Combination of experimental and numerical methods for mechanical characterization of Al-Si alloys

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Abstract. In general, mechanical properties of Al-Si alloys strongly depend on the morphology and arrangement of microconstituents, such as primary aluminium dendrites, silicon particles, etc. Therefore, a detailed characterization of morphological and mechanical properties of the alloys is necessary to better understand the relations between the underlined properties and to tailor the material’s microstructure to the specific application needs. The mechanical characterization usually implies numerical simulations and mechanical tests, which allow to investigate the influence of different microstructural aspects on different scales. In this study, the uniaxial tension and compression tests have been carried out on Al-Si alloys having different microstructures. The mechanical behavior of the alloys has been interpreted with respect to the morphology of the microconstituents and has been correlated with the results of numerical simulations. The advantages and limitations of the experimental and numerical methods have been disclosed and the importance of combining both techniques for the interpretation of the mechanical behavior of Al-Si alloys has been shown. Thereby, it has been suggested that the density of Si particles and the size of Al dendrites are more important for the strengthening of the alloys than the size-shape features of the eutectic Si induced by the modification.

1. Introduction

Al-Si alloys are often the material of choice for many automotive applications such as cylinder heads [1] and engine blocks [2] due to their attractive strength characteristics combined with the low weight of casting components. In this respect, mechanical properties of the alloys play a principal role in assessing their functionality. The mechanical behavior of Al-Si alloys has a morphological genesis, i.e. it is defined by the morphology and arrangement of the microconstituents [3], such as primary aluminium dendrites, silicon particles, intermetallic inclusions and casting defects. Therefore, a thorough characterization of morphological and mechanical properties of the alloys is necessary to better understand the relations between the underlined properties of the material and to tailor its microstructure to the specific application requirements.

Regarding the morphological impact of Si, the connectivity of Si particles has been found to strongly influence the mechanical behavior of Al-Si alloys [4, 5]. In particular, it has been shown that the strength of the eutectic structure increases with the connectivity and the branching of Si particles. Besides, the higher the number of Si particles in disjoint or simply connected structures, the higher the strength of the corresponding structures [6]. While some researchers suggest that the ductility of the alloys depends on the morphology of both the primary and the eutectic phase [7–11], others attribute a
primary role in mechanical properties either to Si particles [3, 12] or to Al dendrites [13]. In general, the ductility of Al-Si alloys decreases with increasing secondary dendrite arm spacing (DAS) [14], with the exception of alloys with large DAS values [8–10].

Different methods of mechanical characterization, such as numerical simulations and mechanical tests, can be used to study the influence of the microstructure on the mechanical behavior of the material. For example, the effect of Si connectivity can only be evaluated in a volume [15], i.e. via finite elements method (FEM) simulations carried out on 3D image data representing geometrical properties of microconstituents. The mechanical behavior obtained thereby can shed light on the local stress-strain state in a volume but is not representative of the entire material since it is limited to the simulation volume solely. On the contrary, tension and compression tests conducted on specimens of casted alloys deliver results that are relevant for the interpretation of the material’s behavior on the macro-scale. Still, the impact of different microconstituents cannot be assessed independently because the material consists of several phases whose amounts and morphology are difficult to control during the manufacturing process.

In this study, the uniaxial tension and compression tests have been carried out on different Al-Si alloys. The mechanical behavior of the alloys has been interpreted with respect to the morphology of the microconstituents and has been correlated with the results of FEM simulations performed elsewhere by the authors [6, 16]. Thereby, the advantages and limitations of the experimental and numerical methods of mechanical characterization of Al-Si alloys have been exposed. The aim of the present investigation has been to show how the combination of both methods can contribute to a better understanding and interpretation of the mechanical behavior of the material observed on the macroscopic level with respect to the morphological properties of its microconstituents, in particular, primary aluminium dendrites and eutectic phase.

2. Materials and methods

2.1. Materials

The Al-Si alloys have been elaborated by Hydro Aluminium Rolled Products GmbH by means of the permanent mold casting. Two types of alloy compositions have been investigated: an unmodified AlSi12 and an AlSi12 modified with 212 ppm of Sr, also referenced as 2X and 3X, respectively. The alloys have been investigated in the as-cast (AC) and solution treated (ST) state. Specimens machined for the compression and tensile tests have been heated in a High Temperature Chamber Furnace type RHF 1600 of Carbolite Company. The heat treatment cycle has been composed of the heating up to 540° C, solution treatment for 4 hours and quenching in water near the boiling point to lower the level of induced residual stresses [17].

2.2. Compression tests

The compression tests have been carried out with the help of the E10000 Linear-Torsion Floor Instrument of Instron® Company, which allows a maximum load capacity of 10 kN. All test specimens have been cut from similar parts of the castings into cubes with the side length of 5 mm. The tests have been performed at a constant cross-head speed of 0.001 mm/s.

2.3. Tensile tests

The tensile tests have been carried out with the same machine as the compression tests. The specimens have been machined according to the European Standard EN ISO 527-2 [18], where the gage has a square cross-section of 2 × 2 mm² and is 10 mm long. The cross-head speed of 0.01 mm/s that corresponds to the strain rate of $1 \times 10^{-3} \text{s}^{-1}$ has been used for the tensile testing procedure. The engineering stress-strain curves have been computed by dividing the force by the initial cross-section area of the specimen and the amount of stretch of the gage by the initial gage length of the specimen, respectively.
2.4. FEM simulations

The FEM simulations have been carried out on 3D data of Al-Si eutectic phase reconstructed via the FIB/SEM (focused ion beam/scanning electron microscope) tomography. For more details on the imaging and data processing techniques, the reader is referred to [16]. The reconstructed and segmented 3D image data have been meshed with tetrahedral elements, and the material properties have been mapped directly into each mesh cell. The following properties have been assigned to the materials: A Young’s modulus of \( E = 70 \text{ GPa} \), a Poisson’s ratio of \( \nu = 0.34 \), and a yield strength of \( \sigma_y = 40 \text{ MPa} \) have been applied to the aluminium. A Young’s modulus of \( E = 107 \text{ GPa} \), a Poisson’s ratio of \( \nu = 0.27 \), and a yield strength of \( \sigma_y = 7 \text{ GPa} \) have been assigned to the silicon. All simulations have been executed with the finite element software Abaqus using linear finite elements and the explicit solver, with a load curve reproducing the conditions of the compression tests (20 % deformation).

3. Results and discussion

3.1. Micrography

The microstructure of the alloys consists of primary Al dendrites and Al-Si eutectic. Although the alloys have the eutectic composition with a Si content of 12 wt.%, in some samples the volume fraction of Al dendrites reaches the amount of nearly 30%. Normally, the modification of hypoeutectic Al-Si alloys results in shifting the eutectic point towards a higher Si level and as a consequence, a higher amount of the primary phase in the solidified microstructure [19–21]. Liao et al. [22] have observed that the amount of the primary aluminium in the near-eutectic Al-Si alloys increases with increasing Sr content, in particular, when the amount of Sr is above 0.015%. However, this effect of the modification has not been observed in the investigated alloys. On the contrary, no significant difference in the primary phase content between the modified and unmodified alloys has been detected in the present investigation: The amount of Al dendrites in the modified alloy with 0.02% of Sr is even slightly lower than in the unmodified one (26% versus 28%, respectively), although they are both higher than the equilibrium level. Therefore, it can be concluded that a higher amount of the primary phase with respect to the equilibrium level is related to the high cooling rate during the solidification. This result is in accordance with the observations reported in [21]. Thus, it is likely that the effect of the high cooling rate dominates the effect of the modification, at least, in the present investigation.

The optical micrographs in figure 1 show the (a) unmodified and (b) Sr-modified AlSi12 alloys, particularly zooming into the eutectic phase. The modified structure is very fine and homogeneous: Si particles have mostly spherical cross sections that are simply the cuts through fibrous or coral-like particles in 3D [23]. The unmodified alloy exhibits less homogeneous Si profiles ranging from spherical through elongated profiles to profiles of irregular shape. Such cross sections belong to the plate-like particles that are typical of the unmodified Al-Si alloys [23]. Intermetallic phases are not observed. Although the unmodified Si particles are normally coarser than those of the modified alloy, both investigated structures are relatively fine because of the small dimensions of the original ingots and high cooling rates during the casting in the permanent mold.
The optical micrographs in figure 2 show the (a) unmodified and (b) Sr-modified AlSi12 alloys after the solution treatment. Both structures have undergone a considerable agglomeration and spheroidization of Si particles.

As reported in [24], Sr modification influences the kinetics of Si spheroidization and coarsening during the solution heat treatment in such a way that modified Si particles have more propensity for the spheroidization due to their initial smooth fibrous shape. On the contrary, unmodified Si plates are more resistant to shape changes and thus, rather undergo coarsening and, to a lesser extent, spheroidization. The authors also distinguish a shape-size diversity in unmodified alloys to be an additional driving force for the coarsening. However, both structures in figure 2 do not exhibit any pronounced difference in shape and/or size of the particles. Even if any difference did exist at a first stage of the temper, it should have been diminished after 4 hours, since, on the one hand, both alloys have a priori shown a similar fine eutectic structure, and on the other hand, the solution treatment time has been too extended for such small samples. Thus, a similar mechanical behavior of the alloys after the solution treatment can be expected.
3.2. Mechanical behavior

The mechanical behavior of the as-cast and solution treated Al-Si alloys has been investigated under compression and tensile loading. The corresponding stress-strain curves are shown in figure 3 and figure 4, respectively.

![Figure 3](image3.png)

**Figure 3.** Engineering stress-strain curves obtained from the compression testing of AlSi12 (2X) and AlSi12(Sr) (3X) alloys.

![Figure 4](image4.png)

**Figure 4.** Engineering stress-strain curves obtained from the tensile testing of AlSi12 (2X) and AlSi12(Sr) (3X) alloys. The oscillations on the curves of solution treated alloys, 2X and 3X, are due to the calibration of the testing machine to a softer material, and can therefore be neglected.

As can be seen in figure 3 and figure 4, the as-cast samples exhibit a higher strength than the solution treated samples of the corresponding alloys. During the solution treatment, Si particles undergo disintegration and spheroidization, which lead to an unavoidable reduction of the load carrying capacity of the structure [4]. According to Requena et al. [5], the stiff Si network in the ductile Al matrix increases the load transfer from the matrix to the reinforcement, which improves the strength.
Therefore, the disintegration of the network of Si particles and as a consequence, the reduction of their connectivity induced by the heat treatment has an adverse effect on the strength of Al-Si alloys, although reducing the strength it improves their ductility.

The experimental results are also consistent with the observations on the influence of the Si connectivity on the compressive strength of Al-Si alloys reported in [6]. In contrary to the partially interconnected Si particles in the as-cast alloys, Si particles in the solution-treated alloys are simply connected. Thus, the load transfer from the matrix to these particles is lower than the one to the Si particles with a higher connectivity. Hence, the strengthening effect of the spheroidized Si in comparison to the more complex-shaped particles is also reduced. The reduction of the load-bearing capacity of spherical particles in relation to the high aspect ratio particles (e.g. fibrous or plate-like particles) has also been discussed in [25–27].

Besides, the ductility of the solution-treated samples is higher than the ductility of the as-cast alloys. Similar observations have been reported by Guiglionda and Poole [26], who have examined an impact of the heat treatment on Si morphology and ductility of Al-Si eutectic alloys. In general terms, the fragmentation of Si particles with the subsequent spheroidization during the solution heat treatment is beneficial for the ductility of the material [9, 24].

There are two more observations that can be made in figure 4. First, in contrary to the commonly accepted superiority of the strength characteristics and ductility of modified alloys as compared to unmodified ones, the unmodified alloy, 2X_AC, exhibits a higher strength than its modified counterpart, 3X_AC. The second observation is that in the ST condition, this difference disappears and the alloys show similar strength characteristics. Although it has been expected that the alloys with a similar microstructure (see figure 2) have a similar mechanical behavior, the alloy 2X_ST shows a higher elongation to fracture than the alloy 3X_ST. Furthermore, the stress-strain curves of both alloys show strong oscillations that are most probably due to the calibration of the testing machine to a softer material, and can therefore be neglected. To exclude the possibility that such a behavior is observed due to statistical issues, complementary tensile tests have been carried out. The results of the tensile tests performed on the modified and unmodified Al-Si alloys in the ST and AC conditions are shown in figure 5 and figure 6, respectively.

![Figure 5](image)

Figure 5. Engineering stress-strain curves obtained from the tensile testing of the unmodified (2X_ST) and Sr-modified (3X_ST) Al-Si alloys. The complementary tests have been carried out on samples 1 and 2 showing higher strength characteristics than the original samples 3 and 4 for both alloys. The oscillations are still present on the curves.

As can be seen in figure 5, the complementary tests (samples 1 and 2) have yielded higher strength characteristics than the original tests (samples 3 and 4). However, the oscillations are still present on
the curves but in contrary to the previous results, the stress-strain curves from the complementary tests show that the alloy 3X_ST has a higher elongation to fracture than the alloy 2X_ST. Yet, as expected, the alloys exhibit similar average strength characteristics and elongation to fracture. The quantitative data on the average mechanical properties of the investigated alloys derived from the stress-strain curved are shown in table 1.

The results deduced from the stress-strain curves include the following mechanical characteristics: yield strength, ultimate tensile strength, and total elongation. Since Al-Si alloys do not exhibit a pronounced yield point, an offset deformation of 0.2% has been used to define the yield strength [28]. The corresponding structural and mechanical properties of the analyzed Al-Si alloys are summarized in table 1.

Table 1. Mechanical properties of the analyzed Al-Si alloys represented by yield strength, YS, ultimate tensile strength, UTS, and elongation, e, and size of Si particles represented by equivalent particle diameter, d, in the corresponding alloys.

| Alloy   | d (µm) | YS (MPa) | UTS (MPa) | e (%) |
|---------|--------|----------|-----------|-------|
| 2X_AC   | 0.89   | 195      | 338       | 12    |
| 2X_ST   | 2.02   | 176      | 265       | 17    |
| 3X_AC   | 0.78   | 184      | 323       | 13    |
| 3X_ST   | 1.53   | 177      | 263       | 16    |

Both the unmodified (2X_AC) and modified (3X_AC) Al-Si alloys have a similarly fine structure of the eutectic Si (see figure 1). Therefore, as has been expected, both alloys also have a similar mechanical behavior under compression and tension loading, though with a slight strength superiority of the alloy 2X_AC. As can be clearly seen in figure 6, on the average, the strength of the unmodified alloy is higher than the strength of the modified alloy. The same observations have been made by analyzing the mechanical behavior of the alloys under compression loading (see figure 3). However, metallographic observations of the eutectic Si morphology as well as the state-of-the-art in the field of Sr modification of Al-Si alloys [19, 23, 24, 29–31] argue for the expectations of the opposite behavior.
According to Hafiz and Kobayashi [3], more fine and regular modified particles have less stress concentration sites and can carry the load much better due to the more gradual damage evolution. It can therefore be suggested that the clue to the understanding of the observed phenomena lies in the three-dimensional nature of the Si structure and/or properties of the primary aluminium phase.

Considering the influence of the primary aluminium phase, it has to be taken into account that the macro samples of Al-Si alloys used for the mechanical tests do not consist of the eutectic phase only but contain up to 30% of Al dendrites. Some researchers [7–11] suggest that both microconstituents, Al dendrites and Si particles, play an important role for the tensile properties and fracture behavior of the alloys. Therefore, the dendrite arm spacing (DAS) characterizing the size of the primary aluminium phase has been determined. It has turned out that DAS in the unmodified alloy (2X_AC) is lower than the one in the modified alloy (3X_AC) and is equal to 14.08 ± 2.01 μm and 19.28 ± 3.07 μm, respectively. In general, the refinement of the primary phase corresponds to the improvement of tensile properties [11], which agrees well with the experimental observations.

To analyze the impact of the three-dimensional structure of Si particles, the connectivity of the eutectic Si in both alloys has to be determined. Here, the connectivity of the eutectic Si is assessed with the help of the Euler number (Euler number density) [15, 32] that represents the difference between the number of individual Si particles and the connectivity and can only be determined in a volume via different image analysis software. To do so, the 3D morphology of the eutectic phase has been reconstructed after the mechanical tests via the FIB/SEM tomography. To measure the initial (prior to deformation) connectivity of Si in the investigated alloys, the cracks in Si particles induced by the mechanical loading have been filled using image editing methods. In doing so, the computed connectivity could represent the connectivity of Si particles in the undamaged state [33]. Furthermore, to compute the Euler number density of Si particles in the undeformed samples, the estimated Euler number has to be divided by the initial (undeformed) volume of the reconstructed samples. By deriving the relation between the initial volume, \( V_0 \), the deformed volume, \( V \), where \( V = V_0 + \Delta V \), and the strain level, \( \Delta L / L_0 \), of the samples given the Poisson ratio of Al-Si alloys, \( \nu \), equation (1) has been obtained:

\[
\frac{\Delta V}{V_0} = (1 - 2\nu) \frac{\Delta L}{L_0}
\]

After having computed the initial volume of the samples, \( V_0 \), using equation (1), the Euler number density has then been determined. According to the results shown by the authors in [6], a positive value of the Euler number density of 4.41 \( \times 10^{17} \) m\(^3\) in the eutectic phase of the sample 2X_AC against 2.04 \( \times 10^{16} \) m\(^3\) in the eutectic phase of the sample 3X_AC indicates a higher density of Si particle clusters in the unmodified alloy, and as a consequence, a higher strength of the material. This result also agrees well with the experimental observations.

Thus, it can be suggested that the strength characteristics observed in the modified and unmodified alloys have resulted from the combined effect of the eutectic Si morphology and the size of the primary aluminium dendrites. In general, the microstructure refinement, which implies the refinement of both phases, is beneficial for the strength [34, 35] and ductility [9] of Al-Si alloys. In particular, the reduction of DAS results in the improvement of the tensile strength and ductility [30]. A higher number of particles in simply connected structures also improves the strength properties of the material [6]. These conclusions are supported by the experimental observations that the unmodified alloy with a lower DAS and a higher density of Si particles in the eutectic volume has a slightly higher strength than the modified alloy. At the same time, the alloys exhibit similar values of the average elongation to fracture (see table 1). While the (slightly) finer and more homogeneous Si structure in the modified alloy should normally lead to a moderate increase of the strength in comparison to the unmodified alloy, the higher DAS values and lower particle density exert an opposite effect. As a result, the density of the second phase particles and the size of the primary aluminium phase have
proven to be more important for the strengthening of the alloy than the size-shape features of the eutectic Si induced by the modification. When the microstructure is fine, the advantages of the modified Si morphology for the ductility of the material might be overridden by the properties of the primary phase.

3.3. Stress-strain state in simulation volume

The stress state within the Al-Si eutectic resulting from the FEM simulations of uniaxial compression is shown in figure 7. It can be seen that some geometrical configurations in Si particles are more prone to a high stress concentration than others. In particular, the increased stress concentration is mostly observed in necking areas and branching points within the particles.

![Figure 7](image_url)

**Figure 7.** The stress state within the (a) Al-Si eutectic and (b) Si particles resulted from the FEM simulations of uniaxial compression along y-axis. The size of the original simulation volume is 36.6 µm × 16.8 µm × 34.9 µm. For better visualization, the simulation volume has been cropped in the middle along x-axis.

Evidently, the state of stress in Si particles and their fracture susceptibility in different morphological scenarios will vary due to the different load transfer from the matrix to Si particles, which depends on the particle size, shape, orientation and spatial arrangement (incl. the connectivity). FEM simulations have been shown to be highly effective in characterizing the mechanical behavior of Al-Si eutectic in 3D [6, 16, 36], and thus complementing the results of FEM simulations performed using a 2D multi-particle model [37] and microstructure based model [27] of Al-Si eutectic phase. 3D FEM simulations have allowed to investigate the influence of the connectivity and branching of Si particles [6], which is not accessible using 2D characterization techniques. Thus, 3D simulations deliver more accurate predictions of the stress state as compared to 2D simulations since they take into account 3D complexity of the structure. On the other hand, 2D FEM simulations have enabled to study the impact of morphological properties of Si particles (size, shape and orientation) on their stress state and consequently, fracture susceptibility in simply connected structures. In particular, the highest stress level has been detected in the particles oriented at 0° and 90° to the compression loading axis and exhibiting a higher aspect ratio [37], where the highest stress concentration within an individual Si particle has been found at sharp edges and bent regions [27]. However, one has to bear in mind that although 2D FEM simulations are in general consistent with experimental observations, they have a limited predictive power in relation to complex irregular or network structures. Moreover, the discussed 2D and 3D simulations do not take into account the residual stresses in the particles and their failure criteria [27].

It has also been observed from the results of FEM simulations [6], that an onset of the plastic deformation in the material occurs at much smaller strain levels than during the real mechanical tests. This is related to the inhomogeneous distribution of strain in the Al matrix within a simulation volume, where certain regions can pursue the plastic deformation while the overall material still remains elastic. A similar effect has been reported by Joseph et al. [27], who have found a localization of strain between Si particles or within Si clusters resulting from the onset of plastic flow at sharp corners of the particles. Although on the macro-scale an averaged effect of the deformation in different
phases is observed, on the micro-scale, an input of plastified regions in the Al matrix is much more pronounced. Thus, an onset of the plastic deformation can be detected on the stress-strain curves from FEM simulations at very small strain levels already.

4. Conclusions and outlook

By carrying out the mechanical tests on the macro specimens of Al-Si alloys, it has been observed that the DAS values and Si particles density correlate better with the measured strength characteristics of the alloys than 2D size-shape features of Si particles. These results have made evident the limits of the approach based on 2D characterization of Si morphology and consideration of features of only one phase while assessing the properties of a two-phase material. Hereby, the advantages and limitations of the experimental and numerical methods of mechanical characterization of Al-Si alloys have been disclosed. In particular, the macroscopic mechanical behavior of the alloys has been correlated with the properties of the primary phase (DAS) whereas the numerical simulations have allowed to assess the impact of 3D morphological properties of the eutectic phase. As a result, the combination of both methods of mechanical characterization has enabled to interpret the behavior of the material observed on the macroscopic level.

Thus, the morphology of both phases has been considered simultaneously when analyzing the results of mechanical tests. In this respect, it has been suggested that the density of Si particles and the size of Al dendrites are more important for the strengthening of the alloys than the size-shape features of the eutectic Si induced by the modification. Besides, it has been suggested that the advantages of the modified Si morphology for the ductility of the alloys might be overridden by the properties of the primary phase.

In order to deduce a morphological scenario of an optimal structure of Al-Si alloys for a certain application, further investigations are required: in particular, the investigations of the damage mechanism, consideration of residual stresses in the particles and their failure criteria during FEM simulations as well as analysis of properties and mechanical impact of the primary phase and its interplay with the eutectic phase morphology. Although it has been suggested that both phases exert an influence on mechanical properties, the extent to which they do so is still not elaborated. It might be possible that one of the phases has a dominating mechanical impact under certain conditions or from a certain amount. Besides, one should bear in mind that the results issued from laboratory experiments and computer simulations cannot be compared directly: Compression and tension tests are performed on the two-phase specimens while FEM simulations are usually limited to the eutectic phase only.

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