Magnetic Properties of Crystalline SmFe$_2$-B Alloys

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**Abstract.** In this paper we report the study of boron substituted SmFe$_2$ compounds belonging to the family of giant magnetostrictive materials RFe$_2$ (R=Tb, Dy, Sm). The dc magnetization up to fields of 60 kOe and low field ac susceptibility has been measured in the temperature range 5-300 K. In SmFe$_2$, the temperature dependence of magnetization shows two magnetic transitions at 190 K and 80 K in the zero field cooled state. The lower temperature transition is suppressed by the addition of even 1 at% B as observed from the dc magnetization. The ac susceptibility shows a pronounced maximum close to 80 K in both the parent compound and in 1 at% B substituted one. This transition presumably occurs due to freezing of domain wall motion.

1. Introduction

The cubic Laves phase RM$_2$ (R=rare earth, M=transition metal) compounds show a host of interesting magnetic and electrical transport properties. In particular, the RFe$_2$ compounds show a variety of magnetic order with added complex spin arrangements due to competition of different magnetic interactions. The compounds DyFe$_2$, TbFe$_2$ and SmFe$_2$ show a large magnetostriction [1]. The B substitution up to 3 at% in SmFe$_2$ is found to have strong effect on the magnetostrictive properties of the melt spun ribbons [2]. The B substitution in Sm-Fe alloy films significantly modifies its microcrystalline structure and optimizes magnetostrictive characteristics when B is 0.3 to 0.8 at% having Sm in the 30-40 at% concentration range [3]. The DyFe$_2$B compounds synthesized by Lim and co-workers [4] have been investigated for magnetostrictive properties. The room temperature magnetization has been found to be nearly same, independent of B content. This has been attributed to the distortions of the cubic RFe$_2$ lattice by introduction of boron. The structure thus once modified, does not undergo further modification due to varying boron concentration. This explanation is also applicable to the SmFe$_2$B system. The two systems DyFe$_2$ and SmFe$_2$ differ in the sign of magnetostriction; the former showing a positive behavior with a change of sign at lower temperature [1] while the latter shows a large negative magnetostriction. In the present paper, the nature of the low temperature magnetic state is investigated in a series of boron (0-3%) substituted SmFe$_2$ alloys by magnetization measurements.

2. Experimental Details

The SmFe$_2$B(x) (x=0 to 3 at%) alloys were prepared by induction melting to get uniform microcrystalline structure as reported earlier [4]. The dc magnetization up to a field of 60 kOe, and ac
susceptibility have been measured in the temperature range 4.2-300 K using a Quantum Design SQUID magnetometer (MPMS-XL7).

3. Results and Discussion

Figures 1(a) and (b) show the temperature dependence of magnetization between 5-300 K of SmFe₂ up to fields of 30 kOe and Figure 1(c) shows the corresponding data for the SmFe₂B(1%) compound in a field of 5 kOe. The magnetization (M) shows a strong temperature dependence below 190 K up to fields of 5 kOe and exhibits strong irreversibility between the zero field-cooled (ZFC) and field-cooled (FC) states. The irreversibility between ZFC and FC states almost disappears at 30 kOe.

![Fig. 1. Temperature (T) dependence of magnetization (M) of (a-b) SmFe₂ and (c) SmFe₂B(1%) compounds in zero field cooled (ZFC) and field cooled (FC) states in different magnetic fields.](image)

At fields below 5 kOe, a shoulder is observed in magnetization at around 80 K. These points are determined as extrema in the corresponding dM/dT curves. This low temperature shoulder is absent in the boron substituted compounds while the higher temperature transition though present, is rounded off, as seen in Figure 1(c) for the 1 at%B compound. The strong irreversibility in moderate fields between the ZFC and FC states remains in the B-doped compounds.

Figures 2(a and b) show the field dependence of magnetization of the undoped SmFe₂ in fields up to 60 kOe at 300K and 5 K. The coercivity (Hₑ) is observed to increase from 215 Oe at 300 K to about 1 kOe at 5K while the value of saturation magnetization Mₛ (60-65 emu/g) is nearly the same. The hysteresis loops for the boron substituted compounds show a similar behaviour. The values of Hₑ and Mₛ for these compounds are tabulated in Table 1. The significant increase of Hₑ at 5 K for the B-substituted compounds is presumably due to the increase in magnetocrystalline anisotropy due to distortion of otherwise highly symmetric cubic lattice by boron addition.

| Table 1. Coercivity (Hₑ) and saturation magnetization (Mₛ) of SmFe₂ at 5 K and 300 K with Boron substitution of 0, 1 and 3 at% |
|---|---|---|---|---|
| Sample | Hₑ (Oe) | Mₛ (emu/g) | 300K | 5K |
| SmFe₂ | 214 | 1000 | 60 | 65 |
| SmFe₂B(1at %) | 322 | 2000 | 65 | 70 |
| SmFe₂B(3at %) | 200 | 2000 | 70 | 65 |
Fig. 2. M-H loop of SmFe$_2$ at the temperatures of (a) 300 K and (b) 5 K. Inset shows low field data.

Figures 3(a) and 3(b) show the low field ac susceptibility measurements on the parent compound (SmFe$_2$) and the 1 at% boron substituted compound. The real and imaginary part of the susceptibility ($\chi_{ac}$) of the parent compound show the presence of both the transitions near 200 K and 80 K, identified from magnetization measurements. In the case of the 1% B-doped compound, the real part of susceptibility does not show any anomaly at the magnetic transition observed in the dc magnetization, but the imaginary part of the ac susceptibility exhibits a peak at 80K.

The earlier thermal and magnetoelastic [5,6] studies on SmFe$_2$ have reported a spin reorientation temperature at around 190 K, where the easy axis of magnetization changes from [111] at high temperatures to [110] below this temperature. The observed irreversibility in magnetization below this temperature in the SmFe$_2$ alloy in moderate fields (few kOe) indicates presence of strong spin disorder caused by the complex magnetic anisotropy effect present in the system [5]. Lanotte et al [7]
have measured the temperature dependent susceptibility on three different magnetostrictive compounds, including terfenol where a transition is observed in low fields at around 150 K. This is attributed to the re-entrant effect, the extent of the effect being related to the intensity of magnetostriction. The low temperature transition observed at 80 K in case of SmFe$_2$ is presumably due to some kind of time dependent spin dynamics since the measurement of ac susceptibility shows strong anomaly at this temperature. The neutron scattering measurements that provide a clear picture of the spin ordering in the magnetic compounds cannot be performed on the Sm-based compounds due to the high absorption of the incident neutrons and hence other supporting measurements have to be performed to identify the low temperature state.

The low field ac susceptibility studies provide the information about the time dependent spin dynamics in a magnetic system. The AC susceptibility studies of a magnetite crystal by Skumryev et al [8] have shown a peak and a corresponding minimum respectively in the real ($\chi'$) and imaginary ($\chi''$) parts of the ac susceptibility, corresponding to the temperature of spin reorientation. An additional drop in $\chi'$ and a peak in $\chi''$ appears at 50 K with significant frequency dependence and is attributed to the freezing out of domain wall motion. This explanation can be applied to the observed effects in the ac susceptibility studies of the SmFe$_2$ reported here. The $\chi_{ac}$ measurement on Boron substituted compound do not suggest a spin reorientation at higher temperature, however the freezing out of domain wall motion at low temperature is evident from these studies.

4. Conclusion

The magnetization and susceptibility studies have complemented in identifying the magnetic transitions in a series of SmFe$_2$B alloys. The role of magneto-elastic coupling is suggested in explaining the magnetic state at low temperature. Further studies on other magnetostrictive compounds are required to clearly identify the determinant role of magnetoelastic effects.

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