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MAGNETIC VISCOSITY OF NANOCOMPOSITE Sm-Fe-Cu-Zr-Ga-C RIBBONS *

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The magnetic viscosity was investigated at temperatures between 100 and 293 K for the nanocomposite $Sm_2Fe_{18.25}Zr_{0.25}Cu_{0.5}Ga_2C_2$ ribbons prepared by melt-spinning and subsequent annealing. It was found that the maximum S and χ_{irr}, located near coercivity, increase with increasing temperature. The viscosity parameter S_v was found to be strongly dependent on the applied fields at lower fields than the coercivities. The relation between S_v and coercivity was analyzed. The coercivity mechanism is mainly controlled by domain-wall pinning. The activation volume associated with magnetization reversal, which can be calculated from S_v, is much smaller than the grain volume.

Keywords: nanocomposite ribbons, magnetic viscosity, coercivity mechanism
PACC: 7550V, 7560E, 7560L

I. INTRODUCTION

Measurements of time dependence of magnetization, or magnetic viscosity, may provide useful information regarding the intrinsic magnetization reversal behavior in permanent magnetic materials.[1−4] The time dependence of magnetization in a constant reversed field is mainly caused by thermal activation processes, which can be described by the relation

$$M(t) = M_0 - S\ln(t + t_0), \tag{1}$$

where M_0 and t_0 are constants, S is the viscosity coefficient, t is the time elapsed since changing the field. From Eq. (1), one can obtain the following relation:

$$S = -\mathrm{d}M/\mathrm{d}\ln t. \tag{2}$$

Since S is sample shape dependent, another quantity S_v, the magnetic viscosity parameter, is more often used to characterize the time dependence of M. S_v obtained is in terms of S and the irreversible susceptibility χ_{irr} (also shape dependent) from the relation

$$S_v = S/\chi_{irr}, \tag{3}$$

where χ_{irr} can be determined as the derivative of the DC demagnetization curves, which is obtained by measuring the remanence after applying progressively larger reverse fields after positive saturation, and by the D. C. Demagnetisation (DCD) method as described by Crew *et al.*[5]

The physical significance of S_v is that it is inversely related to the activation volume v_a associated with the initiation of magnetization reversal. The activation volume can be defined as $\Delta m/M_s$, where Δm is the moment variation between the minimum energy state in H and the maximum, or activated energy state, reached at the instant when the energy barrier is overcome.[6] The activation volume can be estimated from S_v by the relation

$$v_a = kT/S_v M_s. \tag{4}$$

Barbier[7] give a most illuminating plot of S_v against the coercive field H_c in 1954. It can be seen from Barbier's plot that $\lg S_v$ is proportional to $\lg H_c$ for many soft and hard magnetic materials. Magnetic viscosity parameters are directly associated with the microscopic structure of materials. The analysis and interpretation of magnetic viscosity data may, therefore, offer a better understanding of magnetization reversal behavior. Systematic study on the structure and magnetic properties on Sm-Fe-Ga-C compounds has been performed.[8−10] However, few investigations on the magnetic viscosity of melt-spun Sm-Fe-Ga-C have been reported until now. The aim of this paper

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is to examine the magnetic viscosity of nanocomposite $Sm_2Fe_{18.25}Zr_{0.25}Cu_{0.5}Ga_2C_2$ ribbons, in particular, the correlation between S_v and H_c at temperatures from 100 to 293 K.

Ⅱ. EXPERIMANTAL

The $Sm_{2+\delta}Fe_{18.25}Cu_{0.5}Zr_{0.25}Ga_2C_2$ ribbons were prepared by melt-spinning and annealing as described in Ref.[11]. X-ray diffraction patterns indicate that the ribbons consist of a hard magnetic phase with Th_2Zn_{17}-type structure and a soft magnetic α-Fe phase (∼9 vol%). The average grain size is about 35 nm and 23 nm for 2:17-type and α-Fe phases, respectively. The magnetic measurements were carried out using a superconducting quantum interference device (SQUID) with a maximum field of 3950 kA/m with the field applied along the casting direction of the flake-shaped samples. In such a case, the demagnetization factor could be neglected. Viscosity measurements were performed at temperatures from 100 to 293 K. These experiments consisted of initially submitting the ribbons to a positive 3950 kA/m field and then decreasing it to a value in the second quadrant which was kept constant for a period while the magnetic viscosity was recorded. The reverse applied field was established with no oscillation and no significant overshoot.

Ⅲ. RESULTS AND DISCUSSION

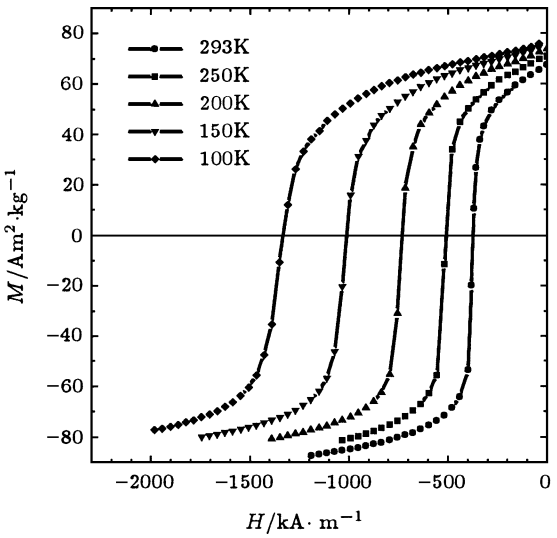


Fig.1. Demagnetization curves for $Sm_2Fe_{18.25}Cu_{0.5}Zr_{0.25}Ga_2C_2$ ribbons at temperatures from 100 to 293 K.

Although $Sm_2Fe_{18.25}Cu_{0.5}Zr_{0.25}Ga_2C_2$ ribbons consist of a mixture of magnetically soft (α-Fe) and hard (2:17-type) phases, they have smooth hysteresis loops characteristic of a single component system. This behavior is described as exchange-spring in nanocomposite magnets by Kneller and Hawig.[12] The remanence enhancement ($m_r = M_r/M_s \geq 0.69$) and comparatively steep recoil curves in $Sm_2Fe_{18.25}Cu_{0.5}Zr_{0.25}Ga_2C_2$ ribbons have been observed.[11] The demagnetization curves at temperatures from 100 to 293 K are shown in Fig. 1.

The time dependence of the magnetization under the selected field at 250 K is shown in Fig. 2. It can be seen that the simple equation (1) holds only for measuring time larger than 500 s, if t_0=0 (open dots). If a fitting parameter t_0=10 s (solid dots), the viscosity data are described by the logarithmic time law, and S can be determined with high accuracy for shorter measuring times as well.

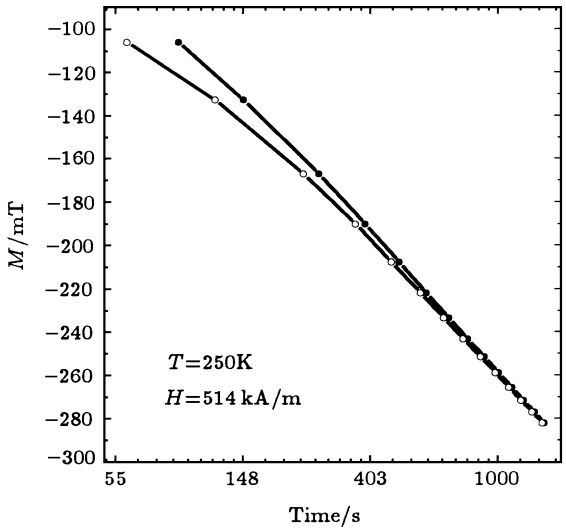


Fig.2. Viscosity data measured at 250 K. ○ : t_0=0; ● : t_0=10 s.

The field dependence of irreversible susceptibility χ_{irr} and viscosity coefficient S at temperatures ranging from 100 to 293 K are shown in Fig. 3. The fields for maximum S and χ_{irr} are consistent with their coercivities at different temperatures. Similar results were reported for $SmCo_5$ [13] and $Pr_4Fe_{78}B_8$.[14] Normally, the relaxation of a system is determined by the activation energies E with a distribution of $f(E)$. And S can also be expressed by $S = 2M_skTf(E)$. So the maximum value of S decreases with decreasing temperature.

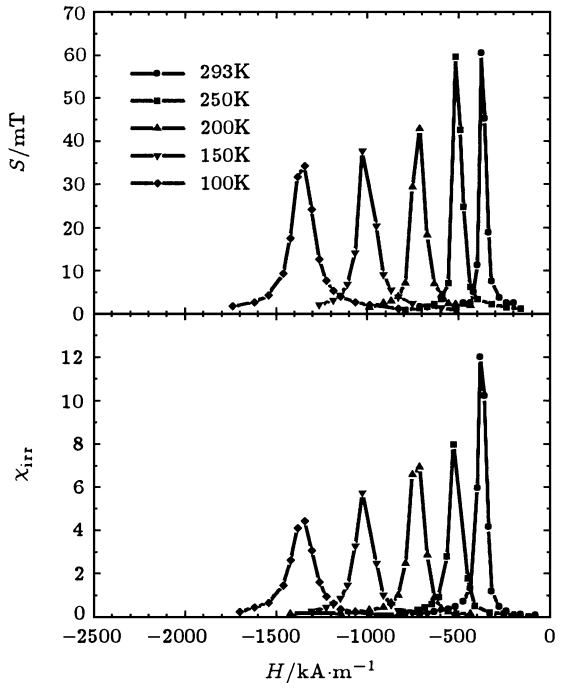


Fig.3. Viscosity coefficient S (a) and irreversible susceptibility χ_{irr} (b) versus the reversal fields at temperatures from 100 to 293 K.

The values of the magnetic viscosity parameter S_v at 100–293 K calculated from χ_{irr} and S by means of Eq.(3) are plotted in Fig. 4. S_v shows a rapidly decreasing trend with increasing reversal field at low fields, and goes slowly near the coercive fields for all investigated temperatures. There is some evidence for a shallow minimum close to the coercivties in different temperatures, but further work is needed to confirm this. The values of S_v near the coercivities increase with decreasing temperature due to the increase of their coercivity. It is interesting to note that the relation between S_v and the magnetic field H here is not similar to that reported for $SmCo_5$[13], NdFeB-type[15] magnets, which shows nearly constant over the entire field range investigated.

There are two common methods for determining χ_{irr}, i.e. the χ_{rev} method and DCD method.[5] The χ_{rev} method has the disadvantage, namely the assumption that M_{rev} is a monotonically increasing function of the field is not applicable for all cases. The DCD definition of M_{irr} is much easier than the χ_{rev} definition and is related to the intrinsic energy barriers within the material because it measures the proportion of magnetization in the two wells at the same field. The large difference in χ_{irr} measured by the two methods has been found, and this difference in χ_{irr} extends to the difference in the resulting S_v. For commercial NdFeB samples,[5] when S_v is derived from measurements by χ_{rev} method, S_v is found to be almost constant at different fields. When χ_{irr} is measured by DCD method, S_v decreases continuously over the field range investigated, just similar to the behavior shown in Fig.4. The strong dependence of S_v on the field, was also observed in Zn-bonded $Sm_2Fe_{17}N_{2.9}$ magnets[16] and melt-spun NdDyFeB magnets with high Dy content.[15]

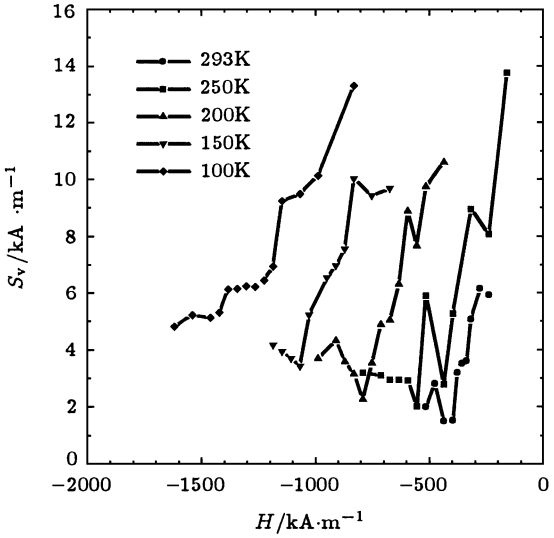


Fig.4. Viscosity parameter S_v versus the reversal fields for different temperatures.

From the temperature dependence of S_v determined, the activation volume for the magnetization reversal has been estimated from Eq.(4). Clearly the activation volume is not independent of the applied field. Physically this arises from the fact that the energy barrier to rotation is lowered by an applied field, and consequently larger volumes become involved in the time dependence process.[17]

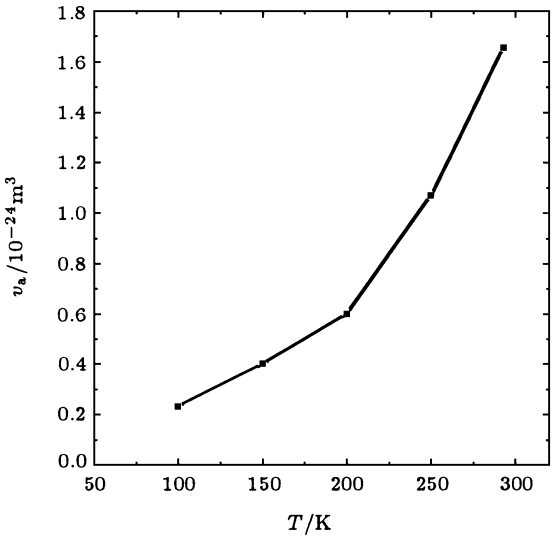


Fig.5. Activation volume v_a versus the temperatures.

The corresponding diameter d_c was calculated from $d_c = (v_a)^{1/3}$, which should be compared with the Bloch wall thickness δ. As can be seen from Fig.5, v_a increases with increasing temperature, which can be explained by the well known increase of δ with T. Using the formula $\delta = \pi(A/K)^{1/2}$, we estimated a typical room-temperature width $\delta \approx 5$nm. These d_c values are 2–2.5 times the Bloch wall thickness δ for $Sm_2Fe_{18.25}Cu_{0.5}Zr_{0.25}Ga_2C_2$ ribbons, which is consistent with the results in NdFeB.[18] Street *et al.*[2] pointed out that in the case of a pinned domain wall, v_a is related to the volume of the pinning site and not to the volume of materials which is covered by a single jump after thermal activation. Under this condition, the domain wall width δ' in the pinning site is $\pi(A'/K'_{eff})^{1/2}$, here K'_{eff} is the effective anisotropy constant at the grain boundary, the magnetically softer sites, in the ribbons. In the assumptions of $A' = A, K'_{eff}$ is lower than that of the hard magnetic phase in the ribbons, because the intergrain exchange coupling between the magnetically hard and soft phases can weaken the anisotropy field. Therefore, the true value of δ' is larger than that of δ, which can approach the value of d_c.

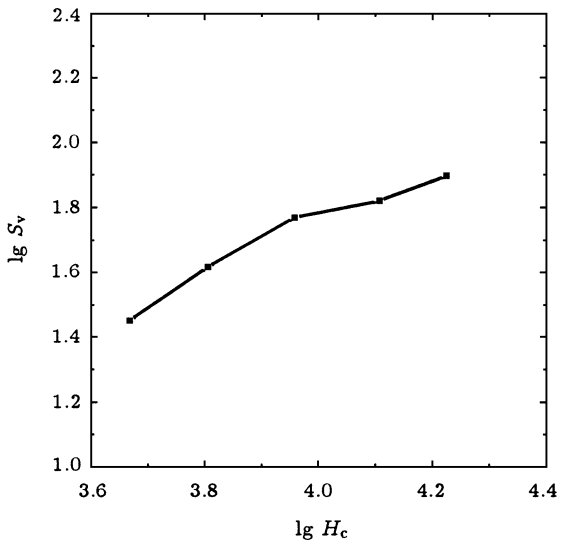


Fig.6. Plot of lgS_v against lgH_c.

The values of S_v at fields close to the coercivity have been used to construct a Barbier's plot of lgS_v versus lgH_c, as plotted in Fig.6. These data approximate to a straight line with a slope of 0.78, and its intercept on the y axis is –1.37. This result is close to the results of coercivity mechanism of weak pinning reported by Liu *et al.*[4]

REFERENCES

[1] P. Gaunt, *Philosophical Magzine,* **34**(1976),775.

[2] R. Street, R. K. Day, J. B. Dunlop, *J. Magn. Magn. Mater.,* **69**(1987),106.

[3] E. P. Wohlfarth, *J. Phys. F: Met. Phys.,* **14**(1984),L155.

[4] J. F. Liu, H. L. Luo, *J. Magn. Magn. Mater.,* **86** (1990),153, *J. Magn. Magn. Mater.,* **94**(1991),43.

[5] D. C. Crew, S. H. Farrant, P. G. McCormick, R. Street, *J. Magn. Magn. Mater.,* **163**(1996),299, D. C. Crew, P. G. McCormick, R. Street, *IEEE Trans. Magn.,* **32**(1996),4356.

[6] P. Gaunt, *J. Appl. Phys.,* **59**(1986),4129.

[7] J. C. Barbier, *Ann. Phys. (Paris),* **9**(1954),84.

[8] B. G. Shen, L. S. Kong, F.W. Wang, L. Cao, *Appl. Phys. lett.,* **63**(1993),2288.

[9] B. G. Shen, L. S. Kong, F. W. Wang, L. Cao, W. S. Zhan, *Acta Physica Sinica,* **43**(1994),846 (in Chinese).

[10] B. G. Shen, L. S. Kong, L. Cao, *Acta Physica Sinica,* **42** (1993),999 (in Chinese).

[11] S. Y. Zhang, H. W. Zhang, B. G. Shen, F. R. de Boer, K. H. J. Buschow, *J. Appl. Phys.,* **87**(2000),1410.

[12] E. F. Kneller, R. Hawig, *IEEE Trans. Magn.,* **27** (1991), 3588.

[13] J. Ding, P. A. I. Smith, P. G. McCormick, R. Street, *J. Magn. Magn. Mater.,* **161**(1996),303.

[14] D. R. Cornejo, V. Villas-Boas, F. P. Missell, *J. Appl. Phys.,* **83**(1998),6637.

[15] V. Villas-Boas, J. M. Gonzalez, F. Cebollada, M. F. Rossignol, D. W. Taylor, D. Givord, *J. Magn. Magn. Mater.,* **185**(1998),180.

[16] D. Eckert, K. H. Müller, P. A. P. Wendhausen, M. Wolf, *IEEE Trans. Magn.,* **30**(1994),574.

[17] A. M. de Witte, K. O. Grady, G. N. Coverdale, R.W. Chantell, *Magn. Magn. Mater.,* **88**(1990),183.

[18] L. Jahn, R. Schumann, W. Rodewald, *J. Magn. Magn. Mater.,* **153**(1996),302.