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Neutron Diffraction Determination of Macro and Microstresses in an Al-Si-Mg Composite and Observed Changes with Plastic Strain

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Neutron diffraction has been used to measure macro- and microstress components as functions of position within tension and compression samples of an Al-Si-Mg composite. The influences on these components of both tensile and compressive plastic deformation have been studied. Deformation to about 1.5% plastic strain (for both tension and compression) relieves the macrostress and most of the thermal microstress but sets up new residual microstresses. The results for the microstresses measured for the silicon phase following plastic deformation and unloading, are compared with the predictions of a finite-element model for the micromechanical behaviour of the alloy.

1. Introduction

Al-7Si-0.4Mg is a widely used casting alloy. Its microstructure comprises age-hardened Al dendrites and a eutectic of Al and Si. The Si is in the form of micron-sized particles having a volume fraction of ~0.06. The material, therefore, can be described as a particulate metal-matrix composite.

The stresses in such a composite are classified as “macro” and “micro”. Macrostresses, associated with applied forces and long-range residual stresses arising from thermal history (for example, rapid quenching from a high temperature to a lower one), are independent of the two-phase microstructure. Microstresses are associated with the misfit between phases resulting from differences in the coefficients of thermal expansion, elastic moduli or yield stresses [1]. For small Al-alloy composites it is sometimes assumed that thermal macrostresses can be ignored because of the small specimen size coupled with the high thermal conductivity of Al. This paper shows that his assumption is not always valid.

Both macro- and microstresses are affected by plastic deformation. Macrostresses are relieved, independent of whether the plastic strain be tensile or compressive. In the case of the microstresses, a major effect is the relief of the thermal expansion misfit stress. But in addition, a misfit stress develops between the plastic matrix and the elastic particles, the sign of which depends on whether the plastic strain is tensile or compressive. Previous work [2-4] has verified the stress relief but to date there are no clear trends to establish the effect of plastic strain on the principal stress components in the particles.

The aims of the current research are (a) to measure the macro- and microstress fields and (b) to investigate the influence of plastic strain on them.

2. Experimental details

The composite used in this research was an Al-7Si-0.4Mg alloy with Sr added to modify the shape of the eutectic Si particles, sand cast as a 140×160×25 mm^3 plate. Slices 25 mm wide were cut from the plate and these were solution treated at 540 °C for 6 h followed by a cold-water quench and ageing at 170 °C for 6 h. Cylindrical test specimens were machined from the heat-treated slices.

In initial experiments at the Wombat instrument (High Intensity Powder Diffractometer) at ANSTO, optimum combinations of λ and {*hkl*} for Si and Al were determined for subsequent experiments at the Kowari (Strain Scanner) instrument. These were: for Si: 0.1577nm, 422; and for Al: 0.1727 nm, 311. Plastic strains were applied to samples using the Instron Mechanical Testing facility at the Materials Engineering Institute, ANSTO.

A gauge volume of 2×2×2 mm^3 was employed for the measurement of the axial component for the Si 422 d-spacing while a gauge volume of 2×2×10 mm^3 was used for the radial and hoop components. In order to overcome the effects of the large Al grain size, the measurements for the Al 311 d-spacing with 2 mm gauge resolution across the specimen diameter, were achieved by rotating the sample continuously around its axis, sweeping out a volume $\pi(r_1^2 - r_2^2)L$ where r_1 and r_2 are the outer and inner radial limits of the gauge volume and L (=10 mm) is its length in the axial direction.

Strain components were determined for Si utilizing a 422 d_0 measured a number of times throughout the experiments using a NIST standard powder sample. The Al 311 d_0 value was determined from the surface force equilibrium condition for the radial component of the macrostress in the sample [5]. Total, or phase, stresses for each of the Si and Al phases, (e.g., ${}^{t}\sigma_a^{Si}$ is the total axial component for Si) were then calculated from the measured lattice strains [5] at several positions across the sample diameter, using diffraction elastic constants for the Si 422 and Al 311, calculated using the method of Gnäupel-Herold *et al.* [6]. From these total stress values the macrostress and microstress components could be calculated [5].

The errors have been calculated on the assumption that the major source of error is that from the determination of each diffraction peak position, as measured by the respective standard deviation in the peak fit. For the Si phase the typical error is ± 10 MPa.

3. Results and discussion

3.1 As-received Samples

Typical results for the distributions of the macrostress components measured for an as-received sample, and the corresponding microstress distributions are shown in Fig. 1.

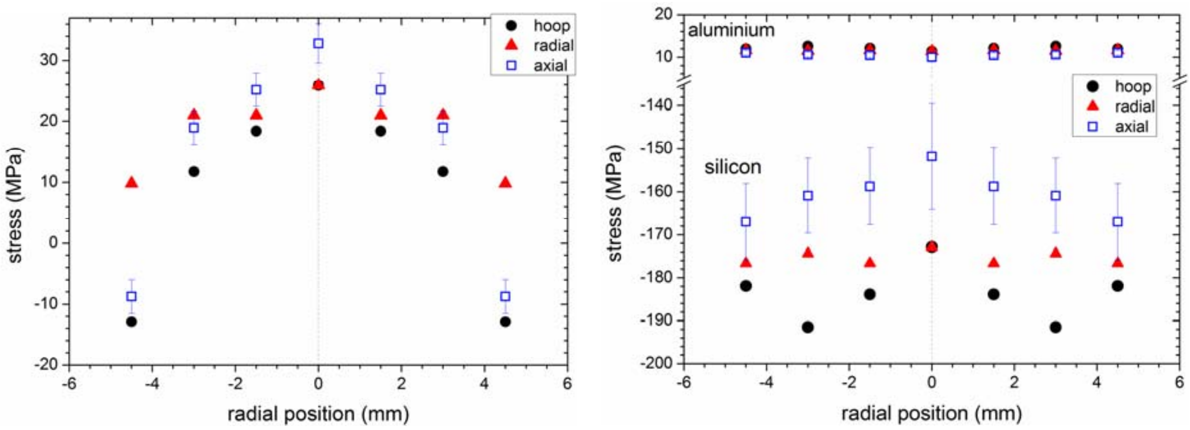

Fig. 1. (Left) Variation of hoop, radial and axial components of the macrostress in an as-received sample. (Right) Al and Si microstress components in the same as-received sample.

Fig. 1 (left) shows that the macrostress components, ${}^{M}\sigma_{ij}$, are not negligible and display a radial dependence. The Si microstress, ${}^{\mu}\sigma_{ij}^{Si}$, is much greater than both the macrostress and the Al microstress, ${}^{\mu}\sigma_{ij}^{Al}$, a consequence of the small volume fraction of Si particles in the composite. ${}^{\mu}\sigma_{a}^{Si}$ exhibits a radial dependence and the Si microstress, surprisingly, is not purely hydrostatic.

3.2 Effects of plastic strain

Samples were loaded in compression and tension to plastic strains of -0.015 and +0.016, respectively, unloaded and re-measured. Results are shown in Fig. 2 for the total phase stresses.

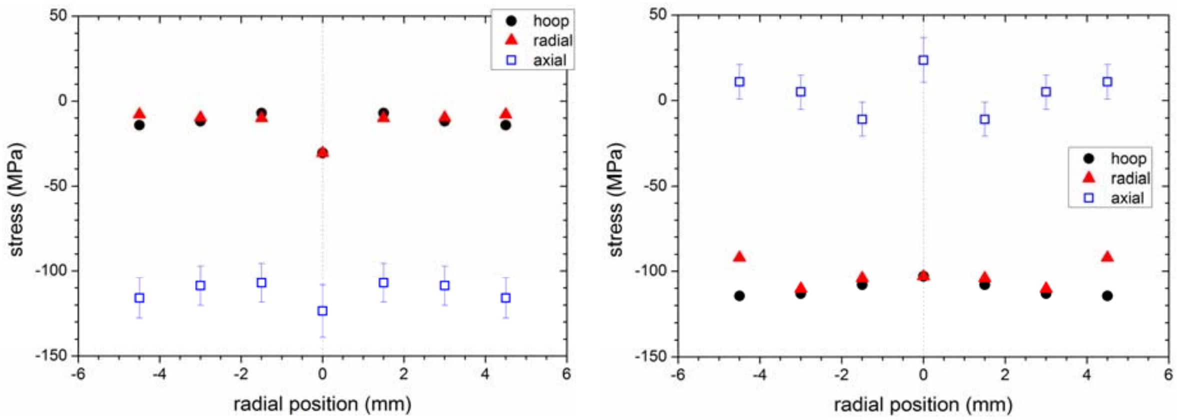

Fig. 2 Total Si phase stresses, ${}^{t}\sigma_{ij}^{Si}$, for (Left) a compression sample ($\varepsilon_{plastic}$ = -0.015), and (Right) a tensile sample ($\varepsilon_{plastic}$ = +0.016).

The following observations can be made from the data. The radial dependence found for ${}^{t}\sigma_{ij}^{Si}$ in the as-received material has been eliminated by plastic strain and it has been reduced in magnitude. On calculating the ${}^{M}\sigma_{ij}$ components, values of 4 ± 4 MPa were found for the hoop and radial components and -5 ± 4 MPa for the axial component for the tensile sample. That is, the macrostress has been relieved by plastic deformation, as expected. The changes in the hoop and radial components for the Si microstress for the compression sample were ~ 200 MPa and for the axial component ~ 30 MPa, while for the tensile sample these figures were ~ 60 MPa and ~ 150 MPa, respectively. Of note are the opposite effects for compressive and tensile plastic strains.

3.3 Numerical model

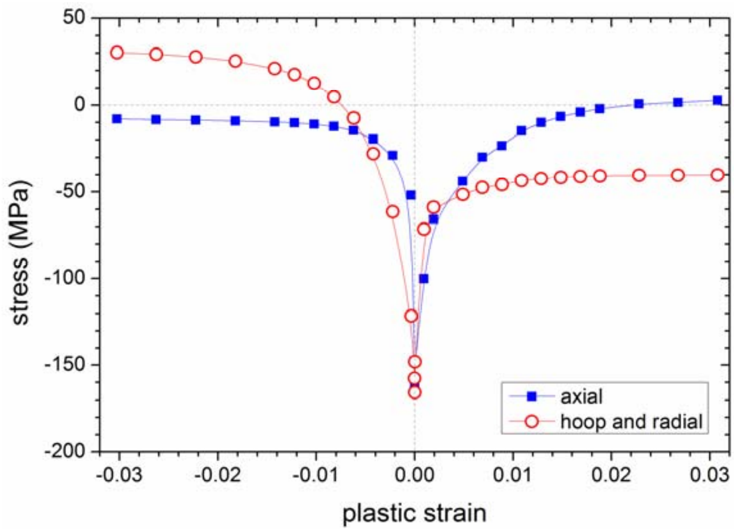

Fig. 3. Predicted effects of plastic strain on the Si microstress after unloading.

Microstresses in the silicon particles were calculated with a finite element simulation, assuming a spherical silicon inclusion in an aluminium matrix, following quenching, plastic straining and unloading. The results are shown in Fig. 3. As expected, the microstress in the silicon, ${}^{\mu}\sigma^{Si}$, is hydrostatic following quenching. Plastic strain destroys the pure hydrostatic stress but symmetry ensures that the hoop and radial components are equal, ${}^{\mu}\sigma_h^{Si} = {}^{\mu}\sigma_r^{Si}$. A saturation of ${}^{\mu}\sigma_{ij}^{Si}$ at $\varepsilon_{plastic} \sim \pm 0.015$ is predicted. The saturation value of the axial component, ${}^{\mu}\sigma_a^{Si}$ is zero while the saturation hoop and radial components are negative following tensile strain and positive following compressive strain.

3.4 Comparison between experiment and model

The experimental data shown in Fig.1 indicate that the microstress in the silicon is not exactly hydrostatic. The result is surprising and requires further experiments to explore it.

The effects of plastic strain are shown in Fig. 2 and are broadly consistent with the model. However, the agreement is not exact. While the axial stress component is zero after a tensile plastic strain, the same is not true for the compression sample. However, the prediction that the hoop and radial stress components are more negative than the axial component after tensile strain (and *vice versa* after compression) is entirely consistent with the experimental data.

4. Conclusions

These experiments have shown that a macrostress field is generated in cylindrical samples of 12 mm diameter. The separation of the measured stress fields into their macro- and microstress components has been demonstrated. Plastic strains of order ± 0.015 relieve the macrostress field and most of the thermal microstresses. Following tensile plastic strain, the hoop and radial components of the silicon microstress are more negative than the axial component (and *vice versa* following compressive strain), consistent with a simple numerical model which assumes a spherical silicon inclusion in an aluminium matrix, following quenching, then deformation to a defined plastic strain and, finally, by unloading.

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