Sensitivity of different Al–Si alloys to centrifugal casting effect

G. Chirita a, I. Stefanescu b,1, D. Cruz a, D. Soares a, F.S. Silva a,∗

a Faculty of Mechanical Engineering, School of Engineering, Minho University, Portugal
b Faculty of Mechanical Engineering, Dunarea de Jos University Galati, Romania

1. Introduction

Al–Si alloys are increasingly used in many applications due to its high tensile strength in relation to density compared to other cast alloys, such as ductile cast iron or cast steel.

As the properties of a specific Al–Si alloys (hypoeutectic, eutectic or hypereutectic) can be attributed to the individual physical characteristics of its main phase constituents (α-aluminium solid solution and silicon crystals) and to their volume fraction and morphology [1], different approaches have been used to control the microstructural features of Al–Si alloys such as adding some alloying elements [2,3] in order to refine the grain. However the most common way to improve mechanical properties of cast Al–Si alloys is by changing the casting technology [4]. Each technology has particular aspects that interfere on microstructure and consequently on mechanical properties.

On a previous paper by Chirita et al. [5] it is shown that the vertical centrifugal technique has some particular processing characteristics namely: fluid dynamics inside the mould; inherent vibration of the system; and centrifugal pressure; that may interfere on the metallurgical features of the obtained castings. On that paper an explanation about how the previous processing characteristics may affect the metallurgical features of the castings is provided. That study was performed on a specific Al18Si alloy.

The aim of the present paper is to quantitatively assess the sensitivity of different Al–Si alloys, from hypoeutectic to hypereutectic alloys, to the vertical centrifugal casting technique on mechanical properties of the castings based on changes in microstructure. Moreover it is intended to establish a global correlation that can be used for a range of Al–Si alloys, between metallurgical features and mechanical properties.

1.1. Microstructural–mechanical properties relations

In order to understand the relation between microstructure and mechanical properties some investigations are found in literature trying to clarify the relation between micro structural features such as secondary dendrite arm spacing (SDAS), eutectic constituents, Si and Fe intermetallics, Si particles size and shape [1,6–11], alloy composition [3], and respective mechanical properties. In Ref. [6] it is discussed the relationship between secondary dendrite arm spacing (SDAS) and tensile properties of both unmodified and Sr-modified A356 aluminium alloys. It is also discussed the micro structural effects on tensile and fatigue behaviour. Results show an increase of the ultimate tensile strength and strain to failure of both A356 and A357 (ASTM) alloys with the decrease of the secondary dendrite arm spacing (SDAS). The ductility of the Sr-modified alloy was reported to be higher than that of the unmodified alloys over the range of SDAS [6]. Other studies performed with an unmodified sand cast A356-T6 obtained by hot isostatic pressing revealed also an increase of ultimate tensile strength and of ductility with a decrease of secondary dendrite arm spacing (SDAS) [7]. Other experiments performed on an Al–7%Si–Mg alloy showed also an increase of the ultimate tensile strength and of the elongation with a decrease of dendrite arm spacing (DAS) [12]. The yield strength was found to be less influenced by the...
SDAS. In Ref. [2] there is a correlation between the amount of dendritic α-Al phase and mechanical properties of the Sr-modified alloy. In Ref. [9] it is reported that an increase of the silicon content of the Al–Si cast alloy causes a decrease of casting density and an increase of Young’s modulus. In another study [8], an increase in the strain to failure was attributed to the increase in the amount of eutectic.

Most of the previous studies are concerned with single alloys. However some companies, although working with a single class of aluminium alloys (e.g., Al–Si alloys – series 4000), they use different grades of those alloys (for e.g., 7% Si, 12% Si and 18% Si, etc.). This paper intends to, besides of quantifying the centrifugal effect on those alloys, establish a global denominator, for Al–Si alloys, that could be used with some accuracy for the prediction of mechanical properties of those alloys, as obtained by the two different casting processes.

In this study, a comparison between the effects of the centrifugal casting technique, as compared to the conventional gravity casting technique, on the microstructure (and consequently on mechanical properties) is made for different Al–Si alloys. It will be shown that a strong correlation between amount of eutectic constituent and mechanical properties, namely ultimate tensile strength, Young’s modulus, and mainly strain to failure, exists for all alloys. It will also be shown that this correlation is very alloy dependent and is more pronounced for alloys with higher Si contents. Additionally it will be shown that the centrifugal effect may strongly increase the mechanical properties of different Al–Si alloy castings.

2. Experimental methods

Three commercial Al–Si alloys with different Si contents were selected and will be referred in this study as alloys A (≈7% Si), B (≈12% Si) and C (≈18% Si) (Table 1). It must be highlighted that alloy C is known commercially as an 18% Si alloy but it has almost 19% of silicon. Notwithstanding in this work it will be referred with its commercial designation namely 18% Si alloy.

![Pouring direction](image1)

**Fig. 1.** Position from where tensile test specimens were taken: (a) gravity castings and (b) vertical centrifugal castings.

### Table 1
**Chemical composition of the alloys as obtained by SEM/EDS.**

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Fe</th>
<th>Co</th>
<th>Mg</th>
<th>Ni</th>
<th>Mn</th>
<th>Zn</th>
<th>Ti</th>
<th>Sb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy A</td>
<td>6.80</td>
<td>0.12</td>
<td>0.61</td>
<td>0.01</td>
<td>0.02</td>
<td>0.12</td>
<td>0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alloy B</td>
<td>12.09</td>
<td>0.27</td>
<td>0.58</td>
<td>1.34</td>
<td>1.26</td>
<td>0.09</td>
<td>0.04</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>Alloy C</td>
<td>18.89</td>
<td>0.90</td>
<td>0.52</td>
<td>1.20</td>
<td>1.37</td>
<td>0.12</td>
<td>0.24</td>
<td>0.04</td>
<td>0.11</td>
</tr>
</tbody>
</table>

### Table 2
**Mechanical properties, chemical composition and volume fraction of constituents for alloy A under gravity and centrifugal castings.**

<table>
<thead>
<tr>
<th>7% Si</th>
<th>Pos.</th>
<th>Mechanical properties</th>
<th>Chemical comp.</th>
<th>Volume fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>σ (MPa)</td>
<td>ε (%)</td>
<td>E (MPa)</td>
</tr>
<tr>
<td>Gravity</td>
<td>1</td>
<td>283</td>
<td>7.1</td>
<td>84,194</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>267</td>
<td>4.7</td>
<td>71,399</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>282</td>
<td>3.3</td>
<td>71,227</td>
</tr>
<tr>
<td>Centrifugal</td>
<td>1</td>
<td>321</td>
<td>10.2</td>
<td>71,557</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>298</td>
<td>8.0</td>
<td>74,837</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>285</td>
<td>4.0</td>
<td>66,620</td>
</tr>
</tbody>
</table>

### Table 3
**Mechanical properties, chemical composition and volume fraction of constituents for alloy B under gravity and centrifugal castings.**

<table>
<thead>
<tr>
<th>12% Si</th>
<th>Pos.</th>
<th>Mechanical properties</th>
<th>Chemical comp.</th>
<th>Volume fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>σ (MPa)</td>
<td>ε (%)</td>
<td>E (MPa)</td>
</tr>
<tr>
<td>Gravity</td>
<td>1</td>
<td>226</td>
<td>0.9</td>
<td>82,946</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>208</td>
<td>0.7</td>
<td>82,780</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>202</td>
<td>0.70</td>
<td>58,790</td>
</tr>
<tr>
<td>Centrifugal</td>
<td>1</td>
<td>264</td>
<td>1.52</td>
<td>80,652</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>249</td>
<td>1.30</td>
<td>62,510</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>227</td>
<td>0.91</td>
<td>70,170</td>
</tr>
</tbody>
</table>
Materials were melt in an induction vacuum furnace at temperatures 100°C above their liquidus temperature and then poured into a steel permanent mould. The permanent mould was preheated at 130°C for all castings. On vertical centrifugal castings the mould was rotating around the central axis of the casting machine at 450 rpm and the molten aluminium was poured into the mould cavity by centrifugal force. For gravity castings the same induction vacuum melting equipment and the same melting temperatures as on centrifugal castings, were used. However, in this last case, the melt was manually poured into the mould.

Alloys A and C were heat treated according to the standard industrial procedures for these alloys:

<table>
<thead>
<tr>
<th>18% Si</th>
<th>Pos.</th>
<th>Mechanical properties</th>
<th>Chemical comp.</th>
<th>Volume fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\sigma$ (MPa)</td>
<td>$\varepsilon$ (%)</td>
<td>$E$ (MPa)</td>
</tr>
<tr>
<td>Gravity</td>
<td>1</td>
<td>169</td>
<td>0.4</td>
<td>80,551</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>165</td>
<td>0.4</td>
<td>85,380</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>132</td>
<td>0.2</td>
<td>69,995</td>
</tr>
<tr>
<td>Centrifugal</td>
<td>1</td>
<td>232</td>
<td>2.0</td>
<td>71,330</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>258</td>
<td>1.7</td>
<td>74,620</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>212</td>
<td>0.9</td>
<td>79,178</td>
</tr>
</tbody>
</table>

Materials were melt in an induction vacuum furnace at temperatures 100°C above their liquidus temperature and then poured into a steel permanent mould. The permanent mould was preheated at 130°C for all castings. On vertical centrifugal castings the mould was rotating around the central axis of the casting machine at 450 rpm and the molten aluminium was poured into the mould cavity by centrifugal force. For gravity castings the same induction vacuum melting equipment and the same melting temperatures as on centrifugal castings, were used. However, in this last case, the melt was manually poured into the mould.

Alloys A and C were heat treated according to the standard industrial procedures for these alloys:

**Table 4**

Mechanical properties, chemical composition and volume fraction for 18%Si aluminium alloy under gravity and centrifugal castings.

**Fig. 2.** (a) Ultimate tensile strength, (b) strain to failure and (c) Young’s modulus results for centrifugal and gravity castings of alloy A in positions 1, 2 and 3 of ingots.

**Fig. 3.** Al and Si contents in positions 1, 2 and 3 of ingots for gravity and centrifugal castings of alloy A.

**Fig. 4.** Constituents’ volume fraction in positions 1, 2 and 3 of ingots for gravity and centrifugal castings of alloy A.
– alloy A – solubilization at 540 °C for 8 h, water quenching and aging at 160 °C for 4 h;
– alloy B – no heat treatment;
– alloy C – tempered for 8 h at 200 °C.

Alloys were tested only in the final condition (after heat treatment) because it is the aim of the paper to study the influence on the centrifugal effect on in service condition materials.

Three ingots of each alloy and of each casting technique were produced. Three specimens from each ingot, from the centrifugal castings and from the gravity castings (Fig. 1), were cut, in order to compare the properties of the aluminium alloys at three different distances from the surface of the ingot. Globally, 54 specimens were tested, 18 of each alloy. The arrows in Fig. 1 shows the direction of pouring of the melt alloy.

Tensile tests were carried out on a Dartec tensile testing machine at room temperature. Samples were analysed by optical and Scanning Electron Microscopy/Energy Dispersion Spectroscopy (SEM/EDS) in three different zones in area mode for 120 s. Volume fractions of constituents were quantified by image analysis.

3. Results

Mechanical properties namely ultimate tensile strength, strain to failure, and Young modulus, as well as constituents volume fraction and morphology, are presented in Tables 2–4 and in Figs. 2–13. In all graphs a linear global tendency among ingot positions 1, 2 and 3 (see Fig. 1) is presented.

3.1. Alloy A (7%Si)

Results, for alloy A, can be summarized as follows:

- ultimate tensile strength shows a tendency to increase from position 3 to position 1 in centrifugal castings but no tendency is found on gravity castings (Table 2, Fig. 2a);
- strain to failure shows a tendency to increase from position 3 to position 1 in both casting processes. A more pronounced effect exists in centrifugal castings (Table 2, Fig. 2b);
- Young’s modulus shows a smooth tendency to increase from position 3 to position 1 in both gravity and centrifugal castings (Table 2, Fig. 2c);
- ultimate tensile strength and strain to failure are higher in centrifugal castings in any position when compared to gravity castings (Table 2, Fig. 2a and b);
- the aluminium and silicon contents are approximately the same in all positions and casting techniques (Table 2, Fig. 3);
- dendrites’ volume fraction shows a tendency to decrease from position 3 to position 1 for both centrifugal and gravity castings (Table 2, Fig. 4);
- eutectic’s volume fraction shows an increasing tendency from position 3 to position 1 for both centrifugal and gravity castings (Table 2, Fig. 4);
- intermetallics’ volume fraction is not significant (always lower then 1%) for all positions and casting techniques (Table 2, Fig. 4);
- porosity is low and does not show any particular evolution along the casting;
- microstructure shows a similar qualitatively structure for both casting techniques but with different volume fractions and constituents dimensions (Fig. 5).

3.2. Alloy B (12% Si)

Results, for alloy B, can be summarized as follows:

- ultimate tensile strength shows a tendency to increase from position 3 to position 1 on both centrifugal and gravity castings (Table 3, Fig. 6a);
- strain to failure shows a substantial tendency to increase from position 3 to position 1 in gravity castings and in particular in centrifugal castings (Table 3, Fig. 6b);
- Young’s modulus show a tendency to increase from position 3 to position 1 in both gravity and centrifugal castings (Table 3, Fig. 6c);
- ultimate tensile strength and strain to failure are higher in centrifugal castings in any position when compared to gravity castings (Table 3, Fig. 6a and b);
- the aluminium and silicon contents are approximately the same in all positions and casting techniques (Table 3, Fig. 7);
- dendrites’ volume fraction shows a decreasing tendency from position 3 to position 1 in both centrifugal and gravity castings (Table 3, Fig. 8);
eutectic’s volume fraction shows a tendency to increase from position 3 to position 1 in both casting processes (Table 3, Fig. 8);
intermetallics’ volume fraction shows a slight tendency to decrease from position 3 to position 1 in both casting techniques (Table 3, Fig. 8);
porosity is low and does not show any particular evolution along the casting;
microstructure is qualitatively similar for both casting techniques and positions but with different volume fractions and constituents dimensions (Fig. 9).

3.3. Alloy C (18% Si)

Results, for alloy C, can be summarized as follows:

- ultimate tensile strength shows a tendency to increase from position 3 to position 1 in both centrifugal and gravity castings (Table 4, Fig. 10a);
- strain to failure shows a substantial tendency to increase from position 3 to position 1 in gravity castings and in particular in centrifugal castings (Table 4, Fig. 10b);
- Young’s modulus shows no substantial difference among positions in both gravity and centrifugal castings (Table 4, Fig. 10c);
- ultimate tensile strength and strain to failure show higher values for the centrifugal casting process in any position, when compared to gravity castings (Table 4, Fig. 10a and b);
- the aluminium and silicon contents are approximately the same in all positions and casting techniques with a small variation from position 3 to position 1 in centrifugal castings (Table 4, Fig. 11);
- (Al) phase volume fraction shows a tendency to decrease from position 3 to position 1 mainly in gravity castings (Table 4, Fig. 11);
- eutectic’s volume fraction shows a tendency to increase from position 3 to position 1 in both casting processes (Table 4, Fig. 12).
intermetallics’ volume fraction shows a tendency to increase from position 1 to position 3 in centrifugal castings and from position 3 to position 1 in gravity castings (Table 4, Fig. 12);

- porosity is low and does not show any particular evolution along the casting;
- microstructure is qualitatively similar for both casting techniques but with different volume fractions and constituents dimensions (Fig. 13).

4. Discussion

The two main issues in this paper are: sensitivity of different Al–Si alloys to the centrifugal process, mainly in terms of mechanical properties, when compared to traditional gravity castings; and the establishment of a global correlation between microstructure and mechanical properties for those alloys and processing techniques.

It should be highlighted that the explanation for the influence of the centrifugal technique on metallurgical and mechanical properties of obtained castings is presented in a previous paper by Chirita et al. [5]. In that paper some particular processing characteristics namely: fluid dynamics inside the mould; inherent vibration of the system; and centrifugal pressure; are presented as the main processing characteristics that interfere in the metallurgical features of the castings.

4.1. Mechanical properties

- The centrifugal effect seems to be alloy sensitive (mainly on ultimate tensile strength and on strain to failure): alloy A is less influenced, (the maximum centrifugal effect in increasing ultimate tensile strength is approximately 13% and in strain to failure is approximately 45%); alloy B is substantially influenced (the maximum centrifugal effect in increasing ultimate tensile strength is approximately 18% and in strain to failure is approximately 65%); and alloy C is strongly influenced by the casting technique (the maximum centrifugal effect in increasing ultimate tensile strength is approximately 60% in strain to failure is approximately 400%) (Figs. 2, 6 and 10).
- The difference in mechanical properties from positions 1–3 (slope of the tendency line), in centrifugal castings, is different. These differences are alloy chemical composition dependent: alloy A has small differences; alloy B has substantial differences; and alloy C has huge differences (Figs. 2, 6 and 10). This is particularly evident in terms of strain to failure.
- Mechanical properties are influenced by the centrifugal casting technique. As a fact, in general the centrifugal castings have better mechanical properties (ultimate tensile strength and in particular strain to failure) then the gravity castings (Figs. 2, 6 and 10).

The relationship between mechanical properties and metallurgical variables involved on the process will be subsequently addressed.

4.2. Microstructure–chemical composition

It is clear in Figs. 3, 7 and 11 that the chemical composition of the ingots (Al and Si contents) in different positions (1, 2, and 3) of the three alloys is not substantially influenced by the casting process. Only alloy C shows a slight difference on the Si and on the Al content between the gravity and centrifugal castings in position 3 of the ingots. Thus, there is no significant displacement of Al or of Si from the inner to the outer positions of the ingot due to the centrifugal effect or due to the gravity force. This displacement is common for materials with phases and/or chemical elements with different densities such as tin bronzes (the density of lead is higher than the density of copper – 11.3 vs 8.9 g/cm$^3$) as presented by Halvae and Talebi [13]. For Al–Si alloys this effect is not significant (Si and Al densities are similar – the density of Si is 2.34 g/cm$^3$ and the density of aluminium is 2.7 g/cm$^3$).

Because no significant difference on the chemical composition of samples was found among positions 1–3 it can be concluded that changes on mechanical properties are not due to chemical composition variation along the ingots but are dependent on constituent’s volume fraction and morphology.

4.3. Microstructure–constituent’s volume fraction

Many researchers already tried to establish relationships between some characteristics of constituents and mechanical properties in Al alloys.

Among those, perhaps the SDAS is the most studied. The secondary dendrite arm spacing (SDAS) versus tensile properties is discussed in Ref. [6] on A356 and A357 (ASTM) aluminium alloys. It was found that ultimate tensile strength decreases with SDAS.
The same correlation was found for ultimate tensile strength and ductility on a sand cast A356-T6 obtained by hot isostatic pressing [7] and on an Al–7%Si–Mg alloy [12]. On this last reference the yield strength was found to be less influenced by the SDAS. Regarding other constituents, Ref. [2] provides a correlation of the amount of dendritic α-Al phase with ultimate tensile strength (UTS) and strain to failure. However in this case the increase of UTS and strain to failure was also accompanied by a grain (SDAS) refinement. Thus it is not clear which feature – dendritic α-Al phase or SDAS refinement, caused the increase in properties. In another study, an increase in the strain to failure was attributed to the increase in the amount of eutectic in a 12.5% Si aluminium alloy [8]. Among the different previous studies the one by Abu-Dheir et al. [8] is the one where the results are similar to the ones obtained in present study (Eq. (3), Fig. 15). As a fact, in the present study, although there is also a grain refinement with increase in Si content (7–18%) and a change in shape of eutectic phase, particles in 7%, lamellas in 12% and coral-like form in 18%, it is clear that with the increase in amount of eutectic both UTS and rupture strain increase.

It is important to highlight that in most of the studies in which a correlation between mechanical properties and metallurgical features was tried, only one alloy was studied. In the present study it is intended the establishment of a correlation that can be suitable for, at least, different grades of a class of aluminium alloys (Al–Si alloys – series 4000) and for different casting processes. As a consequence it is tried a relation between a common denominator in all studied commercial Al–Si alloys. As can be seen in Figs. 5, 9, 10 and 13 and Tables 2–4 the alloys are very different both in constituents as well as in morphology of the constituents: 7% Si alloy does not have intermetallics, the α-Al phase has the form of dendrites, and the eutectic constituent has essentially a particle shape; the 12% alloy has some intermetallics, the α-Al phase has also the form of dendrites, the silicon is present in the form of lamellar eutectic bus also in the form of particles; finally in the 18% Si alloy there is some isolated α-Al phase, there is some intermetallics, and the silicon is essentially in a coral-like morphology.

However, although the substantial difference in terms of constituents and its morphology in the different alloys it was verified that there are common variations of mechanical properties evolution with some constituents, namely with eutectic volume fraction.
Figs. 4, 8 and 12 show this evolution. It is clear the qualitative match between eutectic volume fraction and mechanical properties for all three alloys. It is observed in Tables 2–4 that porosity is low and does not seem to have any substantial influence on mechanical properties since there is no correlation with mechanical properties.

4.4. Microstructure–correlation with constituents

In literature, some quantitative relations between mechanical properties, phases and chemical composition were proposed. Mandal et al. [14], proposed a correlation between tensile strength and silicon particle size:

![Fig. 13. Microstructures of gravity and centrifugal castings of alloy C on different positions of the ingot.](image)

![Fig. 14. Experimental and calculated values of stress for centrifugal and gravity castings of alloys A, B, and C in positions 1, 2 and 3 of ingot.](image)
Tensile strength (MPa) = 252.8 – 3.73 × particle size (μm) (1)

Another relationship was proposed between ultimate tensile strength and secondary dendrite arm spacing and the size of silicon lamellas in interdendritic eutectic regions [1]:

\[ \sigma = k + k_2 \cdot \gamma^{1/2} + k_3 \cdot \lambda^{1/2} \] (2)

where \( \sigma \) is the ultimate tensile strength, \( k, k_2 \) and \( k_3 \) are empirical constants, \( \gamma \) is the size of silicon lamellas in interdendritic eutectic regions and \( \lambda \) is the secondary dendrite arm spacing.

These equations were derived for a specific type of alloys, for example hypoeutectic or hypereutectic Al–Si alloys.

As can be seen none of the previous equations would suit simultaneously the three Al–Si tested alloys in the present study. On the present work, the same type of equation was derived for the three tested alloys which have substantial different Si contents and different morphologies. An equation based on particle size as the one in Eq. (1) is not possible for all alloys since there are no non-eutectic Si particles in alloys A and B (Tables 2 and 3 and Figs. 5, 9 and 10). An equation as Eq. (2) is also not possible for all three Al–Si alloys because there are no dendrites on alloy C (see Fig. 13). However, phases/constituent’s volume fraction as shown in Figs. 4, 8 and 12, reveal that in all alloys A, B, and C, and for both casting techniques, eutectic’s volume fraction shows a clear tendency to increase from positions 3–1. Further, regarding mechanical properties, Figs. 2, 6 and 10, show that ultimate tensile strength and Young’s modulus generally follow the same tendency of the eutectic volume fraction (an exception occurs for Young’s modulus and alloy C). Strain to failure is particularly sensitive to the eutectics volume fraction.

Thus, from the obtained experimental results a correlation between eutectic’s volume fraction and mechanical properties (mainly ultimate tensile strength and strain to failure) could be established for all alloys. An equation with the type as shown in Eq. (3) may be derived for each alloy (for ultimate tensile strength and strain to failure):

\[ \sigma - \epsilon = k_1(\text{stress or strain}) + V_{\text{eut}} \cdot k_2(\text{stress or strain}) \] (3)

where \( \sigma \) is the ultimate tensile strength, \( \epsilon \) is the strain to failure, \( k_1 \) is an empirical factor that introduces the influence of all other non-eutectic metallurgical features (such as SDAS, silicon particles size;
intermetallics type, size, and distribution); \( k_2 \) represents phase morphology and distribution on the eutectic constituent; and \( V_{\text{eut}} \) is the eutectic's volume fraction.

Table 5 presents the obtained values of \( k_2 \) for the three alloys and two casting processes. It should be emphasized that \( k_2 \) values are not in Table 5 because they represent, in Eq. (3), the stress value for a volume fraction of eutectic equal to zero. And the equation is valid for values of eutectic silicon in the range that contains the values obtained in the tested materials, e.g., between 30% and 90%. \( k_2 \), that represents the slope of the equation, is the value that is representative in the equation in its range.

It was found a characteristic \( k_2 \) value for each alloy, that is applied for both casting techniques. The difference in the \( k_2 \) values may correspond to the eutectic's morphology (see Figs. 5, 9 and 13) that is very different among the different alloys (for example, eutectic interlamellar distance on alloy C, is smaller than the one on the other alloys). These results show (same \( k_2 \) for both casting processes) that the mechanical properties are mainly defined by the eutectic volume fraction and that there is a significant change in the volume fraction between casting processes.

In order to compare the experimental results and calculated values, as obtained with the proposed equation (Eq. (3)), Figs. 14 and 15 show the predicted and obtained results for ultimate tensile strength and strain to failure, respectively. It is important to highlight that although the slope of the equation is the same for each alloy, in Figs. 14 and 15 the slopes are different because the x axis identifies the positions and not the volume fraction of eutectic.

The relationship between eutectic's volume fraction and mechanical properties only applies to each alloy and can not be extrapolated from alloy to alloy because there are other variables that were not considered here (for example, some low alloying elements content that are present in commercial alloys – see Table 1). It is worth to note that in the present study, a correlation between eutectic volume fraction and both ultimate tensile strength and strain to failure was found. However the sensitivity of the mechanical properties is different for the different alloys and casting processes.

In order to verify the sensitivity between stress or strain results with eutectics volume fraction the stress and strain results were normalized (see Fig. 16) in relation to the smallest value for each material/condition. It is possible to verify that strain results are more sensitive to eutectics volume fraction then stress results in all alloys and that the sensitivity increases from 7% Si aluminium alloy to 18% Si aluminium alloy. A similar conclusion was found in Ref. [8] for an Al–12.5% Si alloy. Abu-Dheir et al. [8] also found that the dependence of strain to failure on eutectic volume fraction in a 12.5% Si aluminium alloy was more important than the dendritic structure and also than the eutectic structure that transformed from a flaky structure to a fibrous one.

Thus, the relationship found in this study between the mechanical properties (for both ultimate tensile strength and strain to failure) and the metallurgical parameter eutectic constituent, is a useful tool as a generalized prediction of mechanical properties since it is present in a wide range of Al–Si alloys, from hypoeutectic to hypereutectic. However more detailed equations could be defined for specific alloys.

By the results it is also clear that the centrifugal force has a strong influence on mechanical and metallurgical properties of the obtained castings. As a general rule it can be said that the mechanical properties are improved by the use of the centrifugal casting technique and strain to failure is the most sensitive property to the centrifugal effect (Fig. 16). These differences may be properly correlated to the eutectics volume fraction along the ingots.

5. Conclusions

The main conclusions of this work are:

- The centrifugal effect seems to be alloy sensitive. Alloy C is much more sensitive then alloys A and B.
- Centrifugal force affects phases/constituents distribution and morphology along the ingot.
- Strain to failure and ultimate tensile strength can be satisfactorily correlated with the eutectic's volume fraction (for alloys with eutectic volume fraction between 30% and 90%).
- Strain to failure is the most sensitive mechanical property to the centrifugal process, although ultimate tensile strength is also affected.
- Due to centrifugal force it is possible to obtain much improved mechanical properties along the whole casting, especially on the outer layers where the centrifugal force is higher.

Acknowledgments

The research was carried out in Materials Testing Laboratory of the Mechanical Engineering Department of University of Minho, and was supported by FCT – “Fundaçao para a Ciência e Tecnologia” (Portugal) through the PhD Grant with the reference SFRH/BD/19618/2004.

References


