Journal of Korean Magnetics Society, Volume 5, Number 5, October 1995

COERCIVE FIELD AND SPIN-GLASS BEHAVIOR OF AMORPHOUS Y-Fe ALLOYS

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Abstract- The coercive field H_c of amorphous Y-Fe alloys in the spin-glass state has been investigated. For amorphous $Y_{10}Fe_{90}$ alloy, the thermal variations of H_c in the maximum external field H_{max} = 300, 600 and 1 k Oe exhibit a maximum. Since spin-glass behavior is strongly affected by external magnetic fields, the maximum point moves to lower temperature with increasing H_{max}. The appearance of the maximum in H_c has been discussed in terms of the change of the spin-glass state in the external magnetic field. When the value of H_{max} is 55 kOe, the temperature dependence of H_c has no maximum and shows an exponential decrease with increasing temperature. Similar trends have been observed over a wide concentration range. The concentration dependence of H_c is associated with the magnetic phase diagram.

I. INTRODUCTION

Spin-glass behavior in amorphous Y-Fe alloys has been extensively investigated [1-8]. The spin-glass state in amorphous M-Fe (M = Y, Zr and non-magnetic rare earth elements) alloys appears above about 90 at% Fe [1, 9, 10]. It has been pointed out that spin-glass behavior in these systems is closely correlated with the magnetic state of amorphous Fe [9]. The magnetic properties of amorphous Fe based alloys are dominated by both directional and amplitude fluctuations of the local moments [11-13]. In amorphous Y-Fe alloys, the amplitude fluctuations of local moments have been confirmed through a large spontaneous volume magnetostriction [6, 7]. On the other hand, the directional fluctuations of local moments are important for the spin freezing process in the external magnetic field [4].

The spin-glass state in the amorphous Y-Fe alloys is sensitive to an external magnetic field. The magnetic phase diagram in the magnetic field has been determined by means of the differential magnetic susceptibility measurement [4]. In the magnetic phase of the amorphous Y-Fe alloy system, a direct transition from the paramagnetic to the spin-glass state occurs in the entire concentration range [2] in contrast with other amorphous M-Fe alloys which exhibit a re-entrant spin-glass transition around 80 at% Fe [9, 10]. The application of an external magnetic field results in an appearance of two type spin freezing processes in the amorphous Y-Fe alloys [4]. In analogy with the spin-glass transition of Heisenberg spin systems, the higher transition temperature referred as T_g is considered to be a freezing temperature of the transverse component of the spins, while lower one referred as T_f may correspond to a cross-over point from the weakly to the strongly irreversible state. These two freezing temperatures are markedly suppressed with the increase in the external magnetic field. Furthermore, the ferromagnetic phase appears between the paramagnetic and the spin-glass state in the strong external magnetic fields in the concentration range where other amorphus M-Fe alloys exhibit re-entrant spin-glass behavior [4].

Magnetization curves for the amorphous Y-Fe alloy in the spin-glass state show hysteresis [2], which is considered to be attributed to the thermodynamical properties in the spin-glass state. In the present study, the coercive field in the magnetization curve has been investigated under various conditions of the temperature and the maximum external field H_{max}. These data are connected with the magnetic phase diagram.

II. EXPERIMENTAL

Amorphous Y_XFe_{100-X} alloys about 0.2 mm thick were prepared by high-rate DC sputtering on a water-cooled Cu substrate. The Cu substrate was removed by grinding. The magnetization was measured with a SQUID magnetometer. The coercive field was determined from the B-H hysteresis swept between $\pm H_{max}$.

III. RESULTS AND DISCUSSION

The magnetization curves up to a maximum field H_{max} = 55 kOe for the amorphous $Y_{10}Fe_{90}$ alloy is displayed in Fig. 1. The remanent field and the coercive field H_c are observed. In the spin-glass state, the irreversibility caused by the change in the temperature or the magnetic field arises from the broken ergodicity due to the free energy with a many-valley structure [14]. The hysteresis in the magnetization curve is also originated from this characteristics in the spin-glass state. Applying the magnetic field, the magnetic state changes towards the equilibrium state for a long time [15]. However, when the sweep velocity of the external magnetic field is faster than the time scale for establishment of the equilibrium state, a so-called " magnetic viscosity " appears. When a magnetic field is applied, the magnetic state is different even after the magnetic field is reduced to zero. It should be noted that the amorphous Y-Fe alloys exhibit two freezing temperatures in the external magnetic field [4]. That is, the freezing of the transverse component of spins occurs at T_g, and subsequently transforms into a strong irreversibility state at T_f with decreasing temperature. Both T_g and T_f become lower with increasing strength of the external magnetic field H and the spin-glass state is divided by a H-T_f line in the H-T phase diagram. When the strength of the external field exceeds this line at a certain temperature, the spin-glass state changes from a weakly to a strongly irreversible state. Therefore, the hysteresis in the magnetization curve is expected to be different whether H_{max} exceeds the H-T_f line or not.

Figure 2 shows the B-H hysteresis curves measured at 5, 30 and 60 K in H_{max} = 600 Oe. The hysteresis loop becomes larger with increasing temperature from 5 to 30 K. The coercive field H_c persists at 60 K, but its value is smaller than that observed at 30 K. These results mean that the irreversibility of the spin-glass state in 600 Oe changes at a certain temperature between 5 K and 60 K. Similar trends have been obtained from the

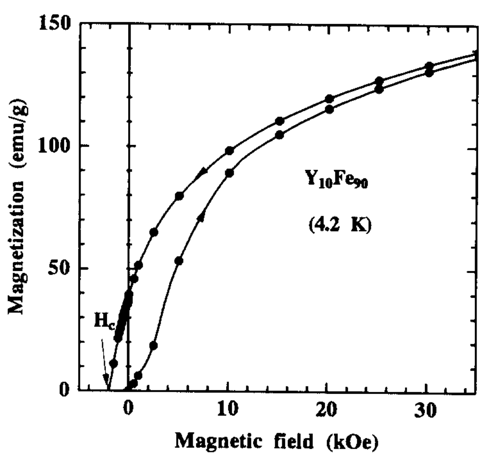

Fig. 1 Magnetization curve for the amorphous $Y_{10}Fe_{90}$ alloy.

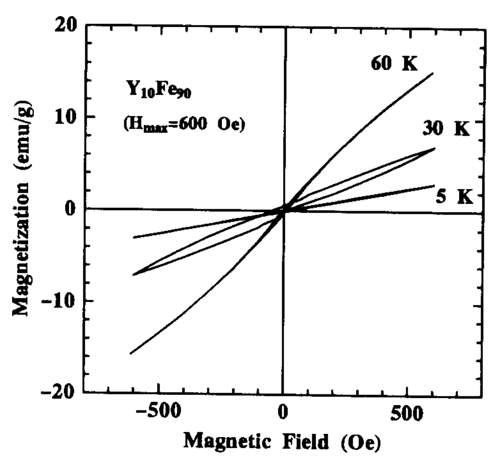

Fig. 2 B-H hysteresis curves at 5, 30 and 60 K in the field up to H_{max} = 600 Oe for the amorphous $Y_{10}Fe_{90}$ alloy.

measurement with H_{max} = 300 Oe and 1 kOe. The temperature dependence of H_c for three kinds of H_{max} is shown in Fig. 3. The value of H_c exhibits a maximum, which moves to lower temperature with increasing H_{max}. The inset in Fig. 3 displays the relations between the magnetic field H and two freezing temperatures T_g and T_f determined from the differential magnetic susceptibility measurement [4]. The dashed horizontal lines indicate the three values of H_{max}. From the inset, the intersecting temperature of H_{max} and H-T_f line is evaluated, which is indicated by the arrows in Fig. 3. It is regarded that the maximum of H_c appears around the intersecting temperature of H_{max} and H-T_f line, although the experimental errors due to the remanent field of superconducting magnet and the accuracy of differential magnetic susceptibility should be corrected. The increase in H_c up to the maximum should be associated with the temperature dependence of strong irreversibility of the state below T_f. The barrier between the valleys of free energy in the strong irreversibility state is considered to be high enough to prevent the spins from following a weak change in the external magnetic field in low temperatures. With increasing temperature, the magnetic state can move to other valleys with a different arrangement of spins. Correspondingly, the hysteresis becomes larger, because the movement to the initial valley takes a long time [15]. In the temperatures higher than the point indicated by the arrows, the spin-glass state changes via a weak irreversibility state by sweeping the magnetic field as 0 → H_{max} → 0. Therefore, the temperature dependence of H_c changes, resulting in the maximum in H_c.

The temperature range above the maximum point of H_c becomes wider by measuring H_c in the larger H_{max}. In order to investigate the thermal variation of H_c in the temperature range above the maximum, the magnetization curves up to H_{max} = 55 kOe are measured and the temperature dependence of H_c is obtained, as seen in Fig. 4. With increasing temperature H_c rapidly decreases and no maximum appears. These data are also plotted in the log(H_c)-T form in the inset in the same figure. The value of H_c decreases in an exponential manner with temperature. The exponential decrease in H_c with temperature is also observed in amorphous Zr-Fe alloy system by Read et al [16, 17]. However, they have discussed that the appearance of the coercive

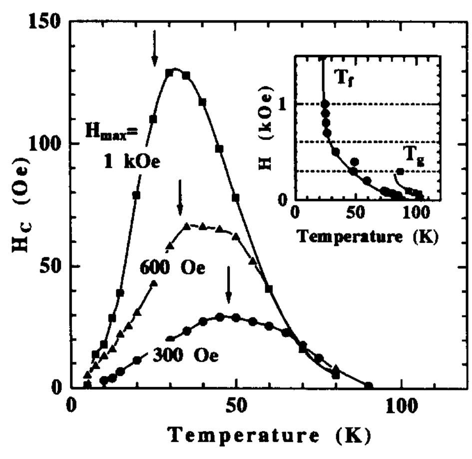

Fig. 3 Temperature dependence of the coercive field H_c for H_{max} = 300, 600 and 1 kOe for the amorphous $Y_{10}Fe_{90}$ alloy. The inset shows the relation between the freezing temperatures and the magnetic field [4].

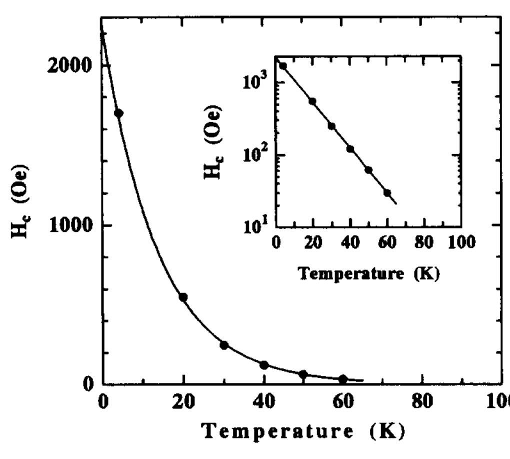

Fig. 4 Temperature dependence of the coercive field H_c measured up to H_{max} = 55 kOe for the amorphous $Y_{10}Fe_{90}$ alloy. The inset is the same plot with a logarithmic scale in the ordinate.

field and its exponential-like behavior are not originated from the spin-glass transition but from the pinning of the magnetic domains due to the inhomogeneity of concentration [16, 17]. If their pinning model is valid, both the H_c-T line for H_{max} = 55 kOe and the H-T_f line should overlap on the H-T plane. In the present results, however, the former is different from the latter, as seen from Fig. 4 and the inset in Fig. 3. Therefore, the existence of T_f and the coercive field in the magnetization curve are originated from the thermodynamic properties of the spin-glass for the amorphous Y_XFe_{100-X} alloys.

Recently, spin-glass behavior in amorphous Fe-concentrated alloy is theoretically explained in terms of the itinerant electron magnetism of Fe by Kakehashi [11-13]. According to his theory, the frustration between the ferromagnetic and the antiferromagnetic interactions in the spin-glass state of amorphous Fe-based alloy is caused by the local environment effect and non-linear exchange interactions. The amplitude of local moment of Fe changes in accordance with the surrounding environment, and the sign of the exchange interaction depends on the amplitude of local moment [11-13]. The local moment of Fe with small amplitude tends to couple antiferromagnetically with the local moments on surrounding Fe sites, while one with large amplitude couples ferromagnetically with the surrounding moments. Because of thermal spin fluctuations, the amplitude of local moment increases and the ferromagnetic interaction gradually becomes dominant with temperature [18]. Although the analytical explanation can not be obtained from this theory, the exponential decrease in H_c is explained qualitatively as follows. The frustration in the spin-glass state is reduced by the increase in ferromagnetic interaction in a finite temperature due to the thermal spin fluctuations. It is known that distribution function of Fe atoms in amorphous Fe-based alloys is approximated by a Gaussian function which is composed by an exponential function [19]. The distribution of amplitude of the local moment should also be connected with the Gaussian form through the local environment effect. The local environment is also reflected in the energy gain of the ferromagnetic interaction caused by increase in the amplitude of local moment. Consequently, H_c decreases with the exponential function.

The exponential decrease in H_c for H_{max} = 55 kOe is also observed in a wide concentration range for the amorphous Y-Fe alloys. The value of $H_c(0)$ at 0 K has been evaluated from the linear extrapolation of the logarithmic plot of H_c at various temperatures. All specimens exhibit a large value of $H_c(0)$ as seen from the concentration dependence of $H_c(0)$ in Fig. 5. In the present system, $H_c(0)$ is relatively small around at 80 at% Fe. The important point to note is that re-entrant spin-glass behavior appears around this concentration range by applying the strong magnetic field [4] or by structural relaxation induced by annealing [5, 8]. From these results, the ferromagnetic phase is stable around 80at% Fe and it does not appear in the concentration range more than 90at% Fe. The magnetic phase diagrams of amorphous Fe-based alloy are also discussed theoretically by the change of atomic short-range order and the local environment effect [18]. Therefore, it is considered that the concentration dependence of H_c, as well as the

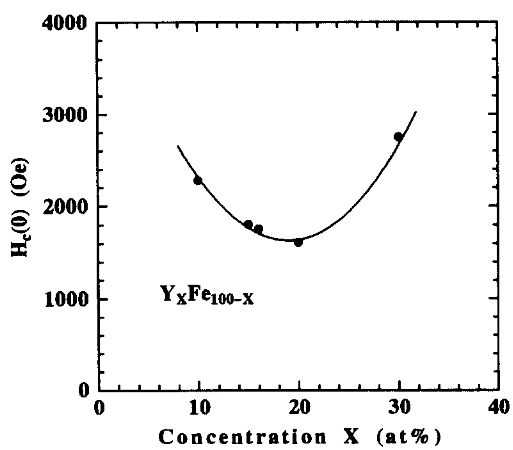

Fig. 5 Concentration dependence of the coercive field $H_c(0)$ at 0 K for the amorphous Y_XFe_{100-X} alloys.

temperature dependence, is affected by the increase in the spins coupled ferromagnetically.

IV. CONCLUSION

The coercive field H_c in the magnetization curve for the amorphous Y_XFe_{100-X} alloys was investigated. The value of H_c was measured by changing the maximum external field H_{max}. The temperature dependence of H_c at the large H_{max} was obtained. The concentration dependence of the coercive field was also investigated. These results lead to the following conclusion.

(a) The temperature dependence of the coercive field H_c at the maximum external fields H_{max} = 300, 600 and 1 kOe exhibits a maximum for the amorphous $Y_{10}Fe_{90}$ alloy. The temperature of the maximum of H_c becomes lower with increasing H_{max}.

(b) The temperature dependence of H_c is associated with the change in the characteristics of spin-glass phase in the external magnetic field.

(c) The temperature dependence of H_c for H_{max} = 55 kOe exhibits an exponential decrease with increasing temperature. A similar trend is observed over a wide concentration range.

(d) The concentration dependence of H_c is correlated with the magnetic phase diagram. The value of Hc shows a minimum around 80 at% Fe where the magnetic state is close to ferromagnetism.

ACKNOWLEDGEMENTS

The study was supported by a Grant-in-Aid for Scientific Research (A), No. 04402045, from the Japanese Ministry of Education, Science and Culture. One of the authors (AF) would like to thank the JSPS Research Fellowships for Young Scientists.

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