Influence of second-phase morphology and topology on mechanical and fracture properties of Al-Si alloys

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Received 3 February 1997; received in revised form 24 March 1997

Abstract

Mechanical behaviour of eutectic Al–Si alloys with different Si particle topology and morphology modified by heat treatment has been studied. The alloy chosen was a model system for understanding the influence of morphological and topological features on macroscopic mechanical properties. The heat treatment was used to transform a percolated structure of Si platelets and needles into an ensemble of well separated spheroidised particles. Different modes of fracture were observed depending on the particle morphology and on the testing temperature. The as-cast specimens appeared to be softer and showed higher ductility than those with spheroidised particles. © 1997 Elsevier Science S.A.

Keywords: Fracture; Metal matrix composites; Plasticity

1. Introduction

Al-based cast alloys are widely used in the car industry [1]. Their main attraction comes from their low density and ability to be cast in complex shapes. However, their properties in fatigue and toughness still need to be improved in order to increase their reliability. From the fundamental viewpoint, these alloys show a variety of second-phase structures, often complex both in shape and topology [2]. In particular, a percolated structure for the silicon phase is observed [3]. This structure coming from solidification can be modified by further heat treatment. These alloys are therefore model systems to study the effect of the topology of the hard brittle phase on the overall damage of a composite material.

Eutectic Al–Si alloys are the basic system for the cast aluminium alloys. In as-cast condition, the brittle Si particles present a coral-like geometry composed of platelets and needles, embedded into a ductile matrix of aluminium. This structure can be altered by adding modifying elements (Sr, Na, etc.), by changing the solidification rate or by additional heat treatments, so that particles change their shape and are no longer connected. The purpose of this paper is to investigate the influence of the topology change induced by prolonged heat treatments on the mechanical properties and fracture mode of the alloy.

The fracture mechanisms of composites are various [4,5]. First, they depend on loading conditions (compression, tension or cyclic loading). Then, different fracture modes may act alone or simultaneously: particle–matrix decohesion, cleavage of brittle particles, grain-boundary failure, shear band decohesion in matrix, etc. Casting defects, such as porosity or inclusions, provide additional weaknesses of cast alloys which limit their reliability.

The relation between the mechanical properties and microstructure of Al–Si cast alloys has been intensively studied [6,7]. Inspired by the work performed on metal matrix composites, most of the studies focus on the influence of the fraction volume, size and aspect ratio of brittle particles on mechanical properties and damage behaviour. The importance of topology of the brittle phase which may be crucial is very seldom studied [8,9]. Similarly, it is worth considering the damage behaviour of the same materials in different loading conditions. We have chosen in this contribution to change the loading temperature between 20 and...
300°C. In order to study exclusively the effect of change in topology of the brittle phase, we have used an alloy totally deprived of porosity [10,11].

2. Materials and methods

The material used was a slightly hypoeutectic alloy AS12 containing 11.4–11.7% of silicon. The main impurity was Fe, its content being smaller than 0.1%. In order to eliminate casting defects, the samples cut from the cast material were re-melted by direct solidification (Bridgman method) in an argon atmosphere with a constant solidification rate of about 10 cm h⁻¹. Primary Al dendrites and Al–Si eutectic were observed at polished surfaces. The Si particles appeared on the polished surfaces as narrow needles with the equivalent diameter approximately 5 μm and the aspect ratio near 5.2. The intermetallic phase FeSiAl₃ had typically the same needle-like shape but in very low volume fraction. In order to visualise the three-dimensional structure of Si particles, specimens were deep etched in order to remove Al from the surface. It was recognized that silicon forms a coral-like structure of platelets and needles in the bulk of material (Fig. 1(a)).

The heat treatment performed in order to modify the topology of Si phase consisted in maintaining the specimens at 563°C for 24 h, then quenching them in water. This heat treatment was chosen as a compromise between kinetics of spheroidisation and the risk of local melting. After the heat treatment, larger well separated particles of Si with the equivalent diameter near 10 μm and the aspect ratio near 2.1 were observed (Fig. 1(b)). A sequence of observations at treatment durations in the range 1–24 h was carried out in order to follow the evolution of the particle geometry. A progressive deformation of the shape of particles was observed.

Tensile tests were performed with constant imposed strain rate $\dot{\varepsilon} = 10^{-4}$ s⁻¹ at ambient temperature and at 300°C. Observations of cracks on the polished surface were performed by scanning electron microscopy (SEM) at a strain level of around 0.4%, when the first cracks had already emerged, and after fracture.

3. Experimental results

Let us first consider the overall mechanical behaviour of the alloys (Fig. 2(a)–(d)). At room temperature, the yield stress of the as-cast material is smaller than that of the spheroidised alloy. The strain to failure of the spheroidised sample is smaller than the value for the as-cast condition. The same results were obtained for the deformation at 300°C. These results, which were cautiously checked, are very counter-intuitive. Indeed, a larger aspect ratio is usually associated with a more efficient load transfer, and therefore the morphological changes associated with the heat treatment should decrease its flow stress. Similarly, one expects qualitatively that a connected hard phase has a stronger effect than a polydispersed one. From these reasons, one would expect the spheroidised sample to be softer and have a larger ductility: the opposite effect is observed. A natural explanation for this discrepancy is to be found in the evolution of the fine structure of the solid solution forming the dendrites. Transmission electron microscopy (TEM) observations have evidenced a population of small precipitates (about 10 nm) in the as-cast specimen, and an increased radius of these (about 20–30 nm) in the heat-treated sample (Fig. 3). This microstructural evolution is related to an increase in microhardness of the dendritic phase. These precipitates, the nature of which is still under investigation, are probably shearable. An increase of their radius at constant volume fraction corresponds to an increased hardness [12]; these precipitates are likely to be responsible for the increased flow stress of the heat-treated alloy.

The fracture behaviour is also substantially modified by the heat treatment. In all specimens we observe a coexistence of brittle cleavage fracture of silicon
Fig. 2. Examples of deformation curves at (a) 20°C and (b) 300°C up to 0.4% of strain and until fracture for as-cast and ‘spheroidised’ specimens.

particles and of ductile fracture of aluminium matrix. However, the relative proportion of these features depends both on temperature and on topology. At 300°C, independently of the heat treatment, fracture appears to be ductile with dimple features. At room temperature, the behaviour of the spheroidised sample is very brittle, and only a few ductile ligaments are observed between cleaved particles. By contrast, the as-cast sample exhibits substantial ductile tearing between cleaved silicon. Again, these observations are opposite to what an intuitive idea of the effect of topology would be and are probably related to the reduced plasticity of the hardened matrix.

Damage accumulation can be observed on polished surfaces. These observations allow to identify the initial steps of damage (Fig. 3). At room temperature, the as-cast sample exhibits numerous decohesion events (Fig. 3(a)). Only the platelets parallel to the loading direction are fractured. By contrast, the spheroidised sample shows almost no decohesion, but abundant particle fracture (Fig. 3(b)). At 300°C, for both samples, interface decohesion between Al and Si phase is dominant. The difference between room-temperature and 300°C 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 particle and matrix. At high temperature, easier plasticity would help to relax these stresses and interfacial decohesion would be favoured. The difference between the as-cast and the spheroidised alloys can be similarly understood, since hardening the matrix (after heat treatment) would impede plastic relaxation and thus favour particle fracture. Another feature which would favour interfacial decohesion in the as-cast sample is the higher surface-to-volume ratio corresponding to this geometry.

4. Conclusion

We have shown that spheroidising heat treatments of Al–Si eutectic alloys led to deep modifications in their mechanical properties and fracture behaviour. Both the increased yield stress and the increased importance of particle fracture compared to interface decohesion asso-
ciated with the heat treatment are influenced by the change in topology but also by the presence of fine precipitation. Further work will focus on the characterisation of the fine precipitation on one side, and on the design of heat treatments which would coarsen this fine precipitation to a point where it would no longer substantially harden the matrix. We will then be able to deconvolute the effect of topology on the load transfer and on fracture mechanisms.

Acknowledgements

We wish to thank the Ministère des Affaires Étrangères for a post-doctoral grant (ML), and O. Madeleine-Dupuich for providing the Al–Si porosity free samples. Our thanks go also to M.C. Cheynet and B. Doisneau for their valuable help.

References