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Damage and plastic flow in a Al-Si-Cu thixocast alloy

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Thixocast samples of an Al-Si-Cu alloy were solution treated at 500°C for 4 h, aged at 170°C for different times and tensile tested at room temperature. Statistical analysis on the fractured Si particles has pointed out how the fraction of damaged particles is influenced by the ageing treatments performed before deformation. The damage accumulation per unit of strain decreases with increasing ductility of the samples. The Considére criterion for plastic instability shows no significative necking.

1. Introduction

The fracture mode of Al-Si casting alloys is generally accepted to occur in three stages: the cracking of Si particles occurring at low strains (1–2%); as deformation proceeds, cracked particles generate localised shear bands which form microcracks by joining adjacent cracked particles; and microcracks coalescence followed by propagation leading to final fracture [1, 2]. The fracture path is transgranular in large dendrite cell size material but it becomes intergranular in small size material [3]. The presence of ceramic particles in the matrix has important consequences in flow and fracture. Notably, the mismatch in the elastic/plastic and thermal expansion characteristics of the particles and matrix leads to inhomogeneous plastic yielding during loading, with yield initiating at stresses which are lower than that required in the matrix alloy alone [4–7]. At higher strains, the mismatch results in the development of large (elastic) stresses within the particles. If the particles are sufficiently strong, the elevation in stress results in an enhancement in the flow stress above that of the matrix alone. In contrast, if the particles break or debond from the matrix, the elastic modulus, the flow stress and the tensile ductility are diminished [8]. The purpose of the present article is to examine experimentally the damage evolution of Si particles in a thixocast 319 aluminum alloy during tensile loading after different ageing conditions. The material used in this study is a thixocast Al-Si-Cu alloy produced by electromagnetic stirring.

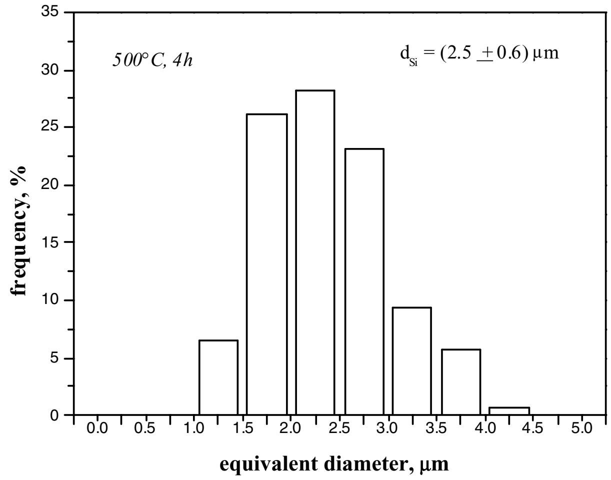
2. Materials and experiments

The 319 thixocast bars were provided by Aluminium Pechiney with a chemical composition (wt%) of Al-5.8 Si-2.9Cu-0.3Mg-0.13Fe-0.02Ti-0.02Mn-0.02Zn. Specimens for tensile tests were previously heat treated at 500°C for 4 h, quenched in water and aged at 170°C for 1, 4 h (underaged conditions) and 16 h (peak aging). Their typical gauge dimensions were 25 mm in length and 6×6 mm^2 in section. The tensile tests were performed at room temperature on a servohydraulic Instron 4507 machine at a nominal strain rate of 0.001 s^{-1}. A set of samples was also tensile loaded to 50% of the final elongation. Scanning electron microscopy observations were performed on strained samples to measure the fraction of damaged Si particles. The measurements of Si broken particles have been performed along the tensile axis direction, starting from the fracture line to the head in the sample brought to fracture and along the gauge length for the sample deformed to half of its final strain. A population of 200 particles was considered for each statistical point. The distributions are presented as number frequency (a two dimensional view of damage). For scanning electron microscopy observations, samples were ground with SiC paper and polished with one-micron diamond paste.

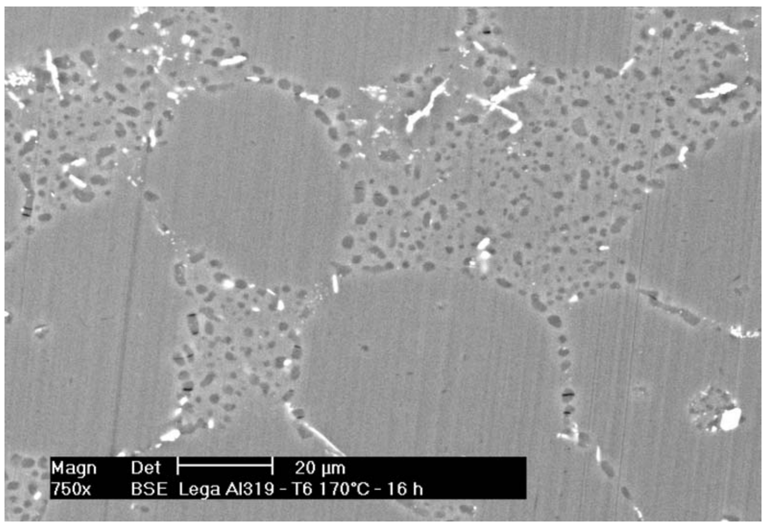
3. Results and discussion

The thixocast structure of the 319 aluminium alloy consists of aluminium globules of 60 μm in diameter, surrounded by the eutectic region which is constituted by Al, Si particles of elongated shape and Al_2Cu. A detailed description and illustration of the microstructure in the as-thixo and solution treated samples is reported in [9–11]. The silicon particles spheroidized during the solution heat treatment to an equivalent diameter of (2.5 ± 0.6) μm after 4 h. at 500°C. Their distribution before tensile loading is shown in Fig. 1a.

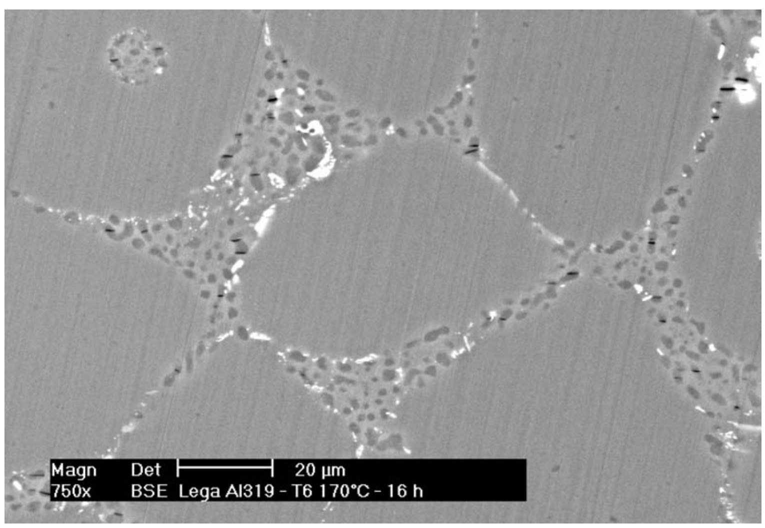
After tensile loading, the appearance of Si particles in the eutectic region is illustrated in Fig. 1b and c after elongation of 5.5 and 11% respectively. The tensile axis is vertical and the particles crack on cleavage planes that are oriented perpendicularly to the tensile direction. The predominant mechanism of fracture at room temperature seems to be the fracture and not debonding of Si particles. Previous investigations performed on this alloy [4] have determined a very light presence of decohesion at Si particle interface and the extensive SEM observations supported that the main damage mechanism



(a)



(b)



(c)

Figure 1 Particle distribution before tensile loading (a) and scanning electron microgrpahs of tensile loaded samples after aging at 170°-16 h showing the fracture of Si particles in the eutectic region (the tensile axis is vertical) (b) at a strain of 5.5% and (c) at a strain of 11%.

remains particle fracture. This behaviour can be qualitatively understood if one admits that decohesion is driven by accumulation of plastic deformation in the matrix neighbouring the particles, whereas particle fracture is associated with incompatibility stresses between particles and matrix. At high temperature, easier plasticity would help to relax these stresses and interfacial decohesion would be favoured. In spheroidized alloys, as in this case, hardening the matrix (after heat treatment) would impede plastic relaxation and thus favour

TABLE I Heat treatment conditions, mechanical properties and damage for 319 thixocast alloy

	Full fracture strain		Half fracture strain	
Heat treatment	Elongation (%)	Damage (%)	Elongation (%)	Damage (%)
500°C-4 h	18	21	–	–
+170°C-1 h	9.6	30	4.8	10
+170°C-4 h	11	26.5	5.5	8.5
+170°C-16 h	5	16.5	2.5	4.3

particle fracture. Moreover, a low surface-volume ratio of spheroidised Si particles would not favour the decohesion, that in turn becomes more likely with particle of irregular shape and high surface-volume ratio [12].

The fracture of Si particles occurs in the eutectic region with the percentage increasing with increasing strain (at a fixed aging condition), as reported in Table I. Some measurements are also illustrated in Fig. 2 for the sample strained to fracture (9.6%) and to half of its total deformation (4.8%) after ageing at 170°C for 1 h. In this plot, each point is not the actual value measured at that distance but is the average of the damage measurements from the fracture to that point. The intensity of the profiles decreases far away from the fracture surface and from the gauge length, approaching zero in the head of the tensile tested sample (absolute values are not reported here).

The average frequency of Si broken particles vs. elongation for the aging at 170°C is illustrated in Fig 3a. It is clear that the underaged samples are more ductile than the peak aged samples and present a higher degree of damage. In fact, when the degree of constraint in the matrix is high, as in the peak aged alloy, the fracture becomes very critical, in the sense that as soon as a few particles crack, the damage propagates very rapidly through the structure. Hence the limited amount of damage in the whole specimen. In the underaged state, plastic relaxation is more feasible, the development of damage is more gradual with the strain, more damage is observed before macroscopic fracture

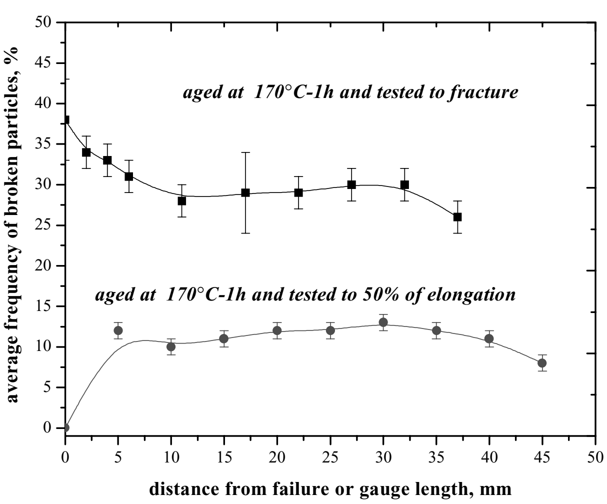


Figure 2 Fraction of Si broken particles vs. distance from the fracture line.

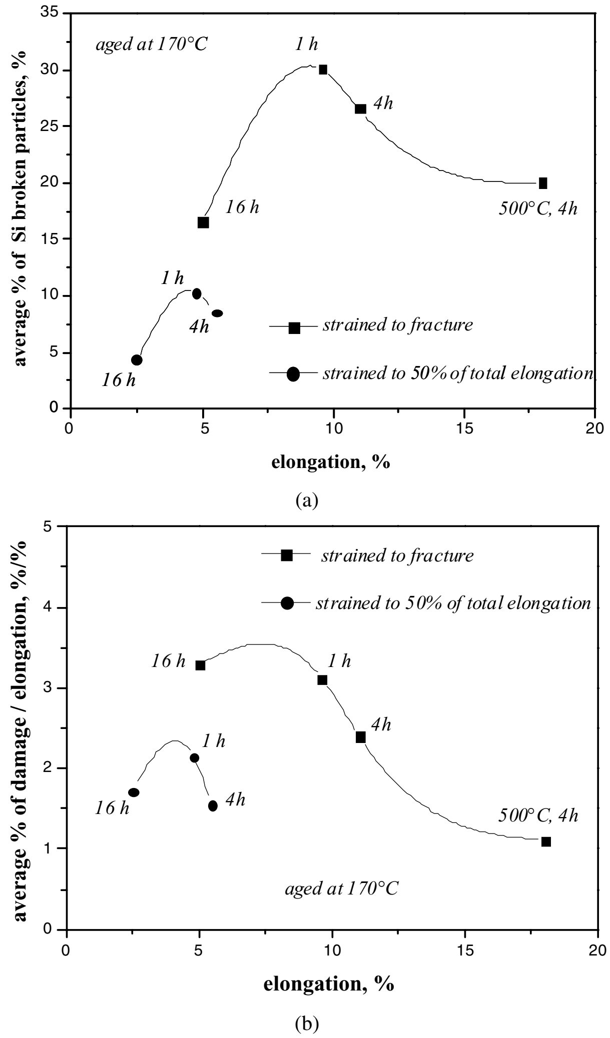


Figure 3 (a) Average frequency of Si broken particles vs. elongation and (b) average frequency of Si broken particles per unit of deformation vs. elongation in samples aged at 170°C.

takes place and the material is more ductile. This point is also illustrated in Fig. 3b, which reports the damage-elongation ratio as a function of the elongation. The values of damage per unit of elongation are maximum for the peak aged sample and are lower for the underaged specimens.

In the same figure, the average frequency of Si broken particles is reported for the samples strained to 50% of their total deformation. The behaviour is exactly the same as before. The frequency values are shifted to the left-hand corner of the graph because of the lower damage and elongations involved.

When a ductile material is reinforced by a dispersion of elastic rigid particles, incompatibility stresses develop in both particles and matrix, resulting from the differences in elastic constants as well as from differences in the deformation mode (the matrix deforms plastically while the particles remain elastic) [1]. The stresses on the particles resulting from plastic deformation of the matrix increase rapidly at low strains and can cause the cracking of the reinforcing phase [13]. At larger strains, their rate of increase is limited by plastic relaxation around the particles and therefore the rate of particle cracking with the applied strain decreases. This is a general principle and it does not consider the effect of thermal treatments on damage and elongation.

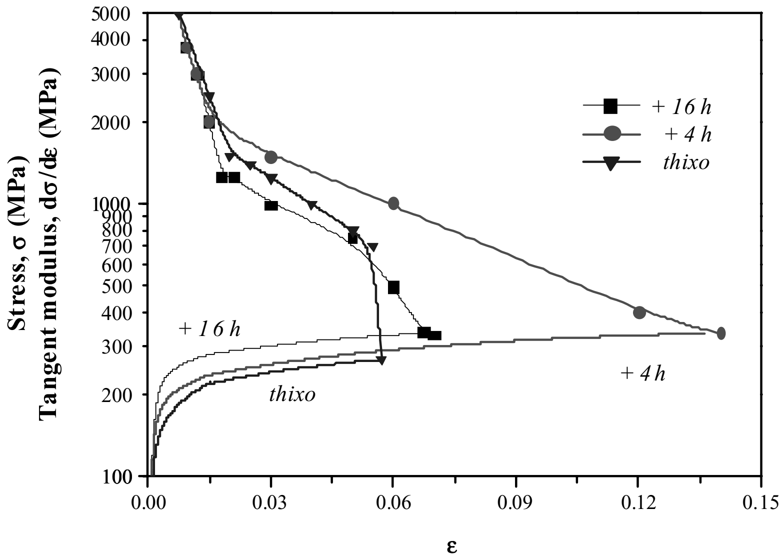


Figure 4 Tensile flow curve and tangent moduli for the as-thixo and aged material.

If one considers the damage per unit of strain increasing with elongation at a fixed ageing condition, it is obvious to occur because the effective cross sectional area of the tensile specimen is reduced during straining due to damage. The stress action becomes higher in the remaining region leading to an increase in the number of fractured Si particle per unit of strain. The fact that the damage-ductility ratio decreases with increasing strain to failure when comparing different heat treatments, is better rationalized by the fact that the stress levels acting on the particles are different depending on the ageing conditions of the tensile sample. In fact the higher ductility corresponds to the underaged samples because of the less effective hardening action respect to the peak aged conditions.

Another point is to check the plastic instability through the onset of the necking. The study of these concepts would help understanding the role of matrix hardening rate and of the Si damage rate on plastic instability, if it does exist in this case. The tensile curves for the underaged and peak aged samples are shown in Fig. 4. In all cases, fracture seems to be not preceded by the formation of a diffuse neck. For ductile, monolithic materials, the onset of instability can be described by the Considére criterion, $d\sigma/d\varepsilon = \sigma$, provided the materials are incompressible and their response is rate independent [14]. Beyond this point, the strain becomes localized and further deformation occurs subject to a decreasing load. To assess the utility of the Considére criterion in describing the onset of instability in this thixocast alloy, the flow stress and the hardening rate are plotted against strain in Fig. 4. In all cases, the instability strain coincides closely with the intersection point of these curves, in accordance with the formula written above. It means that the loss of strain hardening rate due to cracking of the Si particles is not enough to induce general necking in the samples. This is confirmed by literature [8] where it is demonstrated that global instabilities can be caused by damage only when the volume fraction of the particles or reinforcement is of the order of 20%.

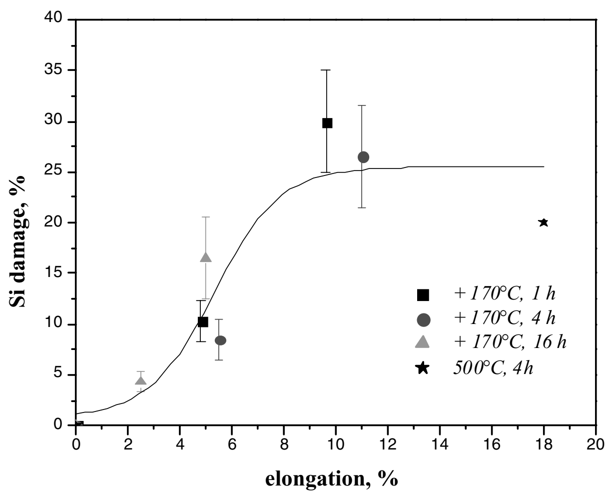


Figure 5 Relation between average frequency of Si broken particles and ductility for samples tested after different aging conditions.

An attempt to relate all the data concerning the fraction of Si broken particles as a function of elongations achieved during tensile tests has been performed (Fig. 5). The data fits a complex relationship (Boltzman relation) with a $\mathrm{chi}^2 = 25$ taking into account also the solution treated sample. It is not useful to consider this relation for a prediction of damage as a function of the aging treatment.

4. Conclusions

The present work was performed on a heat treated AlSiCu alloy to study the damage evolution of Si particles during straining as a function of different ageing conditions. It was found that the damage could be mainly identified by the fracture of Si broken particles and it was higher in specimens previously underaged in respect to the peak aged ones. The damage accumulation per unit of strain decreases with increasing strain to failure when comparing different heat treatments, because the stress levels acting on the particles are different. In fact the higher elongations correspond to the underaged samples where the deformation proceeds faster because of the less effective hardening action in respect to the peak aged conditions.

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