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Arch. Metall. Mater. **64** (2019), 1, 113-118

DOI: 10.24425/amm.2019.126225

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MECHANICAL PROPERTIES AND FRACTURE ANALYSIS OF AlCu4MgSi ALLOY INGOTS OBTAINED BY HORIZONTAL CONTINUOUS CASTING

The article presents the results of research concerning AlCu4MgSi alloy ingots produced using horizontal continuous casting process under variable conditions of casting speed and cooling liquid flow through the crystallizer. The mechanical properties and structure of the obtained ingots were correlated with the process parameters. On the basis of the obtained results, it has been shown that depending on the cooling rate and the intensity of convection during solidification, significant differences in the mechanical properties and structure and of the ingots can occur. The research has shown that, as the casting speed and the flow rate of the cooling liquid increase, the hardness of the test samples decreases, while their elongation increases, which is related to the increase of the average grain size. Also, the morphology of the intermetallic phases precipitations lattice, as well as the centerline porosity and dendrite expansion, significantly affect the tensile strength and fracture mechanism of the tested ingots.

Keywords: AlCu4MgSi alloy, horizontal continuous casting, fracture analysis, mechanical properties of ingots, aluminum.

1. Introduction

Among the currently used engineering materials, metal alloys, ranging from steel and cast iron to non-ferrous alloys, are the most common. In that last group, a continuous upward trend in global production is maintained by aluminum alloys [1]. Aluminum owes its high popularity to its low density (2.6989 g/cm^3 at a temperature of 293 K), and, with appropriate alloying additions, it has a high strength-to-weight ratio. Aluminum alloys are used in the aerospace, automotive, chemical, energy and construction industries [2-4]. Due to its low shrinkage and good castability, aluminum is a good casting material and is a commonly used for composites matrix [2-3,5]. A large part of the global production of aluminum utilizes foundry technologies, such as gravity die casting, centrifugal casting, lost-wax casting, low- and high-pressure casting, to obtain final products. Casting technologies play also a key role in obtaining semi-finished products, made of aluminum and its alloys. Considering the various methods (such as casting, drawing, rolling, etc.) of manufacturing and processing of elements made of aluminum alloys, it is difficult to obtain the optimum structure and properties of those elements using only one of those methods. It is, therefore, important to choose the right technology, and to be able to shape the material structure already at the stage of production of semi-finished products, because this allows for improving the quality, and achieving significant cost savings in the whole production process. The technology of continuous casting has many advantages in this respect. In this process, the ingot is obtained by a controlled flow of molten metal through the crystallizer. The flowing metal, while dissipating heat through the walls of the crystallizer, changes its physical state from liquid to solid. Due to high efficiency, flexibility of parameter control, and the possibility of integration with other processes (e.g. plastic working, heat treatment), continuous casting is finding growing industrial applications. In addition to providing the ability to develop the structure of the cast metal, this process is characterized by lower energy consumption and reduced waste production, when compared to conventional foundry technologies [6-8].

2. Description of research

The aim of the presented research results is to determine the influence of the parameters of the horizontal continuous casting process on the mechanical properties and structure of the obtained AlCu4MgSi alloy ingots. This paper is presents extending investigations of previous research of the authors [9-10]. The determined mechanical properties and structure were correlated with the variable parameters (casting speed and flow rate of the cooling liquid in the primary cooling system) applied during the continuous casting process. Depending on the cooling rate, the intensity of convection during solidification of the alloy, and its chemical composition, there may occur significant differences in the structure and mechanical properties of the

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ingots. The obtained research results can be used to optimize the processes involved in the production of AlCu4MgSi (AW-2014) aluminum alloy profiles.

3. Material and methodology

AlCu4MgSi alloy ingots (EN AW-2017A), 30 mm in diameter, were produced using an aluminum alloys horizontal continuous casting test stand, located in the technological laboratory of the Department of Foundry Engineering at Silesian University of Technology. Chemical composition of AlCu4MgSi alloy is shown in table 1. Casting was carried out by means of sequential ingot extraction, with each consecutive cycle consisting of a pulling phase, of duration t_p, and a rest phase, of duration t_s, with the ratio of the duration times being $t_p / t_s = 1/2$. The velocity of the movement during the pulling phase (V_m) was in the range of 100 to 300 mm/min, which, taking into account the sequential movement of the ingot, allowed for obtaining average casting speed (V_a) in the range between 30 and 100 mm/min. The cooling water flow rate (Q) was in the range of 0.5 to 1.2 l/min., with the temperature of the liquid (T_w) between 45 and 55^{o}C. Obtained ingots (Fig. 1) were cut, and marked according to the applied process parameters (Table 2). The metallographic examination of the ingots was carried out using a Zeiss Axio Observer light microscope, utilizing polarized light and bright field observation techniques. The observations of ingot structure and fractures, as well as the chemical composition analysis in microareas, were performed with the use of a Phenom ProX scanning electron microscope (with EDS detector), and a Zeiss Supra 35 high resolution electron microscope, equipped with EDAX EDS chemical analysis system. The static tensile tests were carried out using a universal Zwick Roell Z100 testing machine, with a load capacity of 100 kN. The tests were conducted on two per each ingot, standard round, five-fold specimens, of initial diameter of 9 mm (L0 = 45 mm), while applying a strain rate of 15 MPa/s. Hardness tests were carried out using a Rockwell hardness tester Zwick/ZHR 4150 TK with ball indenter 1/16“ and automatic conversion to Brinell scale (HB). Hardness results were average values calculated from 10 measurement points per each ingot. The qualitative phase analysis of the ingots was based on X-ray diffraction measurements, performed with the use of a Panalytical X'Pert Pro MPD diffractometer, utilizing filtered radiation of a cobalt-anode lamp ($\lambda_{K\alpha}$ = 0.179 nm), and a PIXcell 3D detector on the diffracted beam axis. Diffraction lines were

Fig. 1. Fragments of AlCu4MgSi alloy ingots obtained in horizontal continuous casting process

TABLE 1

Chemical composition of AlCu4MgSi (EN AW-2017A) alloy

Material designation		Elements mass concentration [% wt]									
ISO:	**EN:**	**Element**	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**other**	**Al**
AlCu4MgSi	AW-2017A	min.	0,2	≤0,7	3,5	0,4	0,4	≤0,1	≤0,25	≤0,15	rest
		max.	0,8		4,5	1,0	1,0				—
		note: Zr + Ti ≤ 0,25									

TABLE 2

Parameters of horizontal continuous casting of AlCu4MgSi alloy ingots

Mark of ingots	t_p, [s]	t_s, [s]	V_m, [mm/min]	V_a, [mm/min]	Q, [l/min]	T_w, [^{o}C]	T_i, [^{o}C]
1	1	2	100	30	0,5	45÷55	150
2	1	2	120	40	0,7		170
3	1	2	150	50	0,9		190
4	1	2	180	60	0,9		210
5	1	2	210	70	1,0		230
6	1	2	240	80	1,2		250
7	1	2	270	90	1,2		270
8	1	2	300	100	1,2		300

recorded in the angular range of 20-120° [2θ], at step = 0.03° and count time per step = 80 s. Analyses were performed using Panalytical High Score Plus software with dedicated PAN-ICSD database.

4. Results and discussion

The structure of ingots obtained by using variable casting speeds and variable cooling liquid flow rates has been characterized on the basis of microscopic observations (Fig. 2) of their cross-sections. All tested ingots, regardless of the parameters used, characterized by dendritic structure, with precipitates of non-equilibrium phases. On the cross-sections, mostly equiaxed grains of irregular shapes, and a low number of small grains (chill crystals), located in the outer ingot zone, were found. In the previous research of the authors [9] where results of average grain size measurement were correlated with the ingots casting speed, has shown that, as the casting speed increases, the average grain size also increases. This relationship is related to the cooling rate, which decreases with the increase of the casting speed, which in turn affects the temperature gradient and convection intensity of the molten metal.

An examination of the ingots with the use of a scanning electron microscope (SEM) (Fig. 3-4) allowed for an assessment of the type and morphology of precipitates. The observed precipitates are mainly located in the interdendritic regions, and form a lattice of a complex shape. The analysis of the chemical composition in microareas showed that the observed precipitates are mainly intermetallic θ-Al_2Cu and β-Mg_2Si phases, and those results were also confirmed by X-ray diffraction (XRD) studies (Fig. 5). The results of ingot examination by means of the EDS technique (Fig. 6, Table 3) also indicate the occurrence of silicon precipitates and complex multi-component phases, presumably $Al_XSi_XMn_XFe_XCu_X$ and $Al_XCu_XMg_XSi_X$. The shape of the precipitates lattice depends to a certain extent on the casting speed applied. At lower speeds, there is a significant share of isolated precipitates of non-equilibrium phases, with shapes close to globular (Fig. 3). It can be assumed that the cause of the observed changes lies in the increase of the cooling rate, which results in an increased deviation from the equilibrium solidification conditions. Another important factor that may cause changes in

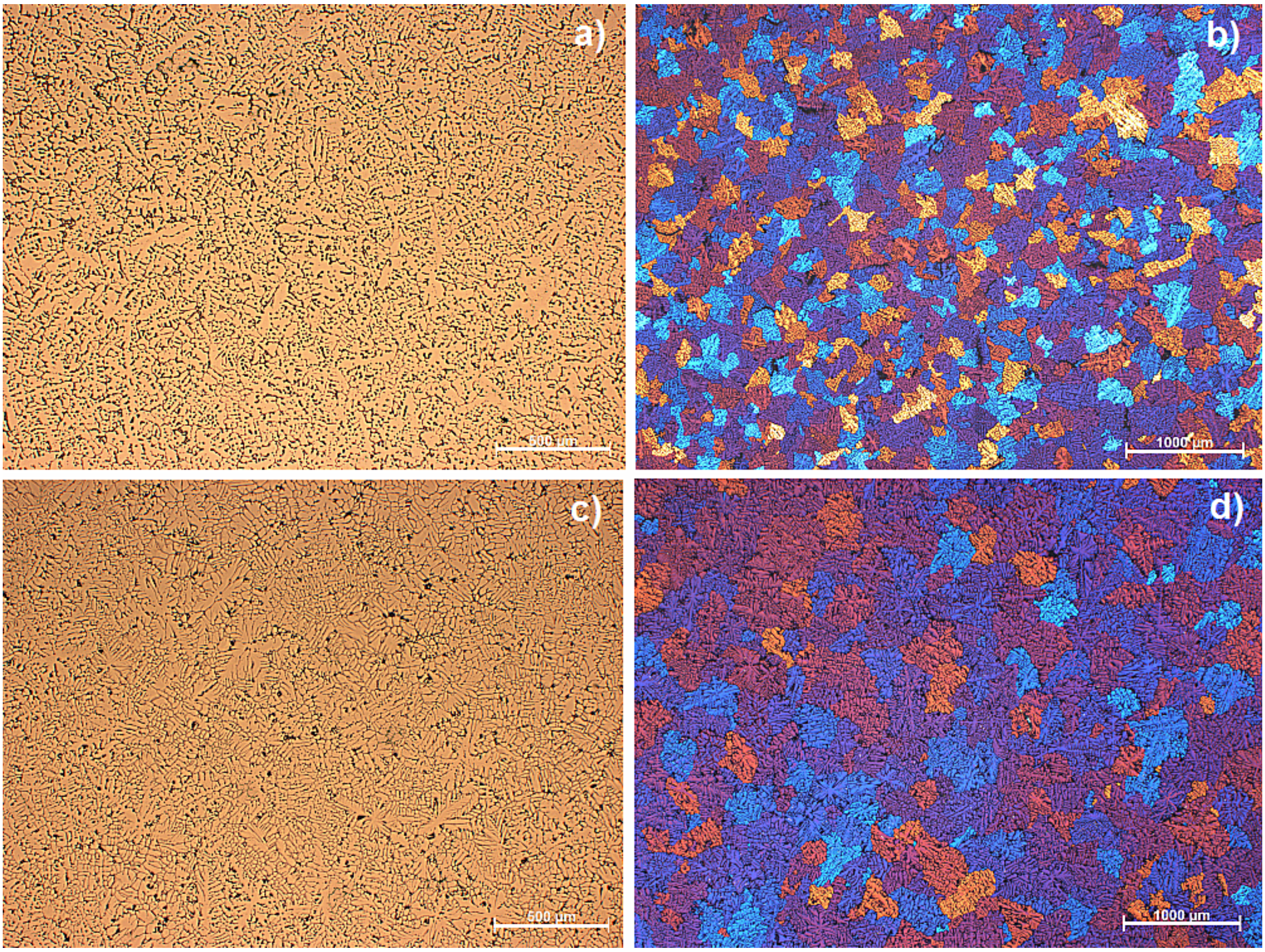

Fig. 2. Structure of the ingots cast with an average speed of; a, b) 30 mm/min; c, d) 100 mm/min (centre area of cross-section, light microscope; bright field and polarized light)

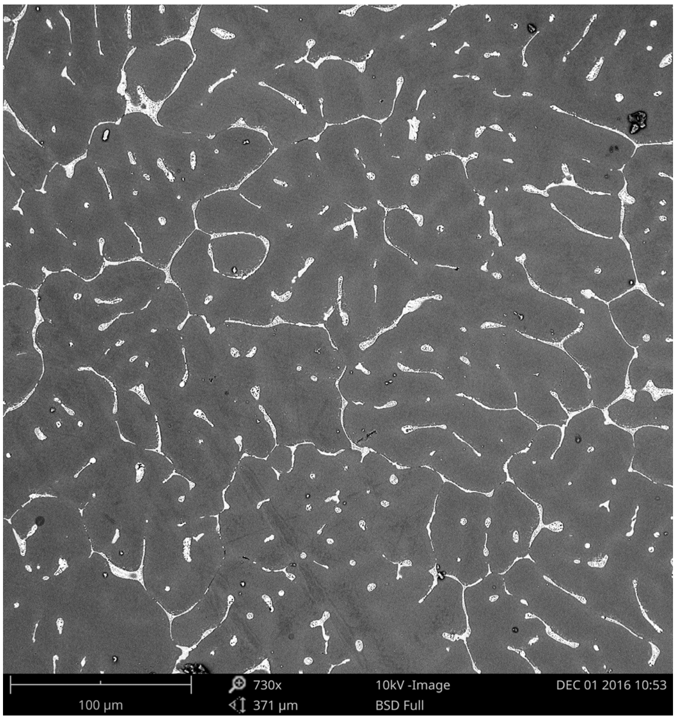

Fig. 3. Structure of the ingots cast with an average speed of 30 mm/min; cross-section (SEM)

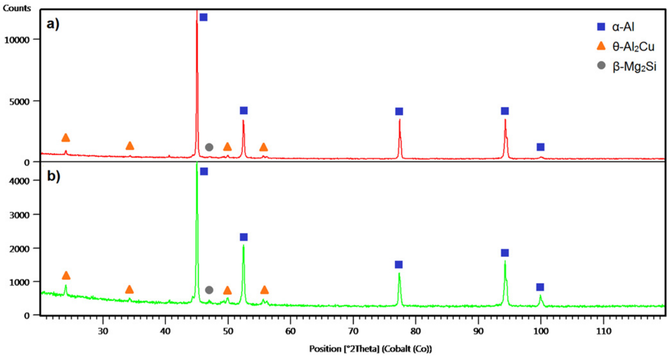

Fig. 5. XRD analysis of AlCu4MgSi alloy ingots cast with an average speed of: a) 30 mm/min, b) 100 mm/min

the structure of the analyzed alloy is dendrite expansion, which is intensified by the decrease in the rate of heat dissipation from the solidifying alloy.

TABLE 3

Results of chemical composition analysis in microareas of analysed samples (SEM – EDS)

Place of analysis (Fig. 11)	Element weight concentration [%]					
	Al	Cu	Mg	Si	Fe	Mn
1	≈99	—	—	—	—	—
2	67,4	27,9	2,3	2,4	—	—
3	63,2	9,5	—	6,9	11,3	9,1
4	56,5	39,8	2	1,7	—	—
5	70,5	6,8	—	5,4	9,4	7,9
6	91,2	2,3	1,2	5,3	—	—
7	94,8	5,2	—	—	—	—

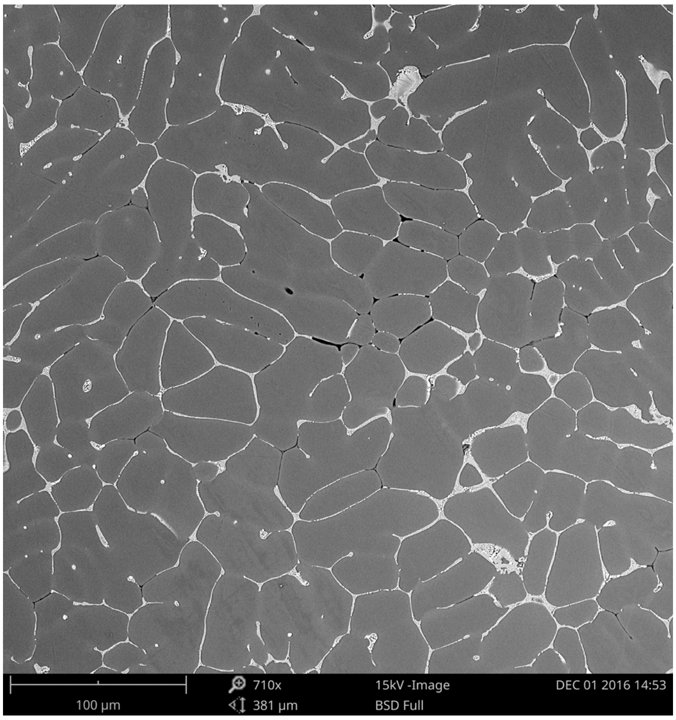

Fig. 4. Structure of the ingots cast with an average speed of 100 mm/min; cross-section (SEM)

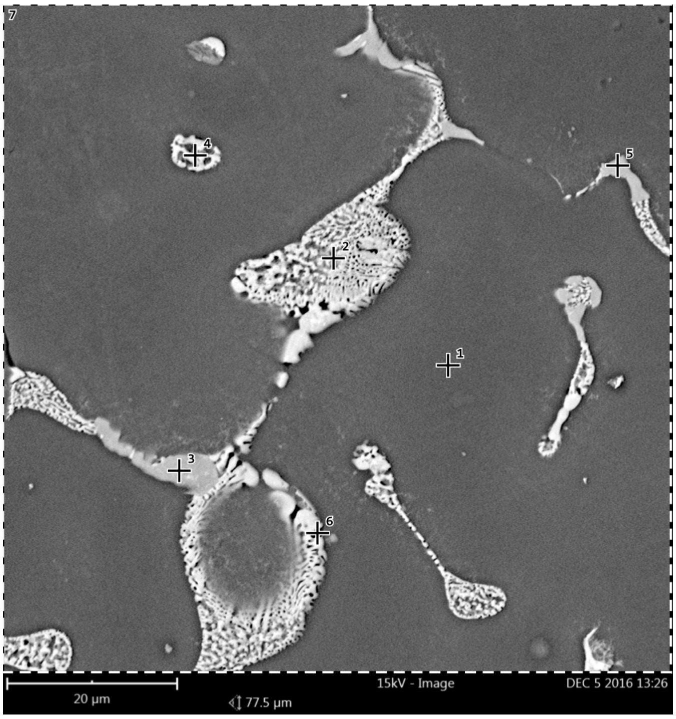

Fig. 6. Structure of the ingot cast with an average speed of 100 mm/min; cross-section (SEM)

The mechanical properties of the analyzed ingots were determined by means of the static tensile test and hardness measurement (Table 4). The obtained results point to some changes in properties, depending on the continuous casting process conditions (casting speed and cooling water flow rate). The tensile strength of the ingots obtained at an average casting speed in the range from 30 to 50 mm/min was 241-248 MPa. The highest $Rm_{\max}$ values (281-284 MPa) were shown by the ingots obtained at a casting speed of 60-70 mm/min. Increasing the casting speed resulted in a slight decrease in the value of measured tensile strength, down to approx. 275 MPa. The elongation, measured on fractured samples, ranged from 0.7 to 2.28 mm. An increase in the casting speed, and in the cooling liquid flow rate, caused an increase in elongation. A reverse dependence could be observed in the results of hardness measurements, where the hardness value decreased with an increase in casting speed. It can be concluded that the main factor influencing the increase of elongation and the decrease of hardness is the increase of the grain size, caused by slower heat dissipation at higher casting speeds.

TABLE 4

Mechanical properties of the analyzed AlCu4MgSi alloy ingots

Mark of ingots	Average casting speed [mm/min]	Tensile strength [MPa]	Maximum force [kN]	Elongation [mm]	Hardness [HB]
1	30	247	15,72	0,70	100
2	40	248	15,75	0,76	99
3	50	241	15,35	0,90	98
4	60	284	18,05	1,48	98
5	70	281	17,85	1,65	95
6	80	275	17,49	2,11	94
7	90	271	17,24	1,87	94
8	100	274	17,44	2,28	93

In the images of fractures (Fig. 7-8), obtained by SEM, clearly exposed areas of dendrites, so-called grape-like dendrites [11], have been observed. Gaps and voids occurring between dendrite arms may indicate shrinkage micro-porosity (centerline porosity) in the interdendritic areas. Existing research [11-15] indicates that the occurrence of this type of porosity is related to the cast wall thickness and to the rate of heat dissipation. Based on the assessment of fractures morphology, it was found that mainly brittle intergranular fracture occurrs. Also, a small number of areas typical of brittle transgranular fracture were observed. The EDS analysis (Fig. 9, Table 5) performed in fracture microareas proves that the crack propagation area shows an increased share of elements such as Cu, Mg and Si, when compared to the chemical composition noted in the area of exposed dendrites (probably α-Al solid solution). The samples after a tensile test are presented

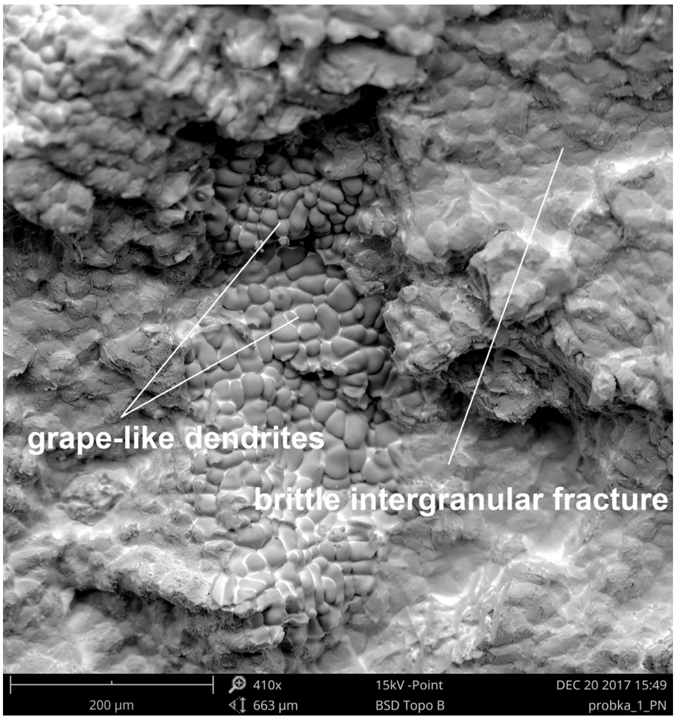

Fig. 7. Fracture of the ingot cast with an average speed of 30 mm/min

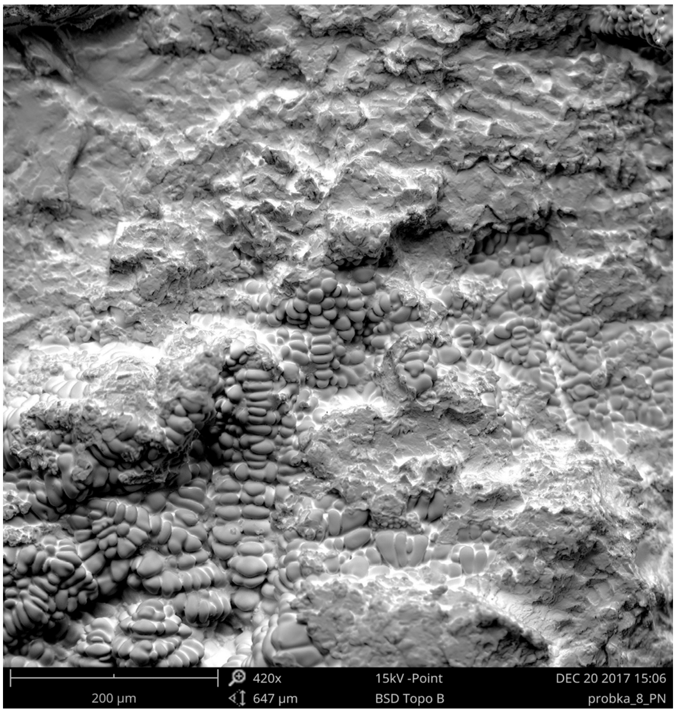

Fig. 8. Fracture of the ingot cast with an average speed of 100 mm/min

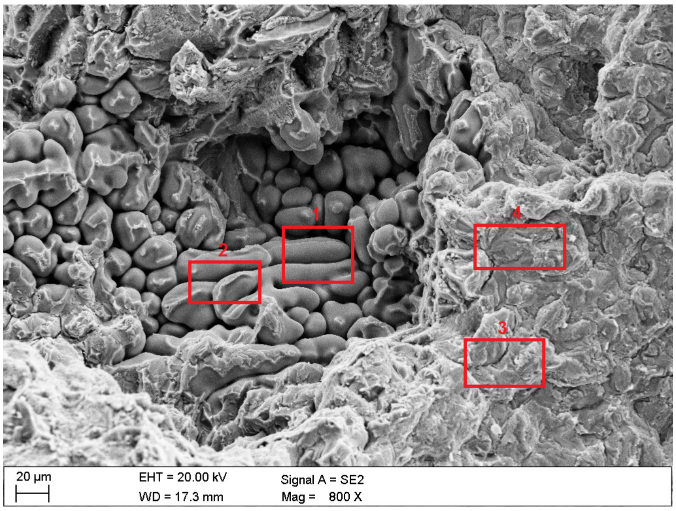

Fig 9. Fracture of the ingot cast with an average speed of 30 mm/min (marked EDS analysis area)

in the figure 10. The analysis carried out at the fractures allows for a conclusion that the main factor conducive to the spreading of brittle cracks was the lattice of precipitates of intermetallic phase (mainly Al_2Cu and Mg_2Si), blocking the dislocation slip. It can be assumed that the difference in the value of maximum tensile strength has been mainly caused by a change in share of centerline porosity, caused by a larger gradient of temperature at lower casting speeds. Also, a large dendrite expansion will affect $Rm_{\max}$ value slightly decreased.

TABLE 5

Results of EDS chemical composition analysis in microareas (analyzed areas are marked in the Fig. 9)

Place of analysis (Fig. 9)	Element weight concentration [%]					
	Al	Cu	Mg	Si	Fe	Mn
1	96,49	2,35	1,16	—	—	—
2	94,45	3,41	1,47	0,67	—	—
3	81,20	14,00	2,28	2,52	—	—
4	78,84	12,66	2,21	3,38	—	2,91

Fig. 10. Samples after a tensile test

5. Conclusions

The presented research results allowed for an evaluation of the influence of variable parameters of horizontal continuous casting process on mechanical properties and structure of AlCu4MgSi alloy ingots. It was shown that an increase in the ingot casting speed and in the rate of the cooling liquid flow through the crystallizer influences the shape of the precipitates lattice. The results of the analysis of the structure of ingots obtained with variable process parameters were correlated with their mechanical properties (tensile strength, elongation and hardness). It has been shown that, as casting speed and cooling flow increase, hardness decreases, and elongation of the analyzed samples increases, which can be related to the increase of average grain size. It can be assumed that the tensile strength and the cracking mechanism of the tested ingots was mostly influenced by the shape and morphology of the lattice of intermetallic phase precipitates. Wider bands of precipitates, and their isolated globular forms, observed in the structure of ingots cast at lower speeds, significantly contribute to the intensification of brittle intergranular fracture. Centerline porosity and dendrite expansion also affected the tensile strength of the studied ingots. Both of these factors depend on the process conditions.

Acknowledgements

This publication was financed by the Ministry of Science and Higher Education of Poland as the statutory financial grant of the Faculty of Mechanical Engineering, Silesian University of Technology.

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