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The Precipitation Hardening of Continuous Ingots of AlSi2Mn and AlCu4MgSi Alloys

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Abstract

The paper presents the research results of the influence of the precipitation hardening on hardness and microstructure of selected Al-Si and Al-Cu alloys obtained as ϕ30 mm ingots in a horizontal continuous casting process. The ingots were heat treated in process of precipitation hardening i.e. supersaturation with subsequent accelerated or natural ageing. Moreover in the range of the study it has been carried out investigations of chemical constitution, microscopic metallographic with use of scanning electron microscope with EDS analysis system, and hardness measurements using the Brinell method. On basis of obtained results it has been concluded that the chemical constitution of the investigated alloys enables to classify them into Al alloys for the plastic deformation as EN AW-AlSi2Mn (alternatively cast alloy EN AC-AlSi2MgTi) and as EN AW-AlCu4MgSi (alternatively cast alloy EN AC-AlCu4MgTi) grades. Moreover in result of applied precipitation hardening has resulted in the precipitation from a supersaturated solid solution of dispersive particles of secondary phases rich in alloying element i.e. Si and Cu respectively. In consequence it has been obtained increase in hardness in case of AlSi2Mn alloy by approximately 30% and in case of AlCu4MgSi alloy by approximately 20% in comparison to the as-cast state of continuous ingots.

Keywords: Aluminum, Precipitation hardening, Continuous casting, Silicon, Cooper

1. Introduction

Alloys from the Al-Si (colloquially called silumins) and Al-Cu (colloquially called duralumins) groups have a great application importance and are used in different industrial branches, e.g. in the automotive industry, the machine-building industry or in aircraft industry. These alloys are characterised by low density, high castability (but Al-Cu alloys show some tendency to hot cracks), good corrosion resistance and machinability. Moreover the Al-Si and Al-Cu alloys have suitably medium and high mechanical properties [1÷4].

Additionally the strength properties of these alloys can be increased in result of result of performed heat treatment of precipitation hardening type. This heat treatment consists of two stages, in the first one it contains supersaturation i.e. heating of the alloy in high temperature above solvus line on phase diagram, until the alloying element is completely dissolved in solid solution and the next one comprising rapid cooling, what enables a solid solution supersaturated with the alloying element and vacancies. The second stage consists of ageing i.e. heating of the alloy at temperature lower than the solvus line. This stage is followed by the precipitation from a supersaturated solid solution of dispersive particles of secondary phases rich in the alloying element. Uniform precipitation of these phases results in hardening of the alloy [5].

Whereas, the continuous casting process can be used to production of ingots from Al-Si and Al-Cu alloys. This technology, often used in the manufacture of ferrous alloys mainly steels [5÷7] and rarely grey cast irons [8] and alloys of non-ferrous metals like Al [9÷14] and Cu [15, 16] mainly, is characterised by high yield and quality ingots as a semi-product generally for plastic deformation or machining.

Table 1.
Chemical constitution of the investigated continuous ingots of the Al alloys

The amount of elements, % wt.										
Si	Cu	Mn	Mg	Fe	Ti	Zn	Cr	Ni	V	Al
EN AW-AlSi2Mn										
2,10	0,22	0,75	0,40	0,45	0,05	0,13	0,05	0,01	0,03	rest
EN AW-AlCu4MgSi										
0,52	4,45	0,82	1,00	0,28	0,01	0,22	0,05	0,02	0,01	rest

Therefore, the aim of the studies was to determine the influence of the precipitation hardening on hardness and microstructure of selected Al-Si and Al-Cu alloys obtained as ϕ30 mm ingots in a horizontal continuous casting process.

2. Range of the studies

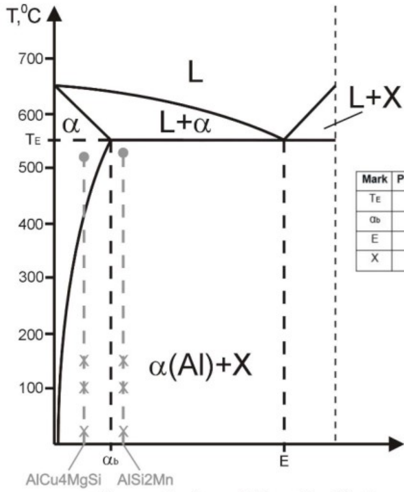
In table 1 the chemical constitution is presented for the investigated Al-Si and Al-Cu alloys determined with use of emission spectrometer of LECOGDS500A type. In the first case the chemical constitution of the tested silumin enables to classify it into the group of Al-Si alloys for the plastic forming (mainly rolling) as EN AW-AlSi2Mn grade on the basis of PN-EN 573-3 standard. Alternatively it is possible to classify this alloy as for casting i.e. as EN AC-AlSi2MgTi grade on the basis of PN-EN 1706 standard. Whereas in the second case the chemical constitution of the tested duralumin enables to classify it to the group of Al-Cu alloys for the plastic forming (drawing, extrusion and rolling mainly) as EN AW-AlCu4MgSi grade on the basis of PN-EN 573-3 standard. As in the previous case alternatively it is also possible to classify this alloy as for casting i.e. as EN AC-AlCu4MgTi grade on the basis of PN-EN 1706 standard.

The both studied Al alloys were obtained as ϕ30 mm ingots in a horizontal continuous casting process. Detailed description of implemented horizontal continuous casting process is presented in paper [13] and [14] respectively, for the studied Al-Si and Al-Cu alloys. In detail in studies were used samples of ingots with dimensions: 30mm in diameter and 15mm high in the amount of two pieces for each variant of heat treatment.

The precipitation hardening of studied ingots in case of AlSi2Mn alloy included the temperature of supersaturation 540°C for 0,5h and next cooling down in water. Whereas in case of AlCu4MgSi alloy was used temperature of supersaturation 520°C for 0,5h and next cooling down in water too. In the second stage of the heat treatment in the both cases it has been performed accelerated ageing at temperature 150 and 100°C during time 1h and 2h, and natural ageing at ambient temperature for time 7 days. Moreover the microscopic metallographic studies of the Al-Si and Al-Cu continuous ingots were carried out with use of scanning electron microscope of Phenom ProX type with EDS analysis. Whereas, hardness was measured with use of the Brinell method at four points (located on the perpendicular diameters of the sample end face) for each of the samples.

3. Results of the studies

The temperature parameters of the precipitation hardening of studied ingots were determined on the basis of the analysis of phase diagrams of Al-Si and Al-Cu alloys. Schematic conception of heat treatment for the both studied alloys is presented in Fig. 1 with use of phase diagram with eutectic transformation which is suitable for Al-Si and Al-Cu alloys. In case of Al-Cu alloys the solvus line is from approx. 0,5%wt. of Cu at ambient temperature to approx. 5,65%wt. of Cu at temperature of 548°C.



Mark	Phase diagram Al-Si	Phase diagram Al-Cu
T_E	577°C	548°C
α_b	1,65%wt. of Si	5,65%wt. of Cu
E	12,6%wt. of Si	33,2%wt. of Cu
X	β(Si)	θ(Al_2Cu)

Fig. 1. Schematic conception of the precipitation hardening for studied Al alloys with use of phase diagram with eutectic transformation: • - temperature of supersaturation, × - temperature of ageing

It may be concluded, therefore, that studied EN AW-AlCu4MgSi alloy has appropriate chemical constitution for the precipitation hardening because at high temperature i.e. between solvus and solidus lines the alloying element is completely dissolved in solid solution α. Whereas in case of Al-Si alloys the solvus line is from approx. 0%wt. of Si at ambient temperature to approx. 1,65%wt. of Si at temperature of 577°C. Therefore it may be concluded that studied EN AW-AlSi2Mn alloy doesn't comply with typical chemical constitution for precipitation hardening because at high temperature i.e. below solidus lines the alloying element is not completely dissolved in solid solution α. However according to [2, 17÷19] improvement of hardness of Al-Si alloys in result of the precipitation hardening process, particularly when in chemical constitution Mg and Cu are present. Their presence in chemical constitution of Al-Si alloy results in precipitation from a supersaturated solid solution of phases Mg_2Si and Al_2Cu in ageing process.

Table 2 presents measurement results of the hardness of studied Al-Si and Al-Cu ingots. On the basis of the obtained results, it was confirmed that after the supersaturation ingots ductility is increased. However, the strength increases with simultaneous decrease of the ductility after subsequent ageing treatment.

Moreover, it was concluded that the hardness increases with decrease in ageing temperature and the ageing time. Therefore the highest hardening of both studied alloys was obtained in result of supersaturation connected with natural ageing. As microscopic studies shows, for this variant of the heat treatment the increase in hardness of Al-Cu alloy results from precipitation of dispersive particles of intermetallic phases Al_2Cu and $Al_5Mg_8Si_6Cu_2$ from supersaturated solid solution. (Figs. 2÷5). Whereas in case of Al-Si alloy it was observed increase in the hardness as a result of small increase of degree of dispersion of eutectic β(Si) (Figs. 6÷8). Moreover in the both alloys it was confirmed presence of hardening phase Mg_2Si in their microstructure (Fig. 9).

Table 2.
The results of hardness measurements of studied Al-Si and Al-Cu ingots

Type of heat treatment	AlSi2Mn	AlCu4MgSi
As-cast	52HB	93HB
After supersaturation	40HB	60HB
After supersaturation and accelerated ageing 150°C/1h	50HB	95HB
After supersaturation and accelerated ageing 150°C/2h	55HB	98HB
After supersaturation and accelerated ageing 100°C/1h	55HB	97HB
After supersaturation and accelerated ageing 100°C/2h	61HB	105HB
After supersaturation and natural ageing	67HB	109HB

a) b)

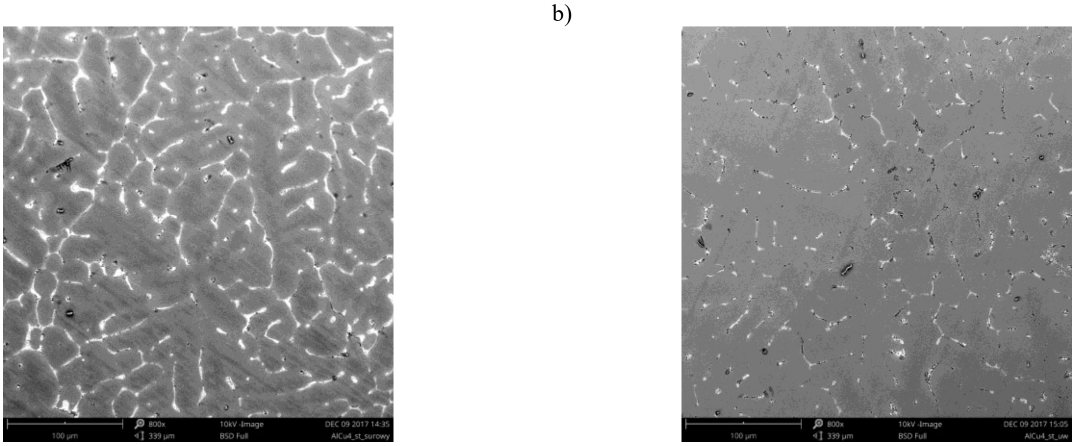


Fig. 2. Microstructure of AlCu4MgSi alloy: a) as-cast, b) after supersaturation and natural ageing, SEM, mag. 800x

a) b) c)

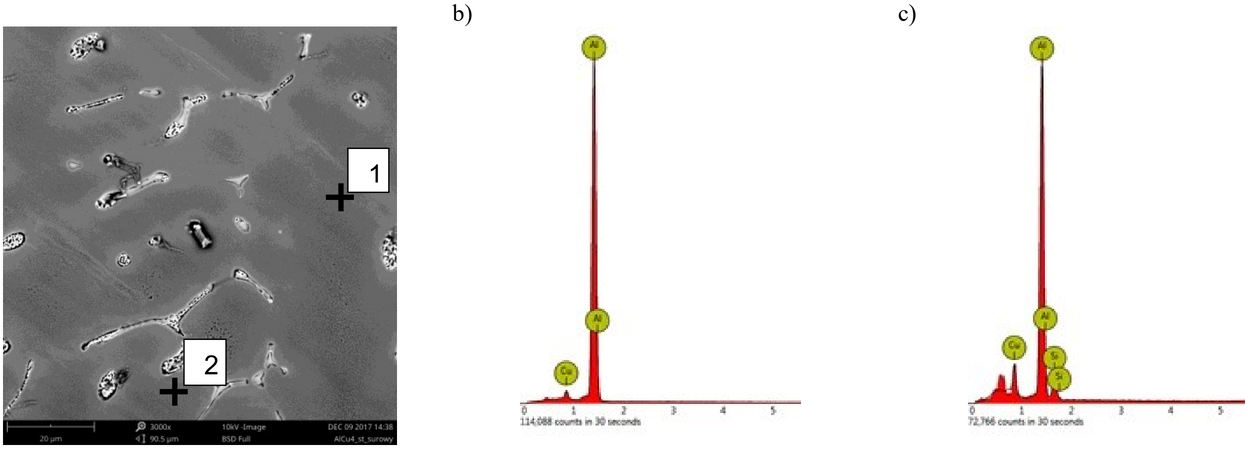


Fig. 3. Microanalysis of the chemical constitution: a) studied area in microstructure of AlCu4MgSi alloy after supersaturation and natural ageing, mag. 3000x, b) the result of EDS in point 1: Al = 91,50%wt., Cu = 8,50%wt., c) the result of EDS in point 2: Al = 77,72%wt., Cu = 12,65%wt., Si = 9,63%wt.

a) b) c)

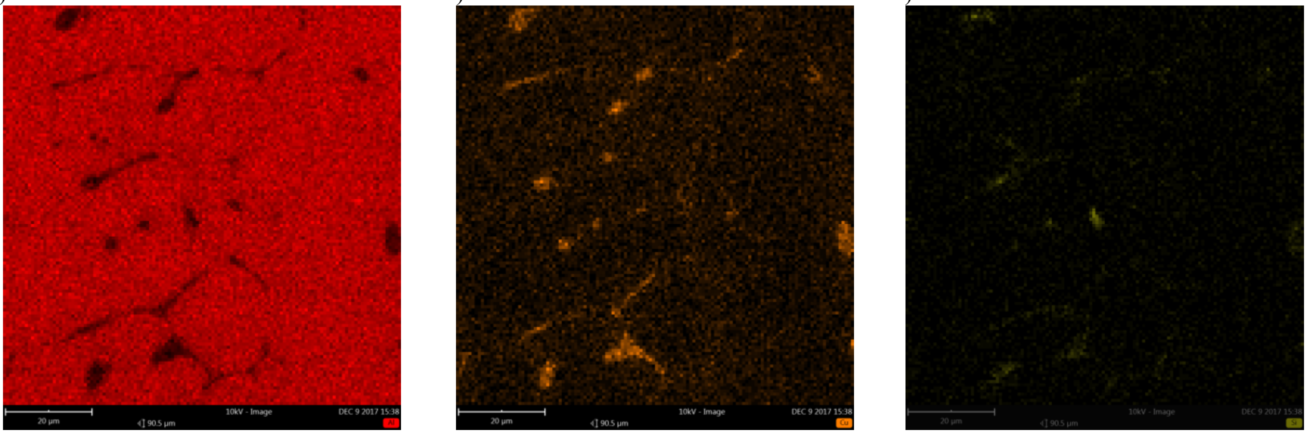


Fig. 4. Microanalysis of the chemical constitution for area shown in the fig. 3a: a) map for Al, b) map for Cu, c) map for Si

a) b)

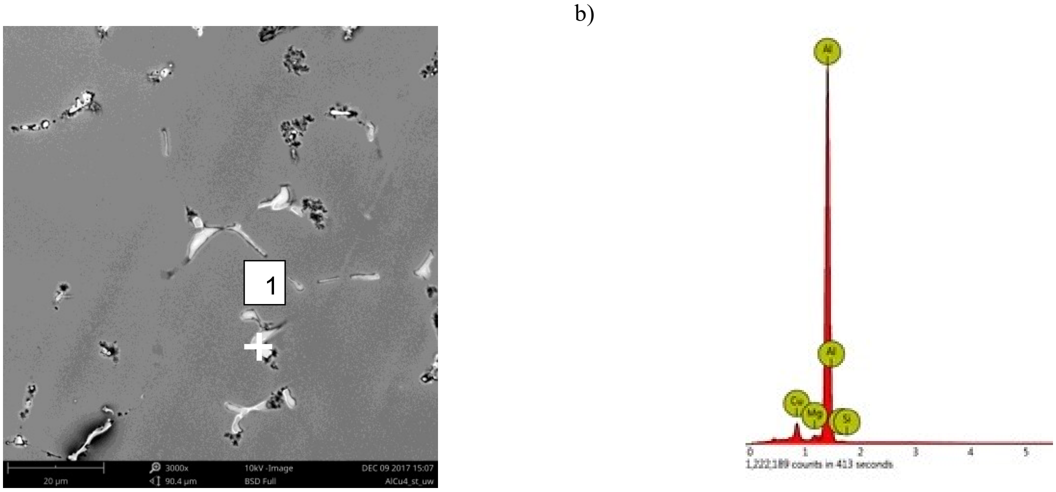


Fig. 5. Microanalysis of the chemical constitution: a) studied area in microstructure of AlCu4MgSi alloy after supersaturation and natural ageing, mag. 3000x, b) the result of EDS in point 1 from fig. a: Al = 90,92%wt., Cu = 7,87%wt., Mg = 1.02%wt., Si = 0,19%wt.

a) b)

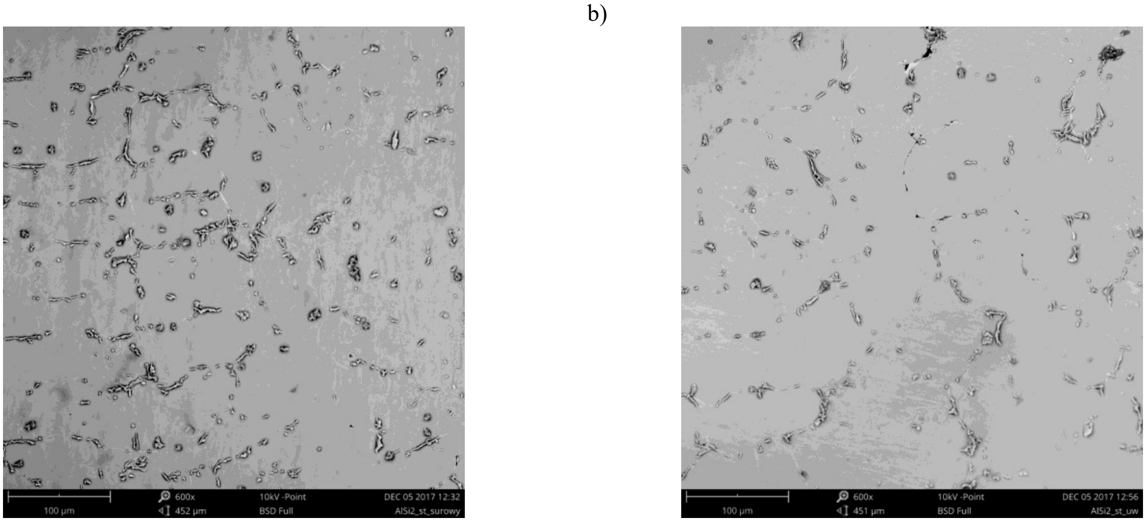


Fig. 6. Microstructure of AlSi2Mn alloy: a) as-cast, b) after supersaturation and natural ageing, SEM, mag. 600x

a) b) c)

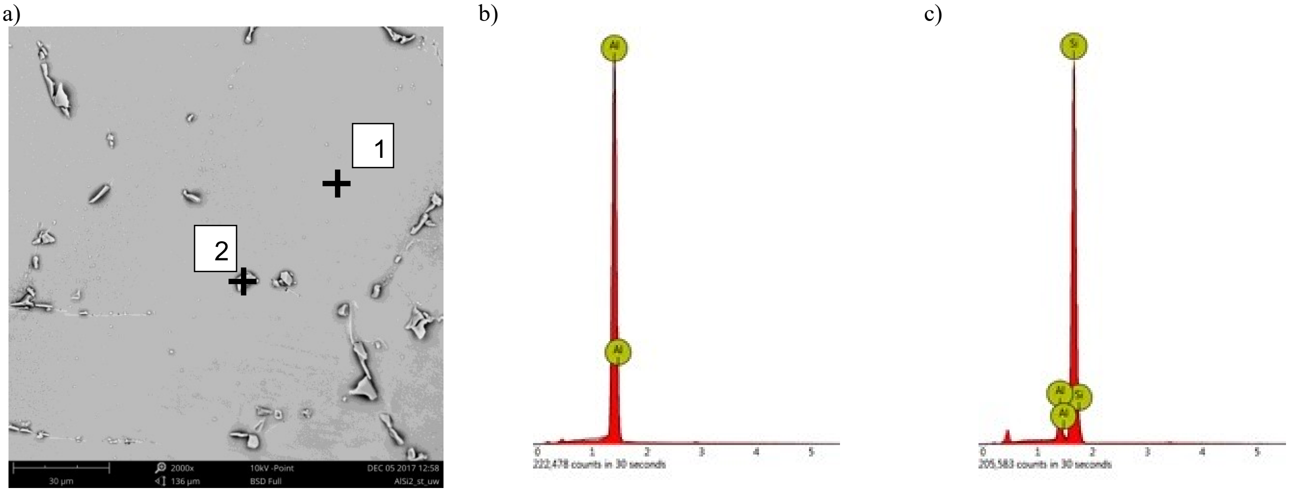


Fig. 7. Microanalysis of the chemical constitution: a) studied area in microstructure of AlSi2Mn alloy after supersaturation and natural ageing, mag. 2000x, b) the result of EDS in point 1: Al = 100%wt., c) the result of EDS in point 2: Al = 5,79%wt., Si = 94,21%wt.

a) b)

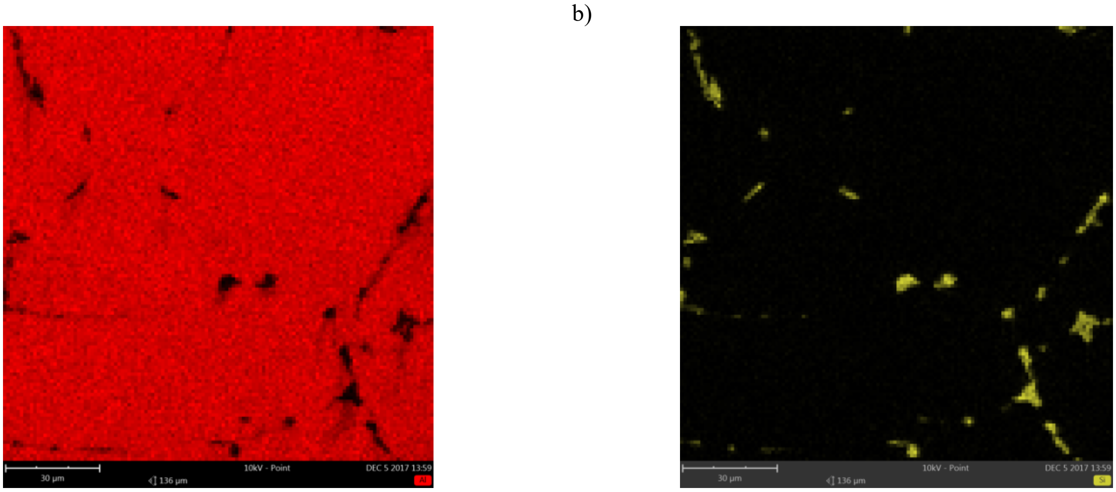


Fig. 8. Microanalysis of the chemical constitution for area shown in the fig. 7a: a) map for Al, b) map for Si

a) b)

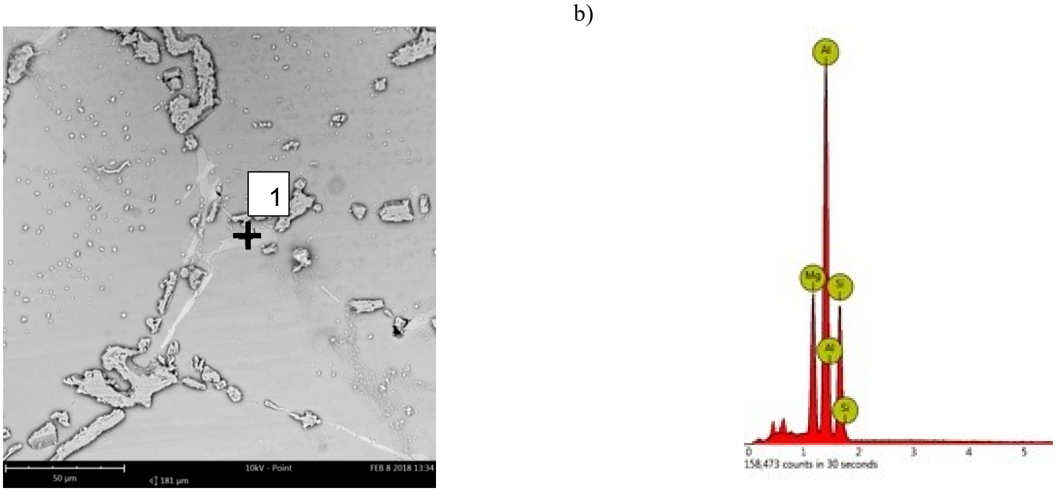


Fig. 9. . Microanalysis of the chemical constitution: a) studied area in microstructure of AlSi2Mn alloy after supersaturation and natural ageing, mag. 1000x, b) the result of EDS in point 1 from fig. a: Al = 54,47%wt., Si = 30,84%wt., Mg = 14,69%wt.

4. Conclusions

Based on the conducted studies the following conclusions have been formulated:

1. In the as-cast state the relatively high hardness of studied AlSi2Mn and AlCu4MgSi alloys results from solidification in water cooled continuous casting mould.
2. Applied treatment of the age hardening results in precipitation from a supersaturated solid solution of dispersive particles of secondary phases rich in the alloying element is observed. In consequence it was obtained increase in the hardness approximately by 30% in case of AlSi2Mn alloy, and approximately by 20% in case of AlCu4MgSi alloy in comparison to the as-cast state of continuous ingots.
3. The obtained maximum hardness after applied heat treatment equal to 67HB and 109HB suitable for AlSi2Mn alloy and AlCu4MgSi alloy, results that in first case is not fulfil the requirement for this type of mechanical property specified in PN-EN 1706 standard, whereas in second case this requirement is fulfil.
4. The value of temperature applied in the precipitation hardening of AlSi2Mn and AlCu4MgSi alloys, mainly in the stage of supersaturation disables combination of this treatment directly with the continuous casting process, for example by using a re-cooling system, because according to [20] the temperature of ingot after leaving the continuous casting mould equals to 120÷220°C in the case of the stand to horizontal continuous casting used in the studies.
5. Application of the supersaturation treatment for continuous ingots of AlSi2Mn and AlCu4MgSi alloys to increase their ductility facilitates the plastic deformation which is difficult for the ingots in the as-cast state when often leads to presence of cracks.

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