Precipitation Strengthening in Al (Sc,Ti) Alloys

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Abstract

Three-dimensional atom probe (3DAP) and field-ion microscopies, together with microhardness measurements, are employed to analyze $Al_3(Sc_{1-x}Ti_x)$ precipitates in an Al-0.06at%Sc-0.06at.%Ti alloy aged at 300°C for different times. The field-ion microscope images show a relatively high number density of precipitates (estimated at $(3\pm2)\times10^{21}$ppt m^{-3}) at the aging times analyzed. Concentration profiles obtained with 3DAP microscopy show that both Sc and Ti partition to these precipitates. While most of the Sc is contained in the precipitates, the Ti resides mainly in the matrix in solid solution. Consequently, the addition of Ti increases the hardness of this alloy only modestly over that of binary Al-Sc alloys. Additionally, the coherent $Al_3(Sc_{1-x}Ti_x)$ precipitates remain stable and coarsening-resistant up to aging times of at least 240 hr. at 300°C.

Introduction

Al-Sc alloys are of interest since they provide a large increase in strength due to the presence of a high number density of nanosize Al_3Sc particles. Recently it was demonstrated that these precipitates remain coherent up to sizes of ca. 40 nm in diameter [1]. To further improve the properties of Al-Sc alloys, the effects of ternary additions to Al-Sc alloys have been investigated. Of particular interest is our recent work on Al-Sc-Zr alloys [2] for which the precipitates are very stable and coarsening-resistant at temperatures of 300°C. It was determined that Zr segregates to the α-Al/Al_3Sc heterophase interface and acts as a barrier for the diffusion of Sc across the interface, which leads to a lowering of the coarsening rate [2] as compared to binary Al-Sc alloys.

In the present study, Ti is investigated as the ternary alloying element since the addition of Ti to the Al_3Sc phase reduces its lattice parameter [3], similarly to Zr. Harada and Dunand [3] showed that Ti is soluble in Al_3Sc up to 12.5 at.% (the same amount as Zr [3]). Thus, Ti may replace up to 50% of the Sc in Al_3Sc precipitates. The Ti-induced reduction in lattice mismatch between matrix and precipitates has the potential to improve the coarsening resistance of the Al_3(Sc,Ti) precipitates, since the elastic strain energy is concomitantly reduced [4]. Additionally, the tracer diffusivity of Ti in Al is smaller than that for Zr in Al by a factor ca. 20 at 300 ºC [5], which may lead to precipitates that coarsen more slowly than in Al-Sc-Zr alloys.

Experimental Methods

An Al-0.06 at.% Sc-0.06 at.% Ti (Al-0.10 wt.% Sc-0.10 wt.% Ti) alloy was produced by dilution casting from Al-2 wt.% Sc and Al-4 wt.% Ti master alloys with 99.99 at.% pure Al. The alloys were melted in air in an alumina crucible in a resistively heated furnace at 750°C and were then cast into a graphite mold resting on a large copper platen. Homogenization was performed at 648°C for 24 hr., after which the alloy was quenched into water at room temperature.

3DAP microscope sample blanks were produced by mechanically grinding down to a square cross-section of ca. 200 μm^2. The samples were then electropolished using a two-stage procedure. The initial polishing was performed using a solution of 10 vol.% perchloric acid in acetic acid. The final polishing was performed using a solution of 2 vol.% perchloric acid in butoxyethanol. Proximity histogram plots (proxigrams) [6] were calculated using an isoconcentration surface of 9 at.% Sc. Samples for Vickers microhardness measurements were ground to a 1 µm surface finish before analysis and were tested with a 200 gm. weight. Twenty measurements were taken on each sample.

Results

The evolution of microhardness with annealing time for the Al-0.06 at.% Sc-0.06 at.% Ti alloy demonstrates that there is no significant hardening at 350°C, while at 300°C the alloy exhibits a classical precipitation hardening behavior (Fig. 1). Comparison with data for the binary Al-Sc alloys demonstrates that addition of 0.06 at.% Ti produces only a relatively modest increase of about 75 MPa in the peak hardness, as compared to the binary Al-0.06 at.% Sc (Fig. 2). By contrast, addition of 0.06 at.% Sc (resulting in the binary Al-0.12 at.% Sc alloy) increases the peak hardness by 300 MPa, demonstrating the Sc is much more efficient than Ti at increasing strength for a given atomic fraction addition.

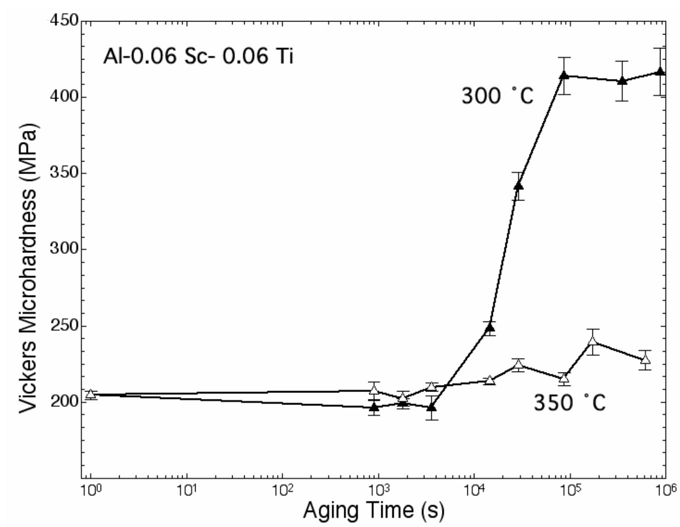

Fig. 1: Microhardness of Al-0.06 at.% Sc- 0.06 at.% Ti as a function of annealing time at 300°C and 350°C.

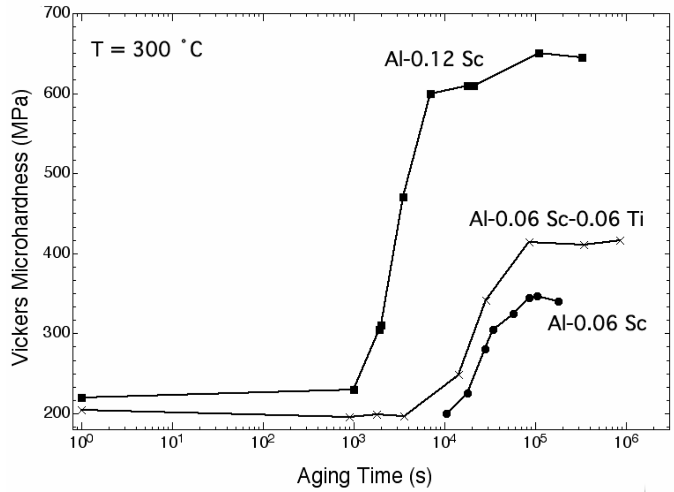

Fig. 2: Microhardness as a function of annealing time at 300°C, comparing two binary Al-Sc alloys [1, 7] with the ternary alloy.

A high number density of $Al_3(Sc_{1-x}Ti_x)$ precipitates (ca. $(3\pm2)\times10^{21}$ppt m^{-3}) is observed in the FIM images (Fig. 3). The 24 and 96 hr. aging times at 300°C were analyzed using 3DAP microscopy. The 3-dimensional reconstructions demonstrate that precipitates of Al_3Sc are present (Figs. 4 and 5). Proxigrams, showing the concentrations of each element at specific distances from the isoconcentration surface, prove that most of the Sc partitions to the precipitates with little Sc remaining in the matrix (Figs. 6 and 7). Compared to the matrix, there is an increase in Ti concentration in the precipitates, indicating that Ti also partitions to the precipitates and/or that it was incorporated in the $Al_3(Sc_{1-x}Ti_x)$ precipitates during the nucleation and growth stages. The concentration of Ti in the precipitates does not change significantly between 24 and 96 hr.

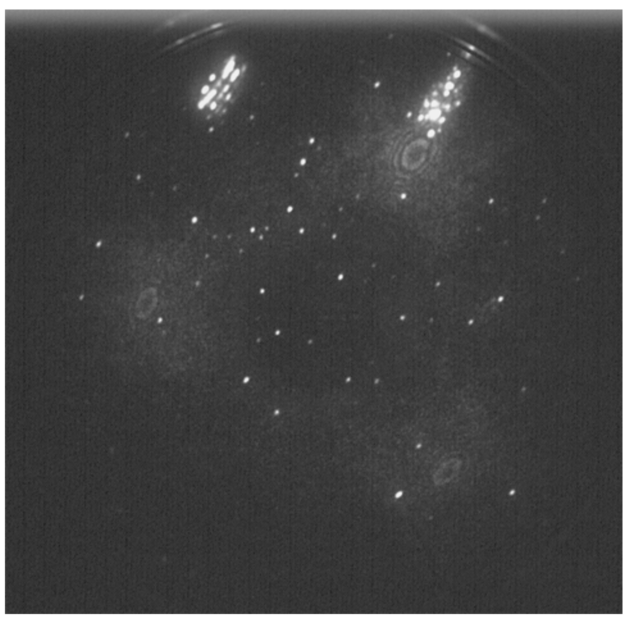

Fig. 3: Field-ion microscope image of Al-0.06 at.%Sc-0.06 at.%Ti aged at 300°C for 24 h. showing two Al_3Sc precipitates. The bright images at the top correspond to Al_3Sc precipitates.

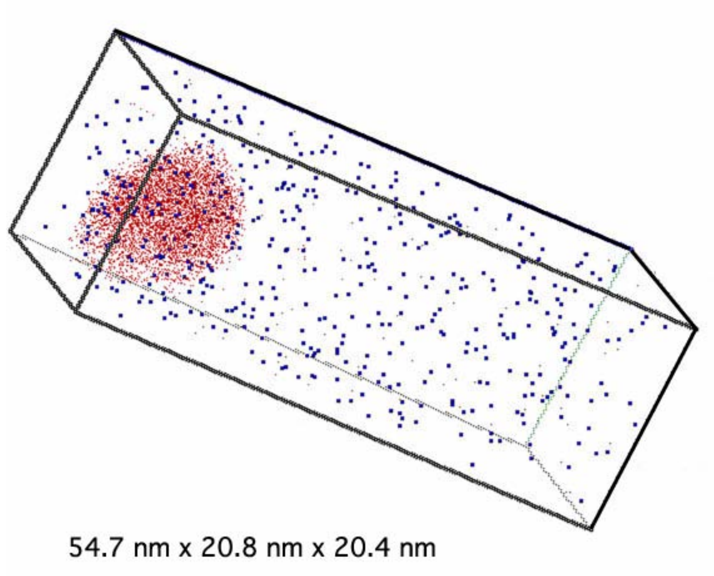

Fig. 4: Three-dimensional reconstruction of Al-0.06 at.%Sc-0.06 at.% Ti aged at 300°C for 24 h. The smaller red dots and the larger blue spheres represent the Sc and Ti atoms, respectively.

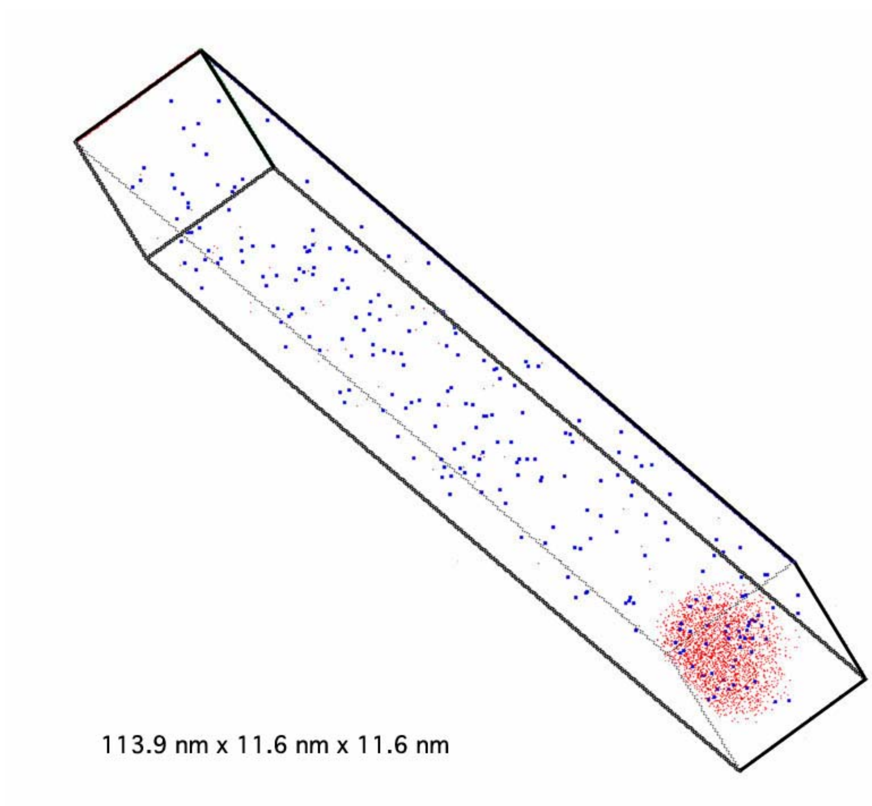

Fig. 5: Three-dimensional reconstruction of Al-0.06 at.%Sc-0.06 at.% Ti aged at 300°C for 96 h. The smaller red dots and the larger blue spheres represent the Sc and Ti atoms, respectively.

Discussion

The concentration of Ti in each of the precipitates is essentially independent of distance from the α-Al/$Al_3(Sc_{1-x}Ti_x)$ interface (Figs. 6 and 7). Thus, for the aging times (24 and 96 h) analyzed, no clear segregation of Ti at the interface is observed at 300°C, unlike the results of Fuller et. al. for Al-Sc-Zr

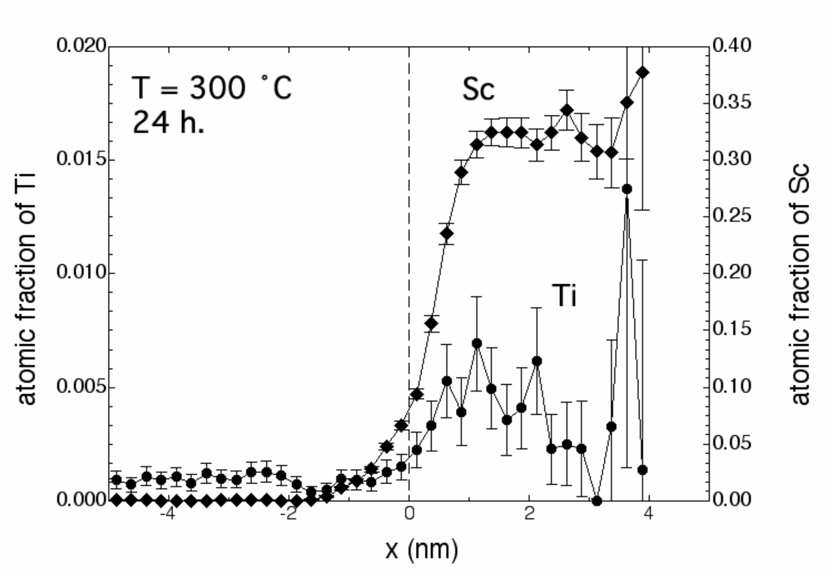

Fig. 6: Proxigram of Al-0.06 at.%Sc-0.06 at.% Ti aged for 24 h. at 300°C. Positive distances are into the precipitate and negative distances are into the matrix.

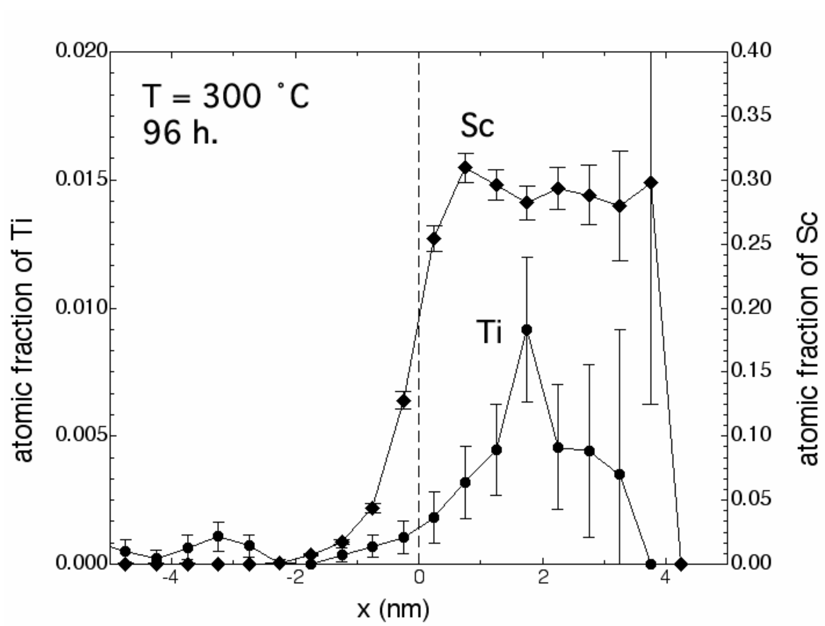

Fig. 7: Proxigram of Al-0.06 at.%Sc-0.06 at.% Ti aged for 96 h. at 300°C. Positive distances are into the precipitate and negative distances are into the matrix.

alloys annealed for up to 2,412 h. at 300°C. In the Al-Sc-Zr system segregation of Zr at the α-Al/Al_3Sc heterophase interface is very pronounced at longer aging times. It is thus possible that the Ti in the Al-0.06 at.%Sc-0.06 at.% Ti alloy may segregate at longer aging times and experiments are in progress toward this end. Indeed, equilibrium has not be achieved, as illustrated by the fact that the average Ti/Sc ratios in the precipitates in Figs. 6 and 7 are 0.016 and 0.017, respectively, well below the maximum achievable value of unity [3].

The increase in hardness of the Al-0.06 at.% Sc-0.06 at.% Ti alloy as compared to the binary Al-0.06 at.% Sc alloy (Fig. 2) can be explained from the 3DAP microscopy results. This data shows that the concentration of Ti in the precipitates (0.5 at.%) is greater than the concentration of Ti in the matrix (0.06 at.%), giving a maximum partitioning ratio of 8. This could lead to an increased volume fraction of precipitates thereby increasing the hardness by the observed value of 75 MPa. The strength increase may also be the result of a reduction in precipitate size due to the presence of Ti. In future work, we will analyze specimens for longer aging times to determine if and when the equilibrium concentration of Ti in the precipitates is achieved.

Conclusions

An Al-0.06at%Sc-0.06at.%Ti alloy was aged at 300°C for various times, leading to the following conclusions:

- Ti partitions to the Al3(Sc1$_{-x}$Ti$_x$) precipitates, although at the aging times analyzed (24 and 96 h.), most of the Ti remains in solid-solution in the matrix.
- There is no evidence that Ti segregates to the α-Al/$Al_3(Sc_{1-x}Ti_x)$ interface after a 96 hr. anneal. This result may, however, change for longer aging times or higher aging temperatures, since a steady-state equilibrium has not been reached.
- After aging at 300°C, Ti does not provide as much of a strengthening effect at room temperature as an equal addition of Sc to pure aluminum. With an addition of 0.06 at.% Ti, the peak hardness of a Al-0.06 at%Sc alloy increases by 125 MPa, while an equivalent addition of 0.06 at% Sc produces an increase of 300 MPa.

Acknowledgements

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