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# Effect of Zn addition and natural aging on the microstructure and mechanical properties of secondary AlSi7Cu2 alloys

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# Effect of Zn addition and natural aging on the microstructure and mechanical properties of secondary AlSi7Cu2 alloys

**G Scampone[1], O Gursoy, S Brutti and G Timelli**

Department of Management and Engineering, University of Padova, Vicenza, I-36100, Italy

[1] Email: giulia.scampone@phd.unipd.it

**Abstract.** The effect of different Zn contents on the microstructure of a secondary AlSi7Cu2 alloy has been studied. The mechanical properties of the alloy during natural aging has been investigated too. The Zn additions range from 0.7 to 8 wt.%, and the tensile testing has been carried out at the as-cast condition and after 3, 7, 12 and 21 days of natural aging. Metallographic and image analysis techniques have been used to characterize the microstructural changes of the alloy. The results indicate that the alloy is strengthened as a function of the aging time and Zn addition. Both yield stress and elongation to fracture tend to stabilize over long aging times, independently of Zn level. The steady-state tensile properties are achieved earlier by increasing the Zn content. Furthermore, high Zn contents promote the formation of eutectic structure and the precipitation of needle-like Fe-rich compounds, which decrease the ductility of the material.

## 1. Introduction

Excellent castability, low density, high mechanical properties and good corrosion resistance are the main features of the Al-Si foundry alloys, which are widely used in the transportation industry. These alloys can reduce the vehicle’s weight without compromising the safety of the cars, improving the fuel economy and the environmental sustainability [1].

In order to maximise the strength of heat-treatable Al-Si alloys, thermal heat treatments can be performed to dissolve coarse intermetallic phases, spheroidize the eutectic Si and promote the precipitation of fine strengthening particles. However, the industrial costs and the energy consumption of these post-casting heat treatments are not negligible. Therefore, self-hardening Al alloys are now increasingly attracting the attention of industrial companies, which are considering these alloys as alternative to the standard heat-treated AlSiMg or AlSiCuMg alloys to produce automotive components [2,3].

Zn-containing Al-Si alloys can naturally age after casting process, and they can strengthen over time without any further heat treatment. Tillová et al. [4,5] demonstrated how the mechanical properties of an AlZn10Si8Mg casting alloy can be maximized after 7÷10 days of storage at room temperature. Moreover, further straightening can be induced by high cooling rates during solidification and through the addition of 3 wt.% Mg [6].

In general, Zn shows great solubility in the α-Al matrix (up to ~83 wt.% at 381°C [7]). Further, after the addition of Zn to Al-Si alloys, the system behaves as though the eutectic point is shifted to a higher silicon content and the eutectic temperature is depressed [8]. The volume fraction of the eutectic increases as well as the size of the eutectic Si particles [8,9]. From the mechanical point of view, the hardness, ultimate tensile strength and yield stress increase after Zn addition, while the elongation to fracture, as well as the impact toughness, is reduced by increasing the Zn amount [8–11].

To the best of authors’ knowledge, even though the performance of Al-Zn alloys by varying the aging parameters has been deeply investigated [12,13], the evolution of the mechanical and microstructural properties during the natural aging of Zn-containing Al-Si-Cu alloys has not been studied yet.

In this study, the influence of Zn content and natural aging time on the microstructure and mechanical properties of secondary AlSi7Cu2 casting alloy was investigated.

## 2. Experimental Procedure

A secondary AlSi7Cu2 cast alloy (EN AC-46600 [14]), provided in the form of ingots, was selected as baseline for the casting trial. The alloy was grain refined and eutectic modified by adding Al-5Ti-1B and Al-10Sr master alloys, respectively. The chemical composition is shown in Table 1.

In order to study the effect of Zn addition on the microstructural and mechanical properties of the alloy, three additional levels of Zn were selected for the analysis. Weighted amounts of pure Zn in the form of waffle-shaped were added to achieve the nominal Zn contents of 3, 5 and 8 wt.%.

**Table 1.** Chemical composition (wt%) of the base AlSi7Cu2 alloy.

| | Al | Si | Fe | Cu | Mn | Mg | Zn | Ti | Sr | B |
|---|---|---|---|---|---|---|---|---|---|---|
| **AlSi7Cu2** | bal. | 6.451 | 0.665 | 2.20 | 0.374 | 0.423 | 0.687 | 0.165 | 0.019 | 0.005 |

The supplied AlSi7Cu2(Fe) alloy was melted at 780 ± 5 °C into a SiC crucible in an electric resistance furnace. The melt temperature was then decreased to 750 ± 5 °C for the Zn addition and the following degassing phase. Pure Argon was blown for 30 mins with a graphite lance and the molten metal was then skimmed according to standard foundry practice. After degassing, Al-5Ti-1B and Al-10Sr master alloys were added to the molten metal, which was then held at 720 ± 5 °C for about 30 min to ensure a complete homogenisation of the bath.

The metal was then poured at 735 ± 5 °C into a permanent steel mould preheated at 250 ± 3 °C and covered with a semi-permanent layer of Foseco Dycote® F34 coating. The die allowed the production of flat tensile specimens whose gauge length, width and thickness were 35, 9.5, and 6.1 mm, respectively. In order to continuously monitor the casting temperature and ensure good reproducibility of the tests, a thermocouple was embedded in the die at 2 mm from the inner surface of the gauge length. A 30 ppi SiC filter was used and located before the die cavity, in order to reduce the entrapment of oxides and inclusions inside the specimens. A batch of at least 15 specimens was produced for each alloy. The as-cast specimens were stored at room temperature and tested after 3, 5, 7, 12 and 21 days of natural aging and were therefore similar to a T1-condition. Generally, this temper designation applies to products that are cooled from an elevated-temperature shaping process, and for which mechanical properties have been stabilised by room-temperature aging.

Tensile testing was performed at room temperature according to ISO 6892-1:2019 standard. An electromechanical MTS Criterion Series 40 system equipped with a 50 kN load cell was used to carry out the tests. At least 3 specimens for each condition were tested, by applying a strain rate of $10^{-3}$ $s^{-1}$. The strain was measured using a 25 mm extensometer.

In order to assess the influence of Zn additions on the hardness of the material, Brinell hardness tests were performed on the cross section of the specimens after 21 days of natural aging. A load of 62.5 kgf was applied, using an indenter of 2.5 mm diameter. The dwell time was 15 seconds according to the ASTM E10-18 standard. Finally, in order to evaluate the strengthening of the α-Al matrix as a function of the Zn level, Vickers microhardness tests were carried out in the aforementioned specimens by applying a load of 0.005 kgf and a dwell time of 10 seconds.

Some samples were selected for the microstructural investigation. A cross-section in the gauge length was drawn and mechanically prepared according to standard metallographic techniques. The microstructure was investigated using an optical microscope equipped with an image analyser to measure the secondary dendrite arm spacing (SDAS), the eutectic fraction, and the precipitation of Fe-rich compounds. In each sample, a total area of more than 17 $mm^2$ was investigated by analysing progressive micrographs of 1.2 × 0.9 $mm^2$. The polished specimens were etched in a 70°C heated solution of 10% sulphuric acid in water, to easily measure the area fraction of Fe-bearing compounds by image analysis software.

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## 3. Results and discussion

### *3.1. Microstructure*

Figure 1 shows the typical microstructure of the experimental AlSi7Cu2 alloy. It consists mainly of a primary α-Al phase, a eutectic mixture of Al and Si, Fe- and Cu-rich compounds. Due to the high cooling rate during solidification (~40 °C/s) and the Sr addition, the eutectic Si particles are fine and fibrous, ranging in size from 0.6 to 3 µm. The Fe-rich compounds appear mainly with a needle-like shape and are uniformly distributed throughout the microstructure.

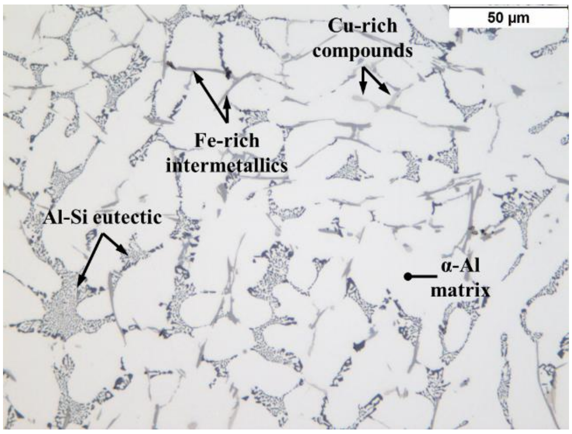


**Figure 1.** Typical microstructure of as-cast secondary AlSi7Cu2 alloy.

Regardless of the Zn content, the SDAS values were measured to be constant and equal to 12 ± 2 µm. Upon increasing the Zn concentration, some microstructural changes can be observed in the AlSi7Cu2 alloy (Figure 2). While the average size of the eutectic Si particles remains almost constant, the eutectic fraction greatly increases with Zn addition. Moreover, the precipitation of Fe-rich compounds, mostly in the needle-like shape, is promoted.

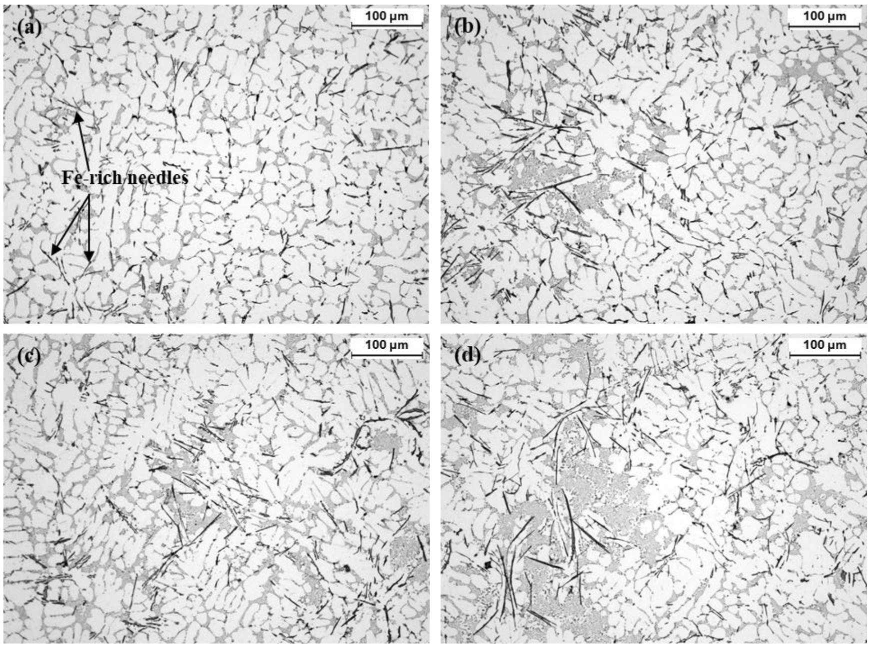


**Figure 2.** Typical etched microstructures of Zn-containing AlSi7Cu2: **(a)** base alloy (0.687 wt.% Zn), **(b)** 3 wt.% Zn, **(c)** 5 wt.% Zn and **(d)** 8 wt.% Zn.

Figure 3 shows the evolution of the eutectic fraction and the area fraction of Fe-rich compounds as a function of the Zn level. Both these microstructural features show an increasing trend, but with different slopes according to the Zn content. The eutectic fraction increases significantly from about 0.26 to 0.36 by increasing the Zn level from 0.7 to 3 wt.%. Further addition of Zn slightly affects the formation of the eutectic structure; upon increasing the Zn concentration from 3 to 8 wt.%, the eutectic fraction increases by 3.3%. This trend can be explained by considering the solidification path of Al-Si and Al-Si-Zn alloys. Upon increasing the Zn level in the Al-Si alloys, the eutectic point shifts toward higher Si content, resulting in an increase of the size and volume fraction of silicon particles, as reported by Alemdağ et al. [8]. In the present work, even though the dimension of the eutectic Si particles remains unchanged, the eutectic fraction increases. The high cooling rate during solidification and the Sr-modification prevented here coarsening phenomena of the eutectic Si particles.

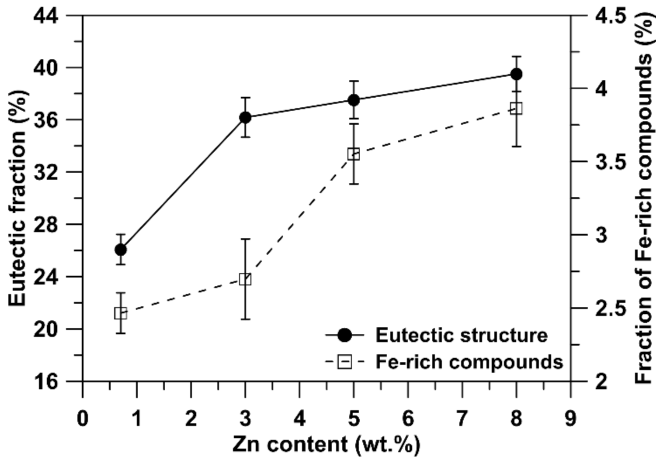


**Figure 3.** Evolutions of the amount of the eutectic and Fe-rich compounds as a function of Zn content in the AlSi7Cu2 alloy. Standard deviations are given as error bars.

The Zn addition facilitates significantly the precipitation of Fe-rich compounds (Figure 3). When the Zn content is about 8 wt.%, the area fraction of Fe-bearing compounds is about 3.9%, which is much higher with respect to the base alloy (~2.5%). The increase is particularly emphasized when the Zn concentration varies from 3 to 5 wt.%; in this range, the fraction of Fe-rich particles increases from about 2.7 to 3.6%. Most of the Fe-rich particles exhibit a needle-like morphology, which is consistent with previous findings by Sanna et al. [15]. From the thermodynamic point of view, high Zn concentrations increase the precipitation temperature of specific Fe-rich phases, promoting the formation of acicular Fe-rich compounds. As demonstrated in [16], this morphology can negatively affect the mechanical properties of the alloy, especially the ductility and the fatigue behaviour.

### *3.2. Mechanical properties*

Figure 4 shows the evolution of the tensile properties of the AlSi7Cu2 alloy as a function of the aging time and Zn content. In agreement with other studies [8,10,11], the yield stress (YS) increases with the Zn addition, while the elongation to fracture decreases. The yield stress shows the same trend as a function of the aging time, independently of the Zn concentration, that is a rapid increase at the beginning of the aging time and a further stabilization (Figure 4a). Different Zn levels affect mainly the YS of the as-cast alloy, the initial increase of the YS during early aging time as well as the stabilization time (see Figure 4a). Upon increasing the Zn content, the YS increases rapidly, and the material reaches a stable condition faster. The yield stress increases by about 15 MPa during the first three days of aging in the alloys with 0.75, 3 and 5 wt.% Zn, while, after the addition of 8 wt.% Zn, it increases from 144 to 180 MPa in the same aging time. Furthermore, at the highest Zn addition, the YS is stabilised at ~190 MPa after 7 days of aging, while longer times are necessary to stabilize the alloy at lower Zn concentrations.

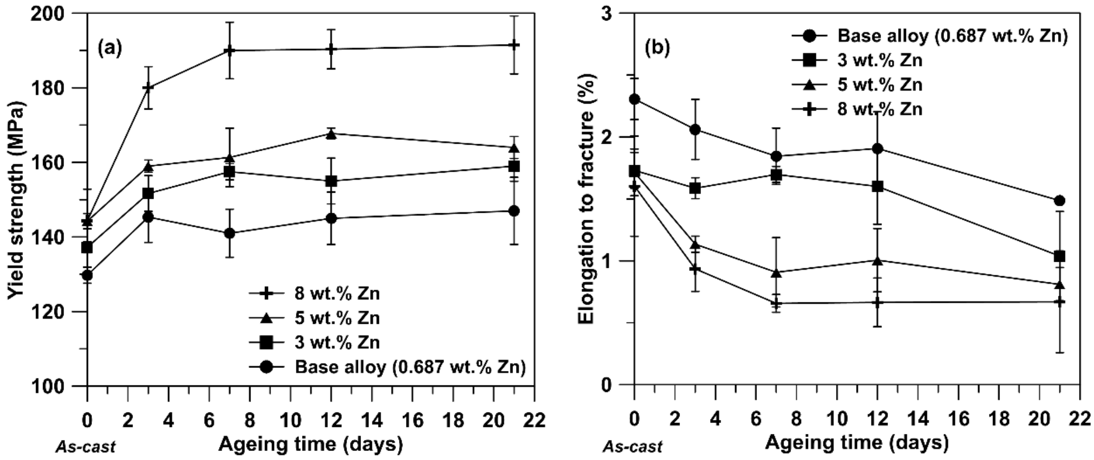


**Figure 4.** Evolution of **(a)** the yield stress and **(b)** the elongation to fracture as a function of the natural aging time and the Zn content in the AlSi7Cu2 alloy.

Figure 4b shows the variation of the elongation to fracture over aging time. After 7 days of aging, the ductility of the 5- and 8-wt.% Zn containing alloys is almost stabilised around 0.8%. At lower Zn levels, the elongation to fracture still decreases after 12 days of aging. This behaviour can be explained by considering the strengthening mechanisms of the alloys. Due to the high solubility of Zn in the α-Al matrix, solid solution strengthening contributes to the hardening of the alloy. Moreover, the addition of this element allows the spontaneous formation of precipitates even at room temperature. Therefore, during natural aging, the YS increases with time due to the gradual formation of Zn-rich precipitates. Higher Zn concentrations result in a greater tendency to form precipitates and require shorter aging times to maximize the strength of the alloy. Therefore, after the addition of 5 and 8 wt.% Zn, the trends of yield stress and elongation to fracture tend to stabilize soon with respect to the base alloy (Figure 4). Furthermore, it worth to be mentioned how higher Zn additions promote the precipitation of Fe-rich needles, which negatively affects the ductility of the alloy. The rapid decrease of the elongation to fracture by increasing the Zn level may also be related to greater precipitation of Fe-rich phases.

The hardness of AlSi7Cu2 alloy and the microhardness of α-Al phase are also affected by Zn addition. The results of the hardness testing after 21 days of natural aging show that the alloy strengthens with increasing Zn content. The hardness increases linearly from 86±2 to 102±1 HB by adding 8 wt.% of Zn to the base alloy. The microhardness of the α-Al phase exhibits the same trend, increasing linearly from 65±1 to 85±2 HV with varying Zn content from 0.7 to 8 wt%. Therefore, as the Zn content increases, a strengthened α-Al phase is formed and the mechanical properties of the alloy are improved through the combined effect of solid solution and precipitation hardening mechanisms.

## 4. Conclusions

In the present work, the influence of different Zn additions on the microstructure and mechanical properties of a secondary AlSi7Cu2 alloy was analysed. The following conclusions can be drawn.

- The formation of the eutectic structure and the precipitation of Fe-rich compounds are affected by the Zn concentration. Higher Zn amounts increase the eutectic fraction formed during the solidification of the alloy and promote the formation of acicular Fe-rich phases, which affect negatively the ductility of the alloy.
- During natural aging, the yield stress increases with time until a stable condition is reached. Similarly, the elongation to fracture decreases over time until it stabilizes over long aging times. The Zn addition affects the stabilization time, which occurs earlier when the Zn content is high.

- The yield stress and hardness of the alloy increases with the Zn content in the alloy. The α-Al matrix results harder due to the presence of Zn as solid solution or strengthening precipitates.

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