine particles, which completely dissolve during extrusion, because of higher material temperature in the deformation zone. On the other hand, too fast cooling after homogenization rises an amount of alloying elements retained in the solid solution and thus increases the flow stress of the alloy during extrusion (due to the solution strengthening).

It should be noticed, that lowering the content of alloying additions makes the preparation and extrusion of the ingots easier as well as solution heat treatment of the profiles on the run-out table.

For alloy with lowered amount of additions:

- higher final homogenization temperature may be selected (due to the higher solidus temperature of the alloy),
- extrusion speed can be increased (because of the lower flow stress of the material).
- Fully effective solution heat treatment on the press can be performed easier due to higher extrusion speed. It means that the quenching zone on the run-out table will be reached faster. In addition, the bigger difference between profile exit temperature and solvus temperature should influence positively on the effectiveness of heat treatment.

The aim of this work was to determine the influence of alloy chemical composition and the homogenization treatment on the microstructure of AlCuMg ingots intended for extrusion in T5 temper, and thus to evaluate the possibility of achieving high efficiency of solution heat treatment on the press and high extrusions quality.

2. Experimental work

The high-temperature homogenization of 2014 and 2024 alloys with the extreme content of additions, intended for extrusion with a solution heat treatment on the press were investigated. The content of such alloy additions like Cu and Mg was varied for the materials analyzed. The chemical compositions of all investigated alloys are shown in tables 1-4.

TABLE 1

Chemical composition of the alloy 2014 with the lowest permissible content of Cu and Mg (A alloy), in wt. %

Element	Cu	Mg	Mn	Si	Fe	Zn	Ti
Weight %	4.00	0.24	1.19	1.15	0.10	0.028	0.03

TABLE 2

Chemical composition of the alloy 2014 with the lowest permissible content of Cu and Mg (B alloy), in wt. %

Element	Cu	Mg	Mn	Si	Fe	Zn	Ti
Weight %	5.00	0.764	1.17	1.11	0.10	0.028	0.03

TABLE 4

Chemical composition of the alloy 2014 with the lowest permissible content of Cu and Mg (D alloy), in wt. %

Element	Cu	Mg	Mn	Si	Fe	Zn	Ti
Weight %	4.90	1.77	0.89	0.06	0.1	0.028	0.03

Ingots with 180 mm in diameter and 2 m in length were supplied in the as-cast conditions. The vertical semi-continuous casting process was applied with the temperature of cast metal of 735-740 °C and the casting speed of 85-90 mm/min. From ingots, the cubic samples with a dimension of 20 mm, were excised and heat-treated with different homogenization cycles in a muffle furnace.

The high-temperature homogenization procedure of 2014 and 2024 alloys was proposed in the research. Special treatment procedure consisted in a slow multistage heating up to the homogenization temperature (close to the solidus temperature), short holding of material at the homogenization temperature, slow cooling with a furnace and then air-cooling after homogenization. Different homogenization temperatures: T_H = 495, 500, 505, and 510 °C were applied in the investigations. Homogenization at standard conditions: 490°C/16 h (2014) and 500°C/15 h (2024) was performed for comparison. Schemes of standard homogenization and the high-temperature treatment are shown in fig. 2.

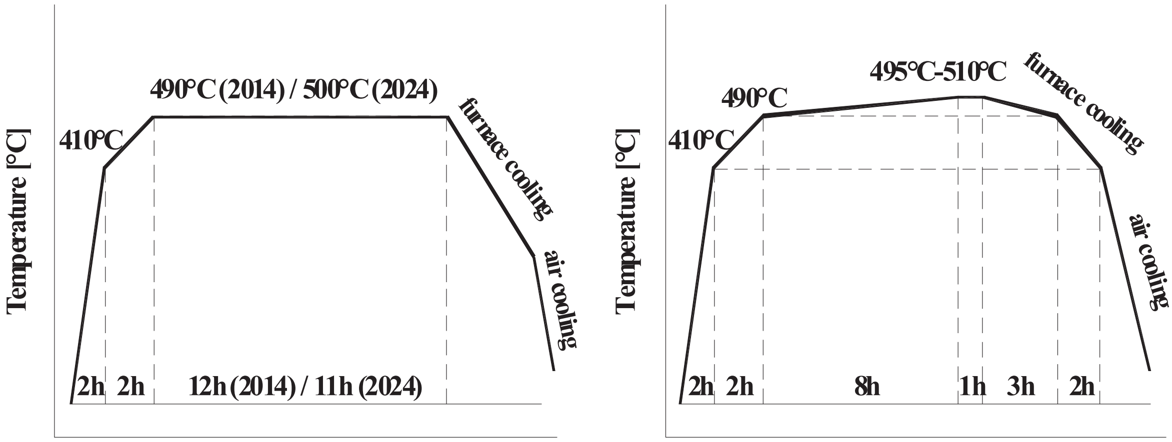


Fig. 2. Schemes of the homogenization procedures of 2014 and 2024 alloys;
(a) standard homogenization (b) high-temperature treatment

The temperature of the homogenized samples was controlled by means of the 8-chanel temperature recorder MPI-L and thermocouples of type K with a diameter of 1.5 mm (fig. 3). The typical temperature-time characteristics registered during the standard homogenization and the high-temperature treatment (510 °C/18 h) of the alloys are presented in figs. 4a-d.

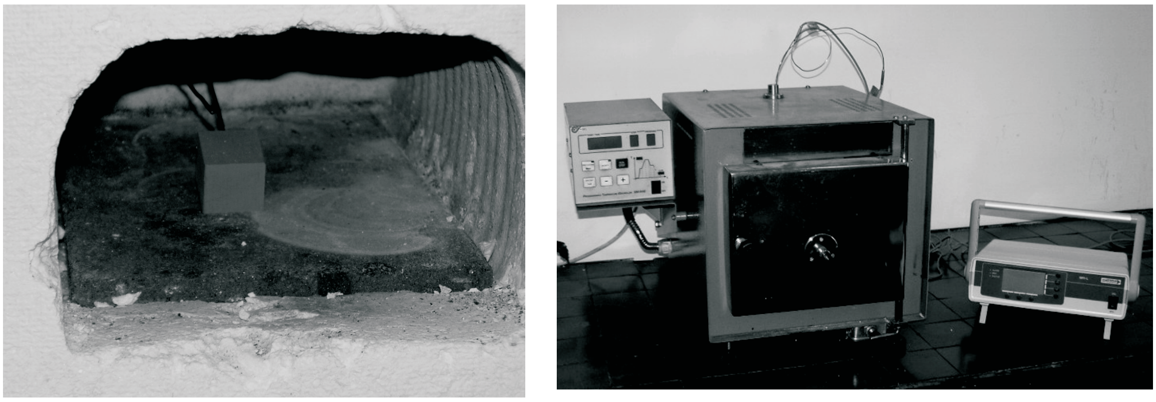


Fig. 3. The exemplary cubic sample with a thermocouple of type K (on the left) and muffle furnace with the 8-chanel temperature recorder (on the right)

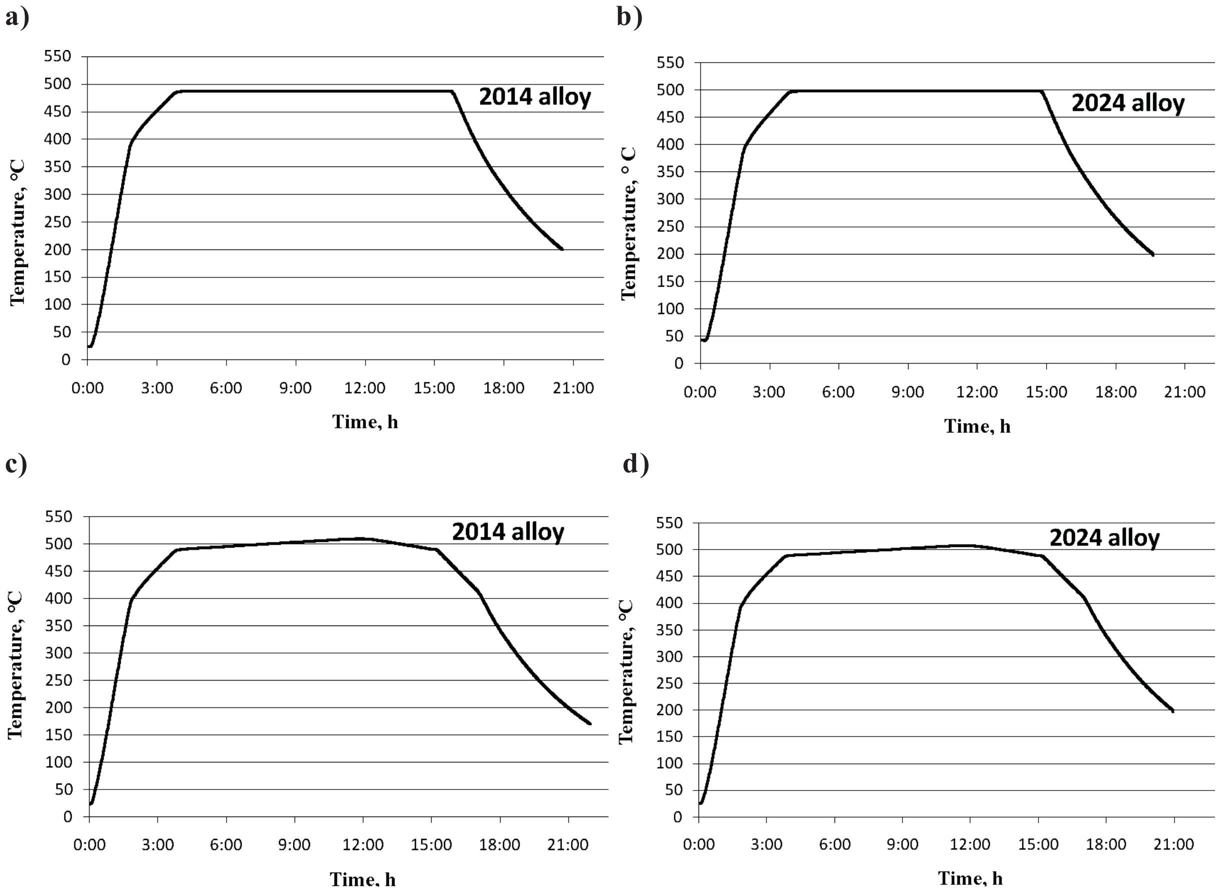


Fig. 4. Temperature-time characteristics for the homogenization process of 2014 and 2024 alloys;
(a-b) standard homogenization; (a) 2014 alloy; 490 °C/16 h (b) 2024 alloy; 500 °C/15 h (c-d) high-temperature homogenization; (c) 2014 alloy; 510 °C/18 h (d) 2024 alloy; 510 °C/18 h

From the heat-treated material, samples were taken for a differential scanning calorimetry analysis. The DSC was done in a calorimeter using 5 mm diameter discs, which were 3 mm thick, heated at 20 °C/min. It allowed the solidus temperatures of the alloys to be determined.

Light optical microscopy and SEM/EDS characterisation of the as-cast and the as-homogenized samples was applied to reveal the most important microstructural features of the alloys and changes produced by different heat treatments. For chemical microanalysis, EDS standard-less method with ZAF correction was applied. Based on the SEM/EDS results and literature data concerning phase occurrence in the AlCuMg alloys, an attempt was made to identify the observed structural components. Finally, investigations of the hardness of homogenized samples were carried out. Brinell hardness was measured on an Instron tester.

3. Results and discussion

The DSC results for the as-cast alloys and alloys after standard and high-temperature homogenization are shown in fig. 5. It was found that applying the high-temperature homogenization for alloys with the lowest permissible content of main alloy additions leads to considerable increase in solvus temperature, especially in case of 2024 alloy (fig. 5c).

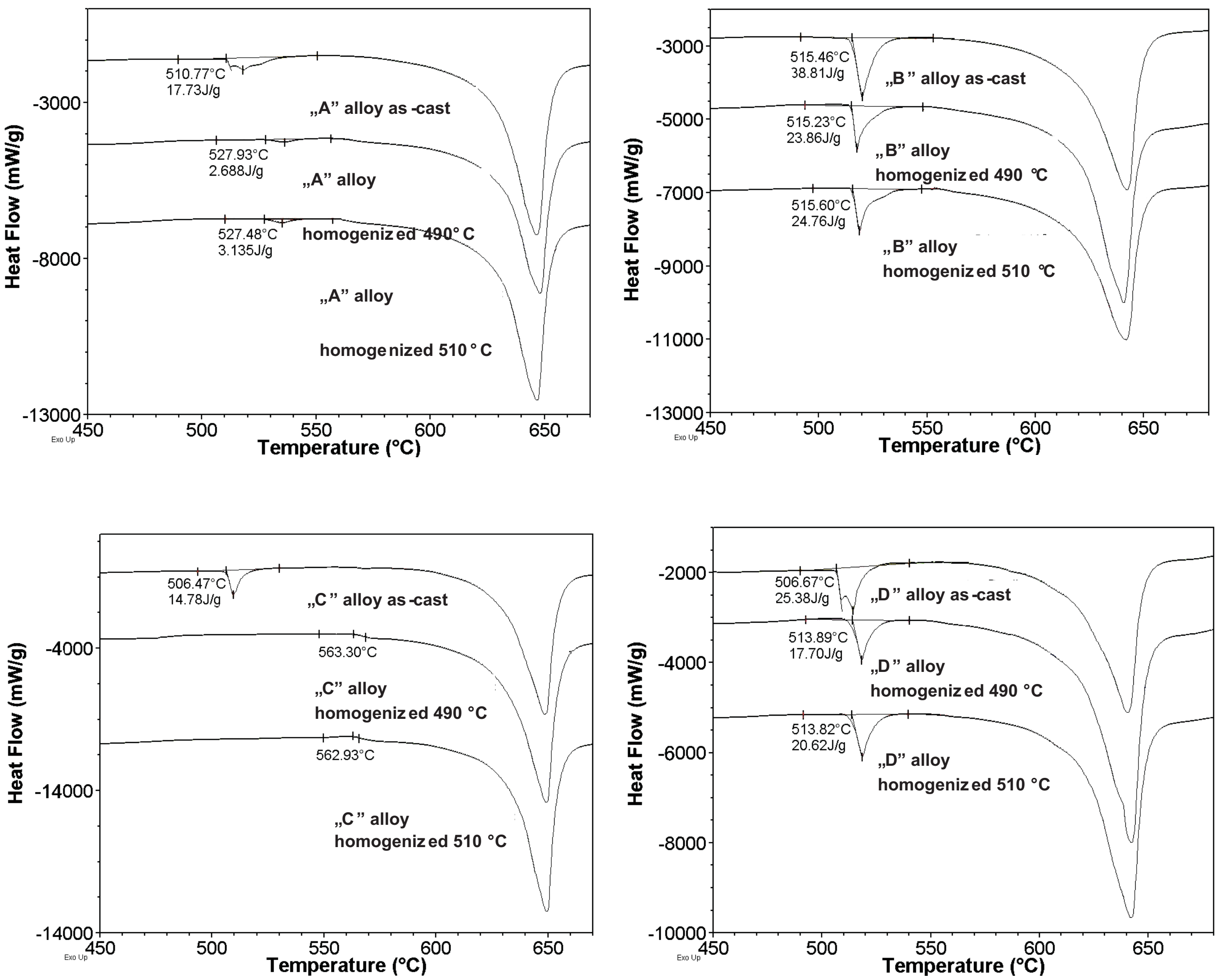


Fig. 5. DSC analysis results of the as-cast and as-homogenized 2014 and 2024 alloys;
a) 2014 alloy “A” b) 2014 alloy “B” c) 2024 alloy “C” d) 2024 alloy “D”

Figs 6-9 present the microstructures of 2014 and 2024 alloys with the lowest and highest permissible content of main alloy additions (Cu, Mg) – after casting, homogenization at the standard conditions and the high-temperature homogenization (495-510 °C for 18 h followed by slow cooling with a furnace and then by air cooling).

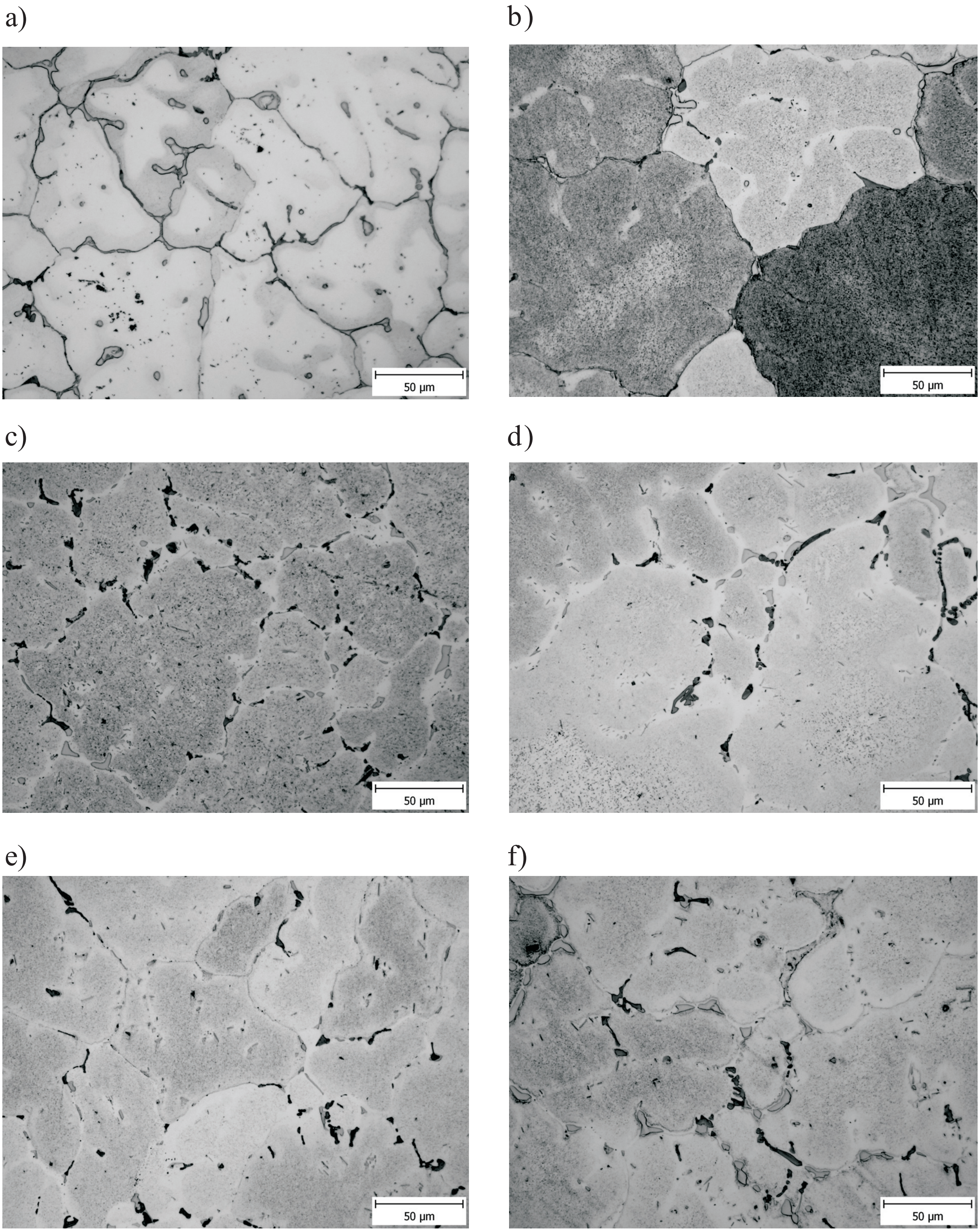


Fig. 6. Microstructures of 2014 alloy with the lowest permissible content of main alloy additions (“A” alloy);
(a) – as-cast, (b) – after standard homogenization 490 °C/16 h, (c) – homogenized at 495 °C/18 h, (d) – homogenized at 500 °C/18 h, (e) – homogenized at 505 °C/18 h, (f) – homogenized at 510 °C/18 h

One can notice that the undesirable microstructure with big particles of interdendritic phases was produced for alloys during casting process (6a-9a). Figures 6b-9b show that the application of traditional homogenization heat treatment after casting process leads to certain improvement in microstructure. More uniform structure with smaller particles of intermetallic phases is produced.

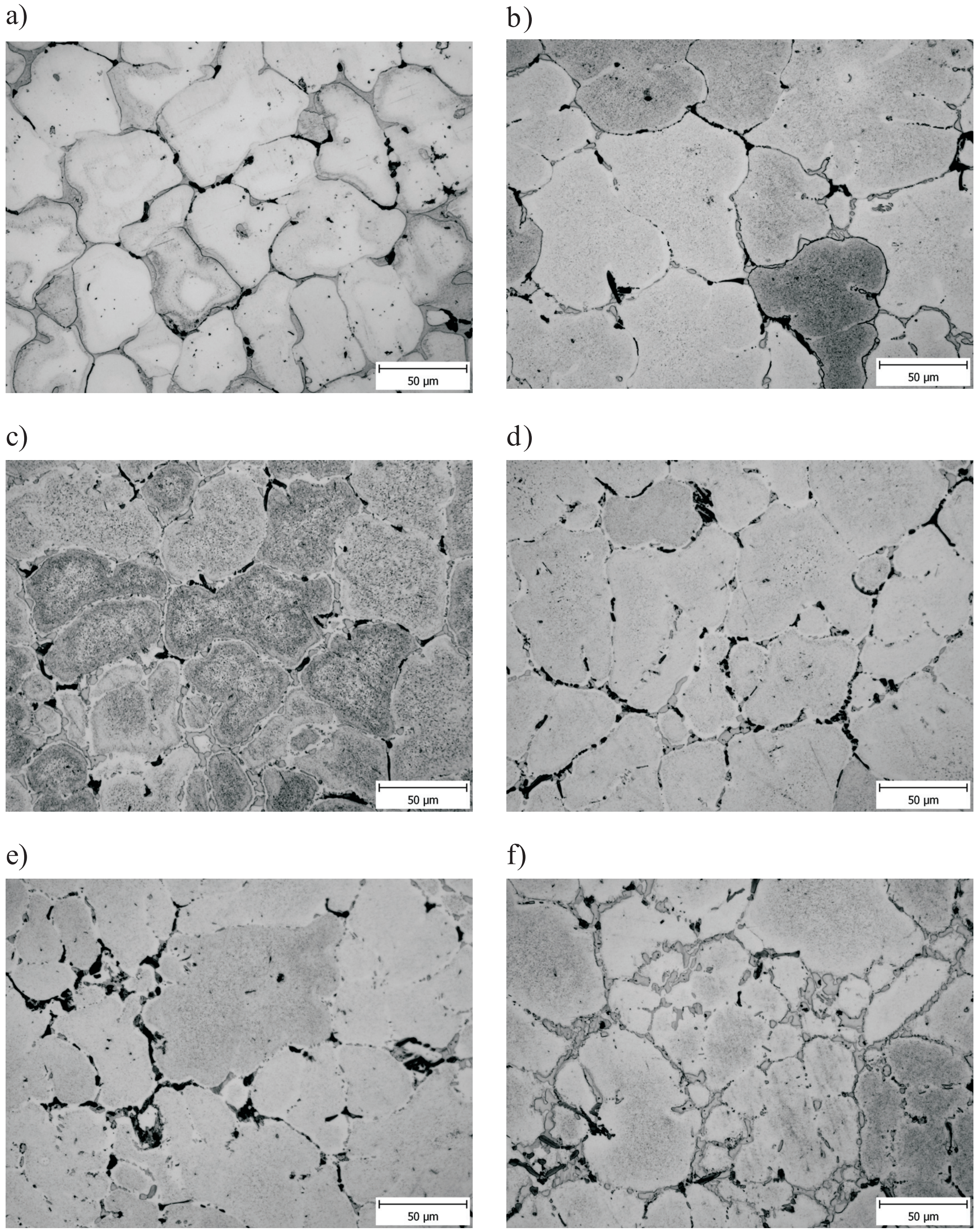


Fig. 7. Microstructures of 2014 alloy with highest permissible content of main alloy additions ("B" alloy); (a) – as-cast, (b) – after standard homogenization 490 °C/16 h, (c) – homogenized at 495 °C/18 h, (d) – homogenized at 500 °C/18 h, (e) – homogenized at 505 °C/18 h, (f) – homogenized at 510 °C/18 h

Minimizing the content of the alloy additions and conducting the homogenization at high temperatures – 500 °C for the 2014 alloy and 500-505 °C for the 2024 one, contribute to the formation of uniform microstructure of the alloys with fine intermetallic particles (figs 6d and 8d-e), which can be easily dissolved within deformation zone during extrusion.

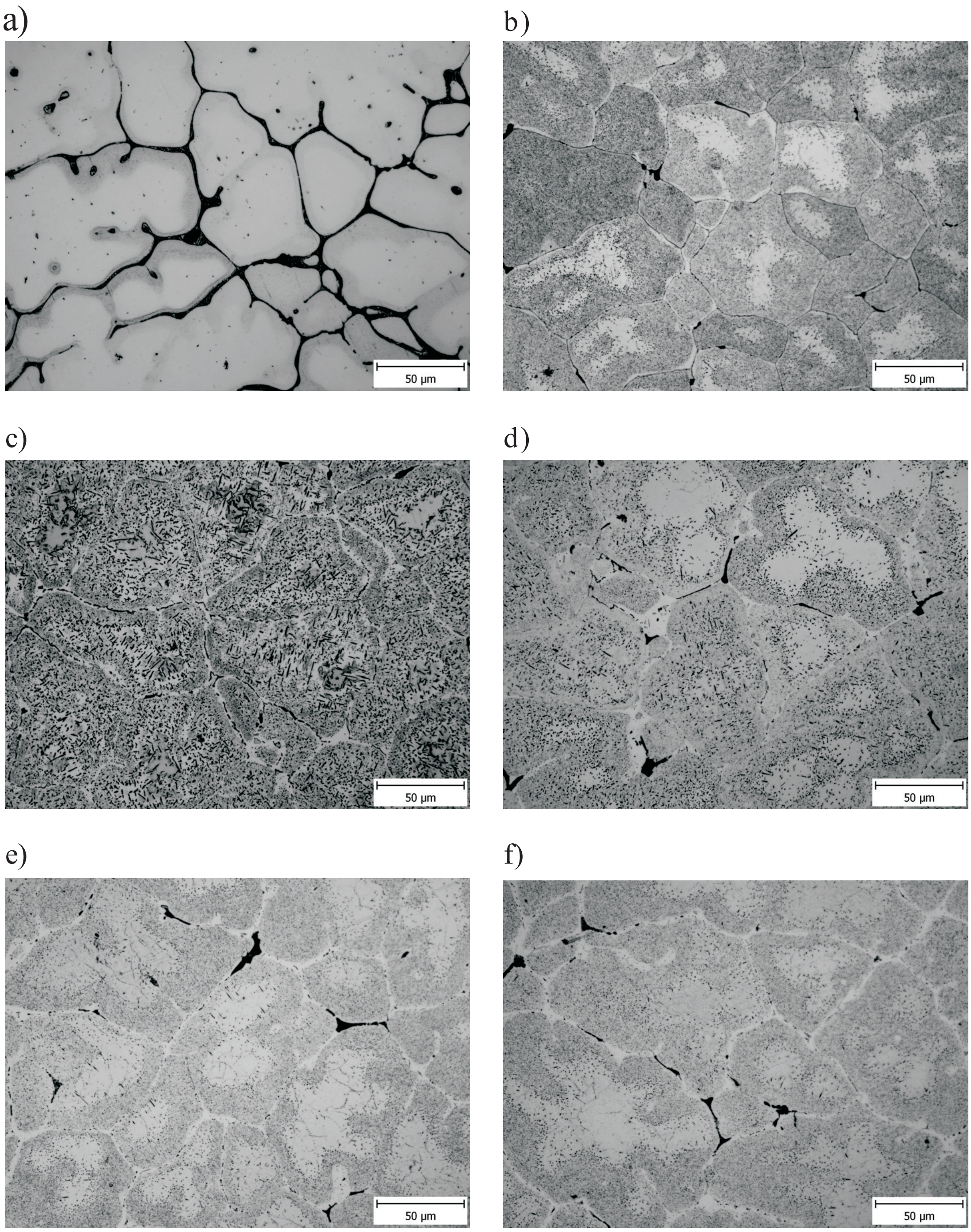


Fig. 8. Microstructures of 2024 alloy with lowest permissible content of main alloy additions (“C” alloy);
(a) – as-cast, (b) – after standard homogenization 500 °C/15 h, (c) – homogenized at 495 °C/18 h, (d) – homogenized at 500 °C/18 h, (e) – homogenized at 505 °C/18 h, (f) – homogenized at 510 °C/18 h

Because of such ingots treatment, the more effective solution heat treatment at the press output and increased strength properties of extrusions in T5 temper is expected. Minimizing the content of main alloys additions (Cu, Mg) should lead to an increase in metal exit speed (the process outlay), what also contributes to the improvement in efficacy of solution heat treatment at the press output for typically used water wave devices.

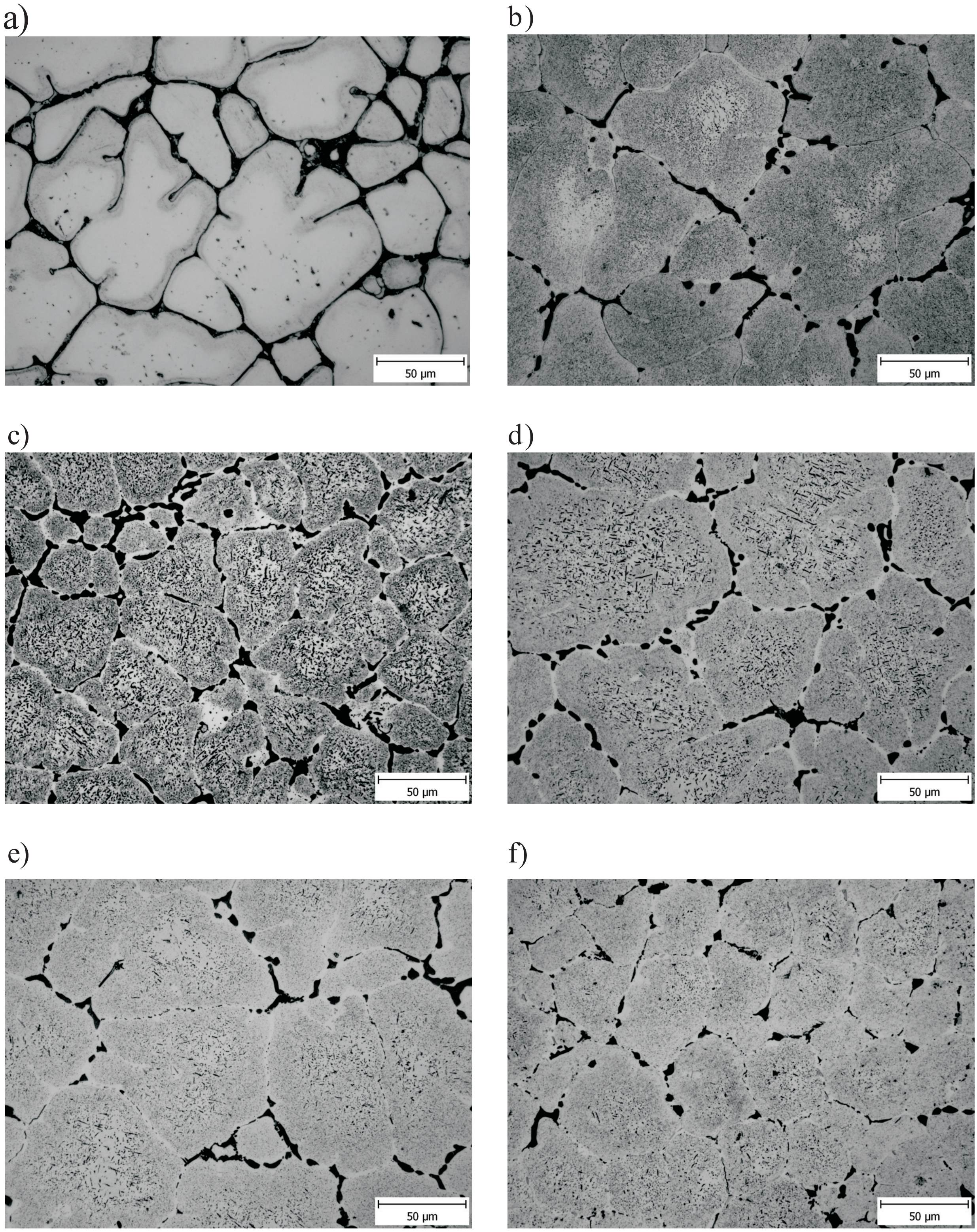


Fig. 9. Microstructures of 2024 alloy with highest permissible content of main alloy additions ("D" alloy); (a) – as-cast, (b) – after standard homogenization 500 °C/15 h, (c) – homogenized at 495 °C/18 h, (d) – homogenized at 500 °C/18 h, (e) – homogenized at 505 °C/18 h, (f) – homogenized at 510 °C/18 h

This is of great importance when extruding hard deformable AlCuMg alloys with the low exit speeds. Taking into consideration the constructional limits of today “water wave” devices (large distance between the die exit and water container), the increased metal exit speed should also contribute to some improvement in efficacy of the solution heat treatment at the press output. Apart from higher strength properties of extrusions, the improvement in material yield in technological process is likely.

However, the increased extrusion speed is also associated with a shorter time for diffusion processes, which is responsible for the dissolution of the particles of intermetallic phases in the main deformation zone. Nevertheless, it seems that for such range of the low extrusion speeds of AlCuMg alloys this factor is probably of less importance.

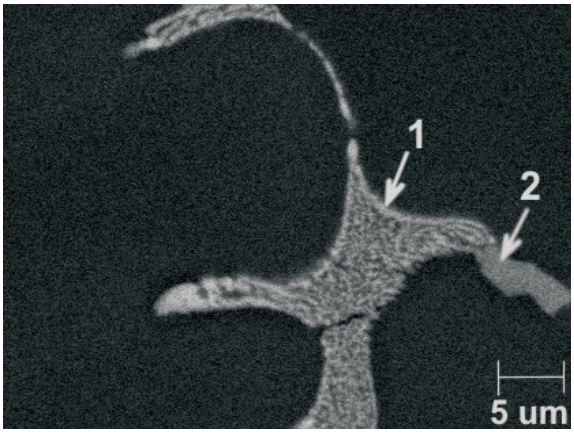
Based on the SEM/EDS results (figs 10-11), an attempt was made to identify the observed phases in the structure of as-cast and as-homogenized 2014 (fig. 10) and 2024 (fig. 11) alloys.

In the case of 2014 alloy with minimal content of Cu and Mg (both for the as-cast and as-homogenized alloy), the occurrence of particles of a phase containing mainly Al and Cu (in proportion of 2:1) was confirmed, what allow us to suppose that the particles constitute the Al_2Cu phase. Moreover, the particles of a phase containing Al, Mn, Cu, Fe and Si were also found.

For the highest permissible content of Cu and Mg in 2014 alloy in the as-cast state (fig. 10a) the Al_2Cu phase was not observed. The eutectic containing Al, Cu, Mg, Si as well as particles of a phase containing Al, Fe, Si and Cu were found. In specimens after homogenization process (fig. 10b), the presence of Al_2Cu phase and phase containing Al, Mn, Cu, Si and Fe was confirmed. However, the mentioned above eutectic was not observed. It is supposed that it was dissolved during homogenization process.

Regarding 2024 alloy with minimal content of Cu and Mg in as cast state (fig. 11 a), the eutectic including Al, Cu and Mg was observed. In case of homogenized specimens (fig. 11 a) only particles of a phase containing Al, Cu, Mn and Fe were found.

a)



2014, composition B, as cast

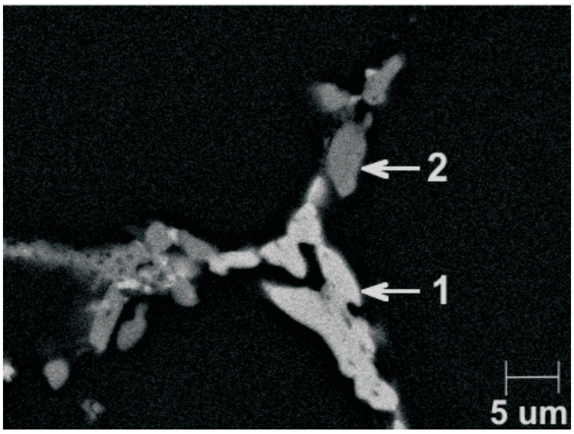
eutectic 1 analysis:

Element	Concentration, wt%	Error 2σ
Mg	3,0	0,5
Al	56,8	2,1
Si	2,9	0,6
Fe	0,3	0,3
Cu	37,0	4,4

particle 2 analysis:

Element	Concentration wt%	Error 2σ
Mg	0,3	0,1
Al	76,8	2,4
Si	7,8	1,1
Fe	8,6	1,7
Cu	6,5	2,1

b)



2014, composition B, homogenized (max. temperature 490 ^{0}C)

particle 1 analysis:

Element	Concentration, wt%	Error 2σ
Mg	0,3	0,1
Al	42,8	1,5
Si	0,3	0,1
Mn	0,5	0,2
Cu	56,0	3,9

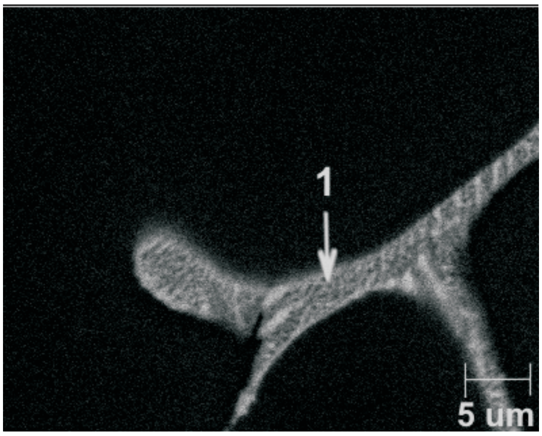
particle 2 analysis:

Element	Concentration, wt%	Error 2σ
Mg	0,6	0,2
Al	60,2	1,6
Si	6,5	0,6
Mn	20,6	1,6
Fe	3,5	0,7
Cu	8,6	1,6

Fig. 10. Microstructures of 2014 alloy with highest permissible content of main alloy additions (“B” alloy), with chemical analysis in micro-areas;
(a) – as-cast, (b) – after standard homogenization 490 °C/16 h

In the case of as cast 2024 alloy with the upper permissible content of the main alloy additions, the eutectic containing Al, Cu, Mg and two different kinds of particles (containing Al, Cu, Mn, Fe and Al, Cu, Mg respectively) were observed. After homogenization process, the eutectic was no present, but only particles of phases with elements mentioned above (the proportions indicate that is probably the Al_2CuMg phase).

a)

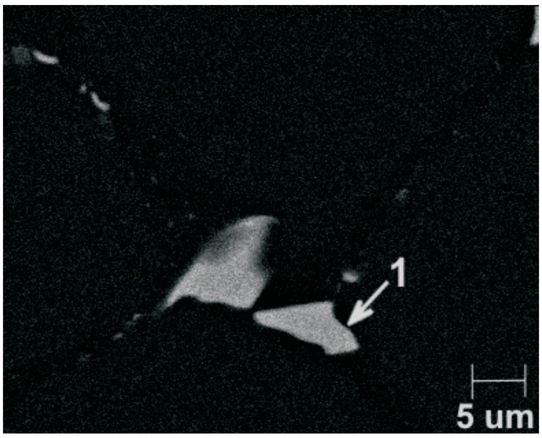


2024, composition C, as cast

eutectic 1 analysis:

Element	Concentration, wt%	Error 2σ
Mg	4,7	0,6
Al	56,0	2,0
Cu	39,2	4,2

b)



2024, composition C, homogenized (max. temperature 490 °C)

particle 1 analysis:

Element	Concentration wt%	Error 2σ
Mg	0,2	0,1
Al	64,4	1,9
Si	0,8	0,3
Mn	12,1	1,1
Fe	7,4	0,9
Cu	15,1	1,8

Fig. 11. Microstructures of 2024 alloy with lowest permissible content of main alloy additions (“C” alloy), with chemical analysis in micro-areas;
(a) – as-cast, (b) – after standard homogenization 500 °C/15 h

The influence of the homogenization temperature and alloy composition on the material hardness (Brinnel hardness HB) after homogenization is shown in figure 12. The minimum hardness was found for material homogenized at 495 °C for all alloy compositions. The hardness of the alloy homogenized at higher temperatures (500-515 °C) was nearly the same as that after standard homogenization (490 °C). In the case of the homogenized 2014 alloys, a little higher values of hardness were found for alloy with upper contents of Cu and Mg additions (compared to that with minimal alloy additions), whereas nearly no difference in hardness was found for the homogenized 2024 alloys with different addition content.

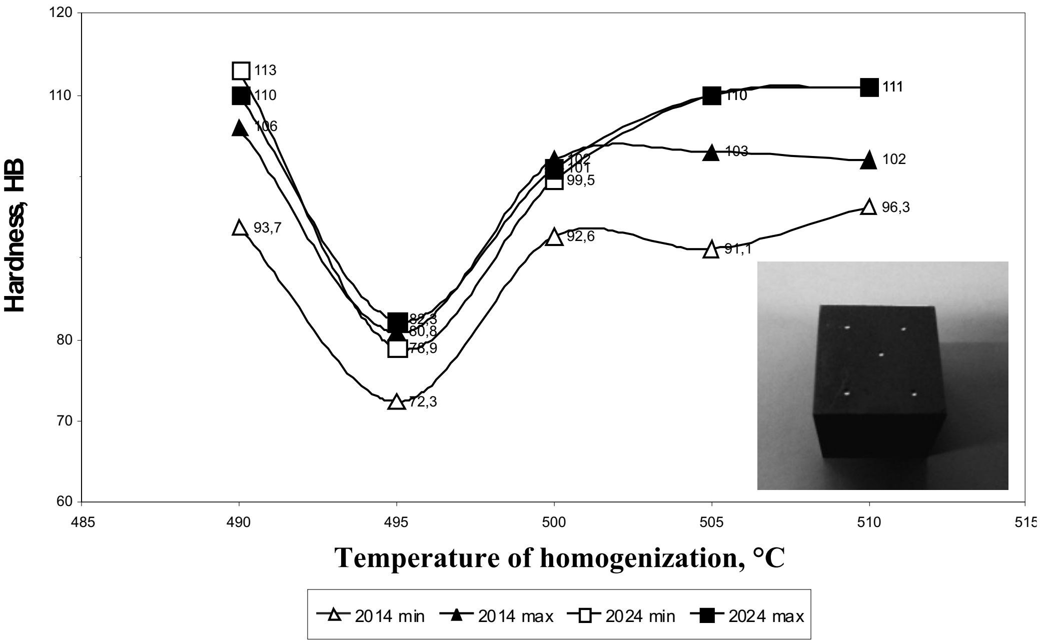


Fig. 12. Influence of alloy composition and homogenization temperature on the HB hardness of 2014 and 2024 alloys with lowest and highest permissible content of main alloy additions

The performed investigations permitted to tentative verification of the homogenization temperatures of analyzed AlCuMg alloys intended for extrusion in the T5 temper. Further, qualitative investigations are needed to determine the optimal homogenization time and cooling rate after homogenization for the minimized alloys compositions. The proper selection of extrusion and quenching parameters also has to be taken into consideration.

4. Summary

Based on the performed investigations of homogenization of AlCuMg alloys intended for extrusion with a solution heat treatment at the press output, the following conclusions can be drawn:

(1) The high-temperature homogenization with slow multi-degree heating and slow cooling with a furnace after homogenization allowed obtaining structure without any over-melting, which would unfavourably affect extrudates quality. It was revealed that such a treatment is possible even for homogenization temperatures close to the solidus temperatures of the analyzed alloys. Higher homogenization temperatures can be applied for alloys with minimal additions content (Cu, Mg).

(2) Optimal homogenization temperatures were found for the analyzed alloys – 500 °C for the 2014 alloy and 500-505 °C for the 2024 alloy, ensuring good uniform microstructure with fine particles of the intermetallic phases, which can be easily dissolved within the deformation zone during extrusion. Because of the proposed ingot treatment, the more effective solution heat treatment at the press output and increased strength properties of extrusions in T5 temper are expected.

(3) For the highest analyzed homogenization temperature of 510 °C, the big particles of different intermetallic phases nucleate on the grain boundaries.

(4) It was shown that minimizing the content of Cu and Mg contributes to considerable increase of solidus temperatures of analyzed alloys (especially for 2024 alloy). This will allow obtaining relatively high temperatures of extruded alloys at the press output (during solution heat treatment), without the risk of approaching the melting temperature of extrusions.

(5) There is nearly no difference in hardness between alloys homogenized at standard temperature (490 °C) and at temperatures in the range of 500-515 °C. However, for homogenization temperature of 495 °C, the minimum of hardness was found for all homogenized alloys.

Acknowledgements

The Polish Ministry of Science and Higher Education supported this work under the project No. PBZ-MNiSW – 3/3/2006. The authors would like to thank Dr Beata Leszczynska from AGH University of Science and Technology for their help in the research.

REFERENCES

[1] K. Laue, H. Stenger, Extrusion, ASME, Metals Park, Ohio, 1981.

[2] ASM Handbook: Aluminum and Aluminum Alloys, ASM International, 1993.

[3] B. Dixon, Extrusion of 2xxx and 7xxx alloys, Aluminum Extrusion Technology Seminar ET 2000, 281-294 (2000).

[4] D. Leśniak, Structure and mechanical properties of extruded AlCuMg sections in T5 temper, Archives of Metallurgy and Materials **54**, issue 4/09 (2009).

[5] J. Senderski, L. Pierewicz, B. Plonka, Technology, devices and control of the solution heat treatment process on the press of extruded sections 2xxx and 6xxx, Rudy i Metale, R.47 2002 nr 6, 284-288 (2002).

[6] L. Bäckerud, E. Król, J. Tamminen, Solidification Characteristics of Aluminum Alloys t.1: Wrought Alloys, Skan Aluminium, 3-156, 1986.

[7] G. E. Totten, D. S. MacKenzie, Handbook of Aluminum Physical Metallurgy and Processes **1**, 385-480 (2003).

[8] 8) M. Plata, C. Bagnoud, Modern precise high-power water cooling systems for press quenching, Aluminium Extrusion 1/06, 7-13 (2006).

[9] C. Kramer, Intensive cooling of light metal alloy extrusion by air and water, Aluminum Extrusion Technology Seminar ET 2000, 397-407 (2000).

[10] U. Gunter, Intensive air cooling of extrusions, Aluminium **80**, 426-432 (2004).

Received: 10 December 2010.