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To cite this version:

HAL Id: jpa-00228732
https://hal.archives-ouvertes.fr/jpa-00228732
Submitted on 1 Jan 1988

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PRESSURE EFFECT ON THE MAGNETIC PROPERTIES OF Fe-La AMORPHOUS ALLOYS

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Abstract. – Pressure dependence of $\chi_{AC}(T)$ for amorphous Fe$_{x}$La$_{100-x}$ has been measured up to 20 kbar. With increasing pressure, the ferromagnetic phase for $x = 87.5$ reduces and finally the spin-glass state is realized below 110 K. Paramagnetic to spin-glass transition temperature observed for $x = 92.5$ becomes low by applying pressure.

Spin-glass behavior has been observed in Fe-rich amorphous alloy systems with early transition metals such as Fe-Y, Fe-Zr and Fe-Hf [1-4]. This indicates that the alloy system is a random spin system with competing ferro- and antiferromagnetic interactions. Recently, we investigated the magnetic phase diagram of Fe$_{x}$La$_{100-x}$ amorphous alloys with $60 \leq x \leq 92.5$ [5]. In the concentration range $60 \leq x < 90$, the alloy is ferromagnetic, but shows a re-entrant spin-glass behavior below a lower temperature than the Curie temperature. The Curie temperature rises to a maximum of 285 K at $x = 30$ and then drops sharply as $x \to 90$. The amorphous alloy with $x \geq 90$ has no ferromagnetic phase and exhibits a direct transition from the paramagnetic phase to the spin-glass phase at about 110 K characterized by a cusp in the temperature dependence of the AC susceptibility.

In the present study, we have measured the pressure dependence of the AC susceptibility for the Fe-rich Fe-La amorphous alloys up to 20 kbar to clarify the spin-glass behavior of the alloy system.

The bulk samples about 0.2 mm thick with nominal compositions of 87.5 and 92.5 at.% Fe were prepared by high rate DC sputtering on water-cooled Cu substrates 45 mm diameter. These samples were confirmed to be amorphous by X-ray diffraction. The AC susceptibility in the temperature range from 4.2 K to 300 K were measured at various hydrostatic pressures up to 20 kbar by a conventional mutual inductance method with an AC field of 13 Oe at 80 Hz using a Be-Cu clamp pressure cell.

We measured the AC susceptibility ($\chi_{AC}$) of two amorphous samples Fe$_{x}$La$_{100-x}$ of $x = 87.5$ and 92.5 with re-entrant spin-glass and spin-glass behavior, respectively [5]. Figure 1a shows the temperature dependence of $\chi_{AC}$ for $x = 87.5$ at various pressures. At 0 kbar, $\chi_{AC}$ increases sharply at the Curie temperature ($T_c$) 241 K to a maximum value and then decreases gradually as the temperature decreases, following an abrupt drop-off at a lower temperature. This drop-off is rather vague, the re-entrant spin-glass temperature ($T_{RSG}$) is defined by a shoulder in the temperature dependence of $\chi_{AC}$. As the pressure increases, $T_c$ decreases rapidly while $T_{RSG}$ increases, indicating a reduction of the ferromagnetic phase. At 20 kbar, $\chi_{AC}$ does not show any sharp increase corresponding to a direct transition from the paramagnetic to the ferromagnetic state, but exhibits a cusp characterizing the spin-glass transition $\sim$ 110 K.

![Fig. 1. – Temperature dependence of $\chi_{AC}$ at various pressures for amorphous Fe$_{87.5}$La$_{12.5}$ (a) and Fe$_{92.5}$La$_{7.5}$ (b).](image-url)
Figure 1b shows the temperature dependence of $X_{AC}$ for $x = 92.5$ at various pressures. The temperature dependence of $X_{AC}$ at 0 kbar shows the cusp at 110 K, indicating the direct transition from the paramagnetic to the spin-glass state. With increasing pressure, the transition temperature ($T_{SG}$) decreases gradually and the cusp of $X_{AC}$ collapses.

The pressure dependence of the transition temperatures $T_C$ and $T_{RSG}$ for $x = 87.5$ and $T_{RSG}$ for $x = 92.5$ are plotted in the magnetic phase diagrams in figures 2a and b. The shifts of $T_C$ and $T_{RSG}$ are estimated to be $-4.8$ K/kbar and $5.0$ K/kbar below 10 kbar, respectively. The shift of $T_C$ is as large as that of Fe-Ni invar alloy [6]. On the other hand, the shift of $T_{RSG}$ for $x = 92.5$ is $-1.4$ K/kbar, whose absolute value is about one-fourth of that of $T_{RSG}$ for $x = 87.5$.

![Magnetic phase diagrams for amorphous Fe$_{87.5}$La$_{12.5}$ (a) and Fe$_{92.5}$La$_{7.5}$ (b).](image)

As described above, the ferromagnetic state of the amorphous Fe$_x$La$_{100-x}$ at 0 kbar becomes unstable as $x \rightarrow 90$ and finally the spin-glass state is realized at $x \geq 90$ [5]. Matsuura et al. measured the interatomic distance between Fe-Fe atoms in the Fe-rich amorphous Fe-La system [7]. The distance becomes short very slightly with increasing Fe concentration. This suggests that the drastic change in the magnetic properties with Fe concentration is not related mainly to the change in the interatomic distance between Fe-Fe atoms, but to the change in the partial Fe-Fe coordination number. Recently, Kakehashi calculated the magnetic phase diagram of the fcc Fe-Ni alloys on the basis of the finite-temperature theory of the local environment effect [8]. According to the numerical calculations, the spin-glass state is realized in the concentration range above 65 at.% Fe. The antiferromagnetic coupling, which is the origin of the formation of the spin-glass state, is caused between Fe atoms with a large number of Fe nearest neighbors. The spin-glass state observed in the Fe-rich amorphous Fe-La system is considered to be derived from the same origin as in the fcc Fe-Ni system. On the other hand, the present high pressure experiments indicate that the reduction of Fe-Fe atomic distance suppresses the ferromagnetic ordering and facilitates the formation of the spin-glass state. These results are considered to be due to a decrease in the average exchange interaction between Fe atoms. The collapse of the cusp of $X_{AC}$ observed at $x = 92.5$ by the application of pressure suggests that the antiferromagnetic interaction prevails between Fe atoms at high pressures.