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# Core/Triple Shell Precipitates in Al-Er-Sc-Zr-(V,Nb,Ta) Alloys

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Al-Sc alloys are strengthened by nanoscale $Al_3Sc$ precipitates [1]. By alloying with faster-diffusing Er and slower-diffusing Zr additions, complex core/double-shell precipitates are formed, consisting of an Er-enriched core surrounded by a Sc- and Zr-enriched shell [2]. The Er-enriched core enhances strength while the Zr-enriched outer shell improves thermal stability. The present study seeks ultimate strength and coarsening resistance by alloying Al-Er-Sc-Zr alloys with Group 5 additions (M = V, Nb, Ta), which are expected to be slower diffusers than Zr [3]. By sequential nucleation of the constituent solutes we have engineered complex core/triple shell $Al_3$(Er,Sc,Zr,M) coarsening-resistant precipitates.

This study investigates the nanostructures and compositions of $Al_3$(Er,Sc,Zr,M) precipitates formed during isochronal aging of dilute Al-0.004Er-0.056Sc-0.060Zr-0.060(V/Nb/Ta) (at.%) alloys made by arc melting. The alloys also contained 0.016–0.019 at.% Si, which decreases the Sc migration energy in Al thereby accelerating the precipitation kinetics [4]. Prior to aging, the alloys were first homogenized for 72 h at 640 °C to eliminate microsegregation of solutes after casting. The alloys were then aged isochronally in 25 °C increments each lasting 3 h, from 200–600 °C. The specimens were water-quenched between each aging increment and precipitation was monitored by Vickers microhardness and electrical conductivity measurements using a LECO AMH43 automatic hardness tester (200 g load) and a General Electric AutoSigma 3000 electrical conductivity meter, respectively. The microstructures responsible for strengthening were investigated by atom-probe tomography (APT) with a Cameca LEAP 4000x Si. Specimens for APT were prepared using standard lift-out and focused ion beam (FIB) milling procedures [5] in an FEI Nova 600 NanoLab DualBeam™ SEM/FIB.

Figure 1 displays the evolution of microhardness and electrical conductivity with temperature for the Al-Er-Sc-Zr and Al-Er-Sc-Zr-V alloys. Between 200 and 225 °C there is a small increase in microhardness and electrical conductivity, which is attributed to precipitation of $Al_3Er$. The largest strength increase, ~220 MPa, occurs between 250 and 300 °C, which is attributed to precipitation of Sc onto the $Al_3Er$ precipitates. This is followed by a secondary increase in microhardness and electrical conductivity between 350 and 400 °C, which is attributed to precipitation of Zr onto the $Al_3$(Er,Sc) precipitates. The alloys reach peak microhardness at 400 or 425 °C and peak electrical conductivity, corresponding to a maximum volume fraction of precipitates, at 425 °C. Above this temperature there is significant overaging, marked by a continuous decrease in strength. The microhardness and electrical conductivity results in Figure 1 indicate no obvious benefits from the addition of V.

Figure 2 displays an atom probe reconstruction of the Al-Er-Sc-Zr-V alloy isochronally aged to 425 °C (peak strength). The core/triple-shell nanostructure of the $Al_3$(Er,Sc,Zr,V) precipitates is seen in the reconstructions and also quantified in the proximity histogram [5]. While some of it partitions to the precipitates, most of the V remains in solid solution due to the slow diffusion kinetics of V in Al.

This study will present the complete precipitate evolution of $Al_3$(Er,Sc,Zr) precipitates during isochronal aging of Al-0.004Er-0.056Sc-0.060Zr (at.%) from 200–600 °C, and also discuss the effects of V, Nb, and Ta to this alloy.

## References:

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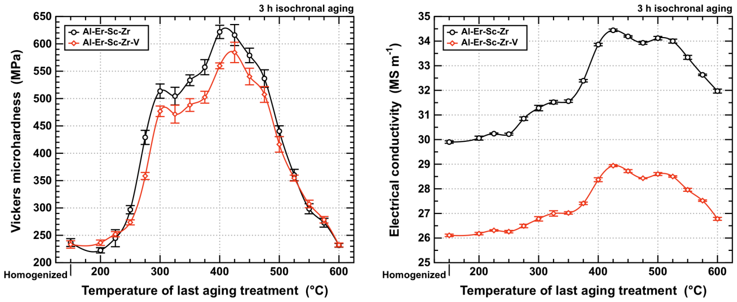

**Figure 1.** Vickers microhardness and electrical conductivity evolution during isochronal aging (3 h at each temperature) of the Al-Er-Sc-Zr and Al-Er-Sc-Zr-V alloys.

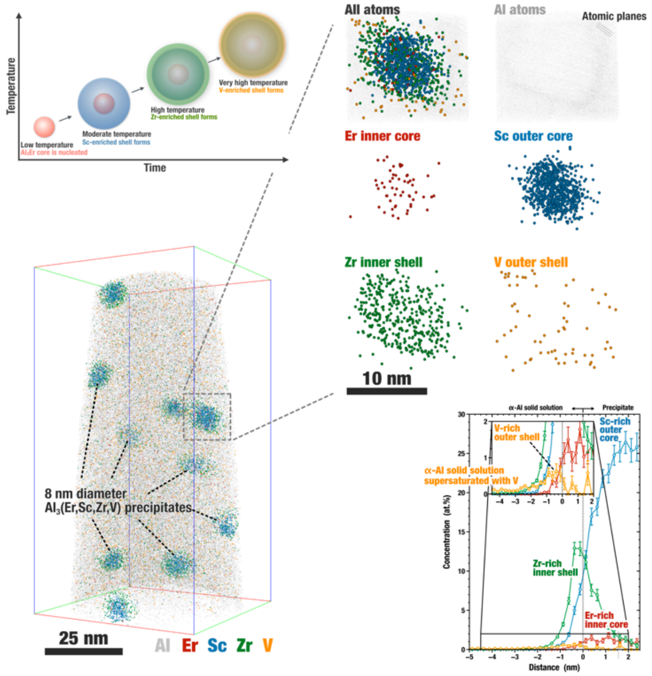

**Figure 2.** Atom probe reconstruction of the Al-Er-Sc-Zr-V alloy isochronally aged to 425 °C. The core/triple-shell nanostructure of the $Al_3(Er,Sc,Zr,V)$ precipitates is seen in the three-dimensional reconstructions and also quantified in the proximity histogram.