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Insight Into Precipitation Synergy of Nano β-NiAl + Cu + Carbide in Austenitic Steel by Atom-Probe Tomography

Colin A. Stewart[1*], Richard W. Fonda[1], Keith E. Knipling[1], Patrick G. Callahan[1] and Paul K. Lambert[2]

[1.] US Naval Research Laboratory, Washington, DC, USA.
[2.] US Naval Surface Warfare Center Carderock Division, Bethesda, MD, USA.
* Corresponding Author: colin.stewart@nrl.navy.mil

Mn-stabilized fully-Austenitic steels are attractive for naval applications due to their reduced material costs compared with Ni-stabilized Austenitic steels, as well as their resistance to ductile-to-brittle transition of the Austenite at lower temperatures [1]. However, one major challenge in Austenitic steels is the reduced effect of solid solution strengthening vs. ferritic steels [2]. Precipitation strengthening offers an alternative strengthening option, with a large design space available to tune the properties of the steel based on the type of precipitates formed and the thermal treatment applied. In ferritic steels, nanoscale β-NiAl (B2) and Cu precipitates have demonstrated a synergy in promoting precipitation of these strengthening phases [3]. These precipitates have not been explored as extensively in Austenitic steels, where Cu may form coherent precipitates that promote the formation of the B2-structured β-NiAl precipitates [4]. The mechanisms behind this β-NiAl – Cu precipitation synergy in Austenitic steels are important to understand for future development of this alloy system.

We present the design of a new fully-Austenitic steel strengthened by nano-scale precipitates of (i) insoluble Cu (FCC) particles; (ii) ordered intermetallic β-NiAl (B2) precipitates; and (iii) carbides. This Austenitic steel was developed by an integrated computational material engineering (ICME) approach with minimal experimentation. After CALPHAD modeling of the effects of various alloying additions, a Fe-10.0Ni-5.0Al-4.7Cr-17.7Mn-4.0Cu-0.48C (wt.%) alloy was synthesized [5] that demonstrates remarkable age hardening, exceeding 500 Vicker's number (>180 ksi estimated yield strength). To elucidate the mechanisms of precipitation, a series of ageing time-steps at 580°C was analyzed by atom-probe tomography (APT). Figure 1 displays APT reconstructions from two aging conditions. At short ageing times (1 h, Fig. 1a), an initial distribution of fine, spheroidal particles forms with the NiAl stoichiometry, yet with significant Cu solubility (~15 at.%). After longer times approaching peak hardness (10 h, Fig. 1b) the microstructure evolves into two distinct but usually juxtaposed precipitate species: Cu-rich particles and β-NiAl platelets that are lean in Cu (~4 at.%).

Insights from these and other APT datasets of this nano-precipitation-strengthened Austenitic steel will be discussed, incuding methods of particle segmentation to quantify precipitate radii, number density, and volume fraction that can be used in precipitation strengthening models. APT also provides unique insights into the evolution of the precipitate compositions, ellucidating the mechanisms and potential of synergistic precipitation in these and similar Austenitic steels. The effects of evolving composition on particle distribution will also be investigated, as well as the challenges of extracting quantitative microstructural values for further ICME modeling.

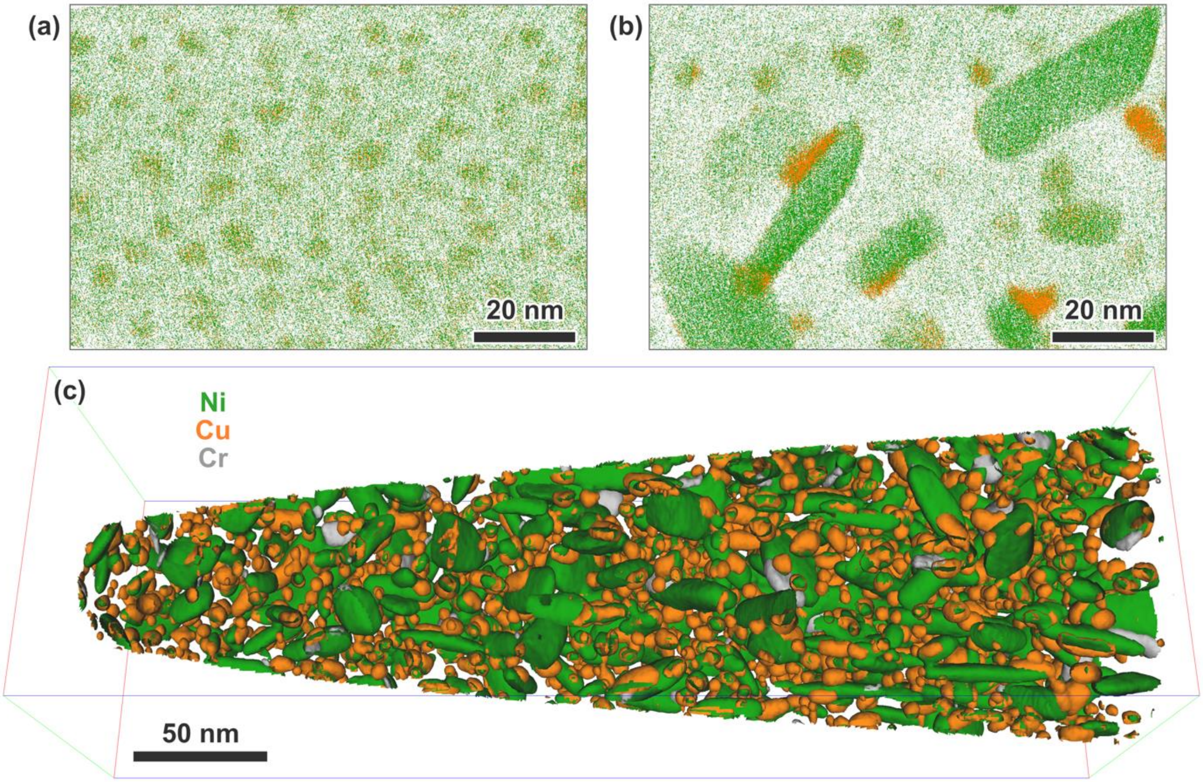

Figure 1: Atom probe tomography reconstructions of a nominal Fe-10.0Ni-5.0Al-4.7Cr-17.7Mn-4.0Cu-0.48C (wt.%) Austenitic steel aged at 580 °C. Top: 5 nm sections of APT datasets showing only Cu (orange) and Ni (green) ions, demonstrating the precipitate evolution that occurs between 1 h (a) and 10 h (b) ageing. Bottom: A full 3D reconstruction with isoconcentration surfaces of Cu (orange) outlining Cu particles, Ni (green) outlining β-NiAl particles, and Cr (gray) outlining Cr-rich $M_{23}C_6$ carbides after 10 h ageing (c), demonstrating particle morphologies.

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