Towards Rare-Earth-Free Permanent Magnets: $L1_0$ $Fe_{50}Pd_{(50-x)}Ni_x$

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Introduction

Permanent magnets are an integral part of modern technology because they convert mechanical energy to electrical energy and back. They are called "permanent" because they are very difficult to demagnetize due to high magnetization M_s, coercivity H_c, remanence B_r, and anisotropy H_k. Current advanced permanent magnets are made from rare-earth elements, 95% of which are currently produced in China. In August 2009, it was revealed that China's Ministry of Industry and Information Technology will restrict the amount of rare-earths exported and place greater controls on rare-earth mines [1]. Consequently, prices have increased tenfold. In order to ensure our technology future, it is imperative to reduce our dependence on foreign rare-earth permanent magnets.

Recent research has focused on equiatomic ordered ferrous alloys such as $L1_0$ type FePt and FePd as model systems for rare-earth-free permanent magnets. While the magnetic properties of these alloys are very promising, platinum and palladium are both expensive. FeNi also forms an $L1_0$ phase that was first discovered in 1962 by Paulevé, Dautreppe, Laugier, and Néel [2]. They formed the phase by neutron irradiation of FeNi and found that it has high uniaxial anisotropy constants (K_1=3.2 x 10^6, K_2 = 2.3 x 10^6 ergs/cm^3) and high saturation magnetization (M_s =1300 emu/cc) but it is only stable to 320 °C and has extremely low diffusivity [3]. Due to such slow diffusion, $L1_0$ FeNi is only naturally found in meteorites, in which the phase forms over millions of years. In order to approach $L1_0$ FeNi, we plan to substitute Ni into FePd to form $L1_0$ $Fe_{50}Pd_{(50-x)}Ni_x$. Végard's law predicts that the thermal stability will vary linearly with Ni concentration. We plan to conduct basic scientific research on $L1_0$ $Fe_{50}Pd_{(50-x)}Ni_x$ to determine magnetic properties and thermal stability.

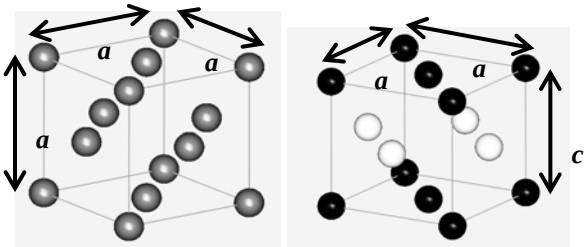


Figure 1: Disordered FCC structure (left) and $L1_0$ ordered FCT structure (right). Black atoms are Fe, white atoms are Pd (or Ni), and gray atoms have equal probability of being Fe or Pd/Ni.

Results and Discussion

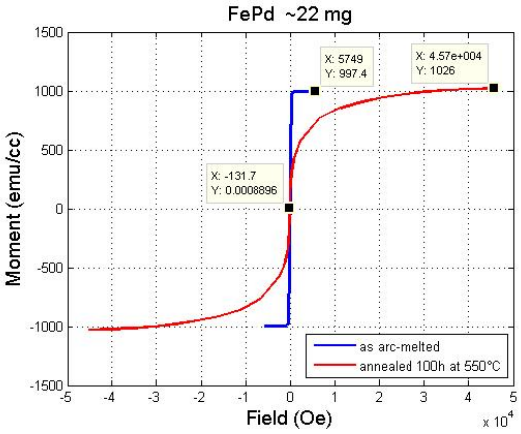
Disordered alloys of $Fe_{50}Pd_{(50-x)}Ni_x$ (x = 0, 2.5, 5) were formed by arc-melting. The samples were then sealed in evacuated quartz tubes and annealed at 550 °C for 100 h. Crystallographic analysis was done by x-ray diffraction (XRD) and magnetic analysis by superconducting quantum interference device (SQUID) magnetometry.

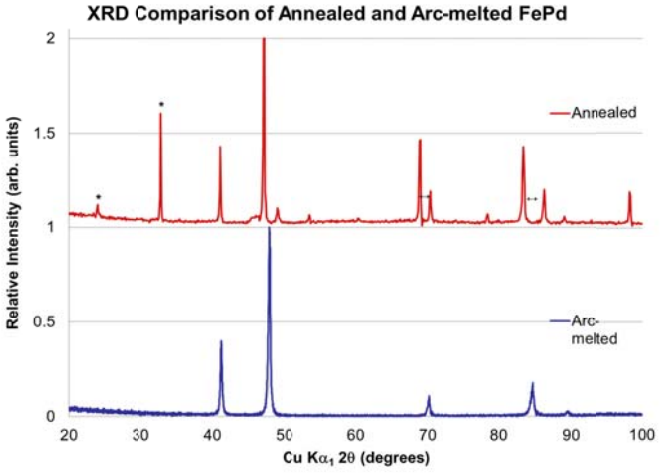
Disordered FePd is FCC but it becomes tetragonal upon ordering. This tetragonality causes a splitting of peaks in the XRD spectra. The $L1_0$ ordered structure is shown in Figure 1 compared to the disordered FCC structure. The $L1_0$ structure has alternating layers of iron and palladium (or nickel) in the [001] and [011] directions. These alternating layers result in additional peaks in the XRD spectra known as superstructure peaks. After annealing, FePd

samples showed clear indications of ordering in (XRD) as shown in Figure 2. The degree of ordering ($0 < S < 1$) can be determined by the ratio of the superstructure peaks to the fundamental peaks. Our results show $S = 0.9$ for FePd.

The annealed FePd samples showed magnetic indications of ordering in (SQUID) magnetometry measurements as shown in Figure 3. Unfortunately, the $x = 2.5$ and 5 samples showed no change in magnetic properties. The SQUID magnetometry measurements show that a very large field ($H \approx 5$ T) is required to saturate the annealed FePd samples. This means that the material is less susceptible to magnetization. The decrease in susceptibility is likely due to chemical ordering, which causes greater anisotropy. In the disordered FePd, there is no difference between the [100], [010], and [001] directions. In $L1_0$ FePd, the [001] direction is easily magnetized while the [100] and [010] directions are harder to magnetize. In order to saturate a magnet, the applied field must be greater than the anisotropy field. The anisotropy field in a polycrystalline material cannot be directly measured easily. An anisotropy constant $\langle K \rangle$ that represents a weighted average of anisotropies due to grain orientation, grain size, and other factors can be calculated from SQUID magnetometry measurements as $\langle K \rangle = \int_0^{Ms} H(M)dM$. By applying this method, we find $\langle K \rangle \approx 5.6 \times 10^6$ ergs/cm^3. Ideally, the anisotropy field H_k is related to the anisotropy constant K by $H_k = 2K/\mu_0 M_s$. An alternative method called singular point detection takes advantage of the discontinuity that occurs when the applied field is equivalent to the anisotropy field. A plot of d^2M/dH^2 v. H shows a peak corresponding to H_k. This method resulted in $H_k \approx 0.2$ T. This value is small considering an applied field of ≈ 5 T was required to reach magnetic saturation.

Overall these results show that ordering was achieved in FePd samples but not in samples containing nickel. Our future work will explore the ordering dependence on composition and annealing conditions. We will also investigate methods to enhance diffusion such as ball-milling.





References

[1] K. Bradsher, "China Consolidates Grip on Rare Earths," 15 September 2011. [Online]. Available: http://www.nytimes.com. [Accessed 12 10 2011].

[2] J. Paulevé, D. Dautreppe, J. Laugier and L. Néel, "Establishment of an ordered Fe-Ni structure by neutron irradiation," *Compt. Rend.*, pp. 965-8, February 1962.

[3] L. Néel, J. Paulevé, R. Pauthenet, J. Laugier and D. Dautreppe, "Magnetic Properties of an Iron-Nickel Single Crystal Ordered by Neutron Bombardment," *Journal of Applied Physics*, vol. 35, no. 3, pp. 873-876, March 1964.