Towards Rare-Earth-Free Permanent Magnets: $L1_0$ FeNi (Tetrataenite)

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Tetrataenite, the nominally-equiatomic FeNi phase with the chemically-ordered $L1_0$ tetragonal structure, is a promising material for next-generation rare-earth-free permanent magnets. Modern technology depends on permanent magnets that convert mechanical to electrical energy and vice versa. Permanent magnets are used in wind turbines, motors for hybrid and electric vehicles, satellite positioning systems, hard disk drives, and many defense applications. Current advanced permanent magnets require rare-earth elements but due to recent geopolitical events, their availability is in jeopardy. $L1_0$-structured FeNi would be an advantageous permanent magnetic material because Fe and Ni are both inexpensive and readily available.

The figure of merit for a permanent magnet is the maximum energy product $(BH)_{max}$ representing its strength. $L1_0$ FeNi has a theoretical maximum energy product comparable to the best rare-earth permanent magnets [1,2]. The reduced symmetry of the $L1_0$ structure induces a strong magnetocrystalline anisotropy, which is the preference for magnetization to lie along a particular direction ([001] for $L1_0$ FeNi [1]). Despite these promising magnetic properties, the phase has not yet been produced in bulk by conventional metallurgy methods due to extremely low atomic Fe and Ni mobilities (1 atomic jump per 10,000 years @ 300 °C [3]) below the critical chemical order/disorder temperature of 320 °C [1, 4]. Tetrataenite has been observed in meteorites, which are studied as Fe-Ni equilibria systems and the structure and stability of $L1_0$ FeNi are deduced from these investigations. However, little magnetic characterization has been conducted since this phase was first synthesized by neutron irradiation in minute quantitites in the 1960s [1,5].

In the presented work, investigations of the magnetocrystalline anisotropy of tetrataenite are undertaken through analysis of magnetic domains revealed by polarized light microscopy and magnetic force microscopy (MFM) to provide guidance for future laboratory synthesis of the phase. Two meteorites, Estherville and NWA 6259, were selected for study. Estherville cooled at 0.2 K/Myr and contains large grains of tetrataenite as well as kamacite (α-Fe) and non-metallic minerals. NWA 6259 is a single grain of tetrataenite with phosphide precipitates (< 1 μm). Results from MFM characterization carried out on tetrataenite in the Estherville meteorite display flower-like and flame-like magnetic domains (Fig. 1), indicating a uniaxial structure that is reminiscent of magnetic domain images observed in high anisotropy $Nd_2Fe_{14}B$ permanent magnets. The flame-like pattern (Fig. 1) can be interpreted as magnetic domains magnetized at different angles to the surface plane and provides evidence that the $L1_0$ structure forms in three orthogonal orientations known as crystal variants. Polarized light microscopy investigations on tetrataenite in NWA 6259 meteorite indicate the presence of three $L1_0$ lattice variants while flame-like patterns are observed in preliminary MFM results. Analysis of magnetic domain behavior in meteoritic tetrataenite will add insight into the magnetocrystalline anisotropy and the potential of $L1_0$ FeNi as a permanent magnet.

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References:

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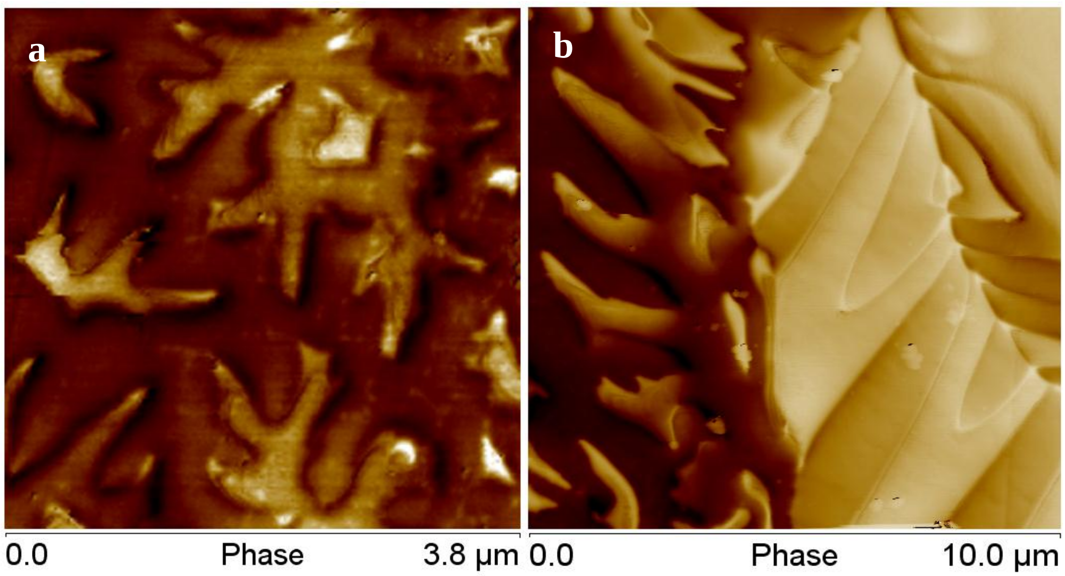

Figure 1: Magnetic domains observed using MFM on Estherville mesosiderite meteorite showing flower-like patterns that indicate strong uniaxial magnetocrystalline anisotropy (a) and flame-like branching patterns that indicate the presence of multiple crystal lattice orientations (b).

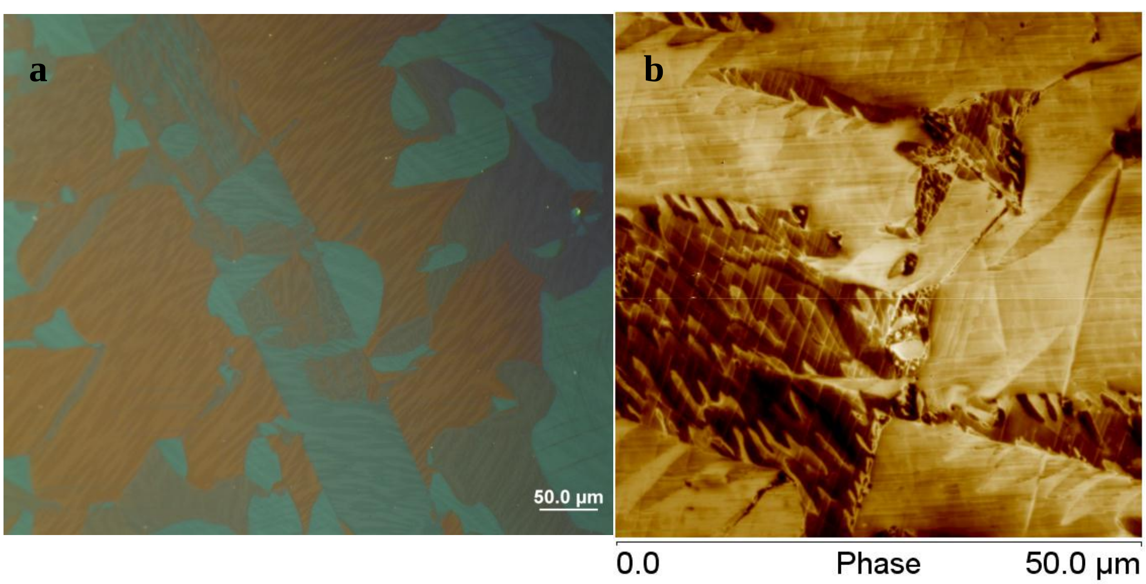

Figure 2: Magnetic domains observed on NWA 6259 meteorite using polarized light where the three colors indicate different variants (a) and using MFM where the flame-like pattern indicates multiple crystal lattice orientations (b).