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Microstructure and magnetic properties of melt spinning Ni–Mn–Ga

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ABSTRACT

Textured $Ni_{51}Mn_{28.5}Ga_{20.5}$ polycrystalline ribbons were prepared by melt spinning method with different spinning speeds. The effect of spinning speed on microstructure, phase transformation and magnetization behavior were investigated. The martensitic transformation temperatures were hardly affected by the spinning speed. The Curie temperature was significantly decreased, the saturation magnetization was reduced, and the critical field driving the detwinning was increased at higher spinning speed. *Local* and *long-range* effects were revealed for the melt spinning ribbons.

1. Introduction

Ni–Mn–Ga ferromagnetic shape memory alloys (FSMAs) are a new type of functional materials featured by the magnetic-field-induced strain (MFIS). The MFIS is intrinsically based on the strong magnetocrystalline anisotropy of the ferromagnetic martensite, and is produced in a mechanism of magnetic-field-induced detwinning (MFIDT) [1–3]. The onset of the MFIDT leads to an abrupt increase in the slope of the *M*–*H* curve, a metamagnetization behavior [4]. Large MFIS has been obtained in Ni–Mn–Ga single crystal and textured polycrystalline bulks, making Ni–Mn–Ga attractive candidate for sensors and actuators [5–9]. Melt spinning is an effective method to produce textured polycrystalline Ni–Mn–Ga ribbons in order to miniaturize actuators and to minimize the ac eddy-current losses [10]. Compared with the master Ni–Mn–Ga alloys, the melt-spun ribbons exhibited lower martensitic and magnetic transition temperatures, lower saturation magnetization and higher coercivity [11–13]. An abrupt slope change of the *M*–*H* curves was observed in the as-spun ribbons of some Ni–Mn–Ga compositions [14,15]. Magnetostrain measurements confirmed that this behavior was due to the occurrence of the MFIDT [16]. The quenched-in internal stress was considered to preferentially orient the twin variants, favoring the MFIDT [17]. In general, the rapid solidification of melt spinning has unique effects on Ni–Mn–Ga ribbons. Thus it is of crucial importance to understand the underlying mechanism of such effects, both experimentally and theoretically. In this letter, textured $Ni_{51}Mn_{28.5}Ga_{20.5}$ polycrystalline ribbons were prepared by melt spinning method with different spinning speeds. The effects of the spinning speed on the microstructure, phase transformation and magnetization behavior of the as-spun ribbons were investigated. *Local* and *long-range* effects were revealed for the melt spinning ribbons.

2. Experimental

Starting elements, nickel, manganese and gallium with the purities of 99.9%, 99.7% and 99.99%, respectively, were remelted four times in an argon atmosphere by arc melting for the preparation of ingot having nominal composition $Ni_{51}Mn_{28.5}Ga_{20.5}$. The weight loss during arc melting was confirmed to be less than 0.5%. The ingot was then encapsulated in a quartz tube backfilled with argon and heat treated at 1123 K for 48 h for homogenization. Ribbons were prepared from the ingot by melt spinning furnace with a 200 mm diameter copper wheel. Three spinning speeds were adopted, 500, 2000 and 4000 rad/min. For the convenience of description the ribbons are hereafter named as 500, 2000 and 4000 according to the spinning speed. Circular disks of 3 mm in diameter were cut from the ribbons for magnetic properties measurements.

Composition analysis using electron probe microanalysis (EPMA) indicated the very small composition difference between

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three ribbons and no significant inhomogeneity within each ribbon. The micromorphologies were observed by scanning electron microscopy (SEM) on the copper wheel contacting surface (CS), the free surface (FS) and the fracture cross sections. The room-temperature crystal structure was identified on both CS and FS by a Regaku D/Max 2200 PC X-ray diffractometer using Cu Kα radiation. The pole figures were measured on a Philips X'Pert MPD instrument using the CuKa radiation. Differential scanning calorimetry (DSC) was used to determine the martensitic transformation temperatures. The temperature and field dependence of the magnetization was measured by vibrating sample magnetometer (VSM), with the magnetic field along ribbon direction.

3. Results and discussions

Fig. 1 shows the SEM morphologies imaged on the fractured cross sections and free surfaces (FS) of the ribbons. When observing on the fractured cross sections, the ribbons were placed with the CS at the bottom and the FS on the top, as indicated in Fig. 1(a). Only grain boundaries were observed on the fractured cross sections, reflecting the typical intergranular fracture feature in all the ribbons. Starting from the CS equiaxial grains are observed, then columnar grains appear and grow upwards to the FS. With the increasing spinning speed, the thickness of the equiaxial grains is decreased and that of the columnar grains is elongated. For ribbon 4000, the columnar grains grow nearly throughout the ribbon thickness. On the FS only typical martensitic twinning morphology is observed. Within each grain the twin lathes are arranged along the same directions. Some twin lathes are even spanned outside to the neighboring grains. Combining the observed columnar grains, texture is believed to exist in the ribbons.

Fig. 2 shows the X-ray diffraction patterns addressed on both CS and FS of the ribbons at room temperature. The appearance of multiple peaks indicates that the specimens are fully polycrystalline. Nearly all the main peaks can be indexed as an orthorhombic structure, while the additional peaks that are not indexed result from the presence of a long-period modulated superstructure referred to as 7 M or 14 M for the orthorhombic [4,18]. No

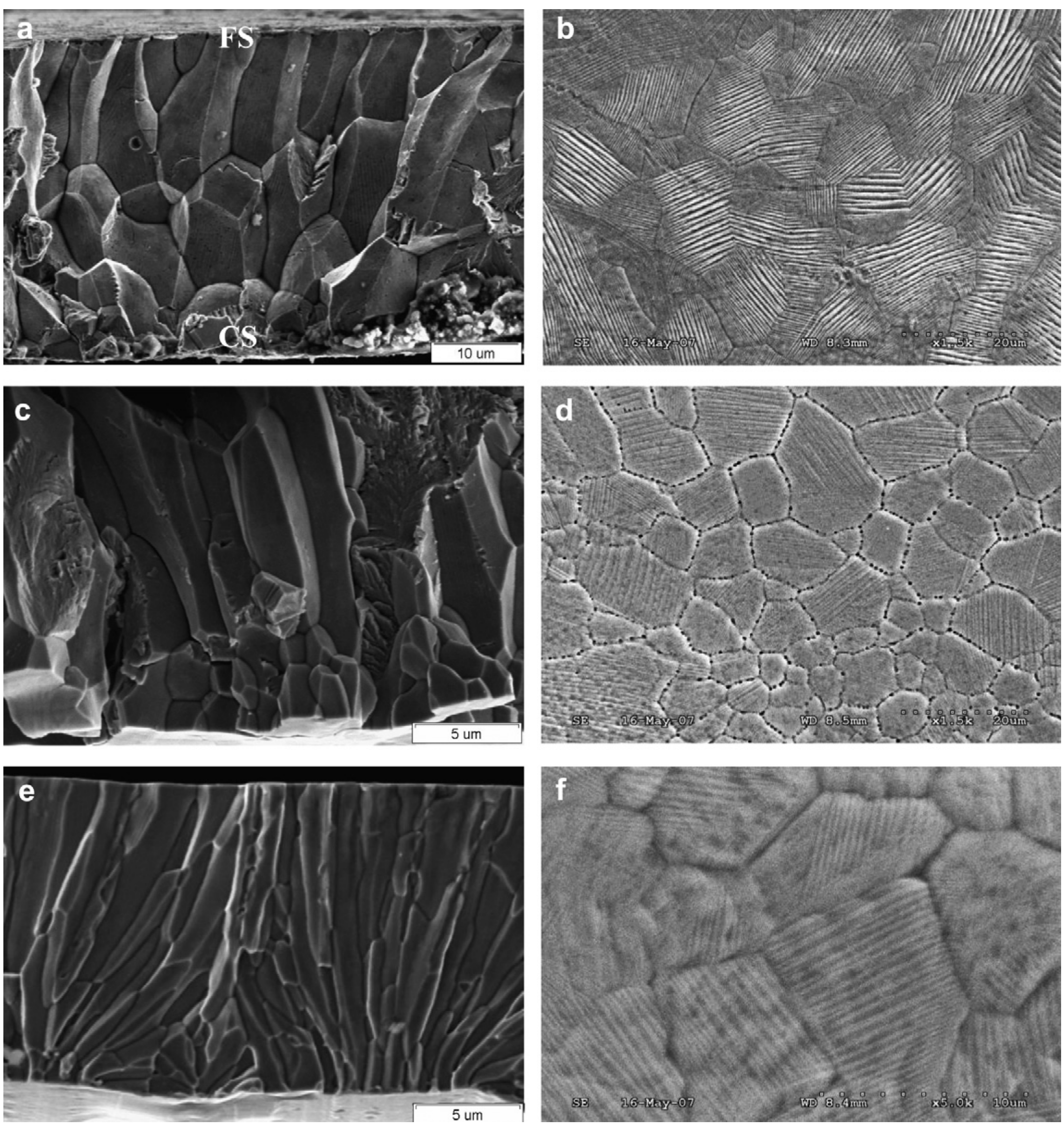

Fig. 1. SEM photographs imaged on the fractured cross sections and the free surfaces of the as-spun ribbons (a) 500, (b) 2000 and (c) 4000. CS means the surface contacting the copper wheel, and FS is the free surface.