A Co-free Precipitation-Hardened High-Entropy Alloy

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Background

- High-entropy alloys (HEAs) are a novel class of alloys
- Consist of multiple (generally 5+) elements in nearly equal proportions
- High entropy of mixing favors single phase composition
- Have unique combinations of properties: high strength, structural stability under heat and irradiation, wear and oxidation resistance
- Properties make it desirable for harsh environments like nuclear reactors

Precipitation

- Most studies of HEAs focus on single phase solid solution structure
- Single-phase alloys have poor mechanical properties, limiting potential applications
- Small additions of precipitate forming elements like Ti and Al can cause precipitation and increased strength
- Precipitates also help improve thermal stability and irradiation resistance of the structure

Alloy Design

- Previous literature has shown $(FeNiCoCr)_{94}Ti_2Al_4$ to exhibit ideal precipitation of $L1_2$ phase
- Co activation under irradiation makes it undesirable for nuclear applications
- Replacement of Co in existing alloys with Mn should still result in $L1_2$ precipitation alloy
- Cr content also reduced to attempt to inhibit Cr-enriched precipitate formation

Characterization

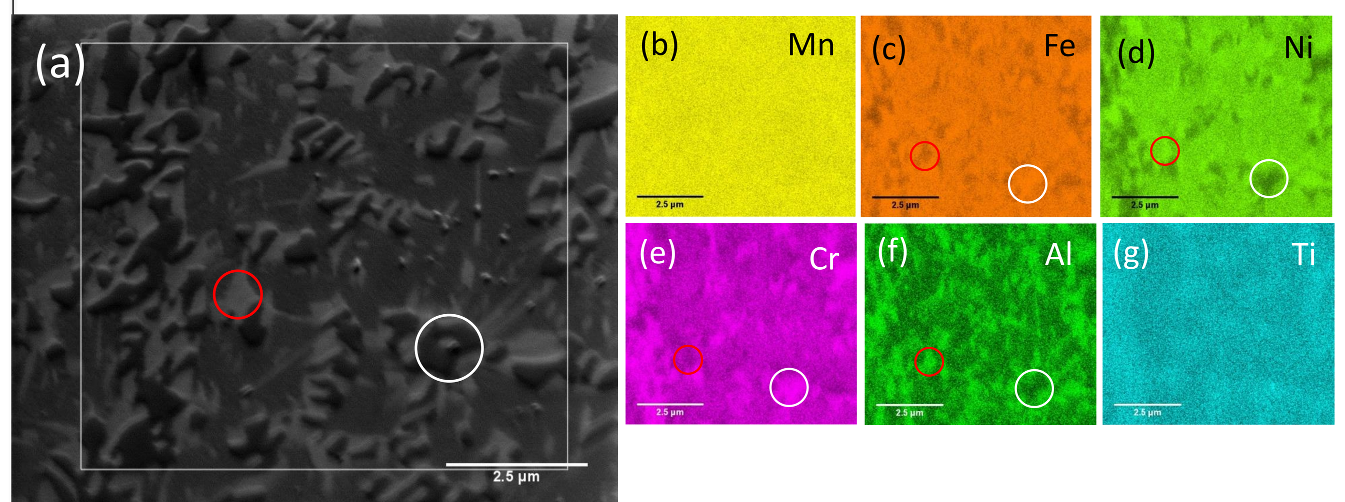


Figure 1: EDS maps of structure in $(FeNiMnCr_{10})_{94}Ti_2Al_4$ aged at 650°C for 120 h. (a) Secondary electron image, and maps of (b) Mn, (c) Fe, (d) Ni, (e) Cr, (f) Al, (g) Ti. NiAl phase, circled in red, shows up light in SEM, FeCr phase, circled in white, shows up dark in SEM

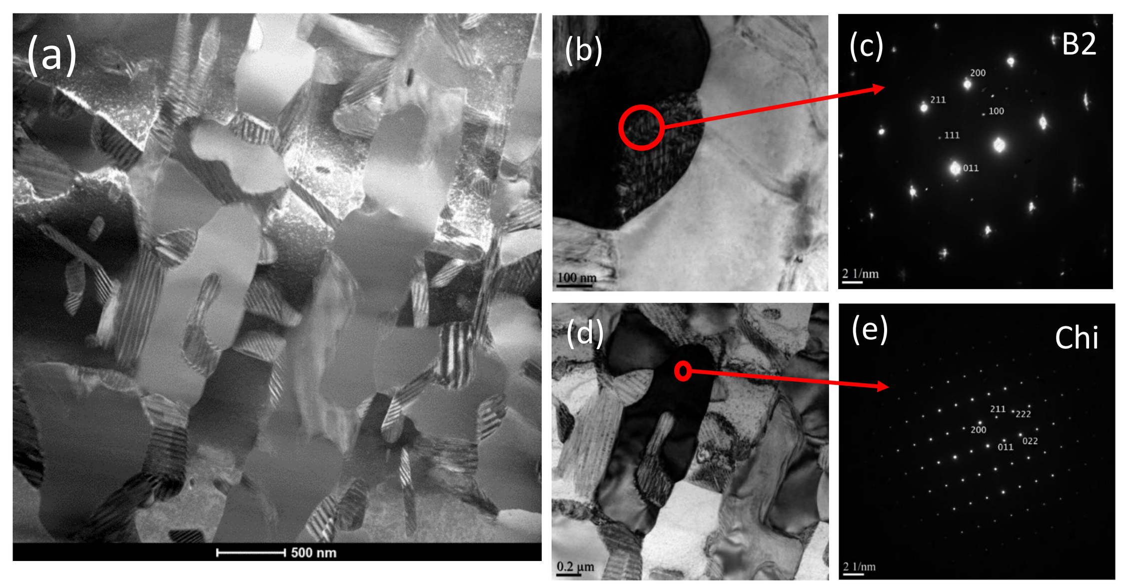


Figure 9: TEM of $(FeNiMnCr_{10})_{94}Ti_2Al_4$ aged at 650°C for 120 h. (a) Bright field STEM, (b) Bright field TEM of a B2 phase, (c) SAED of (b) showing B2 phase. (d) Bright field TEM of a Chi phase, (e) SAED of (d) showing Chi phase.

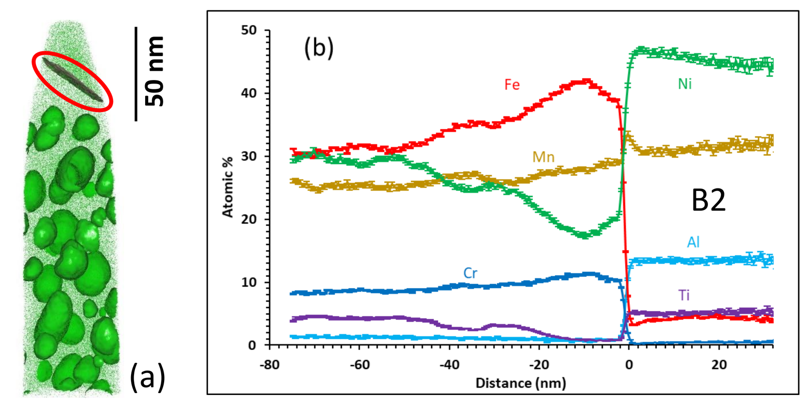
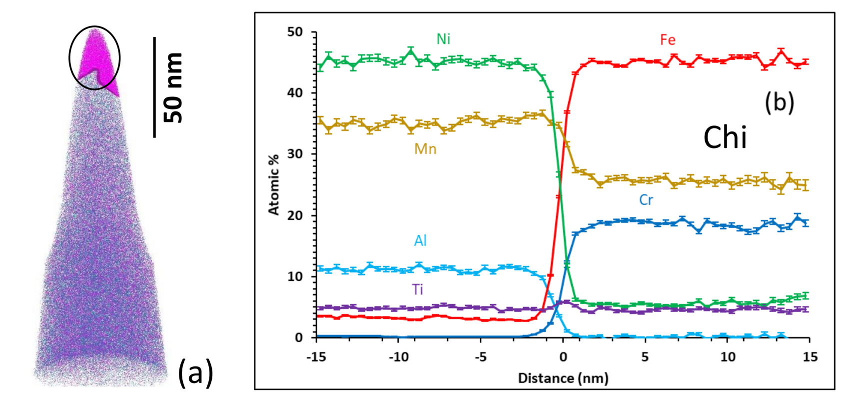


Figure 3: Proxigram of NiAl-rich B2 phase on the end of Figure 5 tip. (a) Isosurface (circled in red) with associated (b) proxigram



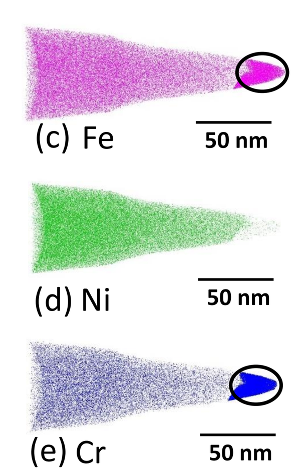


Figure 4: APT tip of $(FeNiMnCr_{10})_{94}Ti_2Al_4$ aged at 650°C for 120 h. (a) 25% Fe isosurface (circled) with (b) proxigram. Atom maps of (c) Fe, (d) Ni, and (e) Cr. Fe and Cr enriched Chi phase indicated with black circles.

Precipitates & Mechanical Properties

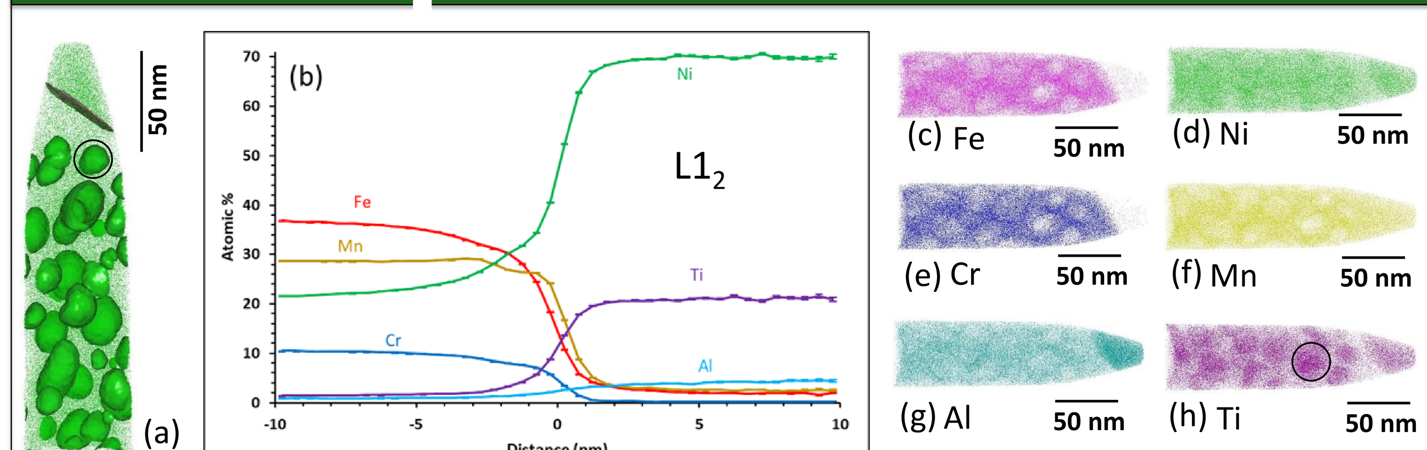


Figure 5: APT tip of $(FeNiMnCr_{10})_{94}Ti_2Al_4$ aged at 650°C for 120 h. (a) 40% Ni isosurface of $L1_2$ precipitates, with (b) statistical proxigram of precipitates. Atom maps of (c) Fe, (d) Ni, (e) Cr, (f) Mn, (g) Al, and (h) Ti. The L12 phase is circled in black.
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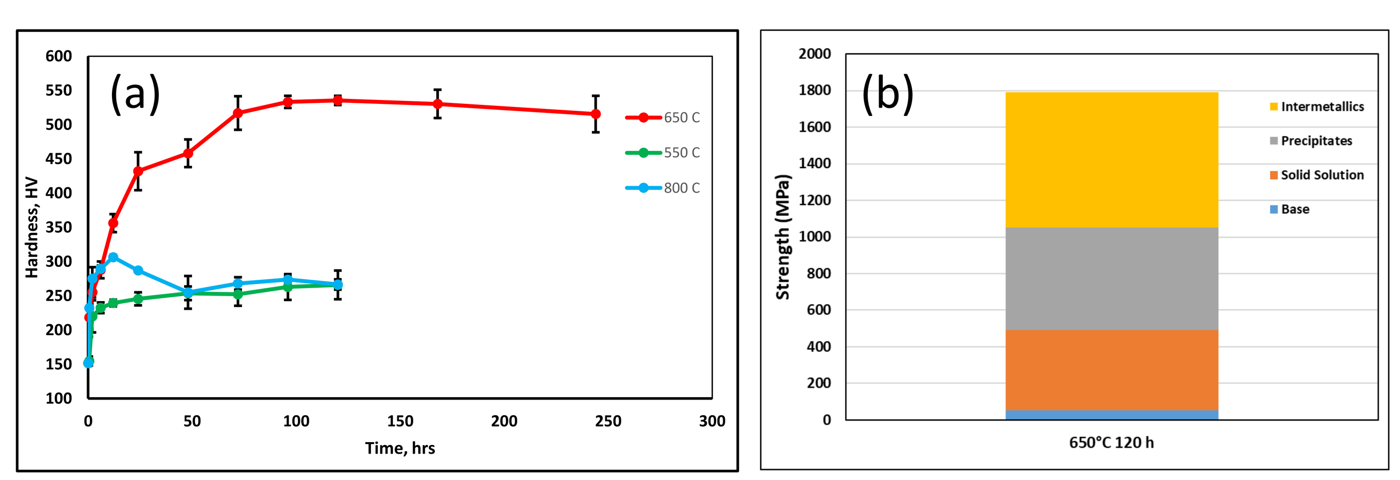

Figure 6: (a) Vickers hardness of $(FeNiMnCr_{10})_{94}Ti_2Al_4$ aged at 550, 650, and 800°C with peak aging at 650°C for 120 h. (b) Strengthening analysis of the peak aged sample, with precipitates referring to $L1_2$ and intermetallics referring to the B2+Chi structure.

Modeling

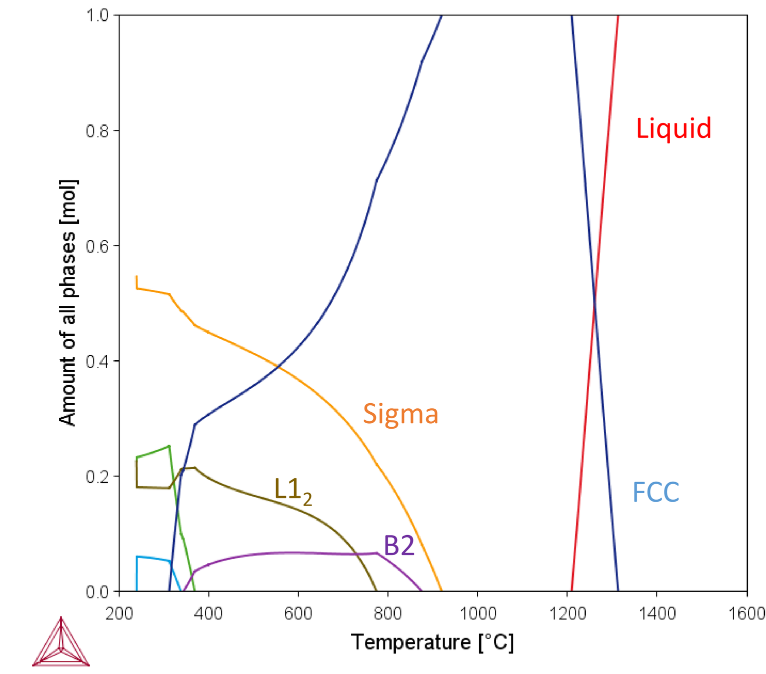

Figure 7: CALPHAD predictions of equilibrium phase formation. Phases relevant to 650°C are labeled.

Summary

Results

- Co-free high-entropy alloy shows promising strength and precipitate structure, may exhibit high thermal stability
- B2+Chi network formed in addition to $L1_2$ precipitates, could impair ductility but provides bulk of strength
- Modeling predicts multiple phases but not Chi phase formation

Future Work

- Perform tensile testing on peak-aged condition to determine ductility
- Further TEM characterization to confirm phases
- Alter composition to improve other properaties such as corrosion resistance

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