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Partitioning Behavior of Al and Si in FINEMET Nanocrystalline Soft Magnetic Alloys, as Studied by Atom-Probe Tomography

K.E. Knipling,* M. Daniil,*, ** M.A. Willard*

* Multifuntional Materials Branch, Naval Research Laboratory, 4555 Overlook Ave, SW, Washington, DC, 20375
** Department of Physics, George Washington University, Washington, DC, 20052

FINEMET, a nanocrystalline Fe-Si-B-Nb-Cu alloy, is an attractive soft magnetic material exhibiting excellent permeability while maintaining a high saturation magnetization [1,2]. This material is prepared by partially devitrifying melt-spun amorphous alloys during post-solidification annealing. In the optimum magnetic state, the alloys exhibit a complex three-phase nanocomposite structure consisting of ~70 vol.% randomly oriented $D0_3$ Fe-Si grains (~10 nm) embedded in the remaining B- and Nb-rich amorphous matrix. The random distribution of the fine ferromagnetic grains causes a reduction in the net magnetocrystalline anisotropy, contributing to the excellent magnetic properties. A very small volume fraction (~1 vol.%) of nanometer-scale Cu precipitates (<5 nm) is also present, which serve as nucleation sites for the Fe-Si crystallites during devitrification. The microstructural evolution of these alloys upon annealing is shown schematically in Figure 1.

The magnetic properties of FINEMET can be improved by substituting Al for Fe, which decreases the magnetocrystalline anisotropy of the nanocrystals leading to reduced coercivity and core losses [3,4]. In this study we employ three-dimensional atom-probe tomography (3D APT) to quantify directly the phase compositions obtained by substituting Al for Fe and Si in a series of four $(Fe,Si,Al)_{87}B_9Nb_3Cu_1$ alloys annealed at 550 °C for 1 h. A representative atom-probe tomographic reconstruction, Figure 2, demonstrates unambiguously that Al segregates to the Fe-Si grains. Figure 2 also indicates, however, that Al segregates to the Cu precipitates, limiting the amount of solute available for incorporation into the Fe-Si crystallites [5]. The relationship between the measured composition of the nanocrystalline phase and the observed bulk magnetic properties (saturation magnetization and coercivity) is discussed.

In addition to identifying the local chemical compositions of the phases in nanocrystalline alloys, the wide field-of-view in modern atom-probes now enables detailed structural analysis, including measurement of grain size, volume fraction, number density, and edge-to-edge intergranular distances directly in three dimensions (Figure 2). We correlate these measurements to structural information obtained by X-ray diffraction.

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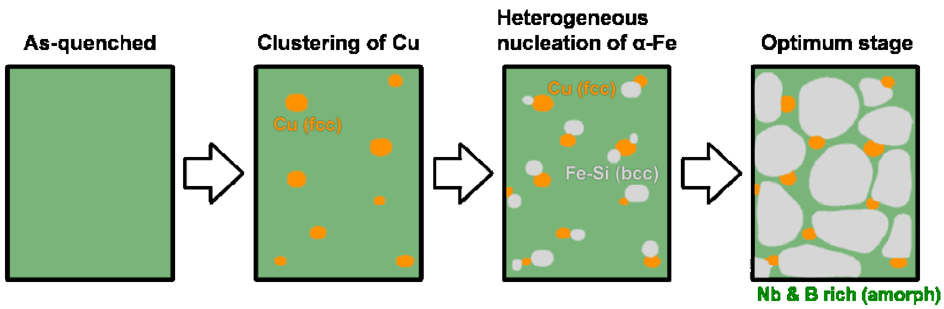

FIG. 1. Schematic illustration of the microstructural evolution that occurs during devitrification of amorphous FINEMET alloys. Adapted from Hono and Ping [2].

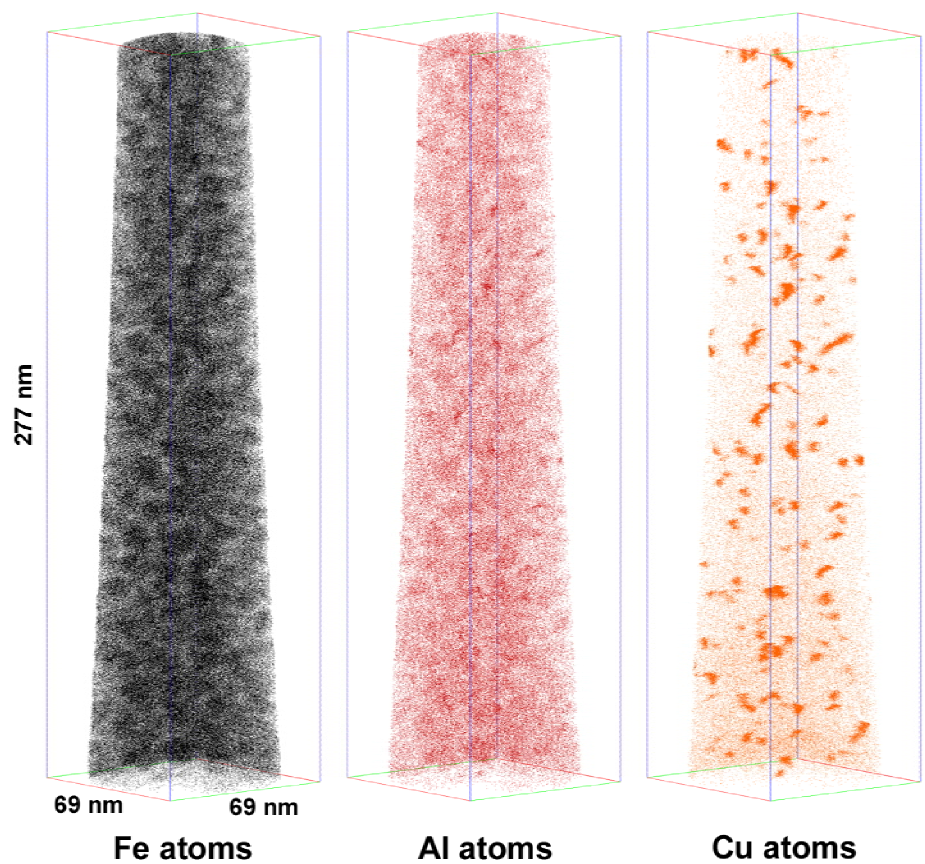

FIG. 2. Atom-probe tomographic reconstructions of $Fe_{65.5}Si_{16.5}Al_{5.0}B_9Nb_3Cu_1$ annealed at 550 °C for 1 h. Hundreds of Fe-rich nanocrystalline grains (~10 nm diameter) are visible, to which Si and Al segregate. Several hundred Cu-rich precipitates are also shown, to which Al also segregates. The entire reconstruction contains 16×10^6 atoms.

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