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Microstructures and Properties of As-Cast $Al_{2.7}CrFeMnV$, $Al_{2.7}CrFeTiV$, and $Al_{2.7}CrMnTiV$ High Entropy Alloys

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High entropy alloys (HEAs) typically contain five or more principal elements in nearly equiatomic proportions, significantly expanding the compositional possibilities and achievable properties of novel metallic materials. In a previous study [1] we reported that equimolar AlCrFeMnV, AlCrFeTiV, and AlCrMnTiV HEAs form body-centered cubic (BCC) solid solutions, with AlCrMnTiV containing an additional minor HCP C14 Laves phase that is enriched in V and Cr. Compared with other engineering alloys, these HEAs have comparable elastic modulus values to that of steel with densities 5.5–6.4 $g \cdot cm^{-3}$, which is between that of steel and titanium. Consequently, these HEAs have ~30% higher specific modulus than either of these other materials with specific microhardness values up to 1.4 times those of Ti-6Al-4V and up to 5.6 times those of 316 stainless steel.

To reduce their costs and densities, we have investigated Al-rich variants of these HEAs that are $Al_{2.7}CrFeMnV$, $Al_{2.7}CrFeTiV$, and $Al_{2.7}CrMnTiV$ on an atomic basis. Here we present the as-cast microstructures and mechanical properties of arc-melted alloys using metallographic analysis, powder X-ray diffraction (XRD), scanning electron microscopy (SEM), atom-probe tomography (APT), and Vickers microhardness, and compare these experimental results with the equilibrium phases predicted by thermodynamic modeling using Thermo-Calc software and the TCHEA3 database.

Like its equimolar counterpart [1], XRD analysis confirm that $Al_{2.7}CrFeMnV$ is a single-phase BCC solid solution, with a lattice parameter a = 0.2968 nm. The $Al_{2.7}CrFeTiV$ alloy is predominantly BCC (a = 0.3006 nm) with additional minor phases observed by XRD. The composition of the BCC matrix, as measured by APT, is depleted in Fe and Ti and is approximately $Al_{34}Cr_{28}V_{27}Fe_7Ti_4$ (at.%). Thermodynamic calculations predict that these additional phases are a AlTi ($L1_0$ structure) phase and a G-phase enriched in Fe and Ti.

The most interesting microstructures are observed in the $Al_{2.7}CrMnTiV$ alloy. XRD analysis indicates that this alloy is composed predominantly of a BCC matrix (a = 0.3043 nm) with a secondary face-centered cubic (FCC, a = 0.3946 nm) phase. SEM imaging, Figure 1, demonstrates that this FCC phase has a needle-like morphology that is ~20 µm long and has a volume fraction ~30%. Energy dispersive spectroscopy by SEM indicates that this FCC phase is enriched in Al and Ti, with an approximate composition of $Al_{57}Ti_{26}Mn_{10}Cr_{3.9}V_{3.6}$ as measured by APT. The measured compositions and lattice parameters suggest that this phase is an Al_3Ti phase, which can exist in a metastable cubic $L1_2$ structure with lattice parameter a = 0.3967 nm [2], consistent with the observed FCC peaks in the XRD spectra. Thermodynamic calculations, however, predict the presence of a AlTi phase with a distorted ordered FCC structure (a = 0.3987 nm, c = 0.4072 nm). Additional transmission electron microscopy (TEM) analyses are needed to ascertain the structure of this FCC phase. Other APT analyses of this alloy, Figure 2, show the presence of nanoscale cuboids, ~30–50 nm long on each side, that are enriched in Al, Ti, and Mn with approximate composition $Al_{46}Ti_{24}Mn_{18}V_{5.9}Cr_{5.7}$, as shown in the inset proximity histogram [3]. Thermodynamic calculations predict the formation of a Al_8Mn_5 phase (rhombohedral structure) of approximate composition $Al_{50}Ti_{25}Mn_{25}$ (depending on temperature), which might be what is detected here by APT. Again, further TEM analysis is needed to ascertain the structure of these nanoscale precipitates.

Compared with our previously studied HEAs with equimolar concentrations of the same elements [1], these HEAs provide similar or increased strength with lower density, and may provide a suitable replacement for titanium alloys in extreme environments [4].

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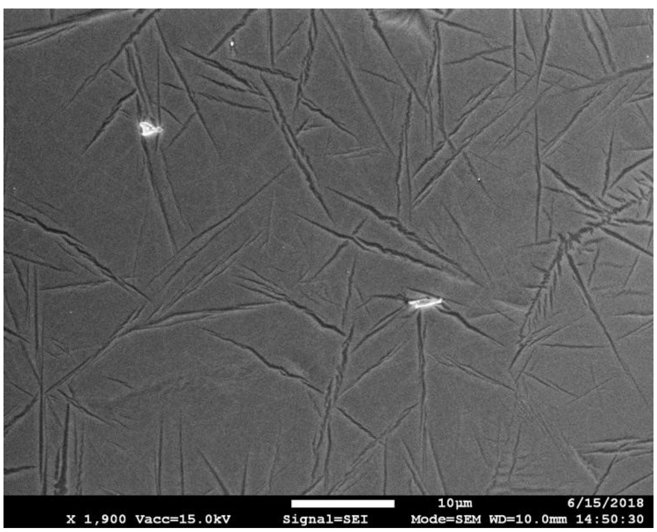

Figure 1. Al- and Ti-rich needle-like phases in the as-cast $Al_{2.7}CrMnTiV$ alloy.

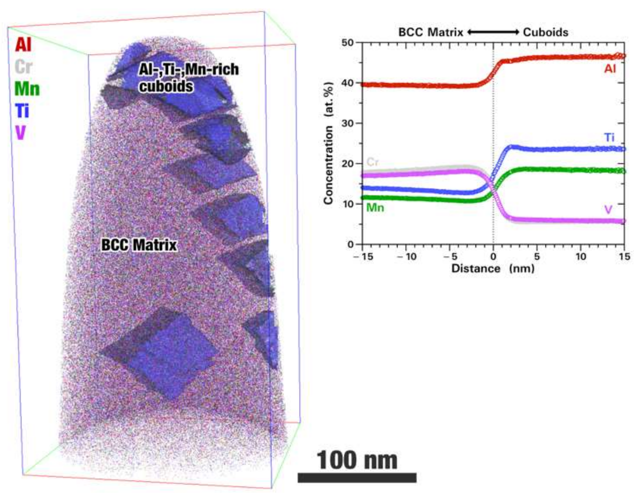

Figure 2. APT reconstruction displaying the chemical segregation between the BCC matrix and Al-, Ti-, and Mn-rich cuboids in the as-cast $Al_{2.7}CrMnTiV$ alloy. The nanoscale Al-, Ti-, and Mn-rich cuboids are delineated by a 20 at.% Ti isoconcentration surface.

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