

**Towards Rare-Earth-Free Permanent Magnets:  
Thermomagnetic Behavior of Meteoritic Tetrataenite ( $L1_0$  FeNi)**

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Much of the modern technology we have come to rely upon depends on the availability of powerful permanent magnets that convert mechanical energy to electrical and vice versa, including 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, however due to recent geopolitical events, their availability is limited. Tetrataenite, the nominally-equiatomic FeNi phase with the chemically-ordered  $L1_0$  tetragonal structure (shown in Figure 1), is a promising material for next-generation rare-earth-free permanent magnets, as Fe and Ni are both inexpensive and readily available, amenable to standard metallurgical processing techniques, and resistant to corrosion.

It is anticipated that tetrataenite would be a very strong permanent magnet, if its nanostructure and microstructure can be controlled. The figure of merit for a permanent magnet is the maximum energy product  $(BH)_{max}$  representing the maximum amount of magnetic energy stored in a magnet. The energy product is calculated as the largest rectangle that can be drawn in the second quadrant of the magnetic induction ( $B$ ) versus applied field ( $H$ ) hysteresis loop. To maximize the energy product, a large remanence ( $B_R$ , the induction a sample retains when the applied field is removed) and a large coercivity ( $H_C$ , the field required to demagnetize a sample) are required; however remanence and coercivity are both extrinsic factors. The intrinsic material properties that, combined with an engineered microstructure, result in a large energy product are the saturation magnetization ( $M_S$ , the maximum magnetization a material can have) and the magnetocrystalline anisotropy constant ( $K_u$ , the preference for magnetization to lie along a particular crystallographic direction).  $L1_0$  FeNi has a theoretical maximum energy product comparable to the best rare-earth permanent magnets [1,2] due to its inherently large saturation magnetization and large magnetocrystalline anisotropy ( $M_S = 1300$  emu/cc,  $K_u = 1.3 \times 10^7$  [1]). However, the phase is only found naturally in meteorites that form over 4.5 billion years; it has not been produced in macroscopic quantities by laboratory methods due to extremely low atomic Fe and Ni mobilities (1 atomic jump per 10,000 years @ 300 °C [3]) below the critical temperature of 320 °C, where the fcc chemically-disordered phase transforms into the  $L1_0$  chemically-ordered phase [1, 4]. While the structure and stability of  $L1_0$  FeNi have been studied from investigations of tetrataenite in meteorites, little magnetic characterization has been conducted since the phase was first discovered in the 1960s [1,5].

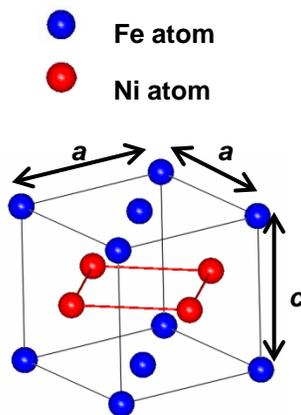
In this work,  $L1_0$  FeNi (tetrataenite) extracted from the NWA 6259 meteorite was utilized as a natural source of the chemically-ordered phase (43 at% Ni composition). The crystal structure, microstructure, magnetic character and phase transition character were studied. Structural characterization by collaborators determined that the NWA 6259 meteorite is composed of the  $L1_0$  phase in three mutually perpendicular crystallographic directions [6]. Investigations of the magnetocrystalline anisotropy of tetrataenite were undertaken through analysis of vibrating sample magnetometry (VSM) results. Characterization of the chemical disordering transformation was studied using VSM and differential scanning calorimetry (DSC) in the temperature range 25 – 700 °C. NWA 6259 tetrataenite features an apparent Curie temperature  $T_C$  at ~534 °C that is consistent with the DSC results, which show an endothermic peak with an onset temperature of ~534 °C and a transformation enthalpy of 4.2 kJ/mol that

corresponds to the  $L1_0 \rightarrow$  fcc chemical order-disorder phase transformation. After heating to 700 °C, the coercivity value measured at 5 K decreases from 1075 to 3 Oe, and the magnetization at 5 T increases by 14%. The coupled magnetic-structural phase transformation temperature is well above the reported order/disorder temperature of 320 °C signifying that the disordering process is kinetically limited [7,8]. By comparing the results from three different heating rates, the activation energy for the  $L1_0 \rightarrow$  fcc transformation has been determined. These results on meteoritic tetrataenite have confirmed that  $L1_0$  FeNi has suitably high saturation magnetization and anisotropy for permanent magnet applications and has furthermore shown that the disordering transformation is slow, which is advantageous for permanent magnet applications in motors and engines. By studying the thermodynamic and kinetic parameters associated with the  $L1_0 \leftrightarrow$  fcc transformation in meteorites, synthesis efforts to make the  $L1_0$  FeNi phase in the laboratory on laboratory time scales may be made possible.

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**Figure 1: Unit cell of the nominally-equiatomic tetragonal  $L1_0$  FeNi crystal structure.**