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Enhanced magnetism in amorphous Fe-based alloys

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Enhanced magnetism in amorphous Fe-based alloys

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Systematic investigations of binary amorphous Fe–T alloys (T = an early transition-metal elements Ti, Zr, Nb, Hf, Ta...) over wide composition ranges reveal depressed magnetic properties with anomalously low magnetic ordering temperature and magnetization. We show in this work, via a prototype amorphous $Fe_{70}Ti_{30}$ alloy, the substitution of Fe by Co, Ni, or Cu greatly enhances the magnetic ordering temperature and the magnetization. Our results indicate that this is primarily caused by the increased Fe moment upon alloying.

INTRODUCTION

In all binary amorphous Fe_yTi_{100-y} alloys (T = an early transition metal, Ti, Zr, Nb, Hf, Ta, ... etc.) over wide composition ranges, anomalously low magnetic ordering temperature (T_c) and magnetization have been observed.[1–6] In fact, regardless of the Fe content, the T_c's of all of these samples are below room temperature, unsuitable for most magnetic applications. For example, the T_c of a-$Fe_{70}Ti_{30}$ is only 215 K, despite its high Fe concentration. In many cases, these alloys do not even exhibit simple ferromagnetic characteristics. The depressed magnetism in these binary alloys is thought to be caused by the drastic reduction of the Fe moment. In this work, we show that both the magnetization and T_c can be greatly enhanced by substituting various amounts of Co, Ni, or Cu for Fe in a prototype alloy of a-$Fe_{70}Ti_{30}$.

The elements of Co, Ni, and Cu are used because of their distinctively different magnetic characteristics. In amorphous alloys, Co retains its high moment, Ni often exhibits only a very small moment, whereas Cu is nominally nonmagnetic. On the other hand, the atomic sizes of Co, Ni, Cu, and Fe are nearly identical (within 1%). One therefore expects no appreciable changes in the structure in the amorphous alloys when different alloying element is used.

The sample of a-$Fe_{70}Ti_{30}$ has been chosen for the following reasons. Earlier we found[2] that amorphous Fe_xTi_{100-x} alloys exist in the composition range of $30 \leqslant x \leqslant 80$. The composition of $x = 70$ is sufficiently far from the boundary composition that the crystallization temperature is high and remains so upon further alloying. In a-Fe_xTi_{100-x} both T_c and the Fe moment increase with x. Relatively high values have already been realized in a-$Fe_{70}Ti_{30}$.

EXPERIMENT

Samples of amorphous $Fe_x(Co, Ni, Cu)_{70-x}Ti_{30}$ alloys with x varying from 0 to 70 have been prepared by a high-rate magnetron sputtering technique with film thickness of 6–20 μm. The amorphous nature of the samples have been confirmed by an energy dispersive x-ray diffraction method. Magnetization of the alloys has been studied by a SQUID magnetometer in the field range 0–50 kG. The magnetic ordering temperature has been determined under zero field by a zero-velocity thermal scan method using ^{57}Fe Mössbauer spectroscopy. The effective magnetic hyperfine fields have been obtained from the analyses of the Mössbauer spectra.

RESULTS AND DISCUSSIONS

Some representations of magnetization curves of amorphous $Fe_x(Co, Ni, or Cu)_{70-x}Ti_{30}$ alloys are shown in Fig. 1. These samples are clearly ferromagnetic, for the magnetization can be easily saturated. Within each series, all $Fe_xNi_{70-x}Ti_{30}$ and $Fe_xCo_{70-x}Ti_{30}$ samples show ferromagnetic characteristics. In $Fe_xCu_{70-x}Ti_{30}$, most samples are ferromagnetic except those with low iron concentration which show paramagnetic or spin glass behavior. The spontaneous magnetization (M_s) of each sample is determined by extrapolating the magnetization curve to zero magnetic field. The variation of M_s with iron concentration of amorphous Fe(Co, Ni, or Cu)-Ti alloys are shown in Fig. 2. It is noted that M_s increases when Co or Ni is first introduced to

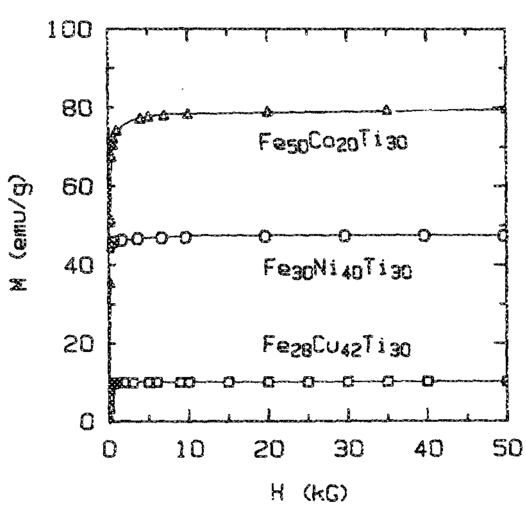

FIG. 1. Magnetization in emu/g of amorphous $Fe_{50}Co_{20}Ti_{30}$, $Fe_{30}Ni_{40}Ti_{30}$, and $Fe_{28}Cu_{42}Ti_{30}$ at 6 K as a function of field.

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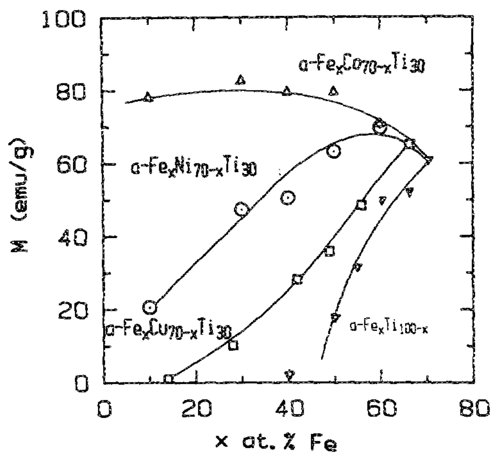

FIG. 2. Spontaneous magnetization measured at 6 K of amorphous $Fe_xCo_{70-x}Ti_{30}$, $Fe_xNi_{70-x}Ti_{30}$, and $Fe_xCu_{70-x}Ti_{30}$ as a function of Fe content.

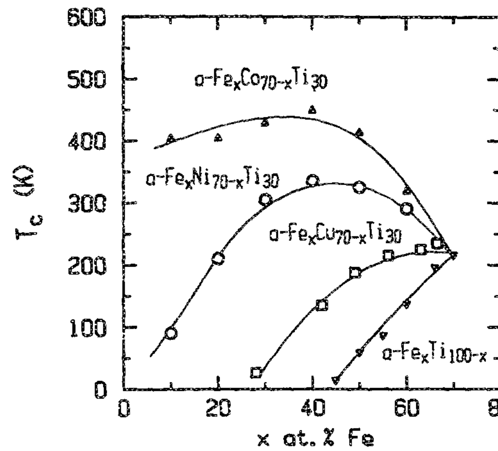

FIG. 4. Magnetic ordering temperature (T_c) of amorphous $Fe_xCo_{70-x}Ti_{30}$, $Fe_xNi_{70-x}Ti_{30}$, $Fe_xCu_{70-x}Ti_{30}$, and Fe_xTi_{100-x} as a function of Fe content.

replace Fe. Beyond that, distinctively different behaviors are observed. In $Fe_xNi_{70-x}Ti_{30}$, the increase of M_s levels off at $Fe_{50}Co_{20}Ti_{30}$. Further replacement of Fe by Co does not noticeably affect M_s. In $Fe_xNi_{70-x}Ti_{30}$, beyond the initial rise, M_s decreases monotonically towards the Ni-rich end. Since Ni has a moment less than that of Fe, the initial rise in M_s is due to the enhancement of the Fe moment. Because both Co and Fe have sizable magnetic moments in Fe-Co-Ti alloys, there is relatively little variation of M_s. In the case of Fe-Ni-Ti alloys on the other hand, Ni only has a very small moment, resulting a monotonically decreasing M_s. In $Fe_xCu_{70-x}Ti_{30}$, Cu is expected to carry no moment. As a consequence, M_s decreases monotonically. At about $Fe_{15}Cu_{55}Ti_{30}$, M_s drops to zero and the alloys with lower Fe content cease to be ferromagnetic.

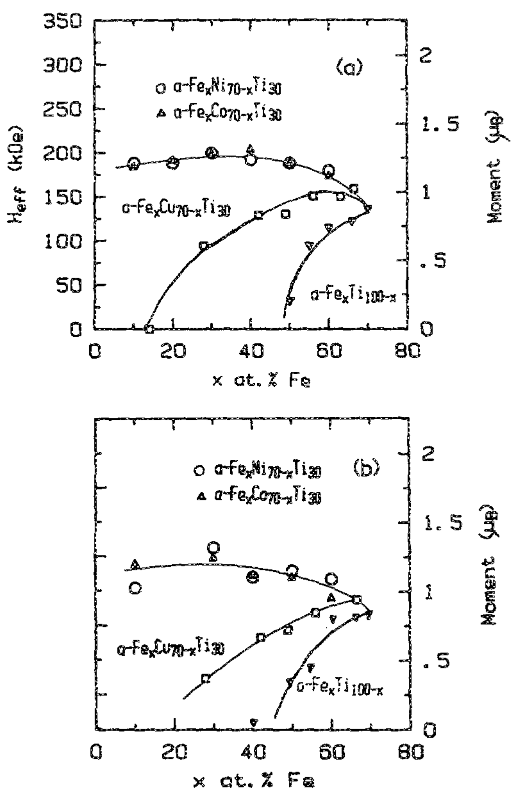

FIG. 3. (a) Magnetic hyperfine field (H_{eff}) at the Fe sites measured at 4.2 K of amorphous $Fe_xCO_{70-x}Ti_{30}$, $Fe_xNi_{70-x}Ti_{30}$, and $Fe_xCu_{70-x}Ti_{30}$ as a function of Fe content. For comparison, the results for amorphous Fe_xTi_{100-x} are also shown. By using a conversion factor of 150 kOe/μ_B, the values of Fe moment are obtained. (b) Fe moment of amorphous $Fe_xCo_{70-x}Ti_{30}$, $Fe_xNi_{70-x}Ti_{30}$, and $Fe_xCu_{70-x}Ti_{30}$ as a function of Fe content. The moments of Co, Ni, and Cu are assumed to be 1.17, 0.17, and 0 μ_B, respectively.

We have also used the magnetic hyperfine field, measured from ^{57}Fe Mössbauer spectroscopy to obtain information about the Fe magnetic moment. It has been known that the magnetic hyperfine field provides a reasonable measure of the Fe moment. The compositional dependence of the magnetic hyperfine fields (H_{eff}) at the Fe sites and the spontaneous magnetization allow the magnetic moments of the constituent elements to be resolved.

First of all, when Ni or Co is first introduced, both H_{eff} [Fig. 3(a)] and M_s (Fig. 2) increase. This further confirms the fact the Fe moment is indeed enhanced. Beyond that, in Fe-Co-Ti alloys, H_{eff} and M_s remain nearly constant below $x = 40$, indicating that the magnetic moments of Fe and Co are approximately the same. In Fe-Ni-Ti alloys, however, M_s reduces rapidly with decreasing x as shown in Fig. 2 while H_{eff} remains nearly unchanged as shown in Fig. 3(a). This indicates Fe retains its moment throughout the composition range, whereas Ni has only a very small moment. In Fe-Cu-Ti alloys, the behaviors of M_s and H_{eff} do not suggest an appreciable Cu moment, as expected.

In Fig. 3(b), we replot the M_s values shown in Fig. 2 as magnetic moment per Fe, assuming that Co, Ni, and Cu moments are 1.17, 0.17, and 0 μ_B, respectively. The remarkable similarity between Figs. 3(a) and 3(b) for all three-alloy systems of $Fe_x(Co, Ni, Cu)_{70-x}Ti_{30}$ indicates that the above choices are reasonable. Also shown in Fig. 3(a) are the data[2] of Fe moment of a-Fe_xTi_{100-x} before the addition of Co, Ni, or Cu for comparison. It is then clear, as displayed in Fig. 3(b), that the Fe moment is greatly enhanced by adding Co, Ni, or Cu into amorphous Fe-Ti alloys. The alloying elements influence the electronic structure and, thereby, the formation of the Fe moment. A similarly sharp increase of iron moment in amorphous Fe-Zr alloy has also been reported by other researchers.[6,7]

Systematic variations of magnetic ordering temperature (T_c) vs the Fe concentration for Fe-(Co, Ni, or Cu)-Ti alloys and Fe-Ti alloys are shown in Fig. 4. The value of T_c is vastly enhanced by substituting either Co, Ni, or even Cu for Fe in amorphous Fe-Ti alloy. It is particularly impressive for alloys with low Fe contents, where the a-Fe_xTi_{100-x} samples with $x < 40$ are not ferromagnetic. The most prominent increase is achieved by substituting Fe with Co. The highest T_c of 450 K is observed in $Fe_{40}Co_{30}Ti_{30}$. Additional Co causes a slight decrease in T_c. Intermediate increase is realized in Fe-Ni-Ti alloys reflecting a much smaller Ni moment and weaker magnetic exchange interactions. Even nominally nonmagnetic Cu has a sizable effect in increasing the values of T_c and the Fe moment.

Finally, it may be mentioned that the atomic sizes of Co, Ni, and Cu are nearly identical. The variation of the average Fe-Fe distance with x should not be appreciably different for amorphous alloys containing Co, Ni, or Cu to give rise to the very different magnetic properties of the three alloy series.

In conclusion, we have systematically substituted Fe by Co, Ni, and Cu in a prototype a-$Fe_{70}Ti_{30}$ alloy. A large enhancement of T_c is realized in all three cases as a result of the increased magnetization and, specifically, the increased Fe moment. The results have demonstrated that the universally depressed magnetism in binary amorphous alloys of Fe with an early transition-metal element can be greatly enhanced by alloying with Co, Ni, and Cu.

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