Cluster ferromagnetism in Nd$_{60}$Fe$_{30}$Al$_{10}$ partially amorphous alloys

O. V. Billoni, L. M. Fabietti, S. E. Urreta and H. R. Bertorello

Facultad de Matemática, Astronomía y Física, Universidad Nacional de Córdoba, 5000 Córdoba, Argentina

In collaboration with:

A. F. Cabrera, C. E. Rodríguez Torres, F. H. Sánchez.

Facultad de Ciencias Exactas. Universidad Nacional de La Plata. 1900 La Plata, Argentina.
Nd Fe Al alloys:

- large glass forming ability --> bulk amorphous alloys --> rods 3 – 4 mm Ø chill casting techniques

- interesting hard magnetic properties for compositions about Nd$_{60}$Fe$_{30}$Al$_{10}$ and relatively low quenching rates (melt spinning at 5m/s)

- the hysteresis properties strongly depend on the cooling rate

Irreversible susceptibility: two magnetic phases at high quenching rates
Reversible susceptibility: spring magnet behavior—low quenching rates
The hard magnetic properties arise in the nominally amorphous phase, containing a high density of these Fe-rich clusters.

The hard magnetic properties observed depend, then, on the particular clustering stage achieved during cooling.
Clustering superferromagnetism model [Ding et al., 2001]

- The strong dependence of the magnetic properties on the quenching rate was then explained on the basis of different values of $A_{\text{eff}}$ and $K_{1c}$. 

\[ A_{\text{eff}} \quad K_{\text{eff}} \]

\[ A_C \quad K_{1C} \]

- $T < T_{\text{system}}$
  - Superferromagnetic

- $T_{\text{system}} < T < T_{\text{cluster}}$
  - Superparamagnetic

- $T > T_{\text{cluster}}$
  - Paramagnetic
From this we conclude that:

The clusters are small crystals of $\mu$-type Nd Fe Al phase ($\mu_0 H_a > 8$ T; $J_s \sim 0.85$ T).

Depending of the iron contend, the amorphous phase surrounding the clusters may be para or ferromagnetic largely affecting the effective value of $A_{eff}$. 

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<th>$\gamma^s$</th>
<th>$\Delta\gamma$</th>
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Nd-rich amorphous

Nd-rich amorphous
Thermal effects:

Hysteresis and Magnetic Relaxation

Sample solidified at 5 m/s: Hysteresis loops as a function of the field rate and relaxation curves.

Magnetic viscosity at different applied fields shows time dependence i.e. the curves of relaxation are not logarithmic.
Since magnetic viscosity is time dependent we use two methods to estimate the fluctuations field,

- from the field rate dependence of the histeresis loops, and

- Performing conventional magnetic viscosity experiments and defining a thermal field, to take into account the effects of the local irreversible susceptibility profile.
Fluctuations field

I. Field rates dependence

\[ H_f^R = \left. \frac{\partial \mu_0 H_i}{\partial \ln R} \right|_J \]  \quad \text{(Eq. 1)}

Fluctuations field obtained from Eq. 1 by making a linear fit, \( \mu_0 H_i \) vs \( \ln R \).
II Magnetic Viscosity experiments

The fluctuations field is estimated from,

$$H_{f}^{th} = \frac{d\mu_{0}H_{th}}{d \ln t}, \quad \text{Eq. 2}$$

by fitting a logarithmic function to the $H^{th}(t)$ curves.

$H_{f} = 14.5 \text{ mT}$ near the hard susceptibility peak in all the conditions.

Since the fluctuations field are nearly constant the alloys behave like a collection of bistable units.
Activation volumes:

$V_{ac} @ 343 \text{ nm}^3 \sim 25 \text{ clusters}$
Comments:

- Large values of $H_f$ are observed for all the quenching conditions
  
  \[ H_f \sim 15 \text{ mT} \]

  Similar results are obtained by the two methods applied.

- From a random anisotropy model for $K_{\text{eff}}$ and estimating the effective exchange constant $A_{\text{eff}}$, following Arcas et al. [1998],

  \[ L_{ex} = (A_{\text{eff}} / K_{\text{eff}})^{1/2} \sim 7 \text{ nm} \sim \text{activation length measured.} \]

  Then the optimally quenched alloys behave as magnetically granular. Further measurement concerning the temperature dependence of these parameters are necessary to verify this hypothesis. A better description of the surrounding amorphous phase is also required.

- In these days we are exploring the effect of changing the cluster substructure, by substitution of Nd and Al, on the hard magnetic properties of the base system obtained at 5 m/s.

  \[
  \begin{align*}
  \text{Nd}_{60-x}C_x\text{Fe}_{30}\text{Al}_{10} & \ (x=0, 1, 5 \text{ and } 10) \\
  \text{Nd}_{60}\text{Fe}_{30}\text{Al}_{10-x}\text{Mg}_x & \ (x=0, 5 \text{ and } 10)
  \end{align*}
  \]

- Both substitutions up to $x = 5$ are found to improve both, coercivity and remanence, leaving the hysteresis loops square. We can say little about these results except that the ME results indicate that these alloys contain similar of $\mu$-type clusters.