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Corrosion behavior of $Nd_{9.4}Pr_{0.6}Fe_{bal.}Co_6B_6Ga_{0.5}Ti_xC_x$ ($x = 0$, 1.5, 3, 6) nanocomposites annealed melt-spun ribbons

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ABSTRACT

The effect of Ti and C additions on the corrosion behavior of $Nd_{9.4}Pr_{0.6}Fe_{bal.}Co_6B_6Ga_{0.5}Ti_xC_x$ ($x = 0$, 1.5, 3, 6) isotropic nanocomposite melt-spun ribbons in 3.5 wt% sodium chloride solution was studied. The melt-spun ribbons were annealed at 750 °C for 10 min in argon-filled quartz capsules. The microstructure of multiphase nanocrystalline samples and corrosion products was characterized using the X-ray diffraction and electron microscopy techniques. The electrochemical behavior was assessed using potentiodynamic polarization and electrochemical impedance spectroscopy. The results show that the addition of Ti and C increases the corrosion resistance of NdFeB ribbons; the best corrosion resistance was obtained for 1.5 wt% Ti and C content.

1. Introduction

In comparison to rare-earth-rich alloys, Fe-rich Nd–Fe–B isotropic nanocomposite permanent magnets composed of $Nd_2Fe_{14}B$ hard magnetic phase and α-Fe or Fe_3B soft magnetic phase, have received considerable attention for their potential applications and their low cost [1–3]. Remanence enhancement ($J_r > J_s/2$) for Nd–Fe–B nanocomposites with very fine grain size and no additional phases at the grain boundaries is an effective way of improving the hard magnetic properties of these isotropic magnets. Higher remanences at acceptable coercivities were reported for magnets with Fe-rich compositions, where an exchange-coupling takes place between the hard magnetic $Nd_2Fe_{14}B$ phase and the soft magnetic α-Fe or Fe_3B phases [4,5]. The grain refinement of the phases by addition of various alloying elements causes an exchange-coupling enhancement, as well as an improvement in the magnetic properties [6–10].

However, the presence of rare-earth Neodymium in the magnets drastically accelerates the corrosion process, consequently reduces the magnetic properties of NdFeB [11]. Therefore, in order to improve the corrosion resistance, most efforts have been focused on the addition of alloying elements such as Co, Ga, Al, Cr and Zr; however, it is always accompanied by the deterioration of the magnetic properties [11–14]. Thus, it is necessary to find a method for improving the corrosion resistance without severely scarifying the magnetic performance of the magnets. Jurczyk et al. [15] were the first to report that corrosion resistance of the Nd–Fe–B/α-Fe nanocomposites in an aqueous 3% NaCl solution with the additions of Al and Co enhanced in comparison to Nd-rich magnets. Esfahani [16] studied the magnetic behavior of $Nd_{9.4}Pr_{0.6}Fe_{bal.}Co_6B_6Ga_{0.5}Ti_xC_x$ ($x = 0$, 1.5, 3, 6) nanocomposites melt-spun ribbons. She proved that the magnetic properties can be optimized by addition of 1.5 at% Ti and C. In this work, the effects of Ti and C addition on the corrosion behavior of the above-mentioned alloys were studied.

2. Experimental

Alloy ingots of nominal composition $Nd_{9.4}Pr_{0.6}Fe_{bal.}Co_6B_6Ga_{0.5}Ti_xC_x$ ($x = 0$, 1.5, 3, 6) were prepared by vacuum arc remelting in a high-purity argon atmosphere. The ingots were remelted four times to ensure homogeneity. The ingots were then broken into small pieces (about 10 g) and melt-spun on a copper wheel at rotational speed of 40 ms^{-1} in a high-purity argon atmosphere. Subsequently, the melt-spun ribbons were sealed in quartz tubes and annealed in a tube furnace at 750 °C for 10 min and quenched in water.

The crystalline phases of heat-treated ribbons were studied by means of X-ray diffraction (XRD). The microstructures of the specimens were investigated by a Technai G2 F30 Lorenz transmission electron microscope at 300 kV equipped with Electron Energy Loss Spectroscopy (EELS). The electrochemical investigations were carried out using a potentiostat/galvanostat (EG&G Princeton Applied Research 273 A) in 100 ml of test

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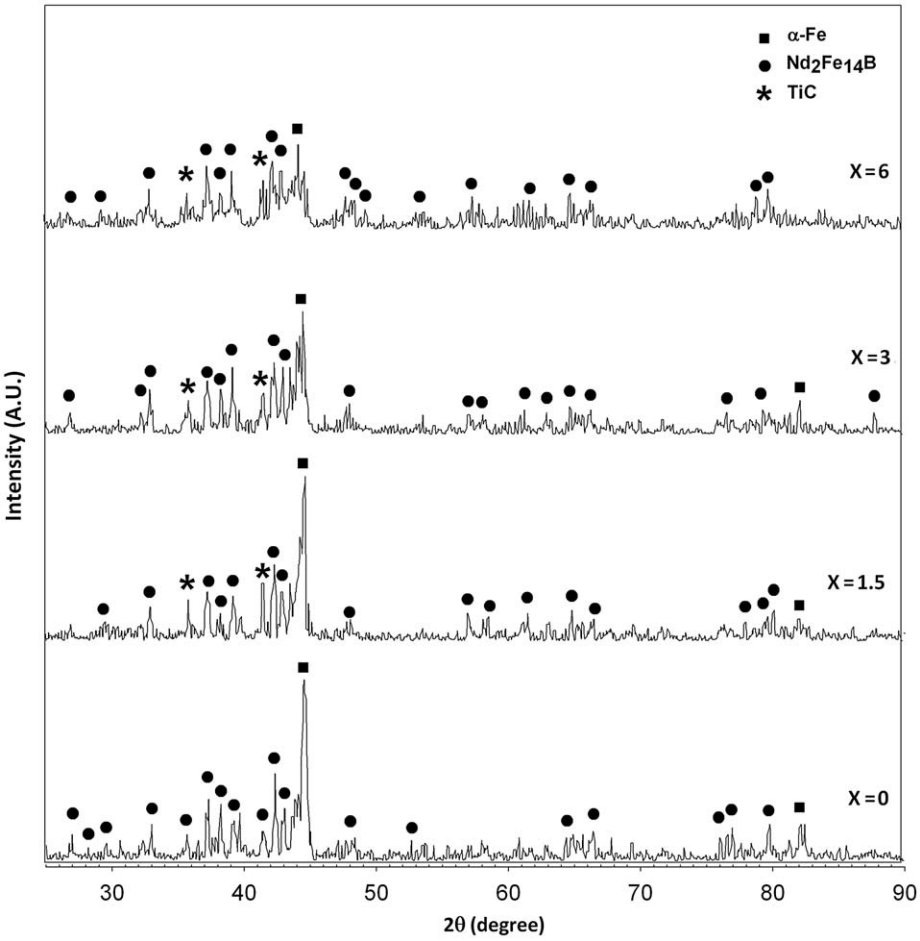

Fig. 1. X-ray diffraction patterns for $Nd_{9.4}Pr_{0.6}Fe_{bal.}Co_6B_6Ga_{0.5}Ti_xC_x$ ($x = 0$, 1.5, 3, 6) ribbons annealed at 750 °C for 10 min.

electrolyte. A conventional three-electrode system was used for electrochemical measurements. The samples were used as working electrodes. The saturated calomel electrode (SCE) and platinum electrodes were used as reference and counter electrodes, respectively. The corrosion electrolyte was a 3.5 wt% sodium chloride solution at 25 °C. Potentiodynamic polarization curves were measured at a scan rate of 1 mV/s after about one hour of stabilization at rest potential. The electrochemical impedance spectroscopy (EIS) data were obtained with a signal amplitude of 10 mV in frequency range of 100 kHz–10 mHz.

The surface morphology and corrosion products of the magnets were characterized using a Camscan scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectroscopy (EDS).

3. Results and discussion

The X-ray diffraction patterns of all the samples annealed at 750 °C are shown in Fig. 1. It is obvious that Ti and C tend to form a TiC compound. The grain size of $Nd_2Fe_{14}B$ phase and α-Fe phases were calculated via the Hall–Williamson method [17] and are shown in Fig. 2. According to this method, the full-width at half-maximum (FWHM) can be expressed as a linear combination of the contributions from the strain (ε) and small particle size (D) through the relation

$$B\,Cos\,\theta/\lambda = k/D + \varepsilon\,Sin\,\theta/\lambda \quad (1)$$

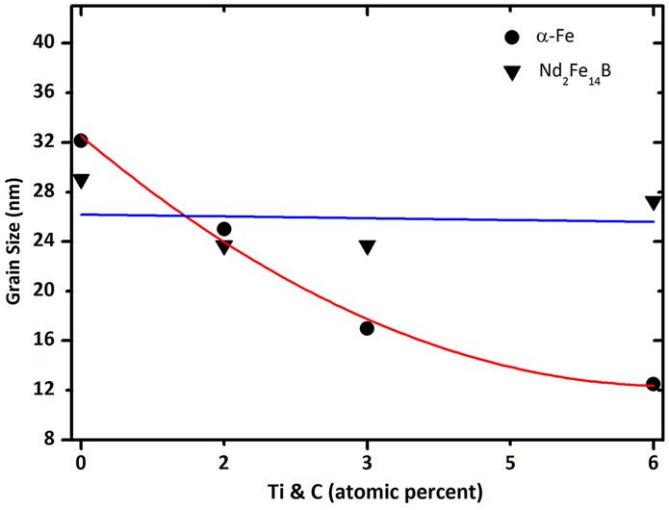

Fig. 2. Variation of $Nd_{9.4}Pr_{0.6}Fe_{bal.}Co_6B_6Ga_{0.5}Ti_xC_x$ ($x = 0$, 1.5, 3, 6) annealed ribbons grain size with Ti and C content.

where D is the crystallite size (Å), $k = 0.9$ is a constant related to the crystallite shape, λ is the wavelength of X-ray radiation, θ is the diffraction angle and β is the full-width at half-maximum of the diffraction line at 2θ.