THE EFFECT OF STRONTIUM AND ANTIMONY ON THE MECHANICAL PROPERTIES OF Al-Si ALLOYS

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In the dynamically developing casting production sector, casting products designed for vehicles must satisfy more and more criteria to meet the increasingly stringent performance requirements. Nowadays, secondary alloys are frequently used in casting production, but the effects of impurity elements on secondary alloys are not yet well-known. It essential to recognize that the quantity of impurity elements in Al-Si alloys is related to the quality of the materials. Two elements are frequently used to modify the eutectic silicon phase of these alloys, namely strontium and antimony. After scrap recycling, these elements are included in the melt, where the strontium and antimony together may lead to the formation of intermetallic compounds. The aim of our research was the examination of the joint effects of antimony and strontium on the mechanical properties of aluminium-silicon alloys with different cooling rates.

**Keywords:** aluminium alloys, silicon modification, wall-thicknesses, mechanical properties.

**Introduction**

In the casting industry the term “modification” describes the method in which inoculants, in the form of master alloys, are added to the aluminium melt in order to promote the formation of a fine and fibrous eutectic silicon structure during the solidification process [1]. Eutectic modification is a common process employed for Al-Si base alloys to improve the mechanical properties, particularly the tensile elongation of the material, by promoting the structural refinement of the inherently brittle eutectic silicon phase. It is well-known that trace additions of strontium to hypoeutectic aluminium–silicon alloys result in a transformation – from a coarse plate-like structure to a well-refined fibrous structure – of the eutectic silicon morphology [2]. Impurities might weaken this modification effect thus, lead to the deterioration of the mechanical properties of the final product.

During our work, we casted a series of samples from a melt containing different concentrations of antimony and strontium. The planned concentration ranges were between 0-300 ppm of strontium and 0–340 ppm of antimony. We designed and then tested a casting geometry with various wall-thickness values (6 mm, 8 mm, 12 mm, 25 mm). Samples for the tensile test were produced from the casted products.

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Cooling curves were obtained and analysed, and quantitative metallography was used to determine the level of eutectic modification. We used an Instron 5982 type electromechanical tensile test machine with a tensile speed of 0.004 mm/mm/s to determine the mechanical properties of the tested samples; and a Zeiss EVOMA 10 scanning electron microscope (SEM) equipped with an EDAX system to investigate the fractured surfaces.

1. Experiment

In order to allow a comparative analysis of the experimental results obtained from the measurements with the respective parameters of industrial castings, a special casting geometry was designed with different wall-thicknesses representing different cooling rates. Figure 1. shows the schematic illustration of the casting die with 4 different wall-thicknesses and the positions of the tensile test specimens. “Solid Edge” software was used to design the multiple casting geometry. The best solution was selected by using “NovaFlow and Solid” simulation. After the simulation process, the casting die with the optimised parameters was produced.

For experimental casting, we used standard AlSi8Cu3 (226.10) alloy ingots, their chemical compositions are given in Table 1. We used AlSr10 (Al-10wt.%Sr, wire) and AlSb10 (Al-10wt.%Sb, ingots) master alloys.
The Effect of Strontium and Antimony on the Mechanical Properties of Al-Si Alloys

Table 1

Chemical composition of the AlSi8Cu3 ingots

<table>
<thead>
<tr>
<th>Elements</th>
<th>Si</th>
<th>Cu</th>
<th>Mg</th>
<th>Ti</th>
<th>Sr</th>
<th>Sb</th>
<th>Fe</th>
<th>Mn</th>
<th>Pb</th>
<th>Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt.%</td>
<td>8.85</td>
<td>2.53</td>
<td>0.30</td>
<td>0.10</td>
<td>0.0005</td>
<td>0.0040</td>
<td>0.51</td>
<td>0.35</td>
<td>0.05</td>
<td>0.01</td>
</tr>
</tbody>
</table>

A total amount of 100 kg of the AlSi8Cu3 alloy ingots were melted and 16 different alloys were casted in 4 experimental series. The strontium and antimony alloying matrix of the 4 experimental series can be seen in Table 2. After the melting process, antimony was added to the melt in the first step, and different strontium concentrations were applied before each casting process. After the addition of both modifier elements (Sb, Sr), the molten alloy was kept at constant temperature for 15 minutes.

Table 2

Strontium and antimony concentrations in the experimental matrix

<table>
<thead>
<tr>
<th>Casting series</th>
<th>Strontium (ppm)</th>
<th>Antimony (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 5 (base alloy)</td>
<td>40</td>
<td>140</td>
</tr>
<tr>
<td>2. 100</td>
<td>240</td>
<td>340</td>
</tr>
<tr>
<td>3. 200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. 300</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unvarying experimental parameters can be seen in Table 3.

Table 3

Unvarying experimental parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting and alloying temperature</td>
<td>775±5 °C</td>
</tr>
<tr>
<td>Casting temperature</td>
<td>765±5 °C</td>
</tr>
<tr>
<td>Preheating temperature applied to the casting die</td>
<td>400 °C</td>
</tr>
<tr>
<td>Stabilization time after alloying</td>
<td>15 min</td>
</tr>
</tbody>
</table>

2. Results

2.1. Modification level of the eutectic structure

The modification level was determined from the cooling curves with the follow the equation [1]:

$$\Delta T_{Al-Si}^{E,G} = T_{Al-Si}^{E,G,UNMODIFIED} - T_{Al-Si}^{E,G,MODIFIED}$$  \hspace{1cm} (1)

Figure 2 shows the calculated values as a function of real strontium and antimony concentrations.
Based on the value of ΔT, two modification categories are mentioned in the published literature. If the temperature difference is less than 9 °C, the eutectic structure is signified as “non-modified”; if ΔT is higher than 9 °C, the structure is called “modified”. Observing the ΔT values on the cooling curve and the system of the tissues, we felt necessary to introduce a new grade. Thus, if the value is higher than 7.5 °C, but lower than 9 °C, the structure is referred to as “partially modified”.

The level of structural modification was also ranked based on the comparative analysis of the casted microstructure with standardized charts of similarly casted microstructures published by the American Foundry Society [3]. The results can be seen in Figure 3.
Based on the results of data analysis, the following can be summarized:

- If Sb concentration is increased, Sr concentration should be likewise increased so as to keep the same modification level.
- It can be observed, that the modification level of the samples with the highest Sb content from a given series with pre-determined Sr content is the same as the modification level of the samples with lower Sb content from another series with lower Sr content.

2.2. Mechanical properties

To determine the mechanical properties of the respective alloys, tensile rods from pre-selected sites were processed, as seen in Figure 4.

In Figures 5–8, tensile test results as a function of wall-thickness can be seen for alloys containing 5 ppm, 100 ppm, 200 ppm and 300 ppm of strontium, respectively. Generally, tensile strength values are decreasing with increasing wall-thickness, with an apparent maximum point at 8 mm wall-thickness.

In Figures 9–12, average tensile strength results as a function of Sr-Sb concentrations for different wall-thicknesses are represented. For 6 mm, 8 mm and 12 mm wall-thicknesses, a maximum distribution of the results can be seen, relative to the strontium concentrations. Depending on the antimony concentration, a maximum distribution of the results can be observed for some cases, however, this tendency cannot be generalized. In the case of 25 mm wall-thickness, it can be deduced from the results (obtained for Rm then for Rp0.2, A) that other effects like porous structure formation could have more strongly influenced the results than the addition of various strontium antimony concentrations.

It can be observed from the diagrams, that ultimate tensile strength tends to reach its maximum when plotted as a function of strontium concentration at the given antimony concentration (Figures 13–15.).
Figure 5. Average tensile strength values as a function of wall-thickness for 5 ppm of Sr

Figure 6. Average tensile strength values as a function of wall-thickness for 100 ppm of Sr

Figure 7. Average tensile strength values as a function of wall-thickness for 200 ppm of Sr

Figure 8. Average tensile strength values as a function of Sr-Sb concentrations at 6 mm wall-thickness

Figure 9. Average tensile strength values as a function of Sr-Sb concentrations at 8 mm wall-thickness
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Figure 11. Average tensile strength values as a function of Sr-Sb concentrations at 12 mm wall-thickness

Figure 12. Average tensile strength values as a function of Sr-Sb concentrations at 25 mm wall-thickness

Figure 13. Average ultimate tensile strength values as a function of Sr-Sb concentrations at 6 mm wall-thickness

Figure 14. Average ultimate tensile strength values as a function of Sr-Sb concentrations at 8 mm wall-thickness

Figure 15. Average ultimate tensile strength values as a function of Sr-Sb concentrations at 12 mm wall-thickness

Figure 16. Average ultimate tensile strength values as a function of Sr-Sb concentrations at 25 mm wall-thickness
The tensile test results for elongation can be seen in Figures 17–20, as a function of strontium–antimony concentrations. With wall-thickness values of 6 mm, 8 mm and 12 mm, it can be observed that by increasing the strontium concentration – relative to the concentration of antimony – the elongation tends toward a maximum.

2.3. Fracture features

Based on the results, we have chosen two types of samples for SEM analysis. The first sample type, taken from a section with 25 mm wall-thickness, exhibited the most unfavourable mechanical properties. The second type, sampled from the section with 8 mm wall-thickness, seemed to have the most favourable mechanical properties. The samples presented below contained 300 ppm of strontium and 340 ppm of antimony.

It is apparent from the image processed on the fracture surface of the sample with 25 mm wall-thickness (with unfavourable mechanical properties), that different phases were
formed in the Al-matrix [Figures 21 a–b]. The EDAX results of the marked phases in Figure 21 b) is shown in Table 4. The phase marked No. 1 represents a strontium–antimony intermetallic compound, phase No. 2 is a Cu-rich phase, while phase No. 3 is a Pb particle. Figure 21 a) shows the fracture surface, characterized by a relatively high porosity volume fraction.

![Figure 21 a–b) SEM fracture surface image for a rod section with 25 mm wall-thickness and unfavourable mechanical properties](image)

<table>
<thead>
<tr>
<th>Elements (wt.%)</th>
<th>No. 1</th>
<th>No. 2</th>
<th>No. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>5.61</td>
<td>2.52</td>
<td>2.93</td>
</tr>
<tr>
<td>Cu</td>
<td>5.11</td>
<td><strong>26.13</strong></td>
<td>2.33</td>
</tr>
<tr>
<td>Mg</td>
<td>5.82</td>
<td>1.14</td>
<td>0.64</td>
</tr>
<tr>
<td>O</td>
<td><strong>15.97</strong></td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Sr</td>
<td><strong>17.38</strong></td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Sb</td>
<td><strong>19.43</strong></td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Pb</td>
<td>2.42</td>
<td>–</td>
<td>54.89</td>
</tr>
</tbody>
</table>

Figure 21 a–b) SEM fracture surface image for a rod section with 25 mm wall-thickness and unfavourable mechanical properties

Table 4: Results of the EDS analysis (25 mm)

In Figures 23 a–b) we examined a sample section with 8 mm wall-thickness and with metallic contents of 340 ppm of Sb and 300 ppm of Sr. Comparing the images in Figures 21 a) and 23 a) it is clearly seen that both porosity volume fraction and the volume fractions of Sr-Sb compounds are considerably lower for the samples taken from the section with 8 mm thickness.

Figure 22. EDS analysis for Point 1
Figure 23.a-b. SEM fracture surface image for a rod section with 8 mm wall-thickness and favourable mechanical properties

Table 5

Results of the EDS analysis (8 mm)

<table>
<thead>
<tr>
<th>Elements (wt.%)</th>
<th>No. 1</th>
<th>No. 2</th>
<th>No. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>7.52</td>
<td>12.21</td>
<td>4.42</td>
</tr>
<tr>
<td>Cu</td>
<td>27.82</td>
<td>2.18</td>
<td>4.25</td>
</tr>
<tr>
<td>Mg</td>
<td>5.82</td>
<td>1.38</td>
<td>0.53</td>
</tr>
<tr>
<td>Mn</td>
<td>–</td>
<td>–</td>
<td>0.68</td>
</tr>
<tr>
<td>Fe</td>
<td>–</td>
<td>–</td>
<td>1.48</td>
</tr>
<tr>
<td>Sr</td>
<td>–</td>
<td>1.23</td>
<td>1.37</td>
</tr>
<tr>
<td>Sb</td>
<td>–</td>
<td>0.54</td>
<td>–</td>
</tr>
<tr>
<td>Pb</td>
<td>–</td>
<td>38.11</td>
<td>–</td>
</tr>
<tr>
<td>Sn</td>
<td>–</td>
<td>2.65</td>
<td>–</td>
</tr>
</tbody>
</table>

Figure 24. EDS analysis for Point 2

Conclusions

In this work, we studied the effect of different concentrations of antimony and strontium on the mechanical behaviour and the level of structural modification of Al-Si alloys, and the tendency of these alloys towards intermetallic compound formation. The concentration of antimony ranged from 40 to 340 ppm, while that of strontium varied between 5 and 300 ppm.

In this work, we presented the results of a comparative analysis of the eutectic modification levels determined with two different methods, namely thermal analysis and AFS standard charts. By evaluating the results obtained from these two types of characterization, it can be stated:

– If Sb concentration is increased, Sr concentration should be likewise increased so as to keep the same modification level.
It can be observed, that the modification level of the samples with the highest Sb content from a given series with pre-determined Sr content is the same as the modification level of the samples with lower Sb content from another series with lower Sr content.

On the basis of the results obtained from the cooling curves, the term “partially modified level” was introduced, pertaining to a ΔT value lower than 9 °C, but higher than 7.5 °C.

Measuring the tensile strength and ultimate tensile strength values for 6 mm, 8 mm and 12 mm wall-thicknesses, we have demonstrated that the results – relative to the strontium concentration – follow a maximum distribution pattern. Relative to the antimony concentration, the same values show a maximum distribution for some cases only, thus, it cannot be called a general tendency. Considering the tensile test results for elongation at wall-thickness values of 6 mm, 8 mm and 12 mm, it can be observed that with an increase in the strontium concentration – relative to the concentration of antimony – elongation tends to reach a maximum. During the fracture analysis, we found some compounds that contained Sr and Sb together. The aim of our long-term research work is to study the effects of Sr-Sb intermetallic compound formation on Al-Si foundry alloys.

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