Magnetic Properties of Amorphous (Fe_<1-x>Cr_x)-P-C and (Co_<1-x>Fe_x)-B-Si Alloys

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Magnetic Properties of Amorphous $(Fe_{1-x}Cr_x)$-P-C and $(Co_{1-x}Fe_x)$-B-Si Alloys*

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Synopsis

The magnetization measurement of amorphous $(Fe_{1-x}Cr_x)$-P-C and $(Co_{1-x}Fe_x)$-B-Si alloys have been made from liq. He temperature to room temperature and the magnetic moments, the temperature dependence of demagnetization and the exchange stiffness constants are determined. The composition dependence of the magnetic moment is similar to that of the crystalline Fe-Cr and Co-Fe alloys but this is not the case with the exchange stiffness constant.

I. Introduction

In recent years a number of studies of amorphous alloys have been performed and the relationship between the magnetic properties of splat-cooled amorphous alloys and the crystalline materials have so far received considerable attention and there are many investigations(1) on the relationship between the magnetic properties of amorphous alloys and the crystalline materials.

In order to investigate the difference between the magnetic properties of amorphous and crystalline materials, we have measured the magnetic moment and the temperature dependence of the magnetization at low temperatures on amorphous $(Co_{1-x}Fe_x)$-B-Si and $(Fe_{1-x}Cr_x)$-P-C and compared the concentration dependence of the magnetic properties of amorphous alloys with that of crystalline alloys.

II. Experimental results

Amorphous samples $Co_{75-x}Fe_xB_{10}Si_{15}$ (x=0, 4.7, 7, 10, 15) and $Fe_{80-x}Cr_xP_{13}C_7$ (x=0, 2, 5, 6, 8, 10), in which the subscripts denote the atomic concentration of the elements, have been prepared by rapid quenching from the liquid state. We have confirmed the structure of these amorphous samples by means of X-ray diffraction measurement. The diffraction pattern of amorphous material consists of a few halo with a small shoulder on the right hand side of the second peak and such a diffraction pattern provides evidence for the presence of amorphous

* The **1668th** report of the Research Institute for Iron, Steel and Other Metals.

(1) T. Mizoguchi, K. Yamauchi and H. Miyajima, *Amorphous Magnetism*, Edited H.O. Hooper and A.M. de Graaf, Plenum Press, New York-London (1973) p. 325.

structure(2).

The field dependence of magnetization of these samples have been measured over the range from 2 to 8 kOe at 4.2 K and the temperature dependence of the magnetization have been measured over the range from 4.2 K to room temperature at an applied filed of 5.7 kOe.

In Figs. 1 and 2, the field dependence of the magnetization of $Co_{75-x}Fe_xB_{10}Si_{15}$ and $Fe_{80-x}Cr_xP_{13}C_7$ at 4.2 K are shown respectively and in Figs. 3 and 4, the concentration dependence of the magnetic moment extrapolated to 0K of Co_{75-x}-$Fe_xB_{10}Si_{15}$ and $Fe_{80-x}Cr_xP_{13}C_7$, respectively, are also shown.

The concentration dependence of the magnetic moments per metallic atom of $Co_{75-x}Fe_xB_{10}Si_{15}$ increases linearly with x from $\bar{\mu}=1.1\ \mu_B$ at $x=0$ to $\bar{\mu}=1.26\ \mu_B$ at $x=15$, however that of the magnetic moments per metallic atom of $Fe_{80-x}Cr_xP_{13}$-C_7 decreases linearly with x from $\bar{\mu}=1.9\ \mu_B$ at $x=0$ to $\bar{\mu}=1.24\ \mu_B$ at $x=10$ similarly to the concentration dependence of binary crystalline alloys.

At low temperatures the demagnetization arises from the excitation of long wavelength spin waves. On the basis of the spin wave theory such a demagnetization is described dominantly by a $T^{3/2}$ temperature dependence as follows:

$$-M(T) \equiv M(0)-M(T) = M(0)BT^{3/2} \tag{1}$$

with

$$B = \frac{g\mu_B}{M(0)}\left(\frac{k_B}{4\pi D}\right)^{3/2} \cdot F_{3/2}(T)$$

where

$$F_{3/2}(T) = \sum_{n=1}^{\infty} n^{-3/2} \cdot e^{-nT_g/T}$$

is the Bose-Einstein integral function, g the g-factor, μ_B the Bohr magneton, k_B the Boltzmann constant, D the exchange stiffness constant (the spin wave dispersion coefficient) with which the long spin-wave energy is usually described in terms of the wave vector q by the dispersion relation $E(q)=Dq^2$, $T_g=g\mu_B/k_B(H+H_A)$ with the anisotropy field H_A and applied magnetic field H, and B shows $T^{3/2}$ demagnetization slope.

By applying the above results of spin wave theory for crystalline ferromagnet to the amorphous ferromagnet, the demagnetization at low temperatures is analysed, and the values of B are calculated from the slope of M vs. $T^{3/2} \cdot F_{3/2}(T)$ plots assuming the anisotropy field $H_A=0$ and the values of D are estimated from the values of B assuming the value of $g=2.0$ and using the density experimentally determined for $Co_{75-x}Fe_x$-B-Si and for $Fe_{80-x}Cr_x$-P-C. In Figs. 5–8, the calculated values of B and the estimated values of D are shown as a function of x. The density of amorphous alloys are experimentally determined using the Archimede's principle.

(2) Y. Waseda, Solid State Phys., **10** (1975) 17 (in Japanese).

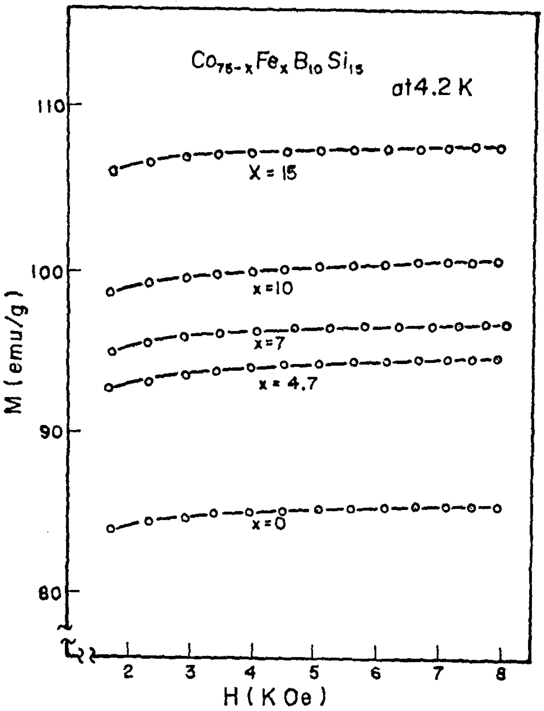

Fig. 1. Magnetization curves of amorphous $Co_{75-x}Fe_xB_{10}Si_{15}$ at 4.2 K.

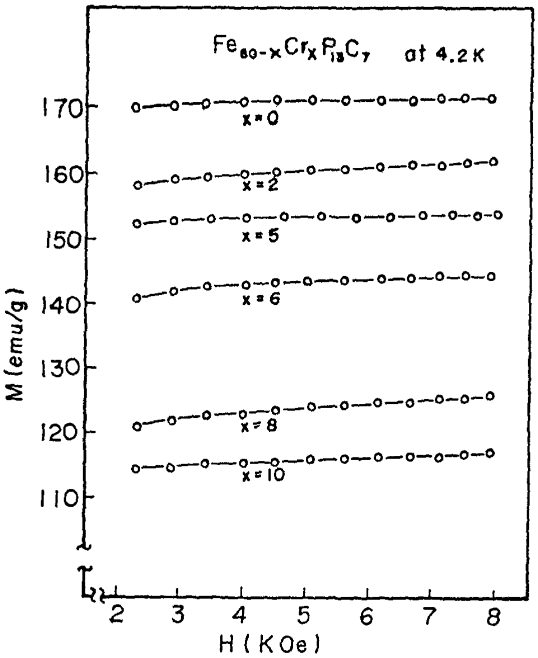

Fig. 2. Magnetization curves of amorphous $Fe_{80-x}Cr_xP_{13}C_7$ at 4.2 K.

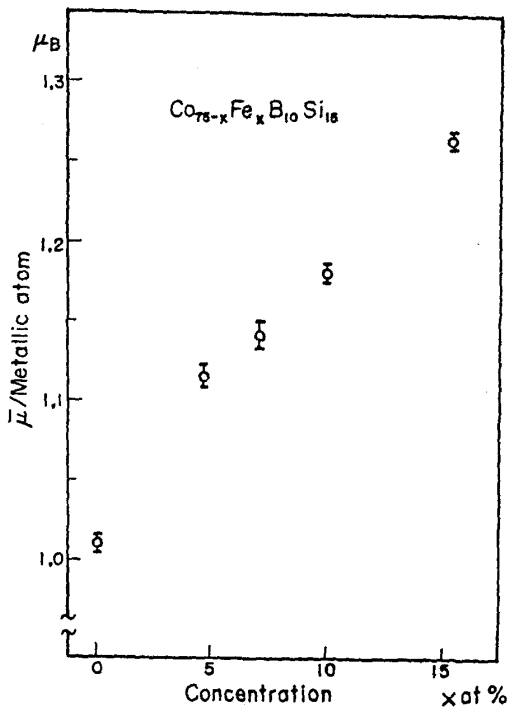

Fig. 3. Variation of the magnetic moment $\bar{\mu}$ per metallic atom with concentration x of $Co_{75-x}Fe_xB_{10}Si_{15}$.

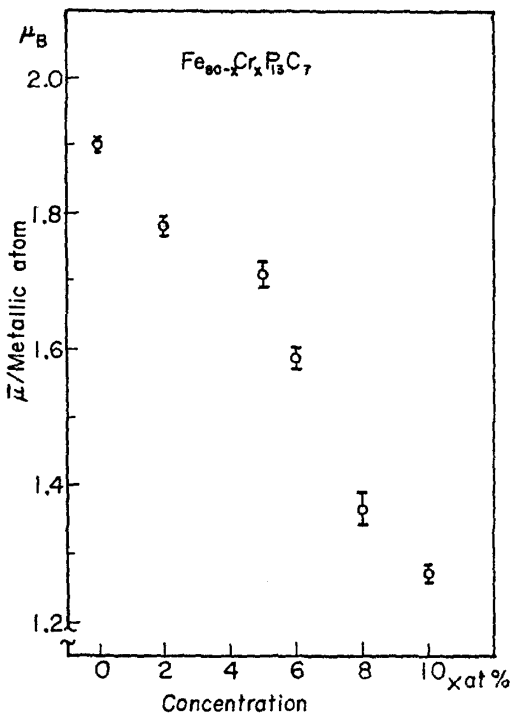

Fig. 4. Variation of the magnetic moment $\bar{\mu}$ per metallic atom with concentration x of $Fe_{80-x}Cr_xP_{13}C_7$.

III. Discussion

1. Magnetic moment

In the case of amorphous $Co_{75-x}Fe_xB_{10}Si_{15}$, the magnetic moment per metallic atom is about $1\mu_B$ at $x=0$, increases linearly with concentration and the extrapolated magnetic moment to $x=1.0$ is about 1.9 μ_B which is smaller than 2.2 μ_B of crystalline Fe. In the case of crystalline Fe-Co alloys, however, the concentration dependence of the magnetic moment per atom which is expressed by the so-called slater-pauling curve has a maximum at about 30 to % Co.

On the other hand, in the case of amorphous $Fe_{80-x}Cr_xP_{13}C_7$, the magnetic moment per metallic atom is about $1.9\mu_B$ at $x=0$ and decreases linearly with concentration of Cr similarly to that of the concentration dependence of crystalline Fe-Cr alloys.

These experimental results are well explained by a model proposed by Mizoguchi et al.[1] in order to interpret qualitatively the concentration dependence of the magnetic moment of amorphous quasi-binary alloys that in the case of quasi-Fe-Co system Fe and Co atoms have parallel 2 μ_B and 1 μ_B moments while in the case of quasi-Fe-Cr system Fe atom and Cr atom has antiparallel 2 μ_B and $4\mu_B$ moments.

2. Temperature dependence of the demagnetization and the exchange stiffness constant

As shown in Figs. 5 and 7, the values of B and D for Co_{75-x}-$Fe_xB_{10}Si_{15}$ system decrease a little against concentration of Fe in contrast with linear increase of the magnetic moment. In general for a crystalline ferromagnet the exchange stiffness constant D is expressed by $D=2a^2SJ$ in which a is the lattice constant, S the spin and J the exchange integral. So these experimental results seem to show qualitatively that the exchange interaction between the magnetic atoms decreases with concentration of Fe.

On the other hand, as shown in Figs. 6 and 8 the value of B for $Fe_{80-x}Cr_xP_{13}C_7$ system increases with concentration of Cr while the value of D decreases with concentration of Cr in contrast with linear decrease of the magnetic moment. These results seem to show that the average exchange interaction between the magnetic atoms is nearly constant with concentration of Cr.

Next we make a trial to compare the exchange stiffness constant of amorphous alloys with that of crystalline alloys. The experimental results of the exchange stiffness constant are shown in Fig. 9. The exchange stiffness constant for crystalline alloys were obtained from the small angle scattering of neutrons by Lowde et al.[3] and for amorphous materials they were determined from the magnetization

(3) R.D. Lowde, M. Shimizu, M.W. Stringfellow and B.H. Torrie, Phys. Rev. Letters, **14** (1965) 698. (E.P. Wohlfarth, *Quantum Theory of Atoms, Molecules and Solid State*, edited by P.O. Löwdin, Academic Press, New York (1966) p. 485.)

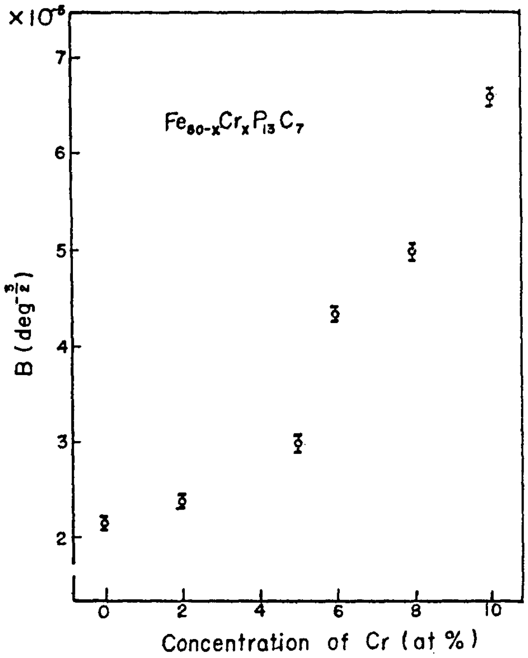

Fig. 5. Variation ot the B with concentration x of $Co_{75-x}Fe_xB_{10}$-Si_{15}.

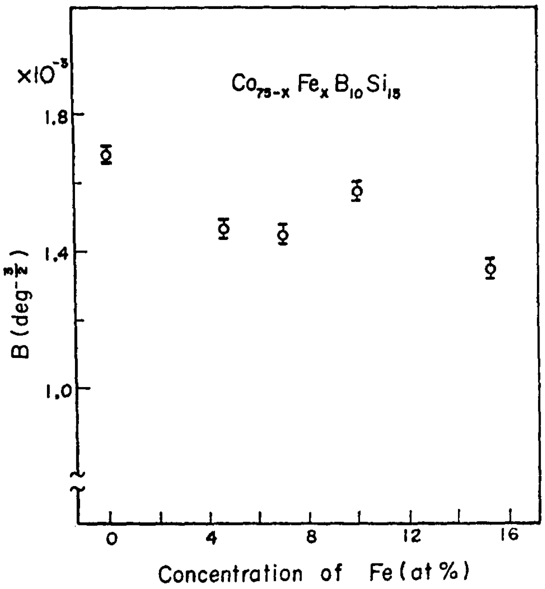

Fig. 6. Variation of the B with concentration x of $Fe_{80-x}Cr_xP_{13}C_7$.

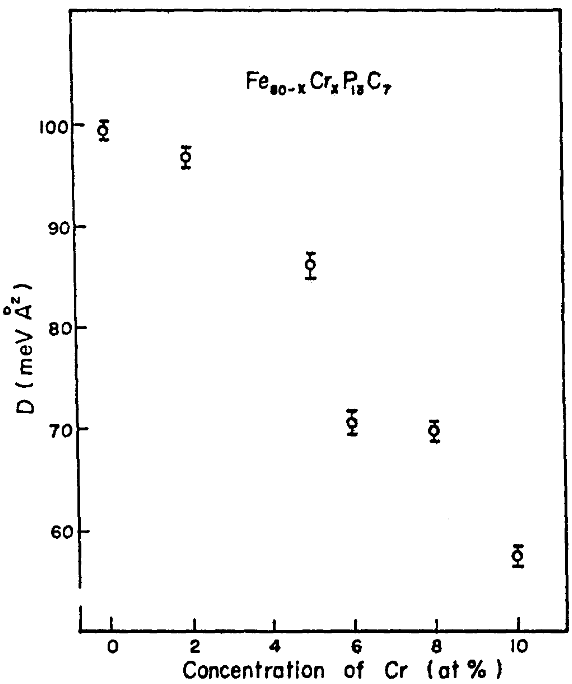

Fig. 7. Variation of the D with concentration x of $Co_{75-x}Fe_xB_{10}Si_{15}$.

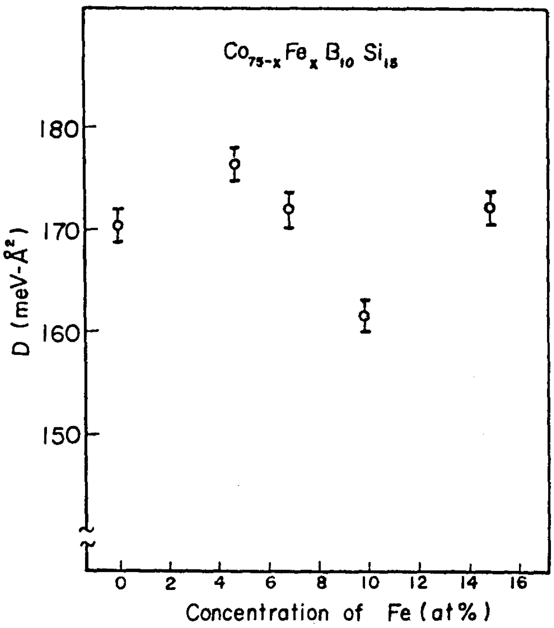

Fig. 8. Variation of the D with concentration x of $Fe_{80-x}Cr_xP_{13}C_7$.

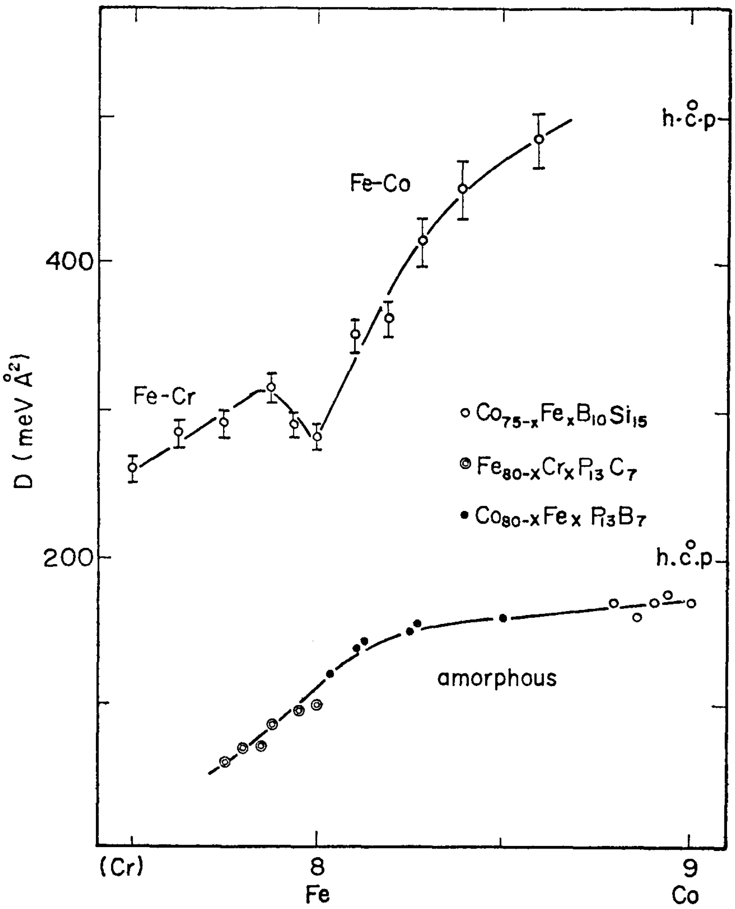

Fig. 9. The exchange stiffness constant D plotted as a function of the average outer electron concentration of a metallic atom. The upside curve is that of crystalline alloys obtained from the small angle scattering of neutrons, and the downside curve is that of amorphous alloys obtained from the magnetization measurement.

measurement at low temperatures by Kazama et al.[4] for Co(Fe)-P-B system and by present authors for Co(Fe)-B-Si and Fe(Cr)-P-C systems. As shown in Fig. 9, the remarkably different feature are found that the value of the exchange stiffness constant for amorphous materials are smaller than those for crystalline materials and that the concentration dependence of the exchange stiffness constants for amorphous materials is simpler and shows a smooth variation while that for crystalline materials is complicated and undergoes a maximum value in Fe-Cr alloys.

(4) N. Kazama, M. Kameda and H. Watanabe, to be published.