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Magnetic properties and magnetic exchange interactions in $Gd_{1-x}RE_x$ (RE=Pr, Nd) alloys

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Abstract: The effect of Pr, Nd addition on the magnetic properties and magnetic exchange interaction of gadolinium alloys was systematically studied. Curie temperature T_C and magnetic moment of $Gd_{1-x}RE_x$ (RE=Pr, Nd) systems with $x<0.05$ were investigated. When $x<0.05$, Pr and Nd formed respectively with Gd continuous solid solution which has the crystalline structure HCP. Study on the magnetic behavior indicated that at near room temperature, the simple ferromagnetism prevailed in these two systems of alloy. The Curie temperature and magnetic moment of $Gd_{1-x}RE_x$ alloy decreased with RE (RE= Pr, Nd) content x increasing. The de Gennes factor of $Gd_{1-x}RE_x$ alloy which was associated with the exchange interaction between magnetic spin components also decreased with RE content increasing. The above results showed that the magnetic exchange interaction between magnetic atoms in gadolinium could be effectively changed by the Pr, Nd addition.

Keywords: $Gd_{1-x}RE_x$ (RE=Pr, Nd) alloys; Curie temperature; magnetic moment; de Gennes factor G; rare earths

Magnetic refrigeration technology is considered to be a green refrigeration technology in the 21st century, due to high efficiency, energy-saving, limited noise and greenhouse effect. The development of magnetic refrigerating material is a key issue in this technology[1–5]. Since the world's first room temperature permanent magnetic refrigerator was developed by American Astronautic Corporation combined with Ames Laboratory in 2001, the prototype magnetic material available for room magnetic temperature has still been lanthanide metal gadolinium due to its easy forming performance, low fabrication cost and large cooling power in comparison with brittle intermetallic compounds[6–8]. At present, in magnetic refrigeration technology, the material for container which holds refrigerant is required to own suitable strength. Furthermore, in the progress of magnetic refrigeration, the container together with refrigerant also participates in refrigeration. So in selecting the material for container, we considered weakly diluted Gd-based alloy[9,10]. The study of the magnetic properties, magnetic structures as well as magnetic interaction between magnetic atoms in pure metal gadolinium has been a hot point[11,12]. It is well known that gadolinium crystallizes in hexagonal structure with c/a=1.6, and it is considered as a prototype ferromagnetic rare earth due to its half-filled 4f shell. Its magnetic structure changes with temperature. At $226<T<292.5$ K, gadolinium is the collinear ferromagnetic with easy magnetization axis directing along c-axis of hexagonal structure. At T=226 K, a second-order spin-reorientation transition takes place. At lower temperature, the easy axis of magnetization tilts away c-axis by angle φ[13–15]. For a free Gd atom, the configuration of its outer shell is usually given as $4f^7 5d^1 6s^2$. The magnetism of gadolinium is determined by the localized, high-spin 4f moment and the RKKY-type indirect interaction between the localized magnetic moments. The indirect interaction is mediated by 5d electrons and is usually correlation with de Gennes factor of alloy[16,17].

In this study, we wanted to know whether the addition of alloy elements into gadolinium has an effect on the magnetic properties and magnetic interaction between magnetic atoms in pure gadolinium, trying to find out how far different types of solid solution atoms added in different amounts affect the magnetic exchange interaction. In view of fundamental study, it is meaningful. The related study can be read in Refs. [18–20], where the long-range interactions between magnetic atoms, the related magnetic properties and the magnetic structures of Gd-based alloys containing solid solution element such as Er, Mn, Y have been investigated. The long-distance magnetic exchange interaction between magnetic atoms is linked to the environment around the magnetic atoms, such as the electron concentration around magnetic atoms and the distance between magnetic atoms, etc. A weakly diluted alloy is an ideal type of material which can be used to study the long-distance magnetic exchange interaction because the addition of small amount of solid solution atoms into matrix can effectively affect

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the above mentioned environment, meanwhile the crystalline structure of the matrix material can be preserved.

We think that more experimental data coming from many kinds of Gd-based alloys with different amounts of solid solution atom addition and different types of solid solution atoms addition are needed. In this report, we systematically investigated the effect of light rare earth Pr, Nd addition on the magnetic properties and magnetic exchange interaction of gadolinium.

1 Experimental

Two series of $Gd_{1-x}RE_x$ (RE=Pr, Nd) alloys with $x<0.05$ were prepared by arc melting Gd (99.9%) and Pr, Nd (99.9%) in argon atmosphere. After the first melting, the button ingots were flipped over and re-melted six times to ensure the homogeneity. The structural analysis of the samples was carried out by X-ray diffraction using Cu Kα radiation with wavelength of 0.154056 nm. The magnetic properties were measured with a SQUID magnetometer. The saturation magnetization was determined by measuring the magnetic field dependence of magnetization up to 5 T at 5 K. The magnetic moment μ_n per $Gd_{1-x}RE_x$ formula unit was obtained from the law of approach of saturation. The Curie temperature was determined from the thermomagnetization curve measured with a SQUID magnetometer in a low magnetic field of 100 Oe.

2 Results and discussion

2.1 Crystal structure

The XRD patterns of $Gd_{1-x}RE_x$ (RE=Pr, Nd) alloys ($x<0.05$) at room temperature are shown in Fig. 1. Comparing the patterns of the samples containing light elements with that of pure gadolinium, we can find that there are not new peak lines appearing, indicating that at room temperature the $Gd_{1-x}RE_x$ samples preserve the hexagonal structure of gadolinium.

2.2 Curie temperature

The thermomagnetization curves of gadolinium-based alloys under a magnetic field of 100 Oe is shown in Fig. 2. In every curve, a dramatic decrease in magnetization has been observed at magnetic transition point T_C, which is the characteristic transition from ferromagnetic state to paramagnetic state. The shape of $M(T)$ curve for $Gd_{1-x}REx$ (RE= Pr, Nd) alloy is almost identical with that of gadolinium, suggesting that the addition of Pr, Nd into Gd with $x<0.05$ does not change the nature of ferromagnetic transition of gadolinium. The T_c values of the alloys are determined at the peak position of $\partial M/\partial T$-T curve. The solute concentration dependence of Curie temperature for diluted Gd-based alloys is plotted in Fig. 3. For every Gd-RE system, the magnitude of T_c is found to decrease with increasing RE concentration x. According to

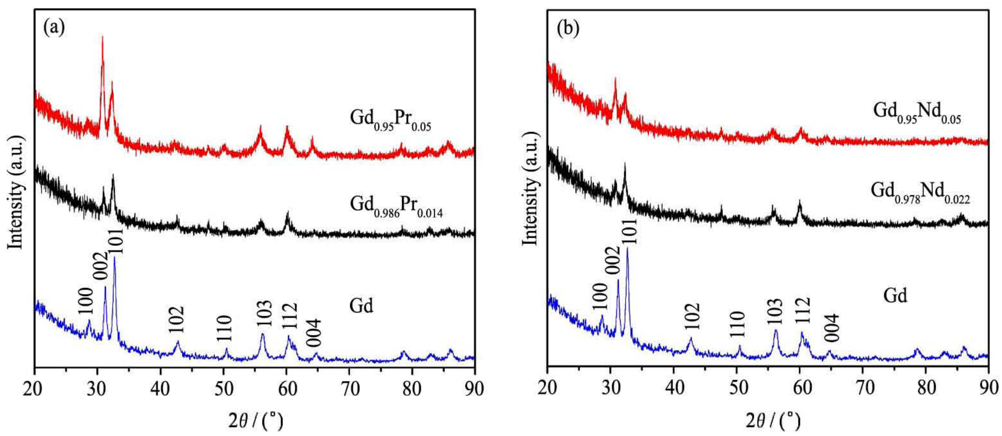

Fig. 1 XRD pattern of $Gd_{1-x}Pr_x$ (a) and $Gd_{1-x}Nd_x$ (b) alloys with $x<0.05$ near room temperature

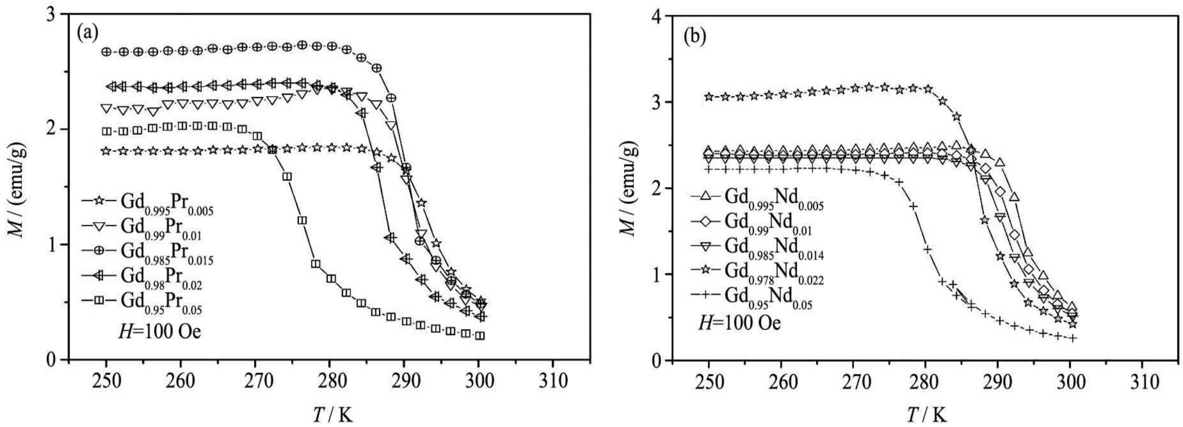

Fig. 2 Temperature dependence of the magnetization in an applied magnetic field of 100 Oe for $Gd_{1-x}Pr_x$ (a) and $Gd_{1-x}Nd_x$ (b) alloys