High-Field Magnetization Measurements on a Ferromagnetic Amorphous Alloy from 295 to 5K

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***Abstract*—Magnetization measurements on an amorphous ferromagnetic alloy $Fe_{78}(SiB)_{22}$ have been made over the temperature range from 5 to 295K and in fields to 5T, using a SQUID magnetometer and a superconducting magnet. As-received and field-annealed samples were measured. Having data over a range of temperatures allows the spin-wave contribution to the magnetization to be determined, and then subtracted. When the spin-wave contribution is removed, a substantial high-field susceptibility remains, which is independent of temperature. Attempts to fit the corrected curves to one of two theoretical equations were not conclusive, but the best fit seems to be to $M = M_0 + aH^{-0.5} + bH$. The annealing treatment has no significant effect on the high-field magnetization.**

INTRODUCTION

Measurements of the magnetization of ferromagnetic amorphous alloys at high fields are of interest because of suggestions that the alignment of atomic moments in some of these alloys may not be strictly ferromagnetic, but canted on some fairly local scale[1][2]. Previous measurements have been made only at room temperature, which meant there was uncertainty about the relative contributions of "normal" high-field susceptibility mechanisms and of possible alignment of canted moments[3]. We report here magnetization measurements on ferromagnetic amorphous alloys extending down to 5K, which allow calculation of and correction for the spin-wave contribution to the high-field susceptibility. We also compare amorphous samples with different thermal histories, and find that there is no appreciable effect of annealing on the high-field susceptibility.

EXPERIMENTAL

Square samples were cut from strips of Allied-Signal Metglas 2605S2, and were measured as-received and annealed in a saturating field parallel to the measurement direction. The annealing treatment was for 30 minutes at 430°C in air, which had been shown to produce a strong magnetic annealing anisotropy without crystallization. Magnetization was measured with a SQUID magnetometer at the Institute of Physics of the Polish Academy of Sciences, at temperatures of 295, 77, and 5K, to a maximum field of 5 T. The as-received samples were also measured at a series of intermediate temperatures. Figure 1 shows examples of the measured data. There is some uncertainty in the absolute values of magnetization because of the uncertainty in weighing such small samples, but the relative changes with temperature for a single sample should be accurate. The statistical uncertainty in each measured magnetic moment, deduced from repeated measurements at fixed field, is less than 0.1%.

SPIN-WAVE CONTRIBUTION

The decrease in magnetization with increasing temperature (at zero field) was assumed to follow the equation

$$M(0,T) = M(0,0) - g\,\mu_B \left[\frac{kT}{4\pi D}\right]^{\frac{3}{2}} \sum_{1}^{\infty} n^{\frac{3}{2}} \qquad (1)$$

and the effect of field is included by multiplying by a factor of the form exp(-CH/kT):

$$M\,(H,T) = M\,(0,0) - g\,\mu_B \left[\frac{kT}{4\pi D}\right]^{\frac{3}{2}} * \sum_{1}^{\infty} n^{\frac{3}{2}} \exp\left[-\frac{ng\,\mu_B H}{kT}\right] \qquad (2)$$

In these equations, M is magnetization, H is magnetic field, T is absolute temperature, g is the gyromagnetic factor, taken equal to 2, μ_B is the Bohr magneton, k is Boltzmann's constant, and D the spin-wave stiffness coefficient. [Note: here, and in later equations, we follow custom and denote magnetization as M, moment per unit volume. Since the theories do not take thermal expansion into account, it would be strictly correct to specify magnetization as σ, moment per unit mass.]

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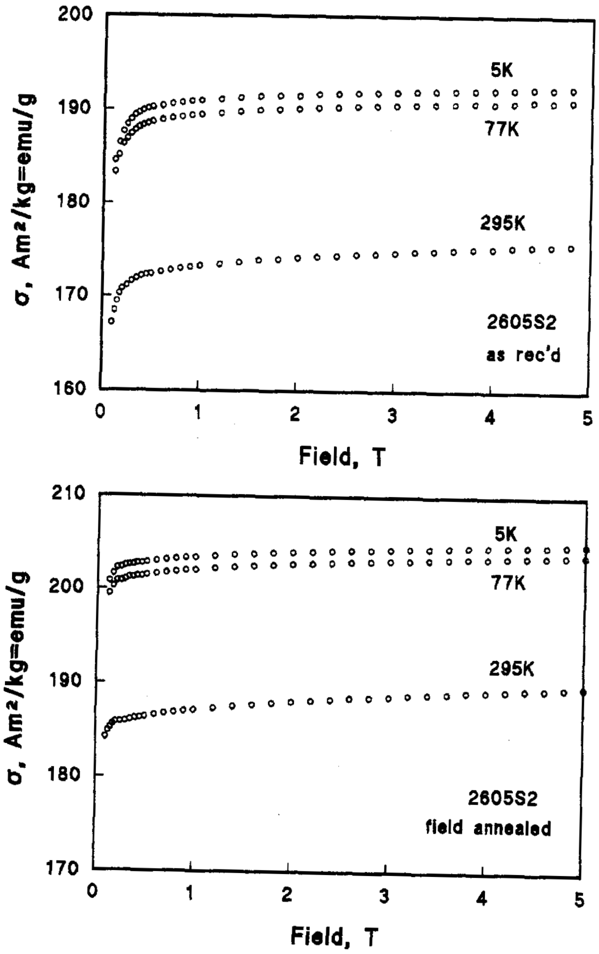

Fig. 1. Magnetization vs. field. Upper figure, as-received; lower figure, field-annealed.

Values of $M(0,T)$ were obtained by extrapolating the high-field portions of plots of M vs H to zero. For the as-received samples, data at 12 different temperatures was available. Fitting these values to (1) gave a value for D of $1.29\text{x}10^{-21}$ eV · m^2, in good agreement with literature values for amorphous alloys[4]. Then the calculated spin-wave contribution could be removed from the measured magnetization at any field and temperature using (2), giving spin-wave corrected curves. Note that the spin-wave contribution *lowers* the magnetization as temperature increases, so the correction for spin-waves increases magnetization. Fig. 2 shows the corrected curves. Note that a significant high-field susceptibility is observed at all temperatures even when the spin-wave contribution has been subtracted from the data. Furthermore, the spin-wave corrected high-field susceptibility is approximately independent of temperature, with a value of $0.26 \pm 10\%$ Am^2/kg · T.

There is no consistent difference between the as-received and the field-annealed samples.

THEORETICAL CURVES

In previous work[3], we found that the best fits to the uncorrected data at room temperature were given by equations that we identified as the Pauthenet and the Chudnovsky equation, as follows:

$$\textit{Pauthenet} \qquad M = M_0 + a_P H^{0.5} + b_P H \qquad (3)$$

$$\textit{Chudnovsky} \qquad M = M_0 + a_C H^{-0.5} + b_C H \qquad (4)$$

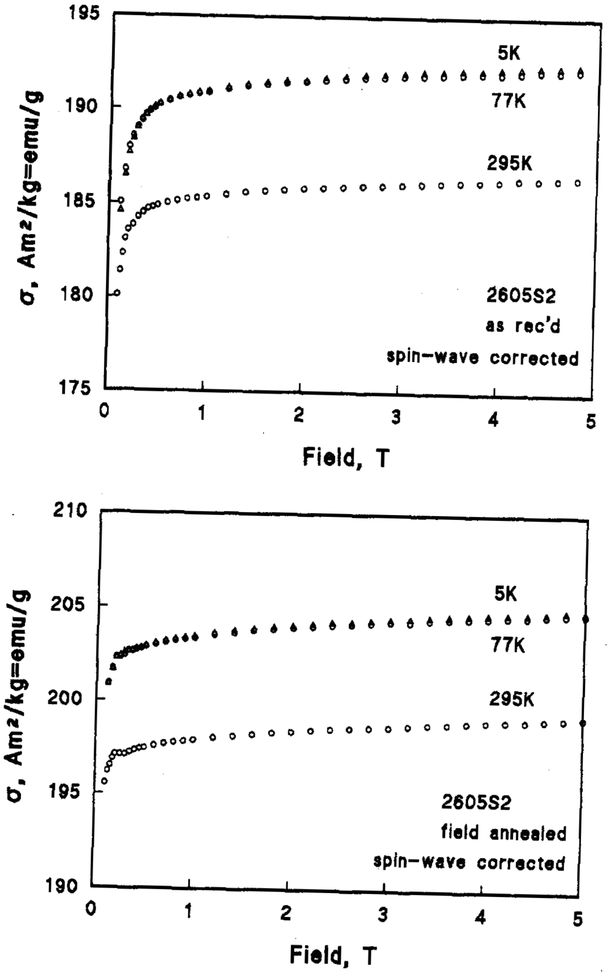

Fig. 2. Magnetization vs field, magnetization corrected for spin-wave contribution. Upper figure, as-received; lower figure, field annealed.

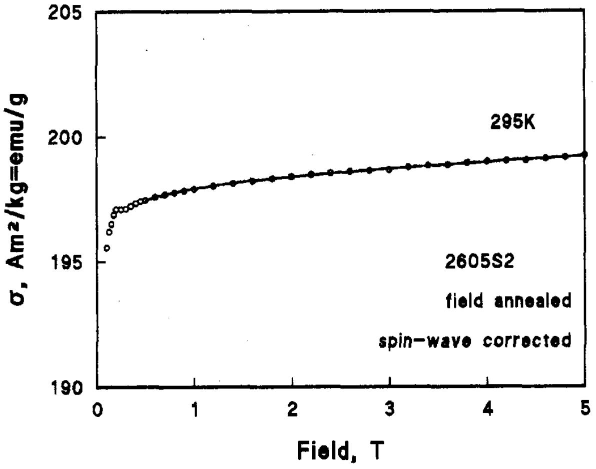

Fig. 3. Chudnovsky fit to room-temperature spin-wave-corrected data for field-annealed sample.

The Pauthenet equation[5] is based on the suppression of spin waves by the applied field[6], and so one might expect it would not apply to data from which the spin-wave contribution has already been removed. The Chudnovsky equation[7] applies to the "wandering axis model" in which the local easy axis varies from place to place in the structure. Fig. 3 shows the Chudnovsky equation fitted to the room-temperature spin-wave-corrected data for the field-annealed samples; the fitted constants were $a_C=-0.92$ and $b_C=0.20$, with M in $A \cdot m^2/kg$ and H in T. Similar plots for the other temperatures and for the as-received sample were closely similar. Only data for fields above 0.5T were fitted, in order to avoid any contribution to the measured magnetization due to domain wall motion. The Pauthenet equation gave an equally good fit to the data points, but with a negative (unphysical) value for b_P. Thus the Chudnovsky "wandering axis" model appears to agree with the experimental data.

Our major finding is that a substantial, temperature-independent, high-field susceptibility is present in these amorphous alloys after the spin-wave contribution is subtracted. The most physically acceptible, although not unequivocal, interpretation of the data is that transition metal amorphous alloys may have a wandering axis structure like that of the rare-earth amorphous alloys.

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