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Casting small-diameter ingots from multicomponent silumins

Odlewanie wlewków o małych średnicach z siluminów wieloskładnikowych

Abstract

The casting of ingots from aluminum alloys with a small range of solidification temperatures currently poses no major technical problems. On the other hand, problems do occur when multicomponent alloys containing elements such as Cu, Zn, or Mg are cast. This applies to alloys both wrought and cast. For these alloys, the differences in temperature starting and ending the solidification process reach 160°C. The difficulties are even more pronounced when the diameter of the cast ingot is less than 100 mm. Casting small-diameter ingots requires a very careful selection of parameters, which – for ingots with a diameter of about 70 mm – usually involve very high casting rates of up to 400 mm/min. The formation of a subsurface zone in the ingot along the crystallizer working length of several centimeters is very difficult at such a high casting rate and requires the precise determination of parameters for each alloy, particularly if this is a multicomponent alloy with a wide range of solidification temperatures. To this family of alloys belong multicomponent silumins, with the special case of phosphorus-modified near-eutectic and hypereutectic systems. Below are the results of technological tests as well as structure examinations of ingots cast from silumins with different ranges of solidification temperatures. Ingots of 100-mm diameters were cast in a vertical system. In this arrangement, ingots with a diameter of 70 mm were also cast, using crystallizers normally operating in a horizontal continuous casting line.

Keywords: silumins, structure, VDC ingot casting

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Streszczenie
Odlewanie we wlewki stopów aluminium o małym zakresie temperatur krzepnięcia nie stwarza obecnie większych problemów technicznych. Trudności występują w przypadku odlewania stopów wieloskładnikowych zawierających takie pierwiastki jak Cu, Zn, Mg. Dotyczy to zarówno stopów do przeróbki plastycznej, jak i odlewniczych. Dla tych stopów różnice pomiędzy temperaturą początku i końca krzepnięcia dochodzą do 160°C. Dodatkowo trudności zwiększają się w przypadku odlewania wlewków o średnicach poniżej 100 mm. Proces odlewania wlewków o małej średnicy wymaga bardzo starannego doboru parametrów, co wiąże się z bardzo dużymi szybkościami odlewania dochodzącymi do 400 mm/min dla wlewków o średnicy około 70 mm. Utworzenie strefy przypowierzchniowej wlewka na kilkucentymetrowej długości roboczej krystalizatora, przy tak wysokich szybkościach odlewania, jest bardzo utrudnione i wymaga precyzyjnego ustalenia parametrów dla każdego stopu, a zwłaszcza dla stopów wieloskładnikowych o szerokim zakresie temperatur krzepnięcia. Do takich stopów zaliczane są siluminy wieloskładnikowe, wśród których szczególnym przypadkiem są siluminy około- i nadeutektyczne modyfikowane fosforem. W artykule zaprezentowano wyniki prób technologicznych oraz wyniki badań struktury wlewków odlanych z siluminów, różniących się zakresem temperatur krzepnięcia. Wlewki o średnicy 100 mm odlewane były na linii do odlewu pionowego. W tym układzie odlewano także wlewki o średnicy 70 mm, z wykorzystaniem krystalizatorów przewidzianych do linii odlewu ciągłego poziomego.
Słowa kluczowe: siluminy, struktura, odlewanie wlewków VDC

1. Introduction

Modern industrial technologies allow the casting of wrought aluminum alloys in a vertical semi-continuous system as well as a horizontal continuous system. Horizontal casting of ingots with small diameters is economically and technically viable. Alloys designed for re-melting, which so far have been produced in the form of bars, are more and more often manufactured by means of the continuous casting method. The Institute of Non-Ferrous Metals, Light Metals Division (IMN-OML) in Skawina has been carrying out research for many years on the vertical (semi-continuous) and horizontal (continuous) casting of ingots.

With single crystallizers available, horizontal casting was mainly applied to ingots of 80-, 70-, and 60-mm diameters (including wrought 6XXX series alloys and the AlCu4Mg1 alloy [1, 2]). As a result of the studies, numerous innovations and improvements were introduced, particularly to the design of the crystallizer.

Casting of multicomponent alloys into ingots with small diameters requires a proper selection of parameters and maintaining at a constant level throughout the entire casting process. In the case of low-capacity casting lines (and such equipment is most often available in research laboratories), a major problem is the significant drop of temperature in metal supplied from the furnace to the casting unit. The use of well-insulated and preheated metal supplying runners does not always guarantee a constant temperature of metal maintained in the casting zone, while a small volume of the melt speeds up metal oxidation on its way to the distributor. The easiest way to ensure a constant temperature level in the distributor is by increasing the volume of metal supplied, which means more ingots cast simultaneously. This solution was adopted in the design of a prototype horizontal casting line.

The research described in this article represents the first stage of the work, the aim of which is to determine the possibility of casting ingots from multicomponent silumins and check for the correct operation the newly-designed 70-mm-diameter crystallizer to be used as a part of the line for horizontal casting.

In this study, tests were conducted on a vertical (semi-continuous) casting system using an AlSi7Mg alloy (according to PN-EN 1676), which was enriched with the addition of copper in subsequent tests in the amounts of 2 and 4 wt%.

This paper also presents the results of tests for the vertical casting of 100-mm-diameter ingots from an AlSi7Mg (Cu) alloy, an AlSi14Cu4Ni3Mg1 piston alloy (according to Federal Mogul), and an AlSi16Cu1Mg1Ni1 alloy of the composition close to LM 28 according to BS 1490.

The modification of primary silicon in the hypereutectic alloys was performed with a CuP8 master alloy.

2. Test results

2.1. Casting of ingots in a vertical semi-continuous system

The solidification point of the alloys tested was measured using an UMSA (Universal Metallurgical Simulator and Analyzer) apparatus. The measurement results are compared in Table 1.

Table 1. Solidification temperature ranges calculated for the studied alloys

Temperature [°C]	Alloy				
	AlSi7	**AlSi7Cu2**	**AlSi7Cu4**	**AlSi14Cu4Ni3Mg1**	**AlSi16CuNiMg**
Liquidus	617	612	606	619	632
Nucleation of the Al-Si eutectic	566	560	554	558	567
Solidus	540	496	496	487	507
$\Delta T = T_{lik} - T_{sol}$	77	116	110	132	125

The first trials were carried out using a 100-mm-diameter HOT-TOP crystallizer, starting from the AlSi7Mg alloy with the smallest solidification range. The pre-determined casting parameters served as a basis for the trial casting of other alloys, using crystallizers with a diameter of 100 mm (first) and 70 mm (next). In hypoeutectic alloys, the granular structure was refined with an AlTi5B1 master alloy added in an amount corresponding to 150 ppm of Ti. Hypereutectic alloys were modified with a CuP8 master alloy.

The quality of ingots was initially evaluated by surface appearance. Ingots with the best surface quality were sliced, and specimens from the slices were taken for microstructure examinations. Grains were disclosed by Barker's method, and average grain size was determined by the secant method on microphotographs taken along the diameter of the ingot.

2.1.1. Test results obtained for hypoeutectic alloys

Casting of 100-mm-diameter ingots

Samples of selected alloys were cast into ingots using a properly-adjusted casting speed and a temperature range of 660 to 670°C. Figures 1a and 1b shows images of selected ingot surfaces.

a)

b)

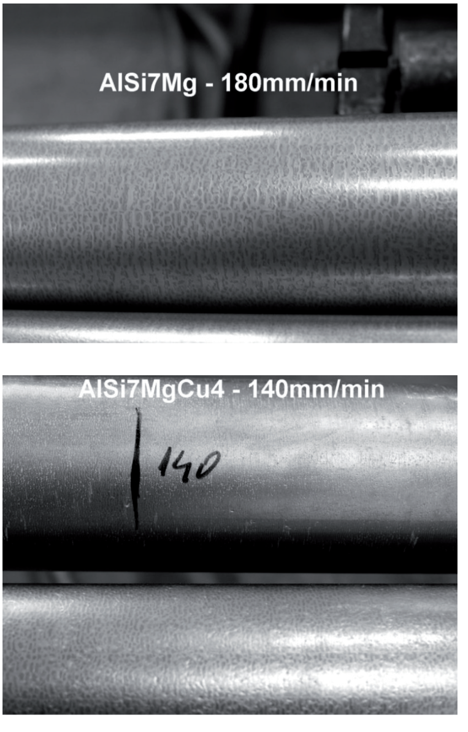


Fig. 1. Surface condition of 100-mm-diameter ingots: a) AlSi7Mg alloy; b) AlSi7MgCu4 alloy

Figures 2–4 depict grain size distribution as measured along the radius of ingots cast from the AlSi7Mg, AlSi7MgCu2, and AlSi7MgCu4 alloys. Photographs of microstructures are shown in Figures 5–8.

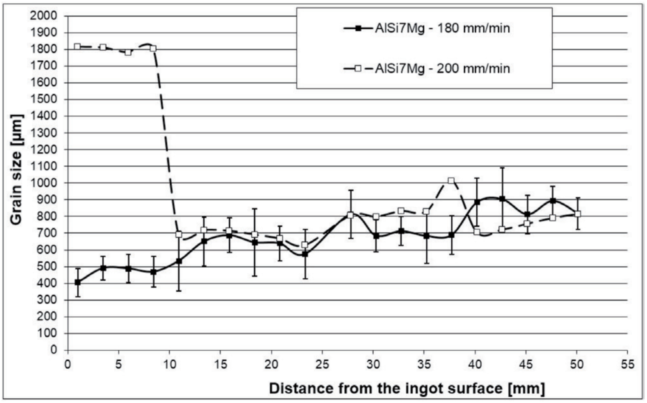


Fig. 2. Plotted graph of grain size distribution measured along the radius of the 100-mm-diameter ingots

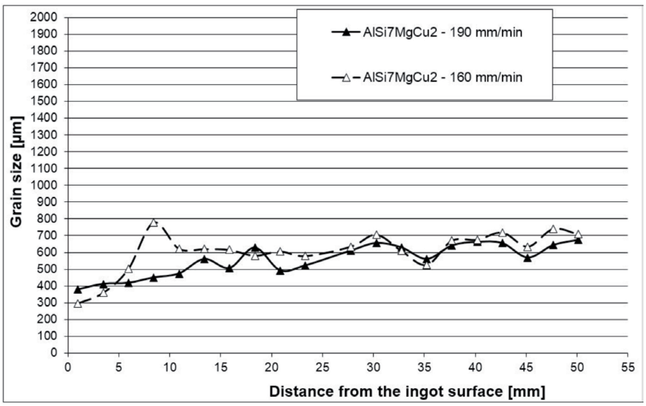


Fig. 3. Plotted graph of grain size distribution measured along the radius of the 100-mm-diameter ingots

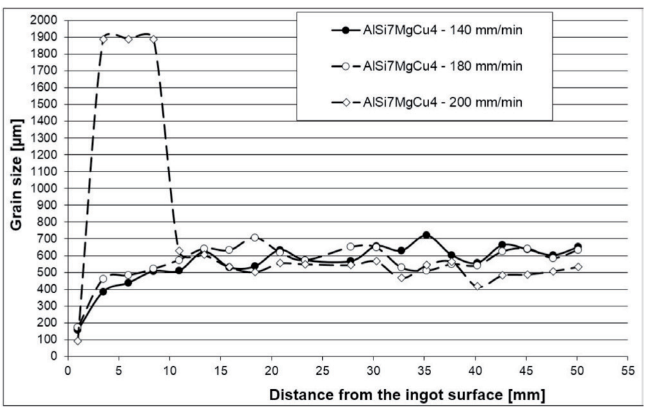


Fig. 4. Plotted graph of grain size distribution measured along the radius of the 100-mm-diameter ingots

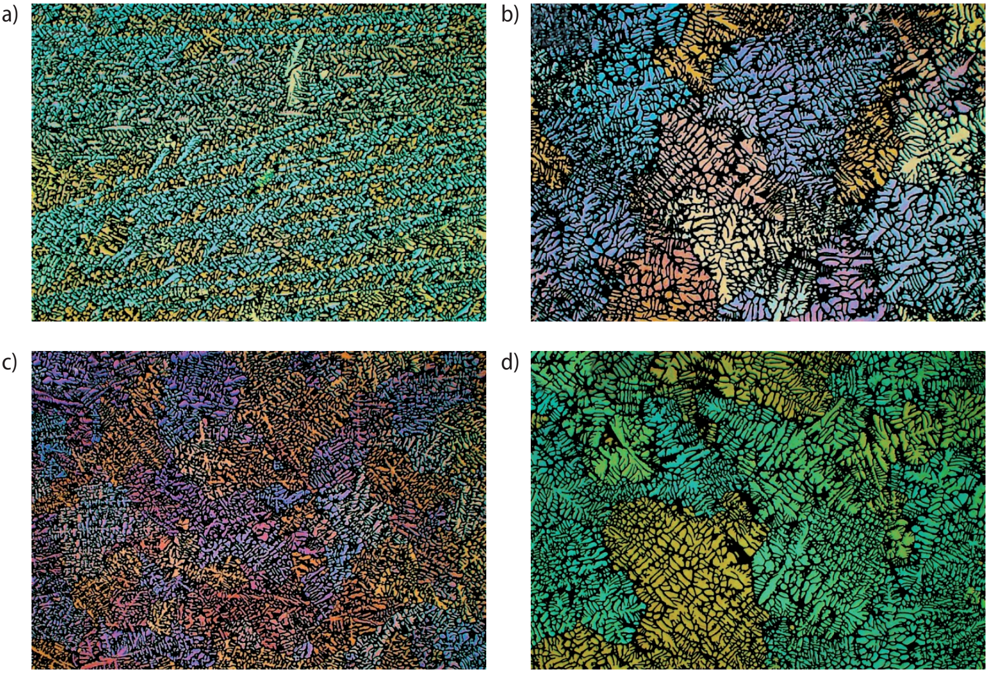


Fig. 5. Microstructure of the AlSi7Mg-alloy ingots: a) ingot edge, casting speeds 200 mm/min; b) ingot center, casting speeds 200 mm/min; c) ingot edge, casting speeds 180 mm/min; d) ingot center, casting speeds 180 mm/min

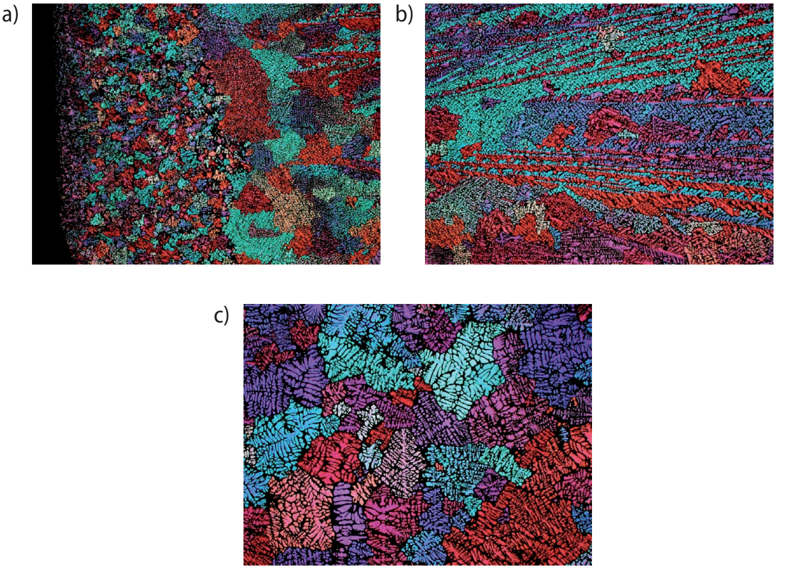


Fig. 6. Microstructure of the AlSi7MgCu4-alloy ingots – casting speeds 200 mm/min: a) ingot edge; b) ingot edge (5 mm); c) ingot center

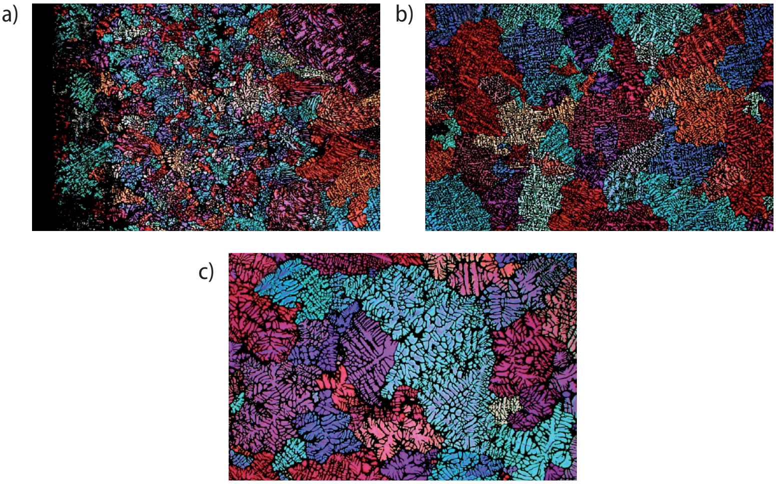


Fig. 7. Microstructure of the AlSi7MgCu4-alloy ingots – casting speeds 180 mm/min: a) ingot edge; b) ingot edge (5 mm); c) ingot center

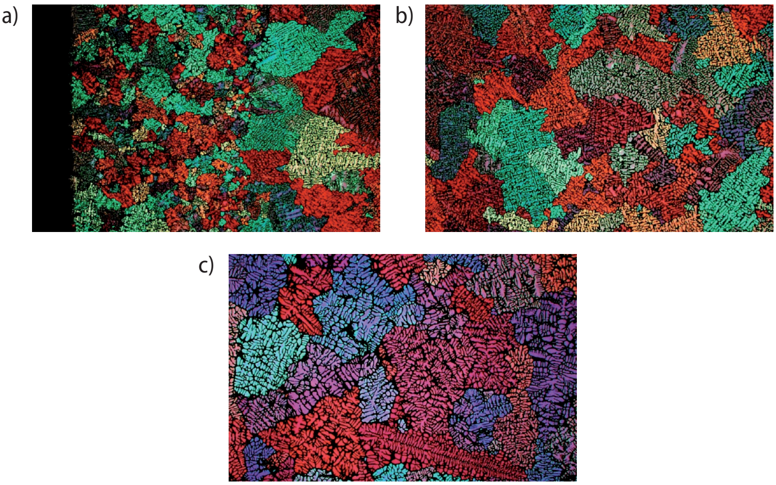


Fig. 8. Microstructure of the AlSi7MgCu4-alloy ingots – casting speeds 140 mm/min: a) ingot edge; b) ingot edge (5 mm); c) ingot center

Casting of 70-mm-diameter ingots

Alloys of AlSi7Mg, AlSi7MgCu2, and AlSi7MgCu4 were cast into 70-mm-diameter ingots in a sequence similar to the 100-mm-diameter ingots. Even the first casting trials of the AlSi7Mg alloy showed that the surface quality of the cast ingots was dependent on the oil lubrication effect rather than on the casting speed and metal temperature. The testing ranges and pre-established parameters of the vertical casting of ingots in 70-mm-diameter crystallizers are compared in Table 2. Images of the cast ingot surface can be seen in Figure 9.

Table 2. Parameters used for the vertical casting of silumins into 70-mm-diameter ingots

Alloy	Range of parameters	Metal temperature in distributor [°C]	Cooling water volume per crystallizer [l/min]	Casting speed [mm/min]
AlSi7Mg	reference	624–690	25–30	206–350
	target	**670**	**25**	**250**
AlSi7MgCu2	reference	608–670	25–33	190–250
	target	**650**	**26**	**250**
AlSi7MgCu4	reference	625–660	26	226–250
	target	**640**	**26**	**240**

a) b)

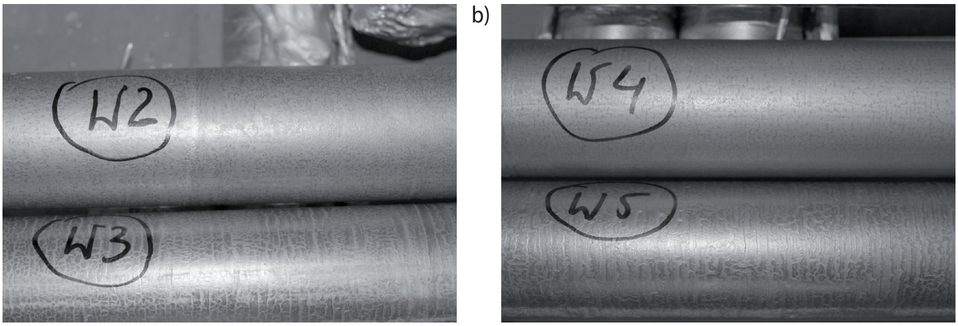


Fig. 9. Surface condition of 70-mm-diameter ingots: a) AlSi7MgCu2 Alloy; b) AlSi7Cu4 Alloy

2.1.2. Test results obtained for hypereutectic alloys

The modified microstructure of hypereutectic silumins is characterized by a uniform distribution of refined silicon. The modification of hypereutectic silumins occurs under the effect of aluminum phosphide introduced into the liquid metal either in the form of a pre-reacted master alloy or a master alloy containing other phosphides (which, due to an exchange reaction, form an AlP phase in the melt). These primary phases mainly include Cu_3P, Ni_3P, and Fe_2P. Analysis of the thermodynamic data as well as practical experience have shown that the formation of the AlP phase is much easier if, as a source of phosphorus, Ni_3P or Fe_2P compounds are used [3]. In the 1990s, patents were granted and production of a number of highly-efficient modifiers was started, allowing for continuous batching in the foundry process.

AlP phosphides obtained in the production process of the primary phases (such as Cu_3P, Ni_3P, and Fe_2P) enable effective and very fast silicon refinement at casting temperatures of approx. 730°C, even when the content is 40 ppm P [3, 4]. One of the first that were used was an AlCuP modifier prepared by pressing aluminum powder together with finelly-ground CuP. In industrial practice, this modifier is offered in the form of rods or pellets. Inducing the formation of aluminum phosphide in the alloy requires a heat treatment of this alloy, activating the exchange reaction that yields AlP. The effectiveness of such a modification was confirmed under laboratory and industrial conditions [4–8]. The use of a traditional CuP modifier (7–15%) requires maintaining the liquid metal temperature well in excess of 800°C, with vigorous stirring of the melt and a long holding time (Fig. 10). Figure 11 shows the impact that this type of modifier has on the size of the primary silicon precipitates [8].

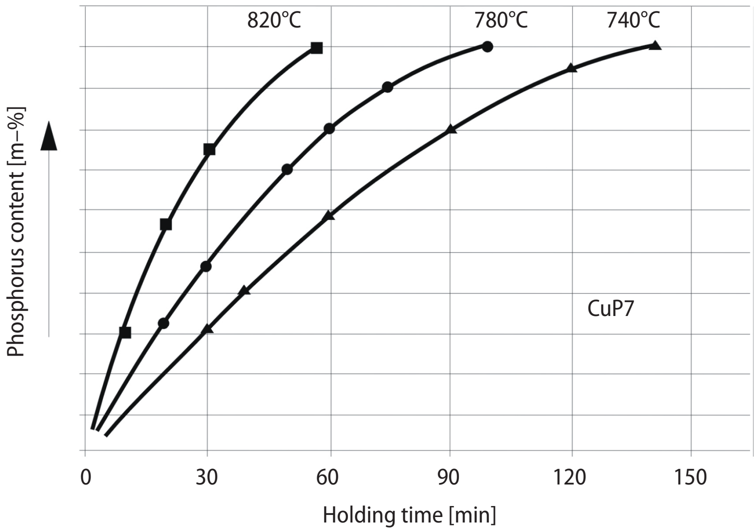


Fig. 10. The effect of metal temperature and holding time on phosphorus recovery from the CuP7 master alloy [4]

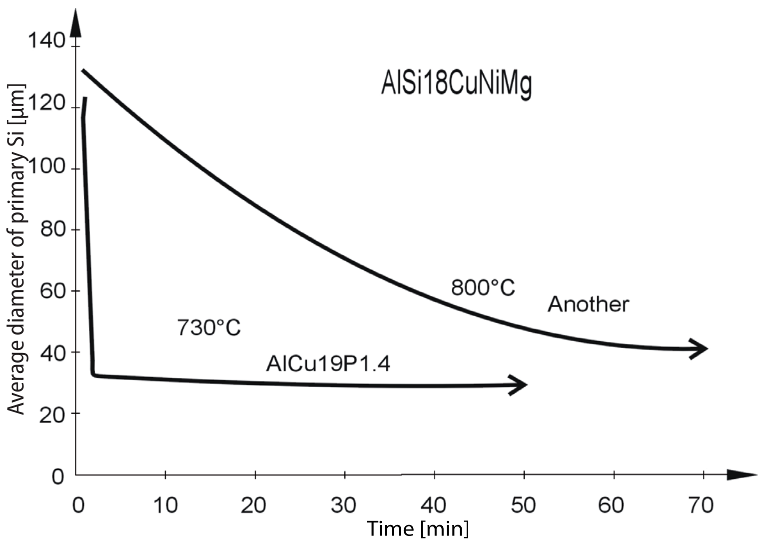


Fig. 11. The effect of different types of modifiers on the size of primary silicon precipitates [8]

In practice, the process commonly used involves modification with "phosphor copper" for economic reasons. Taking into account the advantages and disadvantages of various modifiers, it was decided to use as a modifier the CuP8 master alloy for the purpose of the present study.

The tested alloys were modified, taking into account the technical requirements of modern foundry processes, where the addition of phosphorus is used in a range from 35 to 110 ppm and the dimensions of primary silicon crystals do not exceed 50 μm.

2.1.2.1. Modification of the tested alloys

Trial casting of ingots from hypereutectic alloys was preceded by preliminary studies of the primary silicon modification process. These tests were carried out in a 50 kg Al capacity-induction furnace, from where samples were taken according to requirements of the TP-1 test. It was assumed that both alloying and holding would be conducted at a temperature of about 750°C (i.e., at a temperature much lower than in the common method of introducing phosphorus in the form of a master alloy. After the chemical composition stabilized, phosphorus was introduced into the alloy as a CuP8 phosphor copper in an amount of 100 ppm. Then, samples were taken every 10 minutes to determine the chemical composition. The results of measuring the concentration of phosphorus during the time of holding are plotted in Figure 12. The last two measurements were performed after raising the melt temperature to approx. 800°C. For structure examinations, alloy samples were taken from the melt before the addition of phosphorus as well as 20, 90, and 100 minutes after adding phosphorus. The microstructures of the samples are shown in Figure 13 together with the results of measurements of the size of the primary silicon precipitates. It has been found that the effectiveness of the introduced phosphorus was about 50%, which is comparable to the level obtained in the foundry industry. The presence of a modifier resulted in a significant reduction of the size of the primary silicon precipitates.

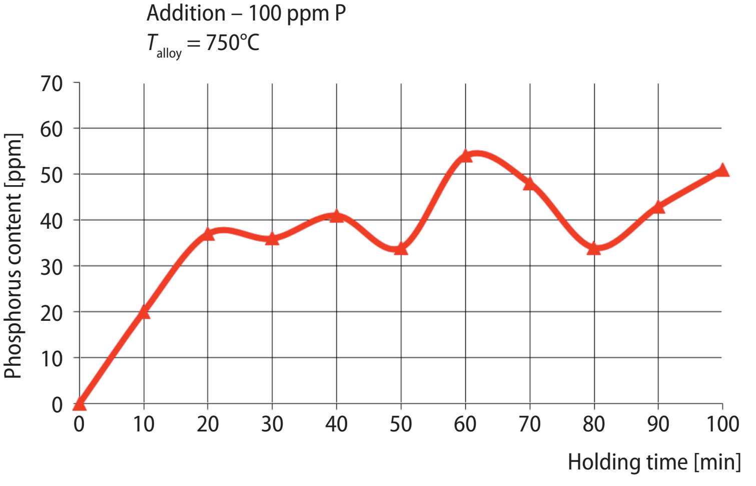


Fig. 12. The results of measurements of the phosphorus content during alloy holding

a) b)

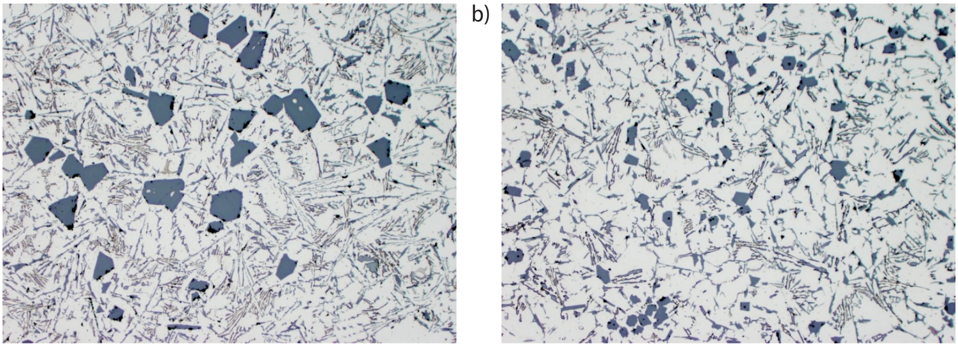


Fig.13. Microstructures of hypereutectic silumin: a) before modification (primary silicon d_{eq} = 36,6 μm); b) 20 min after modification (primary silicon d_{eq} = 16,5 μm)

2.1.2.2. Casting of AlSi14Cu4Ni3Mg1 alloy into 100-mm-diameter ingots

Given the positive results of the introduction of phosphorus at 750°C, an attempt was made to cast 100-mm-diameter ingots in a vertical system with two crystallizers. The first two ingots were cast without the addition of phosphorus. The casting parameters were as follows: $t_{furnace}$ = 725°C; water-cooling rate H_2O = 80 l/min; casting speed $V_{casting}$ = 170 mm/min. When these parameters were observed, ingots with satisfactory surface quality were obtained. The cast ingots were sampled for structural analysis, and the rest of the melt was modified with the addition of the phosphorus master alloy after raising the temperature to 750°C. The addition was converted to 150 ppm P. After 60 minutes of holding, the test samples were taken, the temperature was reduced to 725°C, and the next ingots were cast under similar conditions. Even if larger amounts of phosphorus were introduced, its final content was the same as in the preliminary experiments (i.e. approx. 50 ppm). Microstructures of cast ingots are presented in Figures 14 and 15, while the condition of the cast ingot surface is shown in Figure 16.

a) b)

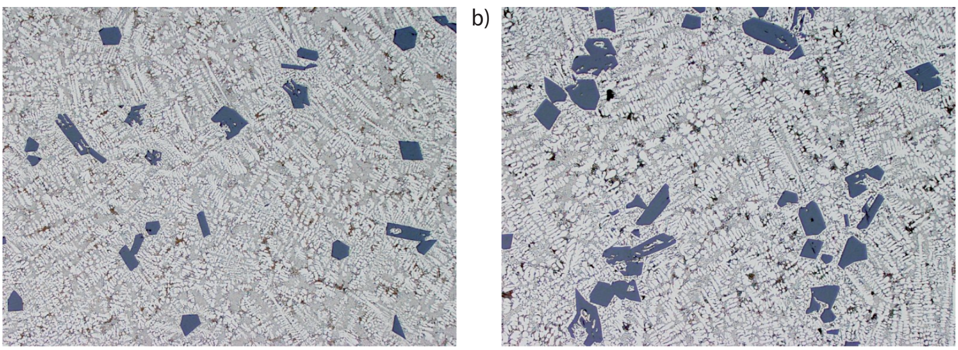


Fig. 14. Microphotographs of the ingot structure before modification: a) ingot edge d_{eq} = 55 μm; b) ingot center d_{eq} = 72 μm

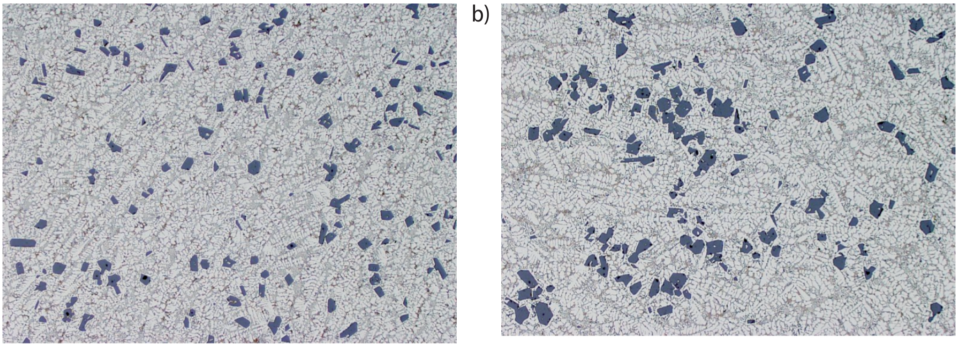
a) b)


Fig. 15. Microphotographs of the ingot structure after modification: a) ingot edge $d_{eq} = 30$ µm; b) ingot center $d_{eq} = 34$ µm

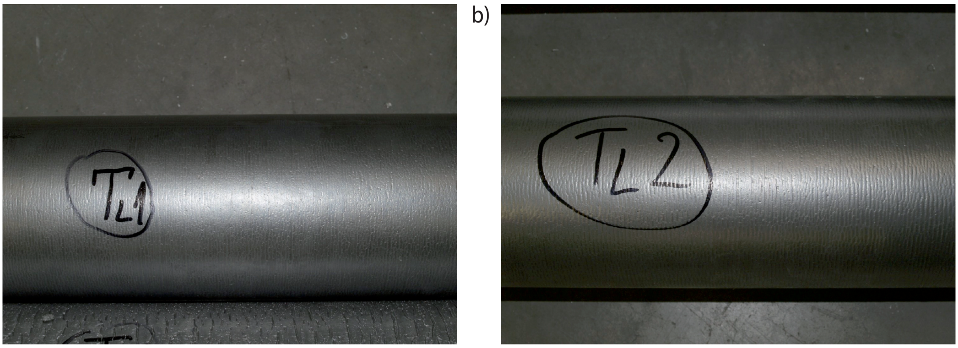
a) b)


Fig. 16. Surface condition of 100-mm-diameter AlSi14Cu4Ni3Mg1 ingots: a) before modification; b) after modification

2.1.2.3. Casting of AlSi16CuMgNi alloy into ingots of 100-mm diameters

Trials of casting the AlSi16CuMgNi alloy were conducted with the phosphorus addition introduced in the amount of 200 ppm. The main objective of the trials was to examine the possibility of reducing the metal temperature in the furnace and the subsequent impact on cast-ingot quality. The alloy was prepared and modified in a 300-kg-capacity furnace at a temperature of 800°C. Sixty minutes after the introduction of the master alloy, the phosphorus content reached only 70 ppm, rising to about 90 ppm after 90 minutes. After reducing the metal temperature in the furnace to approx. 760°C, several ingots were cast with the metal temperature evenly reduced from 695 to 640°C in the distributor. With the decreasing temperature of metal in the distributor, it was found that the size of primary silicon grains increased from 30 to 50 µm in the subsurface area, while in the center of the ingots, it was similar and amounted to approx. 60 µm (Fig. 17). Obtained under these conditions, the quality of the ingot surface was slightly inferior to the quality of the surface of the AlSi14 alloy ingots. Also, the primary silicon precipitates were larger in size.

a) b)

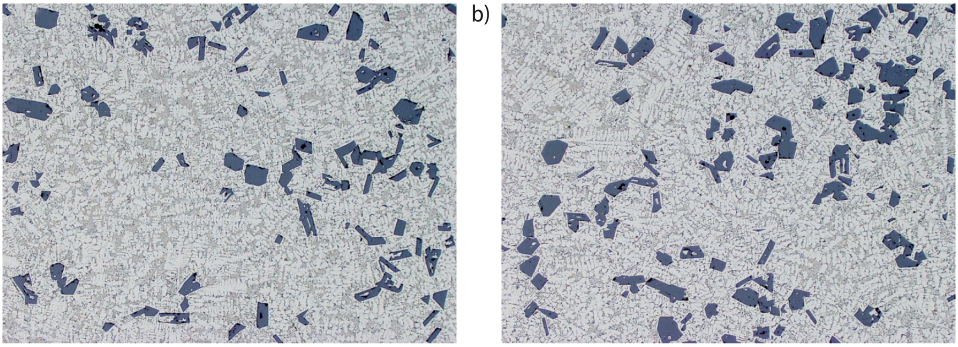


Fig. 17. Microstructure of the AlSi16CuMgNi-alloy ingot: a) ingot edge d_{eq} = 51 μm; b) ingot center d_{eq} = 60 μm

3. Discussion of results

Tests were conducted on five alloys from the family of hypo- and hypereutectic silumins. The study covered alloys with different ranges of solidification temperature. Preliminary tests were performed on a vertical line for the casting of alloys in HOT-TOP crystallizers with a diameter of 100 mm.

Hypoeutectic silumins with varying Cu content were cast at speeds ranging from 140 to 200 mm/min. Tests have shown that these alloys can be cast into ingots with a very fine surface quality. The studies of alloy microstructure revealed an increase in grain size in most cases along the radius from the ingot edge to the center. The exceptions were two alloys (AlSi7Mg and AlSi7MgCu4) cast at the highest speed of 200 mm/min. In these ingots, a subsurface zone with a thickness of approx. 1.5 mm was formed. It was composed of small grains and accompanied by a 10-mm-zone of elongated grains in many places of the twin structure (not observed at lower speeds of casting). The central part formed a zone of equiaxed grains with sizes comparable to those obtained at lower casting speeds. The probable reason for the formation of large grains was the reduced rate of solidification, due to the elongation of the crystallization pool.

As in the case of 100-mm-diameter ingots, tests were also conducted on ingots cast from the AlSi7Mg, AlSi7MgCu2, and AlSi7MgCu4 alloys in the new 70-mm-diameter crystallizers. Despite the small diameter of the crystallizers, it was possible to run the process in a wide range of both temperature and casting-speed values. By comparing different variants, parameters were identified at which the surface quality was best. These parameters (indicated in Table 2 as "targets" ones) will be the basis for studies of the horizontal casting process, performed in the next stage of work.

Examinations of the microstructure of sample ingots with 70-mm diameters showed significant heterogeneity in the subsurface zone. This zone was rich in low-melting phases, such as the silicon eutectic and copper phases. The observed area with a width of several to several hundred micrometers was depleted in the alpha solution to a degree much higher than was observed in the ingots with 100-mm diameters. Compared to 100-mm-diameter ingots, the 70-mm-diameter ingots showed a lack of typical grain refinement in the subsurface zone (Fig. 18). There was also no reduction of average grain size that might be expected in small diameter ingots cast at high speeds. It seems that the probable reason for this effect was a too-high ingot temperature when it was leaving the crystallizer (an insufficient rate of solidification).

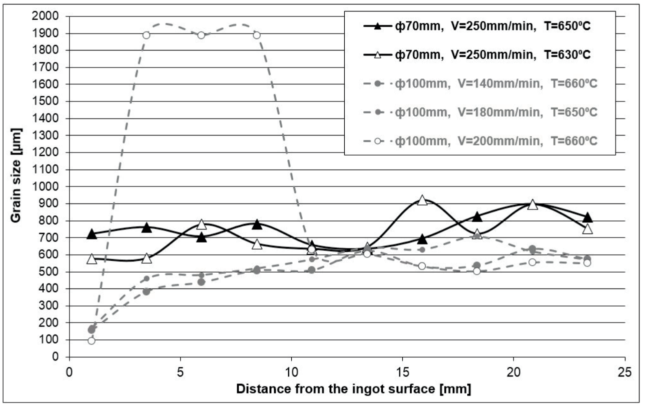


Fig. 18. Grain size distribution compared in 100-mm- and 70-mm-diameter ingots

This thesis is also supported by the occurrence of a "dull" subsurface zone with a width of approx. 3 to 7 mm on polished metallographic sections. This zone is characterized by the presence of coagulated Si precipitates with a shape characteristic of the heat-treated samples (Fig. 19a). Outside of this zone, the precipitates of silicon assume a fibrous shape, which is typical for silumins modified in F (untreated) condition – see Figure 19b. This result leads to the conclusion that the solidified outer zone has remained at an elevated temperature for a longer time, activating the process of eutectic-silicon coagulation. The study of the described effects should continue.

a) b)

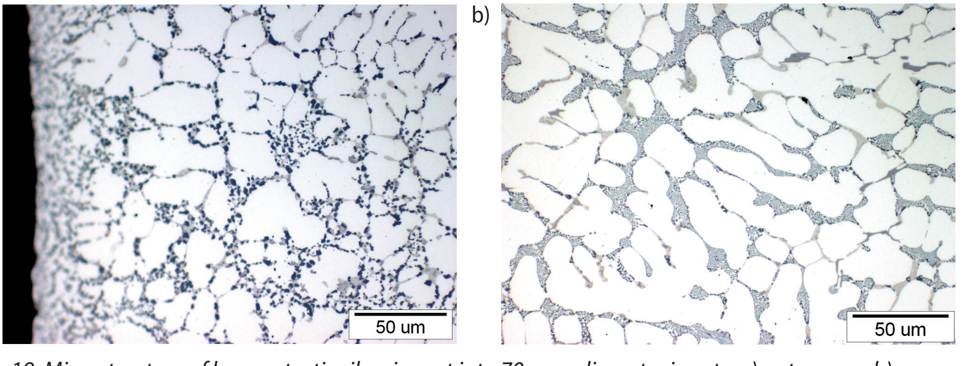


Fig. 19. Microstructure of hypoeutectic silumin cast into 70-mm-diameter ingots: a) outer zone; b) central zone

Trials of the vertical casting were also carried out on hypereutectic alloys using crystallizers with 100-mm diameters.

The alloying conditions were established for the hypereutectic silumins modified with phosphorus to allow the introduction of the required amount of phosphorus to the melt as well as reducing metal temperature to the level of the casting temperature. The results of the study showed that the effectiveness of the addition of phosphorus introduced to the alloys tested differed quite noticeably. Despite changes in the phosphorus addition introduced to the liquid alloy, its final amount in the cast ingot remained at a comparatively-low level; nevertheless, comprised within the limits defined by the requirements imposed onto the alloys for remelting.

In the alloys studied, a satisfactory result of primary silicon refinement was achieved. Tests have shown that it is possible to cast 100-mm-diameter ingots of satisfactory quality from multicomponent alloys containing 16% Si. There was no significant difference in the condition of the ingot surface before and after modification.

The increase in size of the primary silicon precipitates in ingots cast from the AlSi16CuMgNi alloy observed with the decreasing temperature of casting was probably caused by longer time, during which the metal was held at temperatures below the temperature of the silicon-phase nucleation.

Trials of casting small-diameter ingots from near- and hypereutectic alloys will continue.

4. Conclusions

The results of the study have showed that:

- Alloys with a wide range of solidification temperatures can be cast into small-diameter ingots while obtaining a satisfactory surface quality.
- Designed and commissioned for use, the new 70-mm-diameter crystallizers were tested in a vertical casting system using hypoeutectic alloys with varying copper content. By comparing different variants, parameters yielding the best surface quality were identified. These parameters (indicated in Table 5 as "targets") will make the basis for further research carried out on a horizontal casting line in the next stage of work.
- Examinations of the microstructure of sample ingots with 70-mm diameters showed significant heterogeneity in the subsurface zone. This zone was rich in low-melting phases (i.e., the silicon eutectic and copper phases).
- Conditions for alloying hypereutectic silumins modified with phosphorus were established, on the one hand allowing for the introduction of the necessary amount of phosphorus to the alloy, and on the other hand reducing the temperature of molten metal to the casting level.
- The results of the study showed that the effectiveness of the addition of phosphorus introduced to the tested alloys differed quite noticeably. Despite changes in

the phosphorus addition introduced to the liquid alloy, its final amount in the cast ingot remained at a comparatively-low level; nevertheless, comprised within the normal range. In the studied alloys, a satisfactory result of primary silicon refinement was achieved.
– There was no significant difference in the surface condition of ingots cast from hypereutectic alloys unmodified and modified with phosphorus.

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