Journal of Alloys and Compounds 625 (2015) 296–308

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jalcom

Stress states in individual Si particles of a cast Al–Si alloy: Micro-Raman analysis and microstructure based modeling

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ARTICLE INFO

Article history:
Received 6 May 2014
Received in revised form 1 September 2014
Accepted 31 October 2014
Available online 21 November 2014

Keywords:
Al–Si alloy
Polarized Raman technique
Finite element modeling
Si modification
Heat treatment
Stress analysis

ABSTRACT

The stress states in Si particles of cast Al–Si based alloys depend on its morphology and the heat treatment given to the alloy. The Si particles fracture less on modification and fracture more in the heat treated condition. An attempt has been made in this work to study the effect of heat treatment and Si modification on the stress states of the particles. Such understanding will be valuable for predicting the ductility of the alloy. The stress states of Si particles are estimated by Raman technique and compared with the microstructure-based FEM simulations. Combination of Electron Back-Scattered Diffraction (EBSD) and frequency shift, polarized micro-Raman technique is applied to determine the stress states in Si particles with (1 1 1) orientations. Stress states are measured in the as-received state and under uniaxial compression. The residual stress, the stress in the elastic–plastic regime and the stress which causes fracture of the particles is estimated by Raman technique. FEM study demonstrates that the stress distribution is uniform in modified Si, whereas the unmodified Si shows higher and more complex stress states. The onset of plastic flow is observed at sharp corners of the particles and is followed by localization of strain between particles. Clustering of particles generates more inhomogeneous plastic strain in the matrix. Particle stress estimated by Raman technique is in agreement with FEM calculations.

1. Introduction

The dominant mode of damage evolution in Al–Si alloy is Si particle fracture. Coarse and elongated Si particles are found to promote rapid damage evolution and this result in cast Al alloy with low ductility [1,2]. The states of stress in Si particle cause fracture, which depend on the load transfer to the stiffer particles from the complaint and plastic matrix. The particle morphology (i.e., particle size and shape), its orientation and matrix heat treatment play an important role in load transfer to the particles.

There have been a number of theories to estimate the stress states of the second phase particles in a particle reinforced composites [3–5]. These theories may not be applicable to complex shaped and highly clustered Si particles in cast Al–Si alloy. The experimental techniques which can predict the stress states in individual particles are limited in number. The neutron scattering experiments can predict the stress in the particles. However, the values obtained from these experiments are typically averaged over many thousands of particles present in different local environments. Micro-tomography [6,7] utilizing synchrotron X-ray radiation can provide stress states in individual particles of size 1–10 μm. In recent years, micro-Raman spectroscopy has been increasingly used as a technique to study the local mechanical stress in devices and structures used in microelectronics. It has the advantage of being a fast, non-destructive technique with micrometer spatial resolution. Recently, in the work of Harris et al. [8], this micro-Raman technique has been successfully implemented to study the stress states in individual Si particles of Al–Si alloy. The effects of strain and stress on the Raman frequency of the optical phonons of single crystal silicon are well known and extensively documented [9,10].

The most common procedure used in Raman stress measurement is to assume a stress state, monitor the shift in Raman peaks with the magnitude of the applied stress, and generate a calibration curve of Raman peak position against the magnitude of the applied stress. This information is then used to measure the magnitude of the stress on the same material in other loading conditions [11]. The major limitation of this technique is that it fails to resolve the tensor nature of the stress. Instead, the quantity that is obtained is a weighted average of stress components. This limitation is due to the experimental set-up which is used in the conventional back scattered micro-Raman technique, where the incident light is normal to the sample surface and neither the

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http://dx.doi.org/10.1016/j.jallcom.2014.10.207
0925-8388/

incident nor the scattered light is polarized. This particular experimental configuration cannot resolve the full stress tensor. A slight modification of this existing technique can be used to determine the in-plane stress states. Narayanan et al. [12] have proposed a polarized Raman technique to study the in-plane stress states of Si wafers which are having (1 1 1) orientation. Their procedure is adopted in this work to calculate the stress states in individual Si particles of Al–Si alloy in the as-received and loaded conditions. These would include measurements in fractured particles, whose presence can have an important effect on matrix flow, as well as in particles near fractured particles.

Alternatively, the stress states in Si particles can be predicted numerically by finite element simulations using either simple particle model or microstructure based model. Even though the simple particle models predict the stress distributions, they are unable to predict the macroscopic stress–strain behavior as accurately as the microstructure based model, since the local damage characteristics are inherently dependent on microstructure. These simple models do not include the microstructural complexities, such as, the irregular morphology of the particles, anisotropy in particle orientation and inhomogeneous spatial distribution of particles. However, these characteristics significantly influence the deformation behavior. Hence, an accurate prediction of macroscopic deformation behavior and understanding of localized damage mechanisms can only be accomplished by capturing the microstructure of the material as a basis for the model. There have been numerous studies on microstructure based modeling of particle reinforced composites [13–16].

The FEM stress analysis on Al–Si alloys has been reported by few authors [17–20]. Gall et al. [17] have studied the stress distribution near the damaged Si particle cluster. This study was carried out under cyclic loading conditions. The stress state dependent damage evolution in a cast Al–Si–Mg alloy was reported in the work of Horstemeyer et al. [18]. The effect of particle morphology on particle stress is found in the work of Saigal et al. [19] and Wang et al. [20]. However, Saigal et al. have done only the elastic analysis, but the Al matrix in the alloy will undergo elasto-plastic deformation. The above studies on Al–Si alloys are carried out using only simple particle models. There are few microstructure based modeling of Al–Si alloys to understand the fracture behavior of the alloy under tensile [21] and cyclic loading [22,23].

We have carried out a comprehensive experimental investigation to understand the effect of heat treatment [24] and Si modification [25] on particle fracture in a near-eutectic Al–Si based cast alloy. It was observed that the unmodified particles and particles oriented nearly perpendicular to the loading axis fracture more under compression. The heat treatment of the alloy also increases particle fracture. This research attempts to quantify the stress states of individual Si particles in Al–Si alloy with different microstructures under compression using Raman technique and microstructure based finite element simulations. This will reveal the effect of Si modification and heat treatment on the stress states of Si particles which in turn gives an insight into the particle fracture observed experimentally. Further, this analysis compares the experimentally and theoretically found stress values of the individual Si particles in real microstructure, which is not reported previously in the literature.

2. Experimental procedure

2.1. Material and microstructural characterization

Al–Si–Cu–Mg based cast alloys with three different types of microstructures have been taken for the analysis. The different microstructures present in the alloy are unmodified (UM) Si particles in non-heat treated (NHT) matrix, unmodified Si particles in heat treated (HT) matrix and modified (M) Si particles in heat treated matrix. The Si modification was done by controlling the processing parameters carefully. The heat treatment given to the alloy consisted of a solution treatment at 515 °C for 8 h, hot water quenching followed by aging at 175 °C for 6 h and air cooling.

The microstructural characterization of the samples was carried out under Zeiss optical microscope and field emission gun (FEG) scanning electron microscope (FEI-Sirion®) equipped with an energy dispersive X-ray spectroscopy (EDS) analysis. The samples were also subjected to Orientation Imaging Microscopy (OIM) using TSL camera under FEG scanning electron microscope. Samples for microstructural

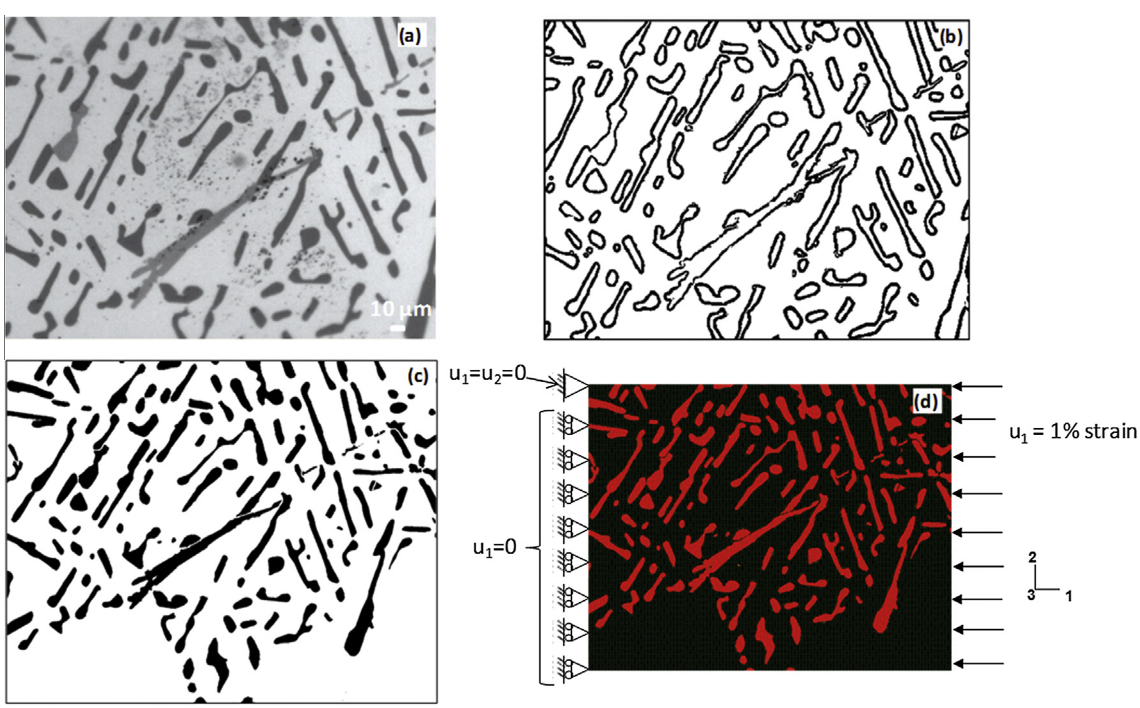

Fig. 1. Process of converting a microstructure as a basis for numerical simulation. (a) Optical image of Al–Si alloy, (b) vectorial format, (c) binary image and (d) boundary conditions of meshed microstructure under 1% compressive strain.