PROCEEDINGS - 37th ANNUAL CONDENSED MATTER AND MATERIALS MEETING, 5 - 8 February, 2013. Wagga Wagga, NSW, Australia

Asymmetric Magnetization Reversal from a Cluster/Spin Glass Model

L.C. Barnsley[a], E.MacA. Gray[a] and C.J. Webb[a]

[a] *Queensland Micro- and Nanotechnology Centre, Griffith University, Queensland 4111, Australia.*

A modified Stoner-Wohlfarth model to describe an ensemble of ferromagnetic clusters interacting with a quasi-isotropic spin glass was developed to account for asymmetric reversal in concentrated spin glass systems. The model used a Gaussian distribution of cluster easy axes orientations, which successfully simulated magnetic hysteresis loops exhibited by two concentrated CuMn alloys. Physically plausible scenarios for the dependences of model parameters on cooling field were extracted.

1. Introduction

The exchange bias effect conventionally occurs in systems with an interface between ferromagnetic (FM) and antiferromagnetic (AFM) components due to an exchange interaction with unidirectional anisotropy, and manifests as shifted magnetic hysteresis loops when the system is cooled in field below the AFM Néel temperature, T_N [1]. Spin glass systems exhibit both positive and negative exchange without magnetic long-range order. Spin glasses display a cusp in the temperature dependent magnetization at the glass temperature, T_g, and unusual behaviour at lower temperatures that is understood in terms of magnetic clusters and a frozen, magnetically frustrated component of magnetization [2]. In recent years, there has been increasing recognition of the analogues between exchange bias systems and spin glasses [3], such as shifted hysteresis loops, training effects and asymmetric reversal. These analogues are even more apparent in concentrated, mictomagnetic spin glasses, where the behaviour is understood in terms of FM clusters interacting with disordered, mostly AFM clusters [2].

Asymmetric reversal was first recognized in Fe/FeF_2 exchange biased multilayers [4], but was observed in mictomagnetic CuMn before then [5]. Asymmetric reversal is defined in general either as an asymmetry between the magnetization reversal mechanisms from positive to negative saturation and the reversal mechanisms in the other direction, or as an asymmetry of the *M*-*H* curve with respect to the field axis [6]. Modified Stoner-Wohlfarth models have been used to account for asymmetric reversal in multilayer systems by allowing the layer easy axes to misalign with the applied field, *H* [7-9]. In this paper, a Stoner-Wohlfarth model is adopted and extended to describe magnetic clusters interacting with a disordered, quasi-isotropic spin glass component. This model is used to successfully account for the cooling field dependence of two mictomagnetic CuMn samples.

2. Model and method

Hysteresis loops measured on spin glass systems at low temperature tend to linear dependence on *H* at high fields with a strong non-linear response in the region where switching of the magnetization occurs. Concentrated spin glasses exhibit hysteresis loops with asymmetric reversal after cooling in field. In CuMn, this typically takes the form of a sharp, high curvature transition on the positive side of the hysteresis loop, and a low curvature, gradual decrease in magnetization on the negative side of the step, typically the signature of a coherent rotation of magnetic moments [5,10].

Monte Carlo simulations involving an ensemble of ferromagnetically aligned clusters that each have a unique easy axis and experience a molecular field due to exchange interactions with the local spin glass, were run to fit the non-linear component of hysteresis loops where noticeable asymmetric reversal was observed. The linear component was fitted in the high field region to extract a value for the high-field susceptibility, $\chi_{H\rightarrow H\max}$ and the linear component was then subtracted from the loop, leaving the non-linear component.

The total cluster energy was expressed using a modified Stoner-Wohlfarth model [7,11] to sum the Zeeman energy, shape (uniaxial) anisotropy energy and exchange (unidirectional) anisotropy energy due to the cluster's interaction with the local spin glass:

$$E(\theta) = -\mu_{\text{eff}}\mu_0 H\cos\theta + KV\sin^2(\phi-\theta) - JV\cos(\alpha-\theta). \qquad (1)$$

Here, θ is the angle between the applied field and the alignment of the cluster moment, μ_{eff} is the magnitude of the effective cluster moment, K is the uniaxial cluster anisotropy energy per unit volume, ϕ gives the direction of the cluster easy axis with respect to the applied field, J is the total energy per unit volume of all exchange interactions between the cluster and the local spin glass moments, α is the angle between the applied field and the effective molecular field experienced by the cluster owing to the local spin glass and V is the volume of the cluster.

The probability of a cluster moment having an alignment θ is given by a Boltzmann distribution over all angles between 0 and 180º. After N Monte-Carlo trials, the resultant normalized magnetization was obtained by averaging the projections corresponding to the trial θ values on the measuring axis (parallel to the field axis).

Assumptions about cluster composition were avoided by using parameters KV, the uniaxial anisotropy energy per cluster and JV, the exchange interaction energy per cluster, instead of K, J and V. Given the large number of interdependent variables, physically reasonable values can only be extracted if assumptions are made about one or more of the parameters. These assumptions differ between samples, however three particular assumptions relevant to the cases of concentrated spin glasses are discussed here.

Firstly, asymmetric reversal was accounted for by allowing the easy axes to deviate from the direction of the cooling field, H_{FC} so that $0 \leq \phi \leq 180$º. The distribution of ϕ was considered to result from freezing of a paramagnetic ensemble cooled in H_{FC}, and was found to be fairly well approximated by a Gaussian in ϕ. A Gaussian distribution for easy axes, with a mean value of 0º and normalized probability over 180º, was adopted for simplicity. This model successfully accounted for hysteresis loops from two concentrated CuMn samples (section 3). The parameter ϕ then becomes ϕ_{stdev}, the standard deviation of this distribution.

Secondly, it was assumed for simplicity that the clusters are mostly internally ferromagnetic in alignment, and interact only with a frozen "spin glass" component but not with each other. The spin glass component was modelled as quasi-isotropic by allowing α to take random orientations between 0 and 180º. Finally, when the observed exchange bias fields were negative, positive values for J were assumed.

3. Results and simulations

Fig. 1 shows the effect changing parameters μ_{eff}, J, K and ϕ_{stdev} has on simulated M-H loops, assuming V to be proportional to μ_{eff}. Increasing the effective cluster size increases the curvature of the loop around the step, while increasing J shifts the loop along the field axis in the negative direction. Increasing K while pinning the cluster easy axis to align with the field also has the effect of increasing the curvature of the loop, but once the variable reaches appreciable values, of the order of 1×10^5 J/m^3, the model becomes relatively insensitive to even large changes in K. However, once ϕ is allowed to deviate from the field axis, changes in K have a drastic effect on the asymmetry of the simulated loops.

Fig. 2 demonstrates how the model can be used to parameterize low temperature magnetic hysteresis loops in an investigation of the cooling field dependence of two CuMn alloys, one prepared via aging at 348 K (Sample A) [10] and the other via neutron irradiation

(Sample I) [12]. The model was used to fit the first "up" branch of minor hysteresis loops measured between ±477 kA/m at 5 K after cooling in various fields between 7 and 637 kA/m.

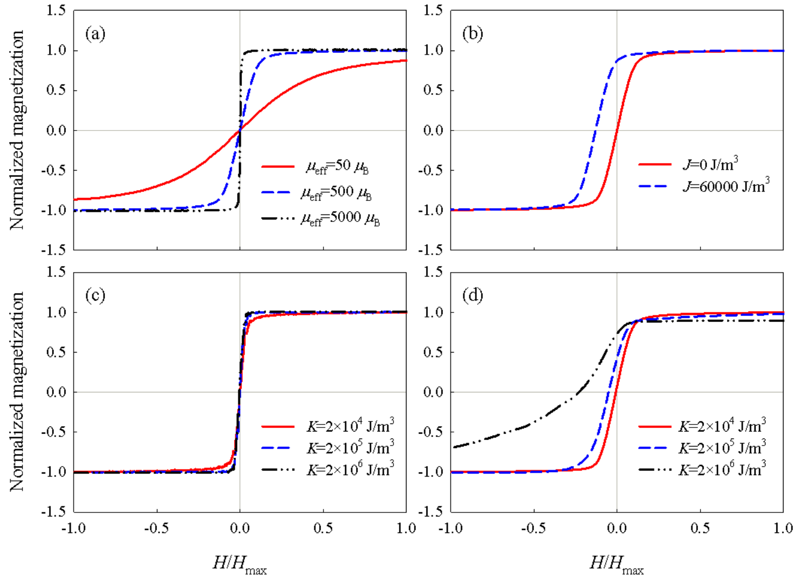

Fig. 1. Simulated *M-H* curves, demonstrating the effects of changing (a) μ_{eff}, (b) J, (c) K with $\phi_{stdev} = 0^o$, (d) K with $\phi_{stdev} = 30^o$.

The values for μ_{eff} extracted from Sample I in Fig. 2(a) suggest a decrease in the cluster moment above $H_{FC} \geq 80$ kA/m, coinciding with the suppression of asymmetric reversal by high cooling fields. This is interpreted as evidence for the fragmentation of clusters into multi-domain particles with high H_{FC}. In comparison, μ_{eff} for Sample A increases monotonically with cooling field.

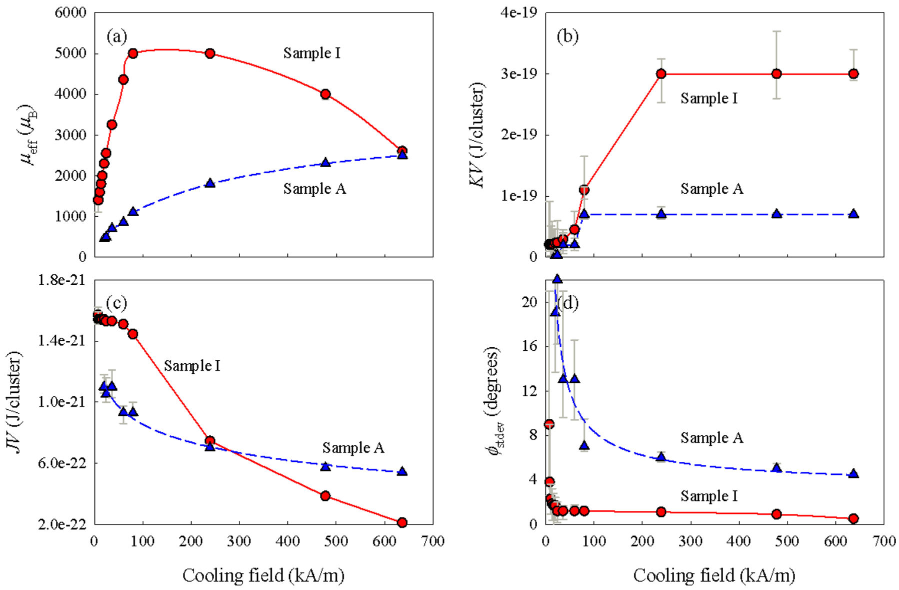

Fig. 2. The model was used to parameterize minor hysteresis loops of two CuMn samples measured between ±477 kA/m at 5 K after cooling in various fields. Parameters (a) μ_{eff}, (b) KV, (c) JV and (d) ϕ_{stdev} are displayed as functions of the cooling field.

For both systems, KV appears to saturate at higher cooling fields ($H_{FC} \geq 80$ kA/m for Sample I and $H_{FC} \geq 240$ kA/m for Sample A). The uniaxial anisotropy energy per cluster is significantly larger in Sample I than it is in Sample A, even at H_{FC} = 637 kA/m, where the effective cluster moments are comparable. The large uncertainty attached to this parameter is due to the model's relative insensitivity to K when K is high and ϕ_{stdev} is low, but the behaviour seen in Fig. 2(b) may also be reconciled with the ramified nature of magnetic clusters in CuMn, as determined by small angle neutron scattering (SANS) [13], in that uniaxial anisotropy may saturate at a certain cluster size [10].

JV for Sample I decreases slowly in the low to moderate cooling field range, before decreasing rapidly once $H_{FC} > 80$ kA/m. In this cooling field range, JV falls with $H_{FC}^{-0.87}$. This decrease in unidirectional anisotropy with H_{FC} is seen as qualitatively consistent with the domain state model for exchange bias, in that it's enhanced by disorder and pinning of domain walls in the AFM (or analogously, "spin glass") component of an exchange bias system [14].

Clusters in Sample I are considerably susceptible to alignment by the cooling field, with ϕ_{stdev} rapidly decreasing to less than 2° once $H_{FC} \geq 24$ kA/m. This, along with the behaviour of μ_{eff}, demonstrates the significantly more ferromagnetic character induced in Sample I by the irradiation process [12], compared with Sample A.

4. Conclusion

A modified Stoner-Wohlfarth model based on an interaction between ferromagnetic clusters and a quasi-isotropic spin glass component was successfully used to parameterize hysteresis loops from two mictomagnetic CuMn samples that exhibit intrinsic exchange bias at temperatures well below T_g. Asymmetric reversal in these hysteresis loops was successfully accounted for using a Gaussian distribution of cluster easy axes, and the resultant scenarios for the dependences of parameters on cooling field were considered as physically plausible. The scenarios explored using the model could be verified with experimental techniques that probe magnetic clusters, particularly SANS.

Acknowledgments

LCB acknowledges receipt of an Australian Postgraduate Award. The research was supported by a grant from the Australian Research Council, grant number R19800120.

References

[1] Meiklejohn W H and Bean C P 1956 *Phys. Rev.* **102** 1413
[2] Beck P A 1972 *J. Less-Common Met.* **28** 193
[3] Ali M, Adie P, Marrows C H, Greig D, Hickey B J and Stamps R L 2007 *Nature Mater.* **6** 70
[4] Fitzsimmons M R, Yashar P, Leighton C, Schuller I K, Nogués J, Majkrzak C F and Dura J A 2000 *Phys. Rev. Lett.* **84** 3986
[5] Mukhopadhyay A and Beck P A 1975 *Solid State Commun.* **16** 1067
[6] Li Z P, Petracic O, Morales R, Olamit J, Batlle X, Liu K and Schuller I K 2006 *Phys. Rev. Lett.* **96** 217205
[7] Camarero J, Sort J, Hoffmann A, Garcia-Martin J M, Dieny B, Miranda R and Nogués J 2002 *Phys. Rev. Lett.* **95** 057204
[8] Chen J, Jin G and Ma Y Q 2007 *J. Phys.: Condens. Matter* **19** 236225
[9] Iglesias O, Batlle X and Labarta A 2007 *J. Magn. Magn. Mater.* **316** 140
[10] Barnsley L C, Gray E M and Webb C J 2013 *J. Phys.: Condens. Matter* **25** 086003
[11] Stoner E C and Wohlfarth E P 1948 *Phil. Trans. R. Soc. Lond. A* **240** 599
[12] Gray E M 1996 *J. Phys.: Condens. Matter* **8** 751
[13] Gray E M, Hicks T J and Smith J H 1982 *J. Phys. F: Met. Phys.* **12** L189
[14] Nowak U, Misra A and Usadel K D 2001 *J. Appl. Phys.* **89** 7269