Anomalous magnetic viscosity in the bulk amorphous ferromagnets \(\text{Nd}_{60}\text{Fe}_{30}\text{Al}_{10}\) and \(\text{Nd}_{60}\text{Fe}_{20}\text{Co}_{10}\text{Al}_{10}\)

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Abstract. The bulk amorphous ferromagnets \(\text{Nd}_{60}\text{Fe}_{30}\text{Al}_{10}\) and \(\text{Nd}_{60}\text{Fe}_{20}\text{Co}_{10}\text{Al}_{10}\) exhibit hard magnetic properties, and time dependent magnetisation measurements have been performed to explore similarities and differences between them. Magnetic viscosity measurements on the major hysteresis loop of \(\text{Nd}_{60}\text{Fe}_{30}\text{Al}_{10}\) are reported, along with data for both alloys showing the behaviour of the irreversible magnetic susceptibility. The fluctuation field, \(H_f\), for each alloy is determined. A focus of the study is investigation of the anomalous magnetic viscosity i.e. non-monotonic behaviour of the time dependent magnetisation susceptibility (where a peak is observed in the magnetisation), on the recoil curve that leads to the dc demagnetised state. Data showing non-monotonic behaviour in both \(\text{Nd}_{60}\text{Fe}_{30}\text{Al}_{10}\) and \(\text{Nd}_{60}\text{Fe}_{20}\text{Co}_{10}\text{Al}_{10}\) is presented. The non-monotonic behaviour is interpreted using the Preisach model, as it predicts a simple functional relationship between the time taken to reach a peak and the applied magnetic field. The experimental data is in good agreement with this simple relationship.

1. Introduction
A feature of ferromagnetic materials is the time dependent behaviour of the magnetic polarization, \(J(t)\), i.e. magnetic viscosity. When observed on the major hysteresis loop (particularly for values of applied field near that of the intrinsic coercivity of the material being studied), over limited time scales, \(J(t)\) follows the well known simple monotonic expression

\[ J(t) = J_0 + S \ln(t + t_0), \]

where \(S\) is the magnetic viscosity parameter, \(J_0\) a constant and \(t_0\) a fitting parameter to establish a reference time. The fluctuation field, \(H_f\), is defined by

\[ H_f = \frac{S}{\chi_{irr}} \]

where \(\chi_{irr}\) is the irreversible magnetic susceptibility [1, 2]. Anomalous magnetic viscosity is where the time dependent magnetic polarization exhibits non-monotonic behaviour, that is the magnetic polarization is seen to increase, reach a peak, and then decrease. Such behaviour, following a two-step (or double-field) magnetic prehistory, has been observed on lower branches of minor loops or recoil curves in melt-spun \(\text{Nd}_{4}\text{Fe}_{77}\text{B}_{19}\) magnets [3], metal particle recording material [4], and the bulk amorphous ferromagnets \(\text{Nd}_{60}\text{Fe}_{30}\text{Al}_{10}\) [5, 6] and \(\text{Nd}_{60}\text{Fe}_{20}\text{Co}_{10}\text{Al}_{10}\) [7]. Observation of non-monotonic behaviour seems to be confined to amorphous ferromagnetic...
materials [6]. Bulk amorphous ferromagnets based on the Nd-Al-Fe alloy system appear to be ideal materials for studying time dependent effects. Unlike glassy metals, where the cooling rates are of order 10^{6} K/s, bulk amorphous ferromagnets are formed with cooling rates of a few tens to hundreds of K/s, enabling the production of rods some millimetres in diameter [8, 9].

Here we present a range of measurements to elucidate the behaviour of the time dependent magnetic polarization in Nd_{60}Fe_{30}Al_{10} and Nd_{60}Fe_{20}Co_{10}Al_{10}. The main focus is the behaviour of the anomalous magnetic viscosity on the recoil curve that leads to the dc demagnetised state. Particular attention is paid to highlighting similarities or differences that may arise due to the presence or absence of Co. The functional relationship between the time taken to reach the peak in the non-monotonic time dependent magnetic polarization is investigated. The Preisach model [10] provides a framework for interpreting the behaviour of the time dependent magnetic polarization in both Nd_{60}Fe_{30}Al_{10} and Nd_{60}Fe_{20}Co_{10}Al_{10}.

2. Experimental
The bulk amorphous samples of Nd_{60}Fe_{30}Al_{10} and Nd_{60}Fe_{20}Co_{10}Al_{10} were prepared by argon-arc melting and suction casting into a split copper mould. Each sample was approximately 2 mm in diameter and approximately 20 mm in length, and X-ray powder diffraction studies showed them to be essentially amorphous with only a trace of crystallinity (< 1%). Magnetic measurements were performed at room temperature (294 K) and in applied magnetic fields of up to 1.5 MA/m, using a Lake Shore Vibrating Specimen Magnetometer mounted on an electromagnet.

Measurement of the anomalous magnetic viscosity on a recoil curve requires a two-step (or double field) process. Initially the field is applied in the forward direction to magnetically saturate the sample. The applied field is then ramped in a negative direction to a turning point on the major hysteresis loop, H_1. This is Step 1. The applied field is then ramped in a positive direction to a field H_2 on a recoil curve and held constant; this is Step 2. Then the polarization is measured as a function of time. There is the special case of the recoil curve that leads to the dc demagnetised state, H_2 equal to zero and the magnetic polarization J equal to zero, i.e. the recoil line terminates at the origin of the J – H plane. In this case H_1 is chosen to meet this condition, and its value for each of the materials studied is given in Table 1.

3. Results and Discussion
Key magnetic parameters, derived from measurement of the major hysteresis loop, for each of the alloys studied are given in Table 1. Experimental results showing the decay in magnetic polarization on the major hysteresis loop (i.e. following a one-step process) in Nd_{60}Fe_{30}Al_{10} are shown in Fig. 1. From these measurements, the value of fluctuation field, H_f, was derived, using the method of Street and Brown (often termed the waiting time method) [1, 6], and it is given in Table 1. Included in Table 1 is the value of H_f for Nd_{60}Fe_{20}Co_{10}Al_{10} from [7]. The irreversible magnetic polarization, J_{irr}, and the irreversible susceptibility, \chi_{irr}(= \partial J_{irr}/\partial H_{int}), for Nd_{60}Fe_{30}Al_{10} and Nd_{60}Fe_{20}Co_{10}Al_{10} are shown in Fig. 2. It is seen that the presence of Co

| Alloy               | J_r  | \(\mu_0 H'_c\) | \(\mu_0 H_f\) | \(\mu_0 H_1\) |
|---------------------|------|----------------|--------------|--------------|
| Nd_{60}Fe_{30}Al_{10}| 123.8| 0.334          | 11.1         | -362.5       |
| Nd_{60}Fe_{20}Co_{10}Al_{10}| 93.1 | 0.348          | 9.4          | -365.3       |
results in a decrease in the remanence by \( \approx 25\% \), a small increase in the intrinsic coercivity by \( \approx 4\% \), a small decrease in the value of \( H_f \), and a reduction of the peak in \( \chi_{irr} \) both in width and height. The rather sharp and narrow peak in \( \chi_{irr} \) appears to be a feature of bulk amorphous alloys, and has been observed by others [11].

Experimental data showing the behaviour of the magnetic polarization on the recoil curve that leads to the dc demagnetised state, for a range of \( H_2 \) values (i.e. a two-step process), for both \( \text{Nd}_{60}\text{Fe}_{30}\text{Al}_{10} \) and \( \text{Nd}_{60}\text{Fe}_{20}\text{Co}_{10}\text{Al}_{10} \) are presented in Fig. 3. Both alloys behave similarly, exhibiting non-monotonic behaviour of the magnetic polarization, as the polarization is seen to increase, reach a peak, and then decrease. The time at which the peak is reached increases as

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**Figure 1.** Magnetic polarization, \( J \), as a function of time, \( t \), on the major hysteresis loop, for \( \text{Nd}_{60}\text{Fe}_{30}\text{Al}_{10} \) for fixed values of applied field (\( \mu_0H_a \)) of (■) \(-291.3\) mT, (▼) \(-301.4\) mT, (●) \(-306.5\) mT, (★) \(-311.6\) mT, (▲) \(-316.6\) mT, and (●) \(-321.4\) mT.

**Figure 2.** Irreversible magnetic polarization, \( J_{irr} \), and insert the irreversible susceptibility, \( \chi_{irr} \), as a function of internal field, \( H_{int} \), for \( \text{Nd}_{60}\text{Fe}_{30}\text{Al}_{10} \) (●) and \( \text{Nd}_{60}\text{Fe}_{20}\text{Co}_{10}\text{Al}_{10} \) (■).

**Figure 3.** Magnetic polarization, \( J \), as a function of time, \( t \), for values of applied field (\( \mu_0H_2 \)) on the recoil curve that leads to the dc demagnetised state, in \( \text{Nd}_{60}\text{Fe}_{30}\text{Al}_{10} \) (top row) of (a1) \(-210\) mT, (a2) \(-180\) mT and (a3) \(-140\) mT, and in \( \text{Nd}_{60}\text{Fe}_{20}\text{Co}_{10}\text{Al}_{10} \) (bottom row) for (b1) \(-231\) mT, (b2) \(-181\) mT and (b3) \(-120\) mT.
Figure 4. The time, $t_{\text{max}}$, at which the peak occurs in the magnetic polarization for a range of $H_2$ values, along the recoil curve that leads to the dc demagnetised state, for Nd$_{60}$Fe$_{30}$Al$_{10}$ ($\bullet$) and Nd$_{60}$Fe$_{20}$Co$_{10}$Al$_{10}$ (■). The solid lines are from a simple linear regression analysis.

$H_2$ increases towards zero (i.e. becomes less negative), and varies from a few tens of seconds to many hours.

The Preisach model [10], with its concept of the Preisach plane, provides a description of the two-step process that results in the observed non-monotonic behaviour. In terms of the Preisach plane two-portions of state-lines relax at exponentially different rates with opposite contributions to the magnetic polarization [10] (see page 503). Collocott and Dunlop [7] have used a simple geometrical approach, based on the relative contributions to the magnetic polarization from the two regions defined by the two portions of the relaxing two state lines, to show that $H_2 \propto \ln(t_{\text{max}})$, where $t_{\text{max}}$ is the time taken to reach the peak in the magnetic polarization. In Fig. 4, $H_2$ is plotted as a function of $t_{\text{max}}$ for both Nd$_{60}$Fe$_{30}$Al$_{10}$ and Nd$_{60}$Fe$_{20}$Co$_{10}$Al$_{10}$, for the recoil curve that leads to the dc demagnetised state, and it is seen that the predicted simple logarithmic relationship is reasonably well obeyed. Simple linear regression analysis of the data in Fig. 4 gives values for the slope of 0.03737 T/s for Nd$_{60}$Fe$_{30}$Al$_{10}$ and 0.04184 T/s for Nd$_{60}$Fe$_{20}$Co$_{10}$Al$_{10}$. The Co containing alloy has a higher slope which correlates with its higher intrinsic coercivity (see Table 1).

In summary, it is seen that the addition of Co results in a decreased remanence, a marginal increase in the intrinsic coercivity, and a small decrease in $H_f$. Both alloys display non-monotonic behavior of the time dependent magnetisation on the recoil curve that leads to the dc demagnetised state, with the constant of proportionality relating $H_2$ and $t_{\text{max}}$ larger in the Co containing alloy.

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