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New relaxation effects in the AuFe and CuMn spin glass investigated by magnetoresistance measurements

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Résumé. — Nous présentons des résultats nouveaux sur la stabilité des aimantations rémanentes des verres de spins. Ces résultats ont été déduits des mesures de magnétorésistance faites sur deux AuFe (1,6 % et 7 % at.) et un CuMn (4,7 % at.) à 1,2 K. Nous avons constaté d'une part que la rotation de l'échantillon dans un champ magnétique constant et d'autre part le cyclage magnétique de l'échantillon ont chacun pour effet de faire évoluer l'aimantation thermorémanente $m_r(H)$ vers une valeur stable. Ce comportement est comparé aux effets bien connus de relaxation dans le temps de m_r en présence d'un champ magnétique statique.

Abstract. — We present new data on the stability of the remanent magnetization of spin glass alloys as deduced from magnetoresistance measurements at 1.2 K on two AuFe (1.6 at. % and 7 at. %) and one CuMn (4.7 at. %) alloys. We find that under field cycling or field rotation the thermoremanent magnetization $m_r(H)$ evolves towards a stable value. This behaviour can be compared with the well known relaxation of m_r with time in a static applied field.

We recently described how the resistivity of AuFe and CuMn spin glass alloys is related to their magnetization state and, in particular, we reported on the first observation of remanence effects on the resistivity (Senoussi [1]). We found — quite unexpectedly — that the magnetoresistance is a function of the macroscopic magnetization M_H and can be written as :

$$\frac{\Delta\rho}{\rho} = -\alpha |M_H|^2. \quad (1)$$

When M_H can be written as the sum of reversible and irreversible magnetizations, χH and m_r respectively, the magnetoresistance obeys the law :

$$\frac{\Delta\rho}{\rho} = -\alpha |m_r + \chi H|^2. \quad (2)$$

The coefficient α of the AuFe system was found to be almost independent of the concentration from 0.02 at. % to at least 7 at. % (with $\alpha \simeq 8 \times 10^{-2} \mu_B^{-2}$ when the magnetization is expressed in Bohr magnetons per Fe atom). By considering that the magneto-

resistance probes the local magnetic order over regions having the dimension of the electronic mean free path (a few atomic distances), we have concluded that, in AuFe and CuMn spin glass alloys, the reversible and irreversible magnetizations are strongly linked to each other and both are homogeneous on an atomic scale. This result is found to hold whatever the magnetic history of the sample. In this paper we want to report on the effects of field cycling on the remanent magnetization as deduced from magnetoresistance measurements by using equation (1).

Much work has been done on the stability or relaxation with time of the remanent magnetization. As was clearly established by Guy [2], a system which has been cooled in a field H to a temperature well below T_g has a magnetization $m_s(H)$ which is stable in time as long as H is kept constant (Guy [2]; de Mayo [3]; Berton *et al.* [4]; Préjean [5]). If the same sample has another history (e.g. cooled in zero field, with H applied subsequently) then it will initially have another magnetization $m = m_s(H) + \delta m$, but over a sufficiently long time scale m will probably tend to relax towards the stable value $m_s(H)$, so δm (which can be positive or negative) will disappear.

Relaxation in zero applied field has attracted the most attention, but it is not different in principle from relaxation in an applied field except that $m_s(0)=0$.

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We have found in the AuFe alloys that changing the strength or direction of the applied field can have effects analogous to relaxation.

First, if we follow the sequence high positive field $\rightarrow$ zero field $\rightarrow$ positive field H_1 , the descending and ascending magnetization curves (deduced from the magnetoresistance) are not identical (Fig. 1a). The cycling of the field down to zero and back has reduced the magnetization in field H_1 from m_A on the descending curve to m_B [6]. Cycling down to a non-zero field and back has a similar but weaker effect — see the dashed branch of figure 1a.

Fig. 1. — Schematic illustration of the effects on the saturated remanence of (a) cycling of the field or (b) rotating it with respect to the sample. In (a) the field is decreased from H_1 to zero ($A \rightarrow A_0$) or a small value ($A \rightarrow A'$) and then increased to H_1 again ($A_0 \rightarrow B$ or $A' \rightarrow C$). In (b) the field is rotated through 90° ($A \rightarrow D$) and rotated back (through -90° , $D \rightarrow B'$) and decreased to zero ($B' \rightarrow A_0$).

Secondly, if the field is reduced from a high initial value to a steady value H_1 , the magnetization is again m_A . If the steady field is now rotated through 90° and back once or a number of times, the magnetization is reduced from m_A to m_B (Fig. 1b); m_B seems to be approximately equal to m_B (Fig. 1). This means that the field rotation has tended to destroy the unstable part of the remanent magnetization δm so that the system has approached the stable condition for applied field H_1 , $m = m_s(H_1)$.

Thirdly, starting with a sample with no remanent magnetization (zero field cooled sample), we increase the field up to a steady value H_1 , giving a magnetization m_E . The field is then rotated through 90° and back. This sequence increases the magnetization which goes from m_E to m_F (Fig. 2). The spins have been swept up by the rotation of the field. This time, the field rotation sequence has increased m , but once again the system is brought closer to the stable $m_s(H_1)$ curve. If the field is subsequently reduced to zero again, the remanent magnetization $m_{0''}$ (Fig. 2) is enhanced compared to the value $m_{0'}$, it would have had (i.e. the usual I.R.M.) if the field had simply been cycled up to H_1 and down to zero again, without any intervening rotations. Figures 3 and 4 present a

Fig. 2. — Schematic illustration of the effect of rotating the field with respect to the sample on the hysteresis loop : the full curve represents the usual hysteresis loop starting with a zero field cooled sample ($0 \rightarrow E \rightarrow 0' \rightarrow G \rightarrow E$) while the dashed curve is the result of rotating the sample through 90° and back once or a number of times in $H = H_1$ ($E \rightarrow +90^\circ \rightarrow -90^\circ \rightarrow F \rightarrow 0'' \rightarrow G \rightarrow E$).

Fig. 3. — The unstable magnetization $m_A - m_B$ (see text and Fig. 1) of AuFe 1.6 at. % versus H_1 at 1.2 K as deduced from magnetoresistance data.

more quantitative determination of the quantities $m_A - m_B$, $m_{0'}$ and $m_{0''}$ as deduced from the magnetoresistance data using formulae (1) and (2) :

$$m_A - m_B = \alpha^{-1/2} \left[\left(\frac{\rho_0 - \rho_B}{\rho_0} \right)^{1/2} - \left(\frac{\rho_0 - \rho_A}{\rho_0} \right)^{1/2} \right]$$

$$m_{0'} = \alpha^{-1/2} \left(\frac{\rho_0 - \rho_{0'}}{\rho_0} \right)^{1/2}$$

$$m_{0''} = \alpha^{-1/2} \left(\frac{\rho_0 - \rho_{0''}}{\rho_0} \right)^{1/2}$$

Here ρ_0 is the resistivity of the sample when it has no magnetic history (zero field cooled) — or when $H = H_{coercive}$ — while ρ_A , ρ_B , $\rho_{0'}$ and $\rho_{0''}$ refer to the resistivities of the sample in the magnetic states A, B, $0'$ and $0''$ as described in the text and in figures 1 and 2.

Fig. 4. — I.R.M. (of AuFe 7 at. %) versus H at 1.2 K as deduced from magnetoresistance data. The lower curve refers to the usual I.R.M. (m_0' , Fig. 2). The upper curve corresponds to the enhanced I.R.M. (m_0'' , Fig. 2) as induced by rotating the field with respect to the sample as explained in the text.

For the CuMn alloys [1], we have recorded the low field magnetoresistance loop (ρ vs. H , $|H| \lesssim 2$ kG, $T = 4.2$ and 1.2 K) after the sample, cooled in zero field, had been isothermally cycled between $H = 0$ and a maximum field H_1 (e.g. cycle could be $H = 0 \rightarrow H_1 \rightarrow 0$; then $\rho(H)$ is measured for

$$|H| \lesssim 2 \text{ kG}.$$

About 10 cycles were performed with H_1 increasing from ~ 5 kG for the first cycle to 35 kG for the last cycle, the magnetoresistance loop being measured after each cycle. This study, where jumps in the magnetoresistance of CuMn have been observed for the first time [1], showed how these jumps correlate with H_1 and thus with the I.R.M. state created by H_1 [7]. In particular, it is found that for a given field H_1 , near or slightly lower than some *threshold* field H_1 at which the jumps begin to take place, the rotation of the sample in the field H_1 (cycle : $H = 0 \rightarrow H_1$, rotation through $\pi/2$ and back to initial position of H_1 , $H = H_1 \rightarrow 0$; $\rho(H)$ measured) either increases the sharpness of the jumps or even makes them appear for $H_1 < H_t$ as illustrated in figure 5. This is probably further evidence that rotating the sample in the steady field H_1 increases the I.R.M. of the sample when it is not yet saturated.

Thus, in each of these three cases, the field cycling or rotation has helped the magnetization to *relax* towards a stable magnetization curve $m_s(H)$. We can understand this in a simple manner : for a given applied field the system has one stable state (or well) and a number of metastable states with rather different magnetizations. Because of its previous magnetic history, it can find itself in a metastable well rather than the stable well. However, if the field is then

Fig. 5. — Low field magnetoresistance ($\Delta\rho/\rho_0$ vs. H) of CuMn 4.7 at. % at 1.2 K. The full line was recorded after the sample had been cooled in zero field (Z.F.C.) from ~ 77 K to 1.2 K and submitted to magnetic cycling (cycle : $H = 0 \rightarrow 15$ kG $\rightarrow 0$) at 1.2 K. The dashed curve was recorded under the same conditions, except that the steady field H , was, in addition, rotated through $\pi/2$ and back (i.e. Z.F.C. sample ; $0 \rightarrow 15$ kG ; rotation through $\pi/2$ and back to the same geometry ; 15 kG $\rightarrow 0$; $\rho(H)$ measured). The time taken to run the cycle ($0 \rightarrow 15$ kG $\rightarrow 0$) was about 4 min. in each case (the rotation $\pm \pi/2$ took ~ 30 s) while the record of $\Delta\rho/\rho_0$ curves took about 2 min. each. For more details see reference [1].

rotated, the relative stabilities of the different wells will change and some of the walls between the wells will disappear temporarily, allowing the system to evolve towards a more stable state without having to jump over or tunnel through the walls.

It would be useful to study these effects by direct magnetic measurements, and to check the effects of temperature on them.

Note that the third effect (which we called the sweeping up of spins) is much more pronounced in the concentrated AuFe sample (7%). This may be due to the fact that the thermoremanent magnetoresistance of the 7 at. % sample is one order of magnitude greater than that of the 1.6 at. % sample and hence much easier to detect. Alternatively, this effect may be due to some kind of chemical clustering which could be present in the sample even though it was quenched in the usual way.

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- [6] No systematic studies of the time effects have been done in this work, but we have checked in two ways that these effects, although present in our work, were generally small relative to the other relaxation phenomena reported in this letter : first, the potential difference across the sample, which is proportional to the magnetic resistivity $\rho(H)$

has been recorded as a function of time for several steady fields $H = H_1$ ($\sim 8, 10, 15$ kG). Although clear changes in $\rho(H_1)$ (especially for the lowest values of H_1) have been observed over the time scale of the experiment (typically 2 to 5 min. depending on H_1), these changes were generally 5 to 10 times smaller than the changes observed by cycling ($H_1 \rightarrow 0 \rightarrow H_1$) or rotating the sample in $H = H_1$ (see text). Secondly, we also checked that varying the time taken to complete a magnetoresistance loop corresponding to figures 1 and 2 (by a factor of about 4), did not result in significant modifications of the hysteresis loop within our experimental precision ($\sim 10^{-5}$ in this experiment).

[7] C. GUY has studied the appearance of jumps in the magnetization loops as a function of H_1 , private communication.