Approach to Magnetic Saturation of Amorphous \( \text{Gd}_{80}\text{Si}_{12}\text{B}_{8} \)

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We present the magnetization study of a melt-spun amorphous alloy \( \text{Gd}_{80}\text{Si}_{12}\text{B}_{8} \) at \( 4.5 \) K in magnetic field up to \( 5.5 \) T. The ratio of the random magnetic anisotropy constant to the exchange interaction constant is estimated at \( 0.176 \). In the intermediate field region the magnetization approaches to saturation as \( B^{1/2} \) owing to a weak random magnetic anisotropy where \( B \) is a magnetic field. The random magnetic anisotropy correlates over 1.0 nm, while the ferromagnetic correlation length is 4.1 nm. We discuss the random magnetic anisotropy of \( \text{Gd}_{80}\text{Si}_{12}\text{B}_{8} \) by comparing with other Gd-based amorphous magnets.

**Key words:** amorphous, approach to magnetic saturation, magnetization, random magnetic anisotropy (RMA), correlation length of RMA

1. Introduction

Amorphous rare earth alloys show a variety of spin structures such as speremagnetism, asperemagnetism and sperimagnetism.\(^1\) We now understand that they come from competition among the exchange interaction, its fluctuations and the random magnetic anisotropy (RMA).\(^2\) Ishio et al investigated magnetic and magnetovolume properties of an amorphous system (\( \text{Gd}_{80}\text{Fe}_{15}\text{Si}_{15}\text{B}_{8} \)). They concluded that Fe has no magnetic moment for \( x=0.7 \) and that amorphous \( \text{Gd}_{80}\text{Si}_{12}\text{B}_{8} \) (hereafter it is referred to as \( a-\text{Gd}_{80}\text{Si}_{12}\text{B}_{8} \)) is an asperemagnet.\(^3\)

Chudnovsky et al predicted that RMA is the dominant factor in approach to magnetic saturation.\(^4,5\) In their model the variation of magnetization with magnetic field was studied for alloys including rare earth elements with non-S states.\(^6,7\) For magnetic systems with Gd only as rare earth elements, on the other hand, it has been believed that RMA is not essential because Gd has an S state configuration. In such a system indeed, however, we expect that a weak RMA plays an important role in the magnetic behavior.\(^8\) This is the first report how the magnet including no other metallic elements but Gd behaves in the intermediate field regime below saturation.

2. Experimental

Ribbons of \( a-\text{Gd}_{80}\text{Si}_{12}\text{B}_{8} \), about 0.3 mm wide and 5 \( \mu \)m thick, were prepared by melt quenching in an Ar atmosphere. The amorphous structure was confirmed by the X-ray diffraction. The magnetization for the ribbons of 0.77 mg in weight was measured with a SQUID magnetometer at 4.5 K in magnetic fields up to 5.5 T.

3. Results and Discussion

Figure 1 represents the dependence of magnetization on magnetic field for \( a-\text{Gd}_{80}\text{Si}_{12}\text{B}_{8} \) at 4.5 K. We find that it is hard to saturate the magnetization in fields up to 5.5 T because the system is asperomagnetic. The high field susceptibility around 5 T is \( 3.50 \text{ JT}^{-1}\text{kg}^{-1} \), which is about ten times as large as that of amorphous ferromagnets such as \( a-\text{Gd}_{2}\text{Co}, a-\text{Gd}_{2}\text{Ni} \) and \( a-\text{Gd}_{2}\text{Cu} \).\(^12\)

The ratio of \( D/J_0 \) is one of the most significant indices to determine the magnetic properties of the amorphous rare earth systems where \( D \) is the RMA constant and \( J_0 \) is the exchange interaction constant.\(^7,11\) Before the main subject of the approach to magnetic saturation, it is worth to discuss how large \( D/J_0 \) is and to compare it with those of other amorphous Gd-based alloys. It is known that there are two methods to estimate the RMA strength \( K \); one is from the

![Fig. 1 Magnetization of \( a-\text{Gd}_{80}\text{Si}_{12}\text{B}_{8} \) at 4.5K as a function of applied magnetic field. The broken line is extrapolation from a high field regime. The hatched area almost corresponds to the integral of Eq. (1). The solid line is the best fit of Eq. (4) for the observed magnetization above 1.3 T.](image-url)
coercivity and the other is from the magnetization curve. We here use the latter or the magnetization-area method \(^{13}\)

\[
K = \frac{3}{2} \int_{M_s}^{M_0} B dM,
\]

where the spontaneous magnetization \(M_0\) is 178.8 JT\(^{-1}\)kg\(^{-1}\), the remanent magnetization \(M_r\) is 9.0 JT\(^{-1}\)kg\(^{-1}\) and \(B\) is the magnetic field. The value of the integral in Eq. (1) almost corresponds to a hatched area in Fig. 1, from which \(K\) is estimated at 1.86\(\times\)10\(^7\) Jm\(^{-3}\). As mentioned above, the magnetization has not yet been saturated in 5.5 T. Therefore the value of \(K\) should be regarded as a rough estimate with some uncertainty. We obtain \(D=6.42\times10^{-24}\) J from the relation

\[
\frac{K}{nD S^2},
\]

where \(n\) is the number of Gd atoms in the unit volume and \(S\) is the spin of a Gd atom. We have \(S=3.04\) from the saturation magnetization \(M_s\) mentioned below. The magnitude of \(S\) is much smaller than the value of 3.5 for the free Gd ion because a-Gd\(_{80}\)Si\(_{12}\)B\(_8\) is asperomagnetic.\(^{13}\) Then \(J_0\) is estimated at 3.66\(\times\)10\(^{-22}\) J from the paramagnetic Curie temperature \(T_p\) of 189 K within the nearest neighbor Heisenberg model as

\[
3k_B T_p = 2z S (S + 1) J_0,
\]

where \(k_B\) is the Boltzmann constant, \(z\) is the Gd coordination number around a Gd atom. Here we have \(z=9.7\) from the extended X-ray absorption fine structure measurement.\(^{14}\) We thus obtain \(D/J_0\) to be 0.176. It is one order of magnitude larger than that of a-Gd\(_2\)Co, a-Gd\(_2\)Ni and a-Gd\(_2\)Cu,\(^{12}\) but still quite smaller than unity. Therefore we regard a-Gd\(_{80}\)Si\(_{12}\)B\(_8\) as a weak RMA magnet.

The main purpose of the work is to investigate how the magnetization of the weak RMA magnet a-Gd\(_{80}\)Si\(_{12}\)B\(_8\) behaves in the intermediate field region below saturation.

**Figs. 2**  Fitting of (a) \(B^{1/2}\) [Eq. (4)], (b) \(B^1\) and (c) \(B^2\) [Eq. (5)] for the observed magnetization of a-Gd\(_{80}\)Si\(_{12}\)B\(_8\) at 4.5K. The solid line shows the best fit. The form of \(B^{1/2}\) is in good agreement with the magnetization above about 1.3 T, while the other forms cannot represent the magnetization.
and to estimate a correlation length of RMA in such a field regime. For some crystalline magnets it is well known that the magnetization varies as $B^1$ and/or $B^2$; the $B^1$ term comes from stress fields of dislocations,\textsuperscript{(13)} nonmagnetic impurities or holes;\textsuperscript{(14)} the $B^2$ form is due to the magneto-
crystalline anisotropy. Within the framework of a continuum version of the Harris-Plischke-Zuckermann Hamiltonian,\textsuperscript{(17)} Chudnovsky et al predicted the magnetic saturation of magnets with a weak RMA as follows.\textsuperscript{(4,7)}

When $B^2/|B_{ex}|<B_{ax}$ (the intermediate field region), the magnetization is expressed as

$$M = M_s \left[ 1 - \frac{1}{15} \left( \frac{B_{ax}}{B} \right)^{1/2} \right] + \chi B,$$

where $B_{ax}=B_{ax}^1/B_{ex}^3$, $B_{ax}^1=2M/M_a$, is the RMA field, $B_{ex}^1=2A/M_a R_a$, is the exchange field, $A$ is the exchange strength, $R_a$ is a characteristic correlation length of RMA and $\chi$ is the high field susceptibility. In $B>B_{ex}$ (the high field region) the magnetization approaches to saturation as

$$M = M_s \left[ 1 - \frac{1}{15} \left( \frac{B}{B + B_{ex}} \right)^2 \right] + \chi B,$$

which is the same form on $B$ as a strong RMA magnet.\textsuperscript{(18)}

We have three forms of approach to magnetic saturation: $B^{1/2}$ [Eq. (4)], $B^1$ and $B^2$ [Eq. (5)]. What should be done is to examine which forms is a correct expression for the magnetization of a-Gd$_{60}$Si$_{12}$B$_8$ up to 5.5 T. The best fit is shown by the solid line in Figs. 2(a) for $B^{1/2}$, Fig. 2(b) for $B^1$ and Fig. 2(c) for $B^2$. We obtain $B_{ax}^1/B_{ex}^1=1.3$ T and $B_{ax}^1=5.3$ T. The solid line in Fig. 2(a) [Eq. (4)] agrees well with the observed magnetization above 1.3 T. A few data at higher field than 5.3 T are somewhat deviated from the line. This is because Eq. (4) cannot be applied to the field region. On the other hand, both the lines in Fig. 2(b) [the form of $B^1$] and in Fig. 2(c) [Eq. (5)] deviate remarkably from the observed magnetization. The fitting of Eq. (4) is also drawn by the solid line in Fig. 1, which gives $M_t=208.7$ JT$^{-1}$kg$^{-1}$ and $\chi=1.36$ JT$^{-1}$kg$^{-1}$.

The model of Chudnovsky et al enables us to estimate how long RMA correlates over in a-Gd$_{60}$Si$_{12}$B$_8$. We have two kinds of measures for such a degree of one: $R_{ax}$ and the other is $R_{ax}=(15/2)(B_{ax}^1/B_{ex}^1)^2 R_a$.\textsuperscript{(4,7)} The former means a characteristic length over which local RMA axes correlate owing to a short-range structural disorder; the latter is the ferromagnetic correlation length in which spins are ordered almost ferromagnetically. The values thus obtained are $R_{ax}=1.0$ nm and $R_{ax}=4.1$ nm, which are somewhat shorter than those of the ferromagnets a-Gd$_2$Co, a-Gd$_2$Ni and a-Gd$_2$Cu.\textsuperscript{(12)} This suggests that RMA of the asperomagnet a-Gd$_{60}$Si$_{12}$B$_8$ is larger than that of them and thus that the magnetization is not easy to be saturated. The ratios $R_{ax}/R=2.9$ and $R_{ax}/R=11.7$ are estimated where $R=0.35$ nm is a near neighbor distance between Gd atoms obtained from the extended X-ray absorption fine structure study.\textsuperscript{(14)} The ratio of $R_{ax}/R$ for a-Gd$_6$Si$_2$B$_8$ is nearly equal to the values for a-Dy$_2$Gd$_2$Ni obtained by Filippi et al.\textsuperscript{(9)}

Eqs. (4) and (5) are deduced from the correlation function of an exponential type, that is, $C(r)=\exp(-r/R_a)$, where $r$ is a distance from an atom.\textsuperscript{(4,7)} Therefore our discussion here is based on the correlation function of this type. As suggested by Chudnovsky,\textsuperscript{(7)} there are another forms of the correlation function such as a Gaussian type $C(r)=\exp(-r^2/2R_a^2)$. Our next step is to test Eq. (5) in higher fields than $B_{ex}=5.3$ T and to investigate what form of the correlation function gives the best representation for the magnetization of a-Gd$_{60}$Si$_{12}$B$_8$.

3. Conclusions

We have found that the magnetization of the a-Gd$_{60}$Si$_{12}$B$_8$ asperomagnet in the intermediate field regime varies as a function of $B^{1/2}$ according to the weak RMA model of Chudnovsky et al. In the field region the local RMA axes correlate over $R_{ax}=1.0$ nm, while the ferromagnetic correlation is over $R_{ax}=4.1$ nm.

References