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Three dimensional post-mortem study of damage after compression of cast Al–Si alloys

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ABSTRACT

The damage introduced by compressive deformation at room temperature and 300 °C in three cast AlSi alloys with different additions of Cu and Ni is investigated by synchrotron X-ray microtomography. The same damage mechanisms are identified for all alloys independent of the heat treatment and test temperature: fracture of aluminides, fracture of eutectic Si, debonding between Si and Al-matrix, debonding between aluminides and Al-matrix and fracture of primary Si. The volume fraction of damage decreases with solution treatment time and deformation temperature due to the partial spheroidisation of rigid phases and increase in flowability of the matrix, respectively. The morphology of voids is quantified in terms of their three-dimensional aspect ratio and is correlated with their orientation to obtain information on the load carrying capability of the networks formed by Si and aluminides.

1. Introduction

From a mechanical point of view, cast Al–Si alloys behave like a metal matrix composite in which the rigid eutectic Si, usually ≥ 7 vol%, acts as the reinforcement (e.g. [1]).The reinforcing capability of rigid phases, as it is the particular case of eutectic Si, depends on their three-dimensional (3D) architecture (interconnectivity, volume fraction, contiguity, morphology, size and distribution) and mechanical/physical properties [2–5]. During loading of binary cast Al–Si alloys, the load is transferred from the α-Al matrix to the eutectic Si. When the stress acting on the eutectic Si reaches its rupture strength, eutectic Si particles break leading to failure of the alloy. The post-mortem microstructural analysis of fractured samples can help to shed light on the reinforcing capability of eutectic Si with different morphologies. For instance, the fracture of eutectic Si during tensile loading of an AlSi12 alloy into many sections with cracks perpendicular to the load directions is an indication of an effective load transfer from the α-Al matrix [6]. Doglione investigated damage mechanisms in a cast AlSi7Mg alloy by in-situ tensile tests in a scanning electron microscope [7]. The damage in this alloy mainly developed by fracture of Si particles or by interface decohesion between the Si and the matrix. Furthermore, an increase in plastic strain resulted in a larger number of fractured Si particles. Finally, several microcracks nucleated at different sites coalesced creating a macrocrack which ultimately led to failure of the material.

The eutectic Si in Al–Si alloys undergoes a spheroidization process during solution treatment, which is a combination of rounding and disintegration of 3D networks of Si [8]. Si particles with large aspect ratio (understanding the aspect ratio as the length-to-thickness ratio in platelet-like particles and as length-to-diameter ratio in fibre-like particles) in eutectic Al–Si cast alloys show more damage than spherical Si particles during tensile loading. This is due to the fact that particles with larger aspect ratio are able to carry more load than spherical ones [9–11]. This is also supported by the findings observed by Nishido et al. [12] during in-situ tensile tests of a hypoeutectic AlSi7 alloy and a hypereutectic AlSi20 alloy in a scanning electron microscope. They reported that the stress at fracture during loading of the hypoeutectic alloy is 500–900 MPa, whereas it is about 200 MPa for the alloy with coarse primary Si particles.

Lasagni et al. [13] reported fracture of Al_2O_3 short fibres during compressive and tensile tests of AlSi7–18/Al_2O_3/20s metal matrix composites at room temperature (RT) as well as at 300 °C in as cast and solution treated conditions. Strain softening during deformation of the composites was lower after solution treatment due to the spheroidization of the eutectic Si network. Primary aluminides in cast Al–Si piston alloys play a reinforcing role analogue to that of short fibres in metal matrix composites [3,4]. The presence of different types of aluminides in cast AlSi alloys increases their RT and high temperature strength due to the formation of highly interconnected 3D networks and their high degree of contiguity with eutectic Si [3,4]. Evidence of fractured particles

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in interconnected networks of aluminides after deformation of Al–Si piston alloys point to an effective load transfer from the matrix to these networks [14]. Asghar et al. [4] reported micro-cracks in eutectic Si, $Al_4Cu_2Mg_8Si_7$ and unidentified Si–Fe–Ni–Cu-containing aluminides in a two-dimensional (2D) post-mortem study of cast AlSi10Cu5Ni1-2 piston alloys after compression tests at RT and at 300 °C. Rigid phases oriented $\sim \pm 30^\circ$ to the loading axis showed microcracking similar to ceramic short fibres in metal matrix composites [15,16], supporting the hypothesis that these phases are able to carry load. In the present study, 3D analysis is performed by synchrotron tomography after compression tests of cast Al–Si alloys with different volume fractions of aluminides and Si. The objectives of this work are to determine damage mechanisms and to quantify damage as a function of volume fraction of rigid phases, matrix strength, strain softening, solution treatment time and deformation temperature.

2. Experimental

2.1. Materials

Three different cast Al–Si alloys produced by gravity die casting were investigated: AlSi12Ni, AlSi12CuMgNi and AlSi10Cu5Ni2. The composition of the alloys is shown in Table 1.

2.2. Compression tests

The alloys were tested in as cast (AC) condition and after spheroidization heat treatments (ST) at 490 °C for 1 h and 4 h. Prior to testing, the samples were overaged at 300 °C for 2 h to stabilize the microstructure. Compression tests were carried out at a strain rate of $10^{-3}\ s^{-1}$ using a high speed quenching dilatometer Bähr-T805 equipped with a deformation rig able to reach forces up to 25 kN. Compression specimens of 5 mm diameter and 10 mm length were deformed at RT and at 300 °C up to ~0.45–0.5 true strain. Two tests were performed for each alloy and condition. Cylinders with a diameter of 2 mm were cut by spark erosion from the centre of samples compressed at RT and 300 °C of the AC and 4 h ST conditions. These cylindrical samples were used for damage investigations by synchrotron tomography.

2.3. Synchrotron tomography

Synchrotron X-ray computed tomography (sXCT) was performed using a pink beam at the ID15 beamline of the European Synchrotron Radiation Facility, Grenoble. Nine hundred projections were taken between 0° and 180° using an acquisition time of 45 ms/projection. The tomographic scans were carried out at the centre of the cylindrical samples cut from the compression tests samples of the AC and 4 h ST conditions. Only these two conditions were investigated by sXCT since previous works revealed that the strength of these alloys is stable after 4 h ST time [3,4]. The reconstructed sXCT volume has a final size of 1023 × 1023 × 1024 voxels, with a voxel size=$(1.4 \times 1.4 \times 1.4)\ \mu m^3$ and 32 bit colour depth. ImageJ [17] was used to remove ring artefacts using the procedure described in [18]. Avizo 6.3 [19] was used for analysis and visualization of the reconstructed volumes.

Table 1
Chemical composition of the alloys (in wt%).

Alloy	Si	Cu	Mg	Ni	Fe	Mn	Al
AlSi12Ni	11.9	–	–	1.2	0.7	0.3	Bal.
AlSi12CuMgNi	12.8	1.0	1.0	0.8	0.6	0.1	Bal.
AlSi10Cu5Ni2	10.4	5.2	0.3	1.7	0.4	0.1	Bal.

3. Results

3.1. 2D microstructure

Fig. 1a–c shows light optical micrographs in AC condition after deformation at 300 °C for AlSi12Ni, AlSi12CuMgNi and AlSi10-Cu5Ni2, respectively. The load direction is the vertical axis. The microstructure of the investigated alloys consists of eutectic Si (dark grey) and different types of aluminides [3,4] embedded in an α-Al matrix. Furthermore, some primary Si particles are present in the AlSi12CuMgNi and AlSi10Cu5Ni2 alloys. Also, the α-Al matrices of these two alloys contain coarse precipitates (not visible in the light optical micrographs) owing to the overaging heat treatment. Damage is neither observed in the α-Al matrix nor at the interface between rigid phases and matrix. However, it cannot be concluded from these light optical micrographs that this type of damage does not take place because voids can eventually be filled by Al particles during the metallographic preparation of

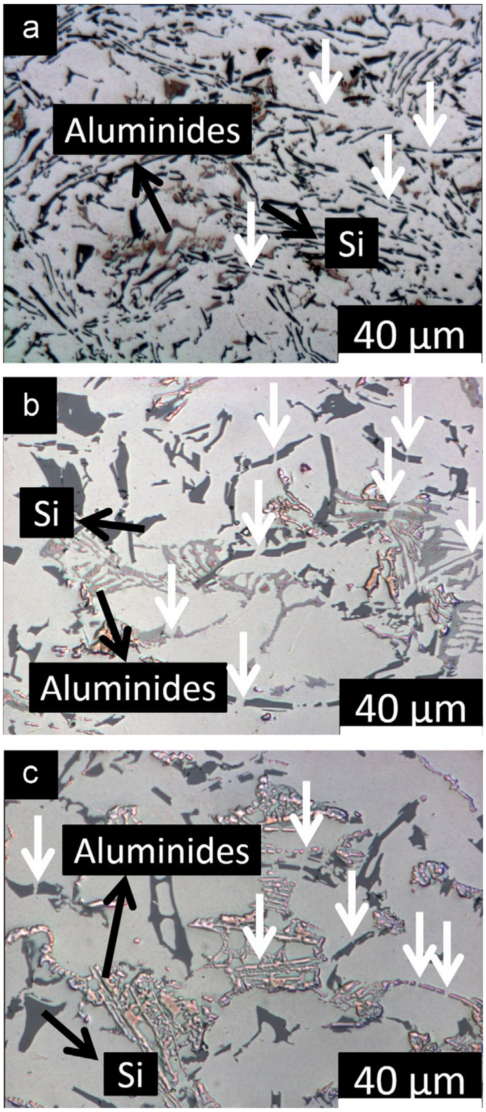

Fig. 1. Microstructures of the alloys in AC condition after compression at 300 °C: (a) AlSi12Ni, (b) AlSi12CuMgNi and (c) AlSi10Cu5Ni2. The compression axis is vertical. The white arrows indicate microcracks in the eutectic Si or the aluminides.