Supersilent AlCoFeNiCux (x = 0.6 – 3.0) high-entropy alloys

Dr. Andreja Jelen[1]
[1]J. Stefan Institute, Ljubljana, Slovenia

BACKGROUND INCL. AIMS
In the search for the materials that possess a combination of excellent magnetic softness and vanishing magnetostriction, the ferromagnetic high-entropy alloy (HEA) system AlCoFeNiCux (x = 0.6–3.0) was investigated.

HEAs are expected to find applications as supersilent (inaudible to a human ear) materials for transformers, magnetocaloric coolers, and other “humming” electromagnetic machinery.

METHODS
The AlCoFeNiCux HEAs with the Cu content x = 0.6–3.0 were prepared from high purity elements (>99.99 wt.%) by arc melting under an argon atmosphere. Altogether, there were seven samples fabricated.

An evolution of the crystal structure and chemical composition was observed with increasing Cu content by XRD and SEM EDS characterization. The phases constitutions and their domain sizes were characterized by correlative SEM and TEM techniques, as HEAs usually have highly complex structures on different spatial scales that contribute to specific physical properties such as magnetic softness and magnetostriction.

The magnetic properties were investigated by a Quantum Design Magnetic Property Measurement System MPMS3 magnetometer. The magnetometer uses a superconducting magnet with variable magnetic field of ± 7 tesla and the temperature range of the measurements is from 1.8 K to 400 K.

Electrical resistivity was measured by a Quantum Design Physical Property Measurement System PPMS 9T by. The apparatus uses a superconducting magnet with a variable magnetic field of ±9 tesla and the temperature range of the measurements is between 1.9 K and 400 K.

RESULTS
XRD revealed the evolution of the samples’ crystal structure. At low Cu contents, x = 0.6 and 0.8, the predominant phase is bcc (≈85 wt.%) with the unit cell parameter a = 2.869 Å, and the second phase is fcc (≈15 wt.%) with a = 3.612 Å. On increasing the Cu content, the fraction of the fcc phase increases, while the bcc phase fraction decreases. Detailed observation of the fcc-phase diffraction peaks reveals that there are actually two fcc-phases with slightly different unit cell sizes, denoted as fcc(L)-large and fcc(S)-small.
For the two highest Cu contents (x = 2.5 and 3.0), the bcc phase is no longer visible in the XRD patterns and the structure is two-phase, composed of the fcc(L) and fcc(S) phases.

The development of the microstructure of all alloys was made visual by SEM BSE imaging. All alloys show inhomogeneous microstructure, where the brighter parts are enriched in the heaviest element Cu.

The TEM analysis of the AlCoFeNiCu2.5 alloy reveals that the three constituent phases are nanostructured on the 10 nm scale due to fine dispersion of the Guinier-Preston (GP) zones that are enriched in Cu. The GP zones were observed in all three phases except at the locations of the highest Cu enrichment. The concentrations of the chemical elements also

show nanometer-scale variations. It is straightforward to anticipate this result to the entire series of the investigated AlCoFeNiCux (x = 0.6–3.0) HEAs, so that the alloys can be considered as nanostructured composite materials with a multiphase (up to three phases) microstructure.

Magnetic softness characterization was performed by determining the magnetization versus the magnetic field, M(H), hysteresis loops in the magnetic field sweep $\mu_0 H = \pm 7$ T. Rapid change of the M(H) curves in the close vicinity of H = 0 and small coercive fields Hc are evident for all samples, revealing magnetic softness.

Magnetostriction experiments were performed at RT in a static magnetic field range $-0.2\ \text{T} < \mu_0 H < 0.2\ \text{T}$ by measuring the samples' elongation (or contraction) with a strain gage. The magnetostriction curves λ(H) at RT show the largest (positive) value $\lambda_s = 21\ \mu\text{m m}^{-1}$ for the lowest Cu content x = 0.6. The positive saturation magnetostriction decreases with increasing x and vanishes ($\lambda_s = 0$) at x = 2.0. For the two alloys with the highest Cu contents, x = 2.5 and 3.0, λ_s remains very close to zero. In practical terms, all AlCoFeNiCux alloys in the Cu content range $2.0 \le x \le 3.0$ can be considered as vanishing-magnetostriction HEAs, so that the precise Cu concentration within this range is unimportant.

Superior parameters were obtained for the composition AlCoFeNiCu2.0, which shows precisely zero magnetostriction, $\lambda_s = 0$, reasonably low coercivity $H_c \approx 650\ \text{A m}^{-1}$ and substantial saturation magnetic polarization of $J_s \approx 0.55$ T, which is about the same as that of the mumetal, a widely used commercial soft magnet.

CONCLUSIONS

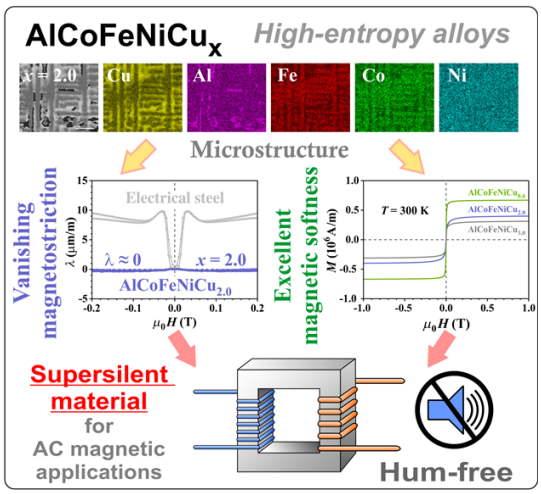
Magnetic softness and vanishing magnetostriction originate from the choice of constituent elements (magnetic Co, Fe, and Ni and nonmagnetic Al and Cu) and the multiphase composite microstructure is nanostructured on the 10 nm scale.

Magnetic softness originates from the nanostructured character of the alloys that are random mixtures of the ferromagnetic Al–Co–Fe–Ni domains and nonmagnetic or weakly magnetic Cu-rich domains on the 10 nm scale, which makes the mechanism of exchange-averaging of magnetic anisotropy efficient.

Since vanishing magnetostriction is a prerequisite for the supersilence of the material in audio-frequency AC applications, such HEAs are expected to find application as supersilent magnetically soft materials in transformers, electromotors, generators, magnetocaloric coolers, and other "humming" electromagnetic machinery.

We found that the alloys in the high Cu content range x = 2.0–3.0 indeed possess the targeted combination.

Graphic:



Keywords:

High-entropy alloys, magnetostriction, supersilence

Reference:

[1] J. Luzar, P. Priputen, M. Drienovsky, S. Vrtnik, P. Koželj, A. Jelen, et al., Adv. Mater. Interfaces, 2022, 9, 2201535.