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Martensitic transformation and mechanical properties in an aged Ni–Mn–Ga–Ti ferromagnetic shape memory alloy

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ABSTRACT

The martensitic transformation behavior and mechanical properties were investigated in a Ti-doped $Ni_{53}Mn_{23.5}Ga_{18.5}Ti_5$ alloy aged at 873 K for different durations. It is shown that the volume fraction of the Ni_3Ti phase increases and the Ni content in the matrix reduces with increasing aging time, resulting in the decrease of the martensitic transformation temperatures. The precipitation of Ni_3Ti particles strengthens the matrix, resulting in the increasing in the fracture toughness. Fracture morphology observation shows the fracture type changing from intergranular brittleness fracture to a mixture of intergranular and transgranular ductile failure is responsible for the improved mechanical properties.

1. Introduction

During the past few years, considerable attention has been devoted to the Ni–Mn–Ga alloy system due to its large magnetic-field-induced strain (up to 10%) and high response frequency (~kHz), which makes it a potential candidate material for new magnetic actuators. Among many ferromagnetic shape memory alloys, Ni–Mn–Ga alloys are the most popular because of superior properties in magnetic-field-induced strain [1,2]. However, several disadvantages of the Ni–Mn–Ga alloys, including the brittleness, the low strength and poor processability, have severely limited their practical applications. In order to overcome these disadvantages, some methods have been developed, such as thermo-mechanical treatment [3–6], aging [7–10] and alloying [11–13]. However, no obvious improvement was achieved.

Recently, we have reported that the addition of Ti in the Ni–Mn–Ga alloy is effective in improving the fracture strength and ductility, resulting from the precipitation of Ni_3Ti phase [15]. It is generally accepted that the precipitation may change the martensitic transformation by changing the matrix composition and/or creating internal stress around the precipitates [16]. For example, internal stress fields near Ti_3Ni_4 precipitates in NiTi alloys can facilitate nucleation and thus modify transformation temperatures and mechanical properties [17,18]. It is hoped that fine particles would precipitate after proper aging improve the mechanical properties without sacrificing the magnetic properties. Therefore, it is of much importance for further investigation on such compositional polycrystalline Ni–Mn–Ga–Ti alloys. In the present paper, the microstructure, martensitic transformation and mechanical properties have been investigated.

2. Experimental

An alloy with a nominal composition of $Ni_{53}Mn_{23.5}Ga_{18.5}Ti_5$ (at.%) was prepared by the consumable arc-melting in an argon atmosphere using 99.97% electrolytic Ni plate, 99.5% electrolytic Mn plate, 99.99% Ga and 99.92% sponge Ti. The ingot was then remelted for five times to ensure the composition homogeneity. The melted ingots were casted into a chilled copper mold to obtain a master rod with a dimension of ϕ 10 mm × 70 mm. The master rod was sealed in a silica tube with a vacuum of 10^{-4} Torr. After homogenizing at 1273 K for 5 h the ingot was quenched into the ice water. Then some rod samples with a dimension of ϕ 3 mm × 5 mm were cut from the ingots and aged at 873 K for 10 min, 0.5 h, 1 h, 3 h or 10 h.

The transformation temperatures were determined by differential scanning calorimetry (DSC) using a PerkinElmer Diamond calorimeter. The heating and cooling rate was 5 K/min and the temperature range was from 200 K to 400 K. Specimens for microstructure observation were mechanically polished to 50 μm in thickness and then electrochemically polished using an electrolyte of 10% perchloric acid and 90% methanol at 253 K. Transmission electron microscope (TEM) observations were performed by a Philips Tecnai-20 electron microscopic operated at 175 kV. Compression tests were conducted at ambient temperature on an Instron-1186 machine at a strain rate of 0.05 mm/s. Fracture surfaces were observed by scanning electron microscope (SEM) on a Mx2600FE machine equipped with an X-ray energy dispersive spectroscopy (EDS) analysis system.

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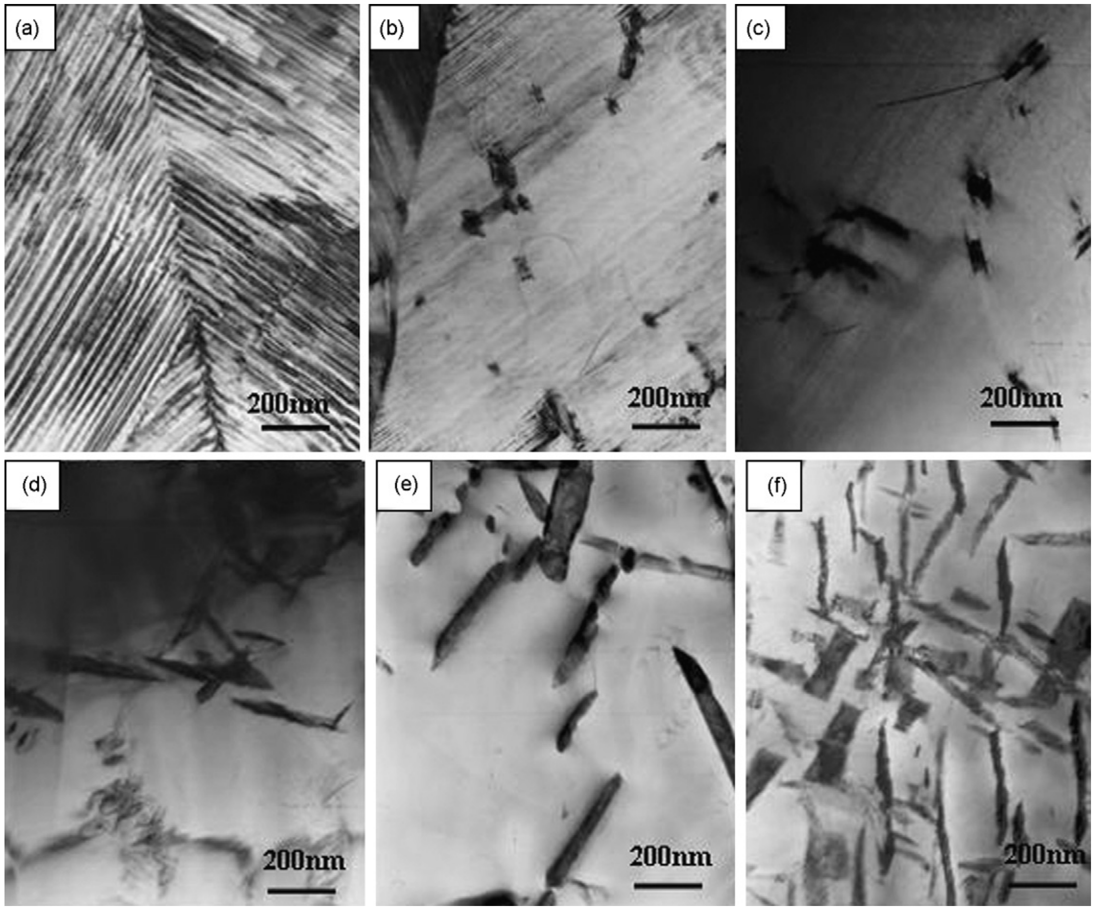

Fig. 1. TEM images of precipitates in the $Ni_{53}Mn_{23.5}Ga_{18.5}Ti_5$ alloy aged at 873 K for different times, (a) t = solution; (b) t = 10 min; (c) t = 0.5 h; (d) t = 1 h; (e) t = 3 h; (f) t = 10 h.

3. Results and discussion

Fig. 1 shows the TEM images of the $Ni_{53}Mn_{23.5}Ga_{18.5}Ti_5$ alloy aged at 873 K for various durations. The typical unitary martensitic phase morphology was observed in the solution-treated samples (Fig. 1(a)) while all aged alloys contains a mount of Ni_3Ti precipitate particles, which is in accordance with the results of Dong et al. [15,19]. It is also noted that the shape and the size of the precipitates would be different with the time prolonging. In the initial time of aging, fine Ni_3Ti particles with a size of about 20 nm formed pin the martensite matrix (Fig. 1(b)). When the aging time was 0.5 h, the size of the precipitates increased to about 40 nm, and the particles still coherent to the matrix, as shown in Fig. 1(c). The precipitates grew to lenticular-like gradually with the diameter of about 70–100 nm and approximate 5 nm thick when the aging time increases to 1 h. Further increasing the aging time to 3 h, Ni_3Ti precipitates formed at extremely high densities with average size of 300 nm, as shown in Fig. 1(d). Further increasing the aging time, the precipitates coarsen and lose the coherency with the matrix gradually. And even sometimes several precipi-

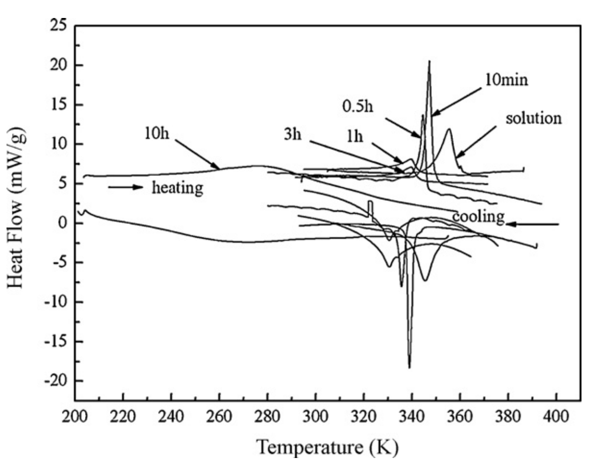

Fig. 2. DSC curves of the $Ni_{53}Mn_{23.5}Ga_{18.5}Ti_5$ alloy aged at 873 K for various time.

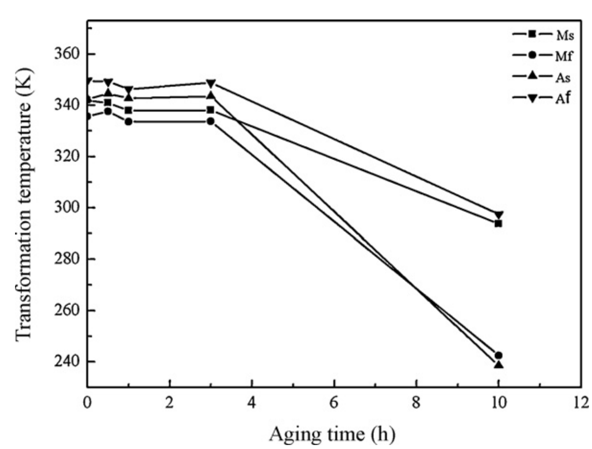

Fig. 3. Martensitic transformations temperatures of aged $Ni_{53}Mn_{23.5}Ga_{18.5}Ti_5$ alloy as a function of the aging time.