Łukasz Poloczek, Bartłomiej Dybowski, Andrzej Kiełbus

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The Impact of Strontium Modification on the Microstructural Characteristics and Mechanical Performance of High-Pressure Die Cast AlSi9Cu3(Fe) Alloy

Wpływ dodatku strontu na strukturę i właściwości mechaniczne stopu AlSi9Cu3(Fe)

Abstract: The microstructure of the HPDC AlSi9Cu3(Fe) alloy is characterized by fine dendrites of α-Al solid solution and α-Al+β-Si binary eutectic mixture. In addition, the alloy contains many intermetallic phases, such as α-$Al_{15}(Fe,Mn,Cr)_3Si_2$, β-Al_5FeSi, Al_2Cu, π-$A_8Mg_3FeSi_6$ and Q-$Al_5Mg_8Cu_2Si_6$. The paper presents results of research concerning the influence of Sr-based modification on the microstructure and mechanical properties of the HPDC AlSi9Cu3(Fe) alloy. The research-related tests involved three different high-pressure die cast specimens, i.e. two castings with different Sr contents (i.e. 40 ppm and 130 ppm) and one without an Sr addition. The addition of Sr was responsible for the fragmentation of eutectic silicate crystals, which was advantageous for the microstructure of the test specimens. However, the aforesaid addition also triggered an increase in the volume fraction of porosity in the structure, which, most likely, resulted in the deterioration of mechanical properties.

Key words: AlSi9Cu3(Fe) alloy, high pressure die casting, strontium modification, microstructure, mechanical properties

Streszczenie: Mikrostruktura stopu AlSi9Cu3(Fe) odlanego metodą wysokociśnieniową charakteryzuje się występowaniem dendrytów roztworu stałego α-Al oraz podwójnej eutektyki α-Al+β-Si. W strukturze stopu występują również fazy międzymetaliczne, takie jak: α-$Al_{15}(Fe,Mn,Cr)_3Si_2$, β-Al_5FeSi, Al_2Cu, π-$A_8Mg_3FeSi_6$ i Q-$Al_5Mg_8Cu_2Si_6$. W poniższej pracy przedstawiono wyniki badań wpływu modyfikacji Sr na mikrostrukturę i właściwości mechaniczne stopu AlSi9Cu3(Fe) HPDC. W badaniach wykonano trzy wytopy wysokociśnieniowe. Dwa z nich charakteryzowały się różną zawartością dodatku Sr (40 ppm, 130 ppm) oraz wykonano jeden wytop bez dodatku Sr. Dodatek strontu spowodował fragmentację eutektyki, co korzystnie wpłynęło na mikrostrukturę badanych próbek. Jednak że w próbkach z dodatkiem Sr stwierdzono zwiększenie udziału objętościowego porowatości w strukturze, co wpłynęło na pogorszenie właściwości mechanicznych.

Słowa kluczowe: stop AlSi9Cu3(Fe), odlewanie wysokociśnieniowe, modyfikacja stront, mikrostruktura, właściwości mechaniczne

1. Introduction

Silumins constitute the most widespread group of aluminum alloys currently used in foundry engineering. Silumins are aluminum alloys containing silicon in a variety of configurations with other alloying elements [1]. These alloys are very widely used in various fields of the machine industry, especially in the automotive, household, precision-optical, and aerospace industries [2]. The aforesaid widespread applications result from highly favorable properties of the alloys such as low density, a relatively low melting point, advantageous thermal and electrical conductivity, favorable mechanical properties, good casting properties (good luting, low shrinkage), good machinability and significant corrosion resistance [3–5]. The most serious disadvantage of silumins is concerned with the presence of large and brittle eutectic silicon crystals in the alloy structure, significantly reducing mechanical and plastic properties. For this reason, it is necessary to refine the eutectic mixture structure with sodium, strontium or titanium, hindering the growth of Si crystals by reducing the eutectic crystallization temperature. The modification of microstructure leads to the formation of fine and fibrous Si crystals, improving the mechanical and plastic properties of the alloys [6, 7]. On the other hand, the above-named additives increase the tendency of porosity formation. The amount of oxides in the alloy increases because of the susceptibility of sodium and strontium to oxidation. [8]. The aforesaid oxides impede the flow of metal between dendrites, favoring the formation of shrinkage

dr inż. Łukasz Poloczek – Łukasiewicz Research Network – Upper Silesian Institute of Technology, Gliwice, Poland
dr inż. Bartłomiej Dybowski – Nemak Poland, Bielsko-Biała, Poland
dr hab. inż. Kiełbus Andrzej – Silesian University of Technology, Faculty of Materials Engineering, Katowice, Poland
Corresponding Author: lukasz.poloczek@git.lukasiewicz.gov.pl

porosity [9]. The increased porosity of the alloy, triggered by the interposition of sodium or strontium, decreases the mechanical properties of the alloy [10, 11]. In such a situation, because of the mechanical properties of the alloy, the effect of the fragmentation of silicon precipitates can be offset by an increase in porosity in the alloy structure. The modification of Al-Si alloys is successfully applied in gravity casting, where cooling rates are relatively low and where the formation of massive silicon crystals definitely needs to be avoided. In terms of high-pressure die casting (HPDC), where solidification rates are very high, the necessity of microstructure refinement is not so obvious. Several researchers have found that, in spite of high cooling rates, it is possible to observe lamellar (platelet-like) or acicular (needle-like) silicon crystals are in HPDC Al-Si alloys. The paper presents results of research concerning the effect of Sr-based modification on the microstructure and properties of the HPDC EN AC-Al Si9Cu3(Fe) alloy.

2. Methodology and test materials

The material used in the research-related tests was the AlSi9Cu3(Fe) aluminum casting alloy. The tests involved three high-pressure die casts, the first one of which did not contain an Sr addition, whereas the two remaining alloys were modified with an Sr addition of 40 ppm and that of 130 ppm. In each case, the chemical composition of the alloy was consistent with the EN 1706 standard (tab. 1).

Microstructural observations were performed using Olympus-made GX71 light microscopes (LM) and Hitachi-manufactured S3400N scanning electron microscopes (SEM). The chemical composition of the phases was analyzed using Thermo Noran energy dispersive X-ray spectroscopy (EDS).

The quantitative assessment of alloy porosity was performed using 20 micrographs recorded with a magnification of 100 times (LM). In turn, the quantitative assessment of eutectic silicon crystals was performed using 40 micrographs recorded with a magnification of 1000 times (LM). The detection and assessment of pores and eutectic silicon crystals were carried out using the Met-Ilo software. Detection procedures are presented in Tab. 2 and Tab. 3.

Static tensile tests were performed at ambient temperature, in accordance with the PN-EN 10602-1 standard. The tests were performed using a 50DS tensile testing machine (Kappa).

Table 1. Chemical composition of the AlSi9Cu3(Fe) alloy

	Al	Cu	Si	Mg	Mn	Fe	Ti	Ni	Zn	Sn	Pb	Na	Sr
EN 1706	Bal.	2.0 – 4.0	8.0 – 11	0.05 – 0.55	<0.55	<1.3	<0.25	<0.55	<1.2	<0.25	<0.35	<0.05	-
Unmod.	Bal.	2.67	7.32	0.156	0.304	0.658	0.043	0.075	0.89	0.030	0.037	0.002	-
40 ppm Sr	Bal.	3.10	9.38	0.193	0.266	0.883	0.043	0.081	0.94	0.036	0.045	0.0011	0.004
130 ppm Sr	Bal.	2.98	9.57	0.183	0.294	0.901	0.041	0.076	0.92	0.038	0.039	0.0017	0.013

Table 2. Procedure used in the assessment of alloy porosity

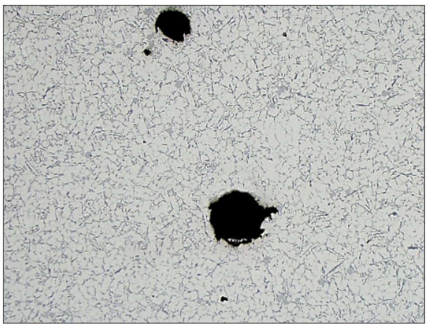


Image A: initial image

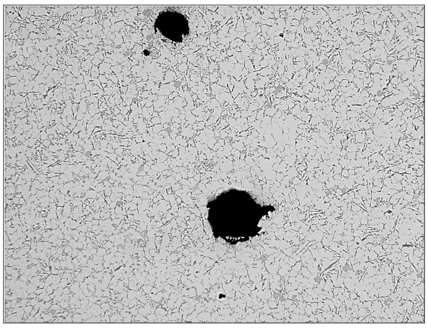


Image B: normalization of the histogram

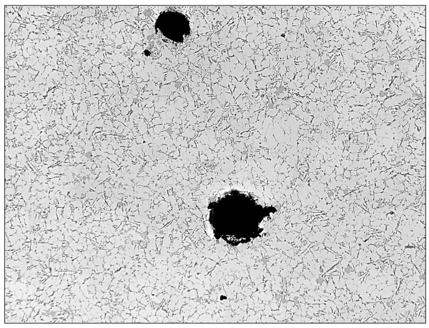


Image C: shadow correction 50

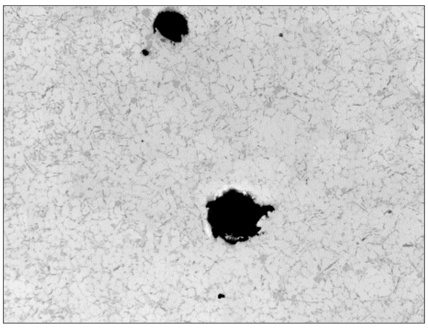


Image D: median 3 3 3

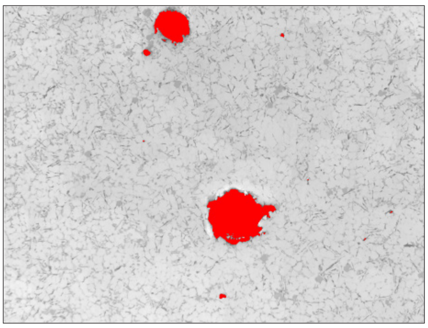


Image E: multiple binarization

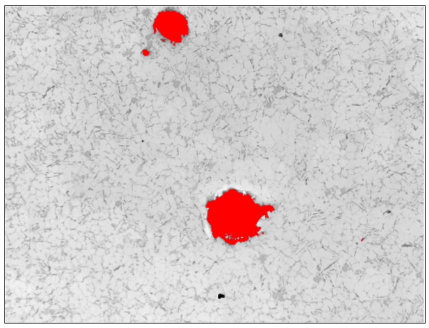


Image F: manual correction

Table 3. Procedure used in the assessment of eutectic Si parameters

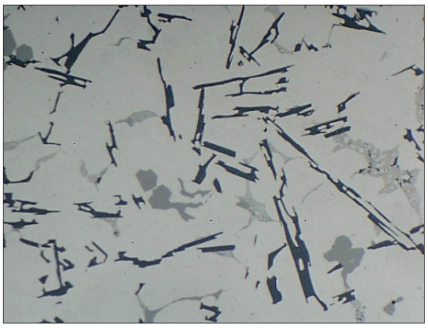
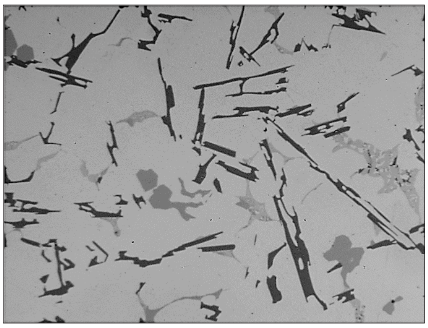
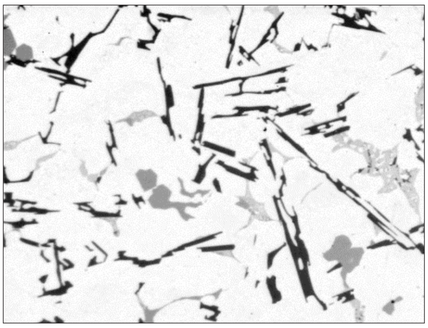
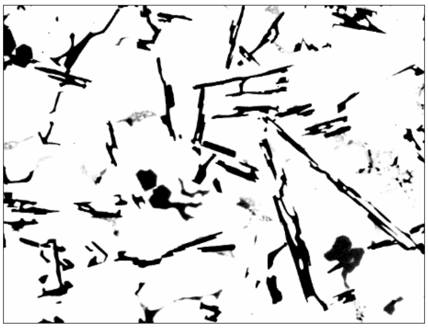
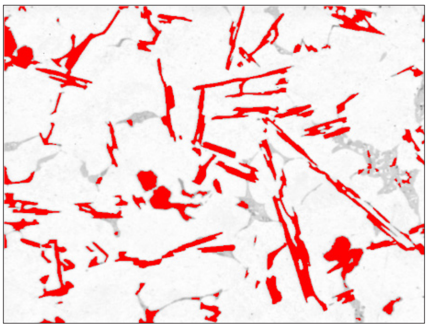
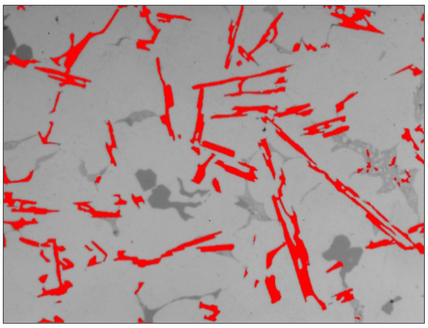
		

Image A: initial image	Image B: normalization of the histogram	Image C: shadow correction 50
		
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Vickers hardness (HV2) tests were performed using a Duramin 5 hardness tester. Each case involved the performance of 20 measurements.

3. Test results

3.1. Microstructure of the AlSi9Cu3(Fe) alloy

The microstructure of the HPDC AlSi9Cu3(Fe) alloy in its cast condition was characterized by the presence of fine dendrites of α-Al solid solution and α-Al+β-Si binary eutectic mixture (Fig. 1). In addition, the structure contained numerous intermetallic phases (crystallized in complicated eutectic transformations), characterized by varied morphology. One of the phases was that of theAl_2Cu type, characterized by the morphology of irregular eutectic. The alloy structure also contained two other types of phases rich in iron, i.e. β-Al_5FeSi and α-$Al_{15}Fe_3Si_2$. The α-$Al_{15}Fe_3Si_2$ phase was characterized by two different types of morphology, i.e. the Chinese script (Fig. 2a), containing manganese, and polygonal morphology (Fig. 2b), containing also chromium. Because of its large size and lamellar morphology, the β-Al_5FeSi phase belongs to the most unfavorable intermetallic phases. The identification of individual phases was based on the analysis of energy dispersive spectroscopy (EDS).

3.2. Microstructure of the AlSi9Cu3(Fe) alloy after Sr-based modification

The structure of the strontium-modified AlSi9Cu3(Fe) alloy is presented in Figure 3. The components forming the alloy microstructure were the same as those of the unmod-

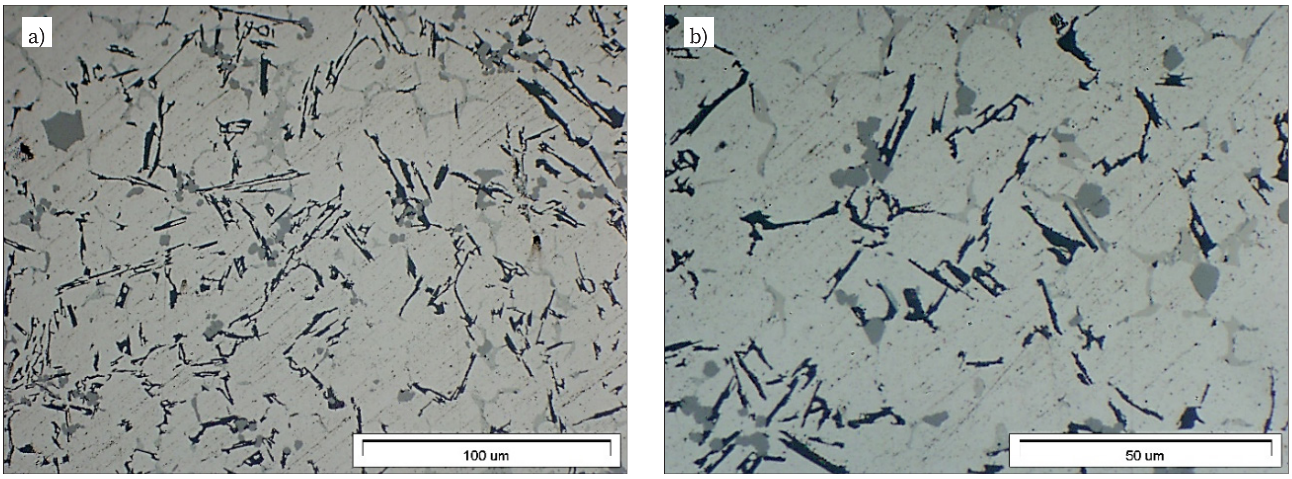

Fig. 1. Unmodified AlSi9Cu3(Fe) alloy microstructure, LM

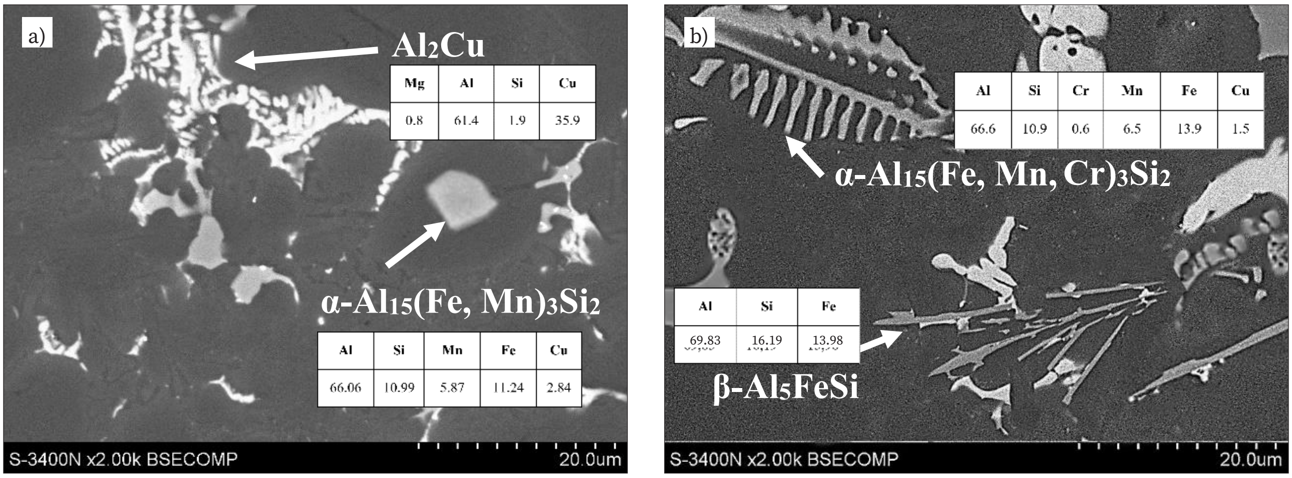

Fig. 2. Intermetallic phases in the structure of the AlSi9Cu3(Fe) alloy (at%), SEM

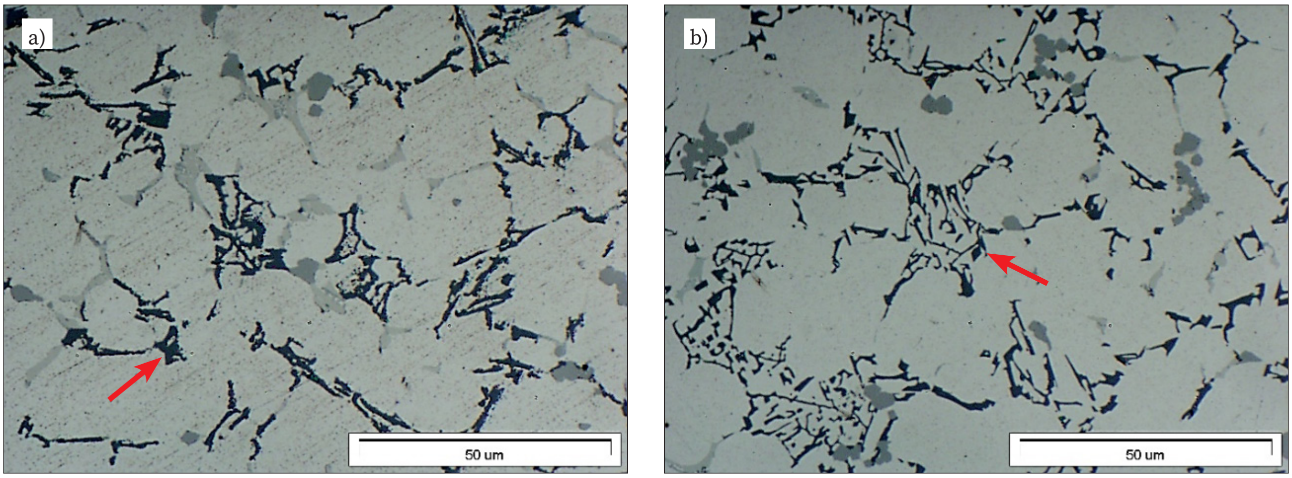

Fig. 3. AlSi9Cu3(Fe) alloy microstructure after Sr-based modification, LM: a) 40 ppm Sr addition, b) 130 ppm Sr addition

Table 4. Results of the quantitative assessment of eutectic silicon crystals

	Unmodified	40 ppm Sr	130 ppm Sr
Volume fraction [%]	7.86	7.82	7.83
Variability factor [%]	15.5	14.5	16.4
Surface area of the Si flat section [μm^2]	6.68	5.11	3.41
Variability factor [%]	137	133	148
Shape factor [-]	0.467	0.489	0.564
Elongation factor [-]	2.96	2.85	2.31
Distance between neighbors [μm]	5.11	4.48	3.47

ified cast. However, it was possible to observe a modified morphology of eutectic silicon crystals – in the form of very fine dendrites or fibers, characteristic of modified alloys (Fig. 3). The results of the quantitative assessment of eutectic silicon crystals are presented in Table 4.

The research-related tests did not reveal any differences as regards the volume fraction of eutectic silicon crystals. All the test specimens were characterized by a volume fraction of approximately 7.8%. The modified 130 ppm Sr specimen was characterized by the smallest surface area of the Si flat section (3.41 μm^2), revealing the most finely fragmented eutectic silicon crystals. An elongation factor of 2.31 and the distance between neighbors amounting to 3.47 were also the smallest as regards the above-named specimen. The foregoing demonstrated the progressing fragmentation of Si crystals and the formation of small silicon colonies in the structure (characteristic of Sr-modified alloys).

Both the modified and unmodified alloys were characterized by shrinkage porosity and the presence of gas pores (Fig. 4). However, the volume fraction of the pores in the Sr-modified alloys was higher than that in the unmodified AlSi9Cu3(Fe) alloy (Tab. 5). The modified specimens were also characterized by greater porosity in the most affected areas (1.37% in relation to an Sr addition of 40 ppm and 3.6% in terms of an Sr addition of 130 ppm). The mean

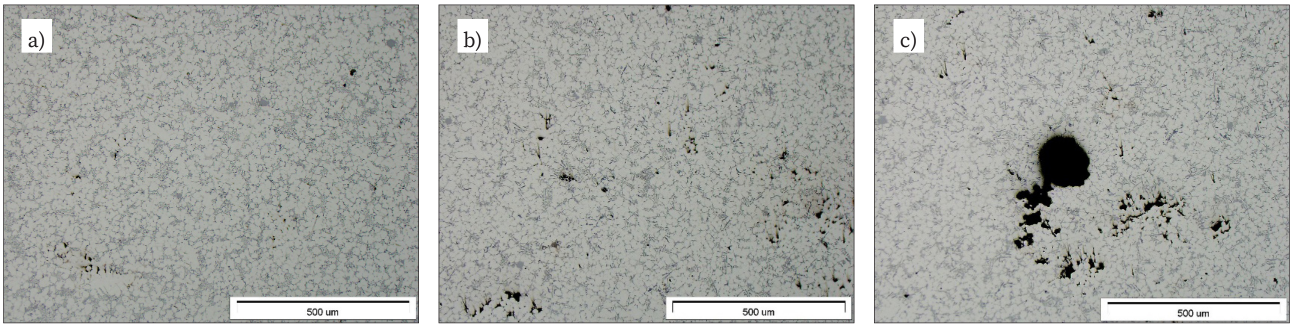

Fig. 4. Porosity in the AlSi9Cu3(Fe) alloy, LM: a) unmodified alloy, b) 40 ppm Sr addition and c) 130 ppm Sr addition

Table 5. Results of the quantitative assessment of porosity in the test alloys

	Unmodified	40 ppm Sr	130 ppm Sr
Volume fraction [%]	0.56	0.8	1.05
Variability factor [%]	50.3	40.6	65.4
Porosity in the most affected area [%]	1.15	1.37	3.6
Mean surface area of the pore flat section [μm^2]	0.98	102.2	134.7
Variability factor [%]	528	442	671
Shape factor [-]	0.927	0.711	0.676
Distance between neighbors [μm]	0.812	0.0747	0.0718

surface area of the pore flat section was the lowest in the unmodified specimen (0.98 μm^2), which indicated the negative effect of Sr on the surface area of the pore flat section. The distance between neighbors was slightly shorter in cases of the modified specimens, which could imply an increased volume fraction of shrinkage pores in the structure of the aforesaid specimens. The foregoing was also confirmed by the shape factor analysis, which revealed that the modified specimens were characterized by the lower index than that of the unmodified specimens. The closer the above-named indicator is to 1, the more likely the occurrence of gas pores in the structure.

3.3. Mechanical properties and fractographic analysis

The mechanical properties of both the modified and unmodified alloys are presented in the Table 6.

The ultimate tensile strength and yield strength were higher in the unmodified specimens. Such a situation could be ascribed to the increased share of porosity in the structure of the modified specimens. In turn, no significant differences were observed as regards elongation. However, the modified specimens were characterized by increased hardness. The foregoing might result from the fragmentation of massive silicon precipitates (characterized by brittleness). The formation of numerous colonies rich in finitely divided Si could advantageously affect the hardness of the alloy.

Fractures observed in both the unmodified and modified alloys were similar in nature and characterized by brittleness. In each case, the fracture surface contained numerous gas pores and shrinkage porosity. The gas pores in the unmodified specimens were not surrounded by shrinkage porosity (Fig. 5b), as was the case with the modified specimens (Fig. 5a). In addition, the modified alloys were characterized by significantly more intermetallic phase particles on the fracture surface (Fig. 5d) than those observed in the unmodified specimens (Fig. 5c).

4. Discussion

The microstructure of the HPDC EN AC-Al Si9Cu3(Fe) alloy consisted primarily of α-Al dendrites and binary AlSi eutectic. In addition, the alloy structure contained various types of intermetallic phases (undergoing crystallization in complex eutectic transformations), i.e. Al_2Cu phase, Chinese script α-$Al_{15}(Fe, Mn)_3Si_2$ phase and polygonal α-$Al_{15}(Fe, Mn, Cr)_3Si_2$ phase (observed as externally solidified crystals (formed in the shot sleeve)) [12]. It was also possible to observe acicular (needle-like) or lamellar (platelet-like) unfavorable β-Al_5FeSi phase and fine lead phases. The structure also contained the β-Al_5FeSi phase, i.e. the most disadvantageous intermetallic phase (characterized by large size and lamellar morphology).

Table 6. Mechanical properties of EN AC-Al Si9Cu3(Fe)

Alloy	R_m [MPa]	$R_{0.2}$ [MPa]	A_5 [%]	HV 2
Unmodified	213±7	147±6	1.03±0.5	81±7
40 ppm Sr	187±11	125±8	1.22±0.7	93±1
130 ppm Sr	205±6	140±9	1.08±0.3	92±2

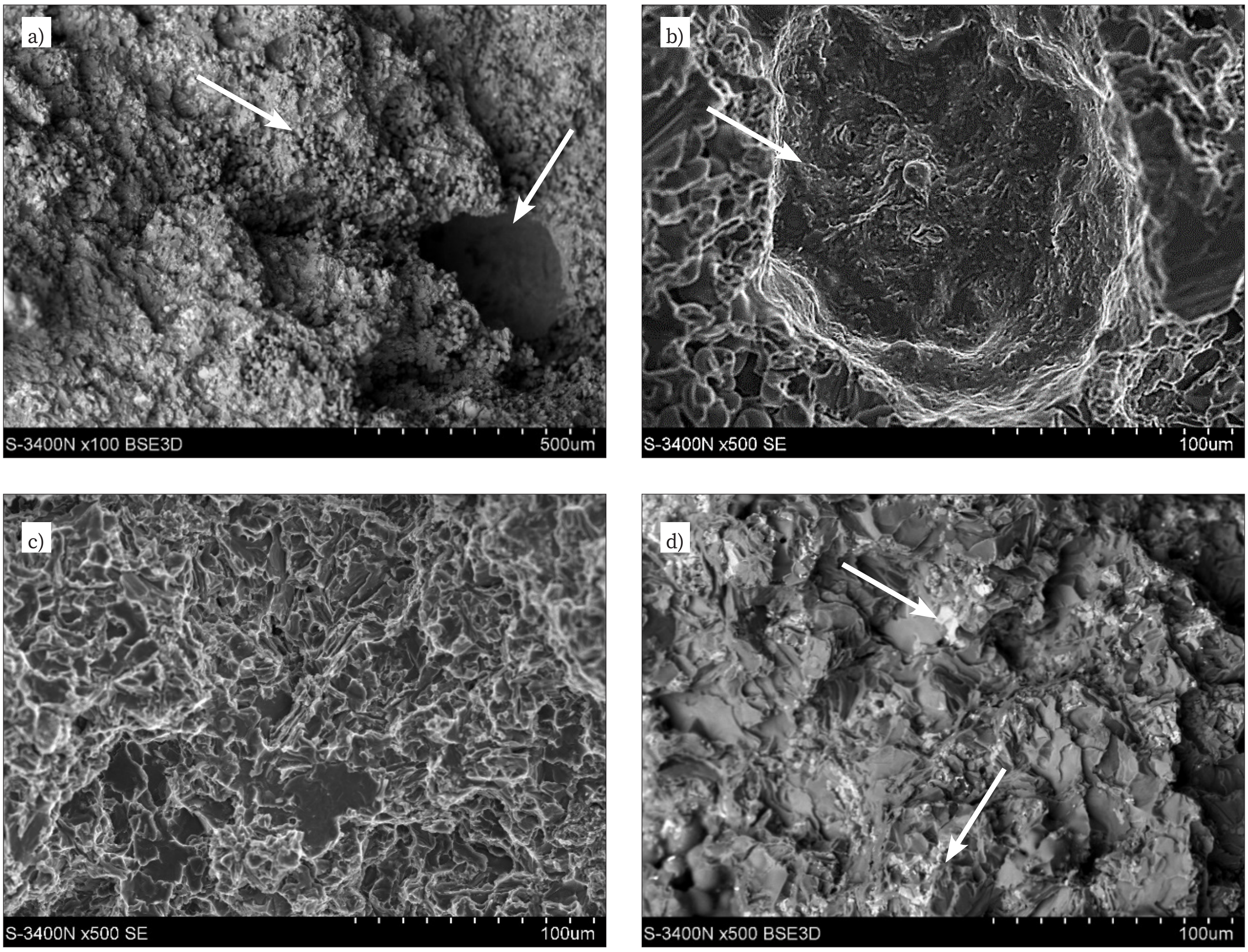

Fig. 5. Fracture surfaces in the EN AC-Al Si9Cu3(Fe) alloy, SEM: a) gas pore surrounded by shrinkage porosity observed on the fracture of the modified alloy, b) gas pore observed on the fracture of the unmodified alloy, c) brittleness of the unmodified alloy and d) intermetallic phase particles on the fracture surface of the modified alloy

The modification of eutectic silumins led to the considerable fragmentation of silicon crystals. The fragmentation Si crystal was responsible for increased interphase boundaries, reinforcing and potentially improving such properties as toughness, tensile strength, fatigue strength and impact strength [13, 14]. Strontium-based modification could be used effectively to reduce the time of solution treatment affecting the alloy [15]. The addition of strontium resulted in the significant fragmentation of eutectic silicon crystals, which contributed to the increased hardness of the alloy (up to 90 HV2). The addition of Sr could increase the porosity of the alloy by forming Sr oxides, favoring the nucleation of pores (which was confirmed by the research-related tests). The Sr-based modification triggered shrinkage porosity in the structure of the test alloy, resulting in a significant decrease in tensile strength, plasticity and elongation.

The presence of intermetallic phases on the fracture surface of the modified alloy could indicate fracture initiation and propagation.

5. Conclusions

1. The addition of strontium resulted in the significant fragmentation of eutectic silicon crystals, which contributed to the increased hardness of the alloy.
2. The structure of the investigated alloy subjected to Sr-based modification was characterized by shrinkage porosity, leading to a significant decrease in tensile strength, plasticity and elongation.
3. The presence of intermetallic phases on the fracture surface in the modified alloy could indicate fracture initiation and propagation.

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