

Modification of Eutectic Silicium in Al-Si-Cu Cast Alloy

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Abstract

The bearing alloy AlSi10 with Cu was developed as a possible replacement for aluminium alloys with Sn and Pb. This alloy is intended for low-speed bearings operating under high pressure, which are mainly used in freight transport. An addition of strontium is often used to modify the morphology of eutectic silicon, which affects the properties of the casting. The report analyses its concentration in the alloy, as well as its changes depending on the time between its application to the melt and the actual casting process. Strontium contents above 0.05% lead to a fine and fibrous (globular in the plane of the cut) Al-Si eutectic. The alloy achieved optimal mechanical properties at a strontium content of 0.12%. Hard and brittle needles of SrAl_2Si_2 appear at a strontium content above 0.35%, with their higher content leading to a decrease in strength, plastic properties, and fluidity. On the other hand, they also increase the hardness and practically do not affect the notch toughness. This ‘pre-modification’ is important when the melt is expected to remain at the casting temperature for a longer period.

Keywords:

Al-Si-Cu alloy, eutectic silicon, modifier, properties of casting

1. INTRODUCTION

Al-Si alloys (silumins) with good foundry properties are widely used for the production of all types of sand and die castings. Al-Si-Cu ternary alloys are aluminium casting alloys that use copper to increase their strength and hardness. These can be optimised by subsequent heat treatment through the exclusion of the Al_2Cu phase. These alloys provide low shrinkage, reducing hot tearing. They are also characterised by excellent fluidity and reduced thermal expansion. A copper content up to 5% improves the mechanical properties and machinability, especially after heat treatment, which increases the hardness [1, 2].

On the other hand, copper also has a negative effect: it impairs the corrosion resistance, weldability, ductility, and casting properties, and at higher contents, as an antagonist of silicon, it decreases the fluidity. A higher copper content can impair the resistance to cracking during solidification. It negatively affects the replenishment of the melt into the mould, which can lead to an increased incidence of microporosity. As an antagonist of aluminium, it increases the specific gravity of castings [3, p. 93, 4, p. 338].

Al-Si-Cu ternary alloys are suitable for hardening due to the ternary eutectic Al- Al_2Cu -Si with a melting point of 525°C. The solution annealing is carried out at 515 ±5°C with a sufficient holding time to ensure complete dissolution, usually 3–12 hours, followed by quenching and ageing at 150–170°C [5].

Silumins containing copper are used primarily for the production of complex-shaped castings where high hardness and strength are required. They are suitable for the production of leak-proof castings such as petrol engine fittings and carburettors, but also cylinder heads, pistons, pump housings, and complex castings requiring strength. Silumins containing 1% copper are suitable for the production of plain bearings as a replacement for Al-Sn-X and Al-Pb-X alloys [6]. They are ideal where a combination of the good casting properties of silicon and the strength of copper is required.

Alloys are classified by their silicon content, which determines their suitability for various casting methods. Alloys with a high silicon content (e.g., Al-10Si-2Cu) are suitable for die casting, where high fluidity is required. Conversely, alloys with a lower silicon content and a higher copper content (e.g., Al-3Si-4Cu) are suitable for gravity casting in sand and in metal moulds. This includes Alloy 319 (Al-6Si-3.5Cu); the ‘workhorse’ of the automotive industry, used for engine blocks and cylinder heads.

For a given composition of the alloy, it is the ability to optimise the grain size, eutectic structure, cell size, casting soundness, and the size and distribution of intermetallics that determines the properties. The morphology of the eutectic silicon has an important influence on the mechanical properties of Al-Si alloys.

Silicon is a faceted phase and makes the Al-Si eutectic an irregular eutectic. The brittleness of Si-crystals, of course, is the main characteristic responsible for the poor properties of silumins since the large eutectic silicon particles lead to

premature crack initiation and fracture in tension conditions. It has been proven that modification of eutectic silicon plays an important role in improving the mechanical properties of Al-Si alloys. Therefore, many efforts have been made in the modification of casting Al-Si alloys to achieve a fine silicon phase with beneficial shapes and distribution [7].

The process of crystallisation of eutectic silicon (β -phase) in silumins leads under normal conditions to the exclusion of plate-like crystals. Its morphology has a significant impact on the values of the mechanical properties. Changing the shape of the eutectic silicon (modification) is based on changing its growth unit from a plate to a rod (fibrous, in the plane of the cut from a needle to a globule). The result is a change in the fracture micromechanism from cleavage of the brittle β phase to ductile fracture of the aluminium α matrix. This change is associated with an increase in the strength and plastic properties of the alloy. It can occur chemically: by adding a modifier, using a higher cooling rate, or overheating the melt. The literature provides a wide range of modifiers, such as Li, Ce, Be, Na, Ca, Rb, Sr, As, Sb, Pb, and Bi.

Due to the limited effectiveness, price, and, above all, due to the toxicity of most of them, only strontium and sodium are practically used [7].

Na and Sr have by far the strongest modifying effect at very low addition levels. Although similar mechanical properties can be achieved by adding Sb, the effect of Sb on the microstructure of the eutectic is significantly different from that of Na or Sr. The addition of Sb refines the Al-Si eutectic, producing a fine flaky structure instead of the fibrous structure produced by Na or Sr [8, 9].

Sb is used mainly in Europe and Japan and is commonly referred to as a permanent modifier [10]. Unlike Sr and Na, once added to the aluminium melt, it remains a permanent component of the aluminium alloy. The modifier is therefore added by the foundry supplier and does not require any replenishment at the foundry [11]. Despite the good properties of sodium as a modifier [3], we used strontium as a modifier in our study due to Na's dosing problems and uneven concentration in the melt (mainly due to rapid burnout).

According to the literature, there are different opinions on the optimal concentration of strontium used as a modifier. Older authors recommended 0.03–1% strontium in the melt [3], while some current authors consider strontium content above 0.02% undesirable, as it can lead to coarsening of the eutectic silicon and deterioration of the mechanical properties of the casting [12].

The modifying effect of strontium is not permanent. The persistence of the melt at the casting temperature causes burnout: a decrease in the modifier content. According to the literature, the modifying effect of strontium lasts 1–2 hours, but up to four hours has also been reported at an initial content of 0.03%. Burnout can be slowed down by adding 0.05–0.2% beryllium, in which case the modifying effect can be longer than 10 hours [3]. In practical experiments and an initial content of 0.015% Sr in a melt at a temperature of 760°C, its content decreased to 0.012% after five hours. After 24 hours, the melt still contained 0.004% Sr.

The cooling rate has a significant impact on the modification process. A high cooling rate results in the formation of numerous crystallisation nuclei, an increase in the number of eutectic silicon particles, a change in their morphology, and a decrease in the interparticle distance. The disadvantage is the inhomogeneity of the structure with the appearance of 'overmodified islands' with fine eutectic silicon.

Unlike sodium, strontium does not fade as quickly in the melt, making it preferred for industrial applications that require long holding times or low-pressure die casting [13].

The modification, although not as significant as with gravity casting, is also important for high-pressure die casting (HPDC), as described by Brzezinski et al. [14] and Malik et al. [15]. Al-Si alloy can also be modified through the use of mechanical techniques, such as centrifugation, sonic and ultrasonic vibration, squeezing, etc. These mechanical means have been identified to cause grain refinement, density increase, shrinkage, degassing, change in size and shape, and distribution of the second phase [16, 17].

2. EXPERIMENTAL MATERIALS AND METHODS

The experiments aimed to study the influence of the strontium content in the melt, its temperature, and the time from the application of strontium on the microstructure and mechanical properties of the castings, and also the fluidity of the melt. In addition, the possible undesirable influence of the increased strontium content (premodification) on the microstructure and mechanical properties of silumin castings was evaluated. The silumin used contained: 10% Si, 1% Cu, 0.5% Fe, and 0.2% Mn. The strontium content in the castings was at five levels: 0%, 0.025%, 0.07%, 0.12%, and 0.35%. Chemical analysis was performed by the atomic absorption method on a Perkin Elmer 306A spectrometer. The undesirable influence of iron, present as an impurity, on the mechanical properties was compensated by manganese. The alloy was melted in a graphite crucible in an electric resistance furnace. Refining was carried out with Degasser and Tiboral six preparations. The casting temperature was 570°C. The oxide layer (smear) was mechanically removed before each casting.

A lump (up to 5 mm) of AlSiSr10 master alloy containing 8.35% strontium was used as a modifier. The melt was cast without a modifier or 30, 60, 120, and 300 minutes after the application of the modifier. The alloy was cast into an open steel mould, and its cooling rate ranged from $2^{\circ}\text{C}\cdot\text{s}^{-1}$ in the centre of the casting to $20^{\circ}\text{C}\cdot\text{s}^{-1}$ at its edge in contact with the mould. Before casting, the mould had an ambient temperature of 18–22°C.

To determine the fluidity Y_z , part of the melt was cast into a vertical steel mould (harp). A detailed description of the mould and the method of evaluating the fluidity is described by Petrík [18] and Futáš et al. [19].

Uniaxial tensile tests were carried out, and the parameters R_m (ultimate tensile strength), $R_{p0.2}$ (yield strength), Z (reduction of the area /contraction), and A_5 (total elongation) were evaluated. A 200 kN Zwick-Extensometer (Zwick GmbH&Co., Ulm, Germany) was used for both tests. For the tensile test, the mean strain rate $\dot{\epsilon}_{LC} = 0.0004 \text{ s}^{-1}$, and it was

carried out by the 200 kN Zwick-Extensometer according to the ISO 6892-1:2016 standard [20].

The HV10 and HV0.05 hardness tests were performed according to STN EN ISO 6507-1:2023 [21], and the HBW 5/250/30 hardness test was performed according to STN EN ISO 6506-1:2014 [22] on a HPO 250 hardness tester (Fritz Heckert, Leipzig, Germany). A Hanemann hardness tester (Carl Zeiss, Jena, Germany) with a diamond pyramidal indenter with a magnification of 480× fitted to a Neophot 32 optical microscope was used as a measurement device for the micro-hardness HV0.05 measurement. Hardness measurements were performed on polished and etched metallographic surfaces, the production of which is described below.

The impact toughness test in bending (KC and KCV2 Charpy test) was performed on normalised samples, i.e., 10 mm × 10 mm × 55 mm with a 'V' notch depth $c = 2$ mm, and on 10 mm × 10 mm × 55 mm samples without a notch (resp. 5 mm × 10 mm × 55 mm) according to STN EN 10045-1:1990 [23]. A PSW 30 tester manufactured by Prüfmaschine Fritz Heckert, Leipzig, Germany was used.

The testers for macro- and micro-hardness were calibrated using certified reference blocks (CRM) with hardness (H_{CRM}) and standard uncertainty (u_{CRM}), which are listed in Table 1. As can be seen from the results of the calibration, which was carried out according to the EN ISO 6506-2:2025 [24] and EN ISO 6507-2:2023 [25] standards, all the devices used for hardness measurement meet the requirements. The table shows the values determined by the calibration: the repeatability r_{rel} , the error of tester E_{rel} , and the relatively expanded uncertainty of calibration U_{rel} (all in percentages).

Table 1.
Results of calibration hardness testers

Hardness	H_{CRM} [HV]	u_{CRM} [HV]	r_{rel} [%]	E_{rel} [%]	U_{rel} [%]
HBW 2.5/250/30	185	1.65	0.92	−0.27	2.37
HV10	194	1.65	1.13	−0.20	2.16
HV0.05	195	4.00	1.86	−0.42	5.11

Macro- and micro-hardness were measured according to the ISO 6892-1:2016 [20] and EN ISO 6507-1:2023 [21] standards; the average hardness value from five indentations is reported. All hardness measurements were performed by a single operator.

A test load of 0.49035 N (HV0.05), with a 15-second dwell time was applied for microhardness HV0.05. The macrohardness was measured by the Vickers test (HV10) and the Brinell test (HBW 2.5/187.5/30). Manual control of the micro-hardness tester required maintaining consistent indenter penetration rates, which inherently influence the measured hardness values; the speeds fluctuated around $0.5 \mu\text{m}\cdot\text{s}^{-1}$.

The samples for metallographic analysis and hardness tests were cut from the notched toughness test samples with a water-cooled diamond cast into epoxy resin (dentacryl) for consolidation. Metallographic surfaces were prepared by grinding on 120 to 3000 ANSI/CAMI grit papers and subsequently polished with spineline (Al_2O_3)

moistened with water. This was followed by polishing with a diamond paste ($0.5 \mu\text{m}$) moistened with petroleum. The metallographic surface was etched with 25% H_2SO_4 at 75°C in order to make iron-containing particles visible, and subsequently with a 0.5% aqueous solution of HF.

The morphology of eutectic silicon was evaluated using a NEOPHOT 30 optical microscope (Carl Zeiss, Jena, Germany) according to the STN 42 0491:1978 standard [26].

Its interparticle spacing (distance) was evaluated using Formula (1):

$$\lambda_\beta = \frac{1}{M} \times \sqrt{\frac{A}{N}} \quad (1)$$

where:

M – magnification,

N – number of particles in a defined area A .

The particle size of the eutectic silicon was evaluated using the ImageJ software.

3. RESULTS

If the alloy cast from a temperature of 570°C did not contain strontium, eutectic silicon was precipitated in the centre of the casting in the form of isolated needles (lamellae) (Fig. 1), with a width of up to $4 \mu\text{m}$. The increased cooling rate at the edge of the casting was manifested by the shortening of the needles with a slight decrease in the interparticle distance (Fig. 2). When applying 0.07% Sr to the melt and its subsequent casting (after removing the smear, unannealed casting UC), oval silicon particles with a diameter of $1\text{--}3 \mu\text{m}$ with a rare occurrence of needles were precipitated in the centre of the casting (Fig. 3). The difference between the centre and the edge of the casting, in terms of microstructure parameters, is not as pronounced as in the unmodified state. A further increase in the strontium content is minimally reflected in the microstructure: the globular form of eutectic silicon dominates with a decrease in the interparticle distance towards the edges. A strontium content of 0.35% leads to premodification with the exclusion of needle-like SrAl_2Si_2 formations (marked by two arrows), whose microhardness reaches up to 1200 HV0.05 (Fig. 4).

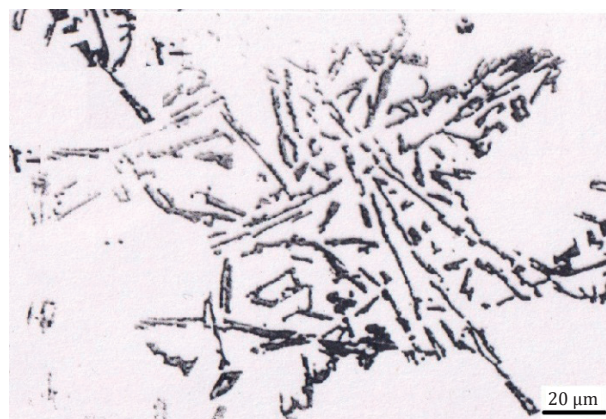


Fig. 1. Alloy without modifier, centre of casting

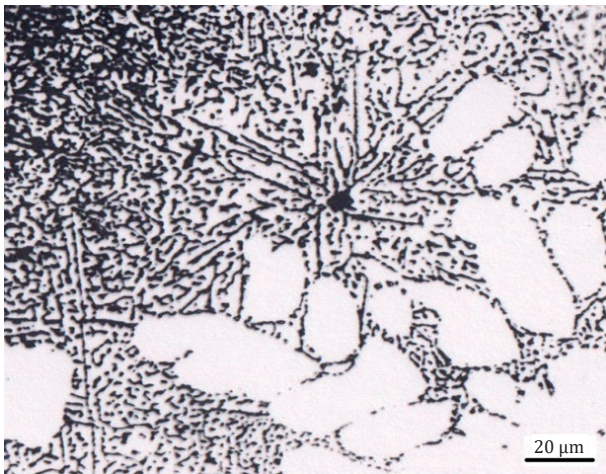


Fig. 2. Alloy without modifier, edge of casting

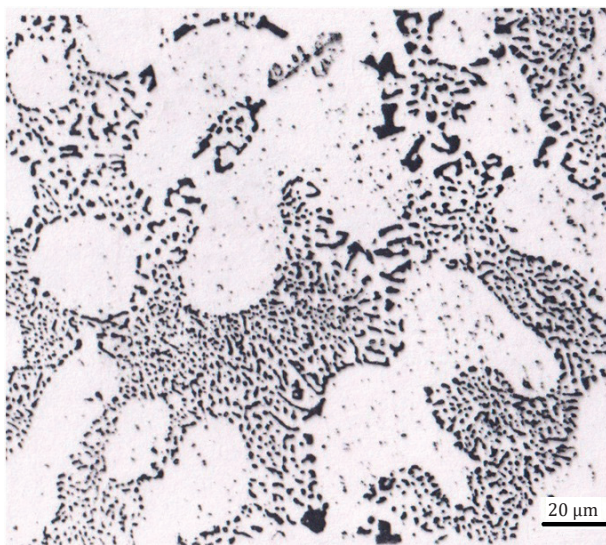
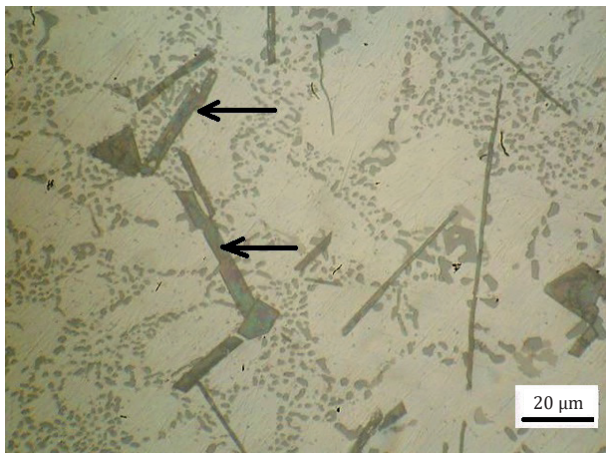


Fig. 3. Structure of an alloy modified with 0.07% Sr

Fig. 4. Precipitation of SrAl_2Si_2 needles after premodification

Figures 5 and 6 show the average values of the strength properties of the samples. Both characteristics increase with an increase in the strontium content up to 0.12%, with a more pronounced effect for R_e , while at higher contents, there is a decrease.

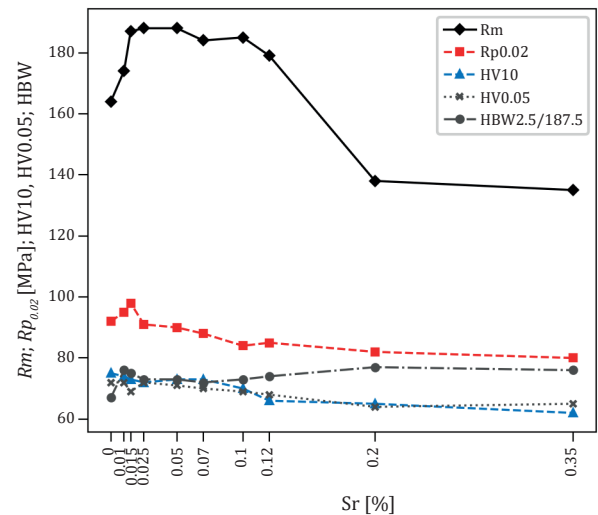


Fig. 5. Effect of strontium content on strength and hardness

Increasing the strontium content leads to a decrease in plasticity, as documented in Figure 5. The decrease at a content of 0.05% is an anomaly, probably due to an influence other than the strontium content. Increasing the strontium content (Fig. 5), leads to an increase in hardness, which is related to the exclusion of hard needle-like formations of SrAl_2Si_2 . The notch toughness reaches maximum values at a content of 0.12% Sr, with a subsequent minimal decrease; a similar trend was also found by the authors [27, 28].

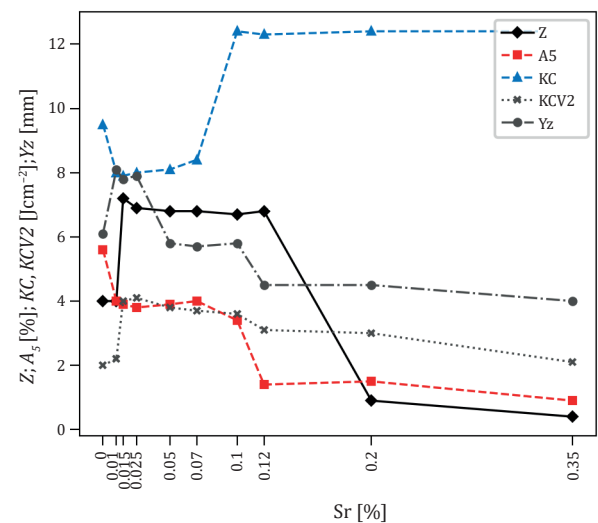


Fig. 6. Effect of strontium on plastic properties, notch toughness/impact value, and fluidity

Increasing the strontium content leads to a decrease in plasticity, as documented in Figure 6. The decrease at a content of 0.05% is an anomaly, probably due to an influence other than the strontium content. Increasing the strontium content (Fig. 5) leads to an increase in hardness, which is related to the exclusion of hard needle-like formations of SrAl_2Si_2 . The notch toughness reaches maximum values at a content of 0.12% Sr, with a subsequent minimal decrease; a similar trend was also found by the authors [27–29].

In the next step, the strontium content and the time between the application of the strontium and the casting were varied. The alloy was cast from a temperature of 570°C into an open mould; the microstructure in Figure 7 is from the centre of the casting.

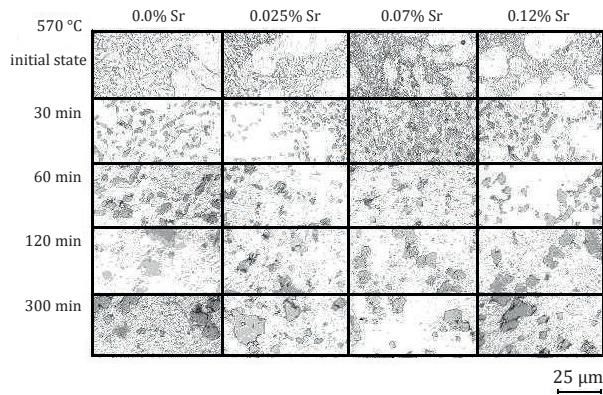


Fig. 7. Effect of strontium content and the time between adding strontium and casting the melt on the microstructure

The simultaneous influence of the initial strontium content and the time between its application and casting on the morphology of eutectic silicon particles is shown in Figure 8 (particle diameter) and Figure 9 (interparticle spacing λ_p).

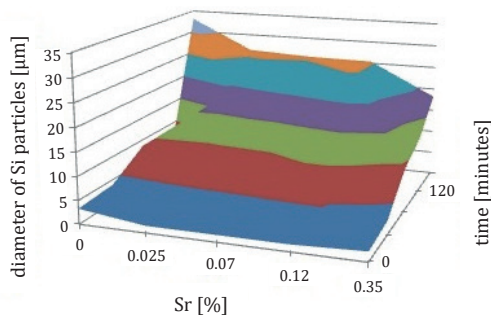


Fig. 8. Effect of strontium content and the time between adding strontium and casting the melt on the diameter of Si particles in the eutectic

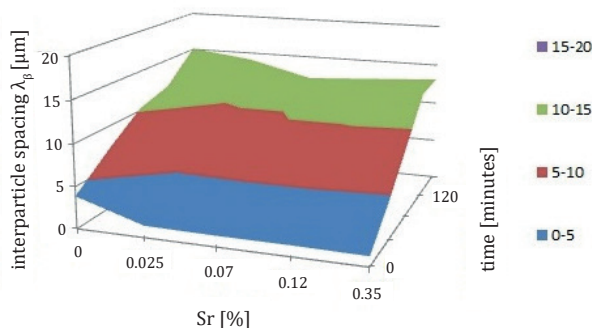


Fig. 9. Effect of strontium content and the time between adding strontium and casting on the melt the interparticle spacing λ_p of Si particles in the eutectic

Figure 10 shows the effect of the simultaneous influence of the initial strontium content and the time between its

application and casting on HV10 hardness. As the time between the application of the strontium and the casting increases, the hardness decreases, which is related to the coarsening of the microstructure. The effect of the initial strontium content (beyond its zero level) is less pronounced.

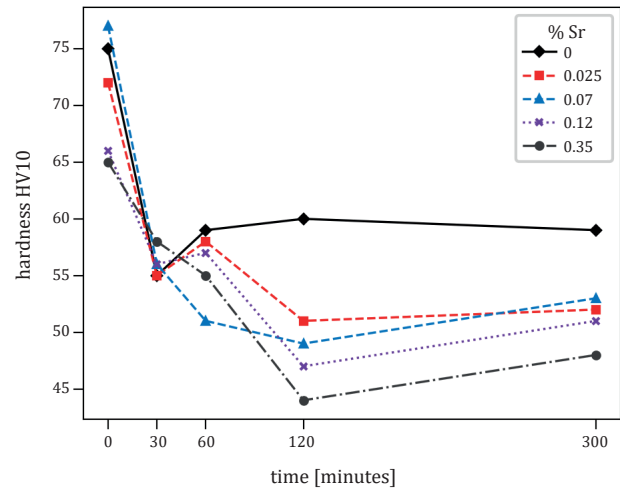


Fig. 10. Effect of strontium content and the time between adding strontium and casting the melt on the HV10 hardness

4. DISCUSSION

The AlSi10 bearing alloy with 1% Cu studied in this work is intended for highly loaded, low-speed plain bearings, where it represents a possible replacement for the traditional Al-Sn-X and Al-Pb-X bearing alloys [6]. In such applications, the combination of strength, plasticity, and castability is decisive, and all of these properties are controlled to a large extent by the morphology of the eutectic silicon. The results of the present experiments confirm that the modification of eutectic silicon by strontium is an effective tool for optimising the microstructure and, consequently, the mechanical properties of this alloy.

In the unmodified state, eutectic silicon precipitated in the form of lamellae (needles in the plane of the metallographic surface), and the alloy exhibited low mechanical properties, particularly the plastic ones (elongation A_5 and reduction of area Z). This observation is in full agreement with the literature: coarse plate-like silicon acts as an internal notch, the fracture proceeds by cleavage of the brittle β phase, and the ductility of the alloy is therefore low. Timpel et al. [30] showed by atom probe tomography and transmission electron microscopy that the addition of strontium changes the growth mechanism of the silicon phase: Sr co-segregates with Al and Si within the eutectic silicon, promotes multiple twinning (impurity-induced twinning), restricts the growth of silicon crystals, and thus transforms the coarse plate-like silicon into a fine fibrous network. In the plane of the section, the fibrous silicon appears as globules, which corresponds to the microstructures observed in our castings at strontium contents of 0.05% and higher.

A strontium content of 0.05% was sufficient for the complete modification of eutectic silicon, and the optimal mechanical properties were achieved at 0.12% Sr, with the most pronounced increase in strength (R_m). The growth of strength and plastic properties associated with the change of the fracture micromechanism from cleavage of the β phase to ductile fracture of the α matrix is consistent with the results of Zamani and Seifeddine [31], who correlated the level of modification (35–500 ppm Sr) with tensile strength and elongation to failure, and with the classical practical analysis of Sigworth [32]. It should be noted that the optimal content found in this work is higher than the values usually recommended for hypoeutectic silumins (approximately 0.01–0.05% Sr [31–33]); this difference can be attributed to the chemical composition of the studied bearing alloy, the relatively low casting temperature (570°C), and the moderate cooling rate in the open steel mould. In accordance with the literature [31, 32], the hardness (HBW, HV) was not significantly influenced by the modifier content, since hardness reflects mainly the volume fractions of the phases present rather than the morphology of the eutectic silicon; a measurable increase in hardness appeared only after the precipitation of hard SrAl_2Si_2 needles.

A further increase of the strontium content up to 0.35% (overmodification) led to the precipitation of brittle needle-like SrAl_2Si_2 phases with a microhardness of up to 1200 HV0.05 and to a decrease in the mechanical properties and fluidity. The same phenomenon is described in the literature: an excess of strontium forms $\text{Al}_2\text{Si}_2\text{Sr}$ intermetallics, which reduce the modification effect, act as internal stress concentrators, and deteriorate the properties of the casting [34]. Emadi et al. [35] further showed that Na and Sr additions decrease the surface tension of the melt and increase the volumetric shrinkage, which supports the observed negative influence of higher strontium contents on castability. The threshold of overmodification found in this work (above 0.35% Sr) is, however, considerably higher than the contents reported as harmful in the literature, which is one of the important practical findings of the present study.

The deliberate overmodification may nevertheless be technologically justified when a longer time interval between the application of strontium and casting is expected. The modification effect of strontium is not permanent: its content in the melt gradually decreases (fades), predominantly by oxidation [35]. Zhang et al. [34] reported that in an A356 melt held at 760°C with an initial addition of 0.06% Sr, the modification effect began to fade after approximately 150 min and disappeared completely after 240 min, when the residual strontium content dropped below approximately 0.008%. Djurdjevic et al. [36] quantified the fading rate and showed that it depends mainly on the melt temperature, the surface-to-volume ratio of the bath, and the furnace size, with sodium fading considerably faster than strontium. A higher initial strontium content therefore acts as a reserve that guarantees complete modification even after longer holding times, which was confirmed by our

experiments with casting 30–300 min after the modifier addition.

Besides strontium, other elements (Na, Sb, Be, Ca, and rare earths) can be used as modifiers. Sodium is the most powerful modifier, but its application is complicated by dosage problems, rapid burnout, and an uneven concentration in the melt [36]. Lu et al. [37] demonstrated that combined Sr + Na additions can be beneficial, but that controlling the sodium content remains difficult in foundry practice. Antimony acts as a permanent refiner, producing a fine lamellar rather than a fibrous structure; it does not fade, but it is less effective, toxic in the form of stibine, and it neutralises the effect of Sr and Na [38]. For these reasons, strontium, added conveniently in the form of an AlSr master alloy with a recovery of up to 90%, remains the preferred modifier for industrial applications, which was also the reason for its selection in this work.

Finally, a modification effect can also be achieved by increasing the cooling rate (quench modification). A cooling rate exceeding approximately $50^\circ\text{C}\cdot\text{s}^{-1}$, typical of thin-walled high-pressure die castings, can refine the eutectic silicon even without a chemical modifier [36]; the influence of the cooling rate on the nucleation and growth of the eutectic was analysed in detail by Dahle et al. [33] and McDonald et al. [39]. This was also confirmed in our experiments by the finer microstructure at the edge of the casting (cooling rate up to $20^\circ\text{C}\cdot\text{s}^{-1}$) compared to its centre ($2^\circ\text{C}\cdot\text{s}^{-1}$). However, the cooling rate is limited by the shape of the casting, the casting method, and the moulding material, and an excessive cooling rate may lead to distortion or even to a loss of integrity of the casting. Chemical modification with strontium therefore remains the most robust and universally applicable method for the studied bearing alloy.

5. CONCLUSIONS

When analyzing the influence of strontium content in an Al-Si alloy on its microstructure and properties, the authors of the paper reached the following conclusions:

1. A strontium content of 0.05% is sufficient for complete modification of eutectic silicon.
2. Optimal mechanical properties were achieved by the alloy at a 0.12% strontium content.
3. A further increase of the strontium content to 0.35% worsens the mechanical properties of the alloy without significantly affecting the microstructure or fluidity.
4. Coarseness of the structure and the beginning of a decrease in mechanical properties were observed at strontium contents above 0.35%, which is higher than reported in the literature.

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