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Effect of Ge addition on the martensitic transformation temperatures of Ni–Fe–Ga alloys

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ABSTRACT

A systematical study of substitution of Ge for Ni, Fe, and Ga in the non-stoichiometric NiFeGa alloys was performed in this work. The effect of Ge addition on the structure and martensitic transformation in NiFeGa alloys was investigated by an optical microscope, X-ray diffraction, and differential scanning calorimeters. The results show that the transformation temperatures decrease almost linearly with increasing Ge content in all the three types from higher than 100 down to −90 °C and even lower. The decreases in rate of the martensitic transformation temperatures are different for the three cases. It is large for Ni substituted by Ge, slow for Ga and intermediate for Fe. The determined relationship will be significant for designing a suitable NiFeGa alloy with a required martensitic transformation temperature for application at specific temperature.

1. Introduction

In recent years, the NiFeGa ternary alloy systems have been developed as new member of the ferromagnetic shape memory alloys (FSMAs) [1,2], which are potential alternative to the well-known Ni–Mn–Ga alloys due to their fabricating more easily than Mn-contained alloys because Mn vaporizes at relatively low temperature, as well as their significantly improved ductility [1,3]. Furthermore, NiFeGa alloys exhibit thermoelastic martensitic transformation (MT) upon cooling and heating process. The MT in these alloys is correlative with a structural transition from a parent phase B2/$L2_1$ Heusler structure to modulated layered structures (i.e. five layered, 10 M and seven layered, 14 M) [1]. The MT temperatures are very important for the application of these alloys. It is well known that the MT temperatures are very sensitive to the compositions of this alloy [1,3–5]. The MT temperatures decrease with increasing Fe content at a fixed Ga content. By increasing the Fe content, the MT can occur from either paramagnetic parent phase or ferromagnetic austenite phase to ferromagnetic martensite [1]. Moreover, heat treatment plays a significant role in tailoring the MT temperatures of NiFeGa alloys. Some researchers have reported the aging effects on martensitic and magnetic transitions of NiFeGa alloys [3,6,7].

Presently, alloying is thought to be an effective way to adjust the MT temperatures and the magnetic properties. Guo et al. [8] found that the substitution of Ga element with Fe increased the MT temperatures. However, Liu et al. [9] observed that as the Mn atoms were substituted with Fe, the MT temperature shifts to lower temperature, while the thermal hysteresis of transformation and the Curie temperature are increased. The effect of Bi, Pb, Sn, Zn, Si, In, Co, and Cu on the MT of NiMnGa alloys has been reported [10–12]. Tsuchiya et al. [13] and Gao et al. [14,15] doped Ni–Mn–Ga alloys with rare-earth elements (Nd, Sm, Tb, Dy, and Gd) and found that the addition of rare earth significantly influenced the MT behaviors of the alloys. Imano et al. [16] reported that the MT temperatures decreased with the substitution of Ni atoms with Co in Ni–Fe–Ga alloys, while the Curie temperatures increased with increasing Co content. However, Zheng et al. [17] reported that substitution of 4.5 at.% Ga with Co in Ni56.5Fe19.0Ga24.5 alloy leads to an increase of the M_s temperature from 300.54 to 388.24 K. Furthermore, it is suggested that alloying with In is an effective way to change the microstructure and the MT temperatures of Ni–Fe–Ga alloys [18]. The addition of Ge will greatly influence the microstructure, the MT behaviors and the magnetic properties of Ni–Fe–Ga alloys. However, there is no report on the substitution of Ge in Ni–Fe–Ga alloys up to date. In the present work, a systematic study of Ge substitution for Ni, Fe, and Ga was performed to characterize the effect of the addition of Ge on the microstructure and the MT temperatures of polycrystalline $Ni_{56.5}Fe_{17}Ga_{26.5}$ shape memory alloy.

2. Experimental

Three types of alloys with the nominal composition of $Ni_{56.5-x}Fe_{17}Ga_{26.5}Ge_x$ (x = 0, 0.5, 1, 2), $Ni_{56.5}Fe_{17-y}Ga_{26.5}Ge_y$ (y = 0,

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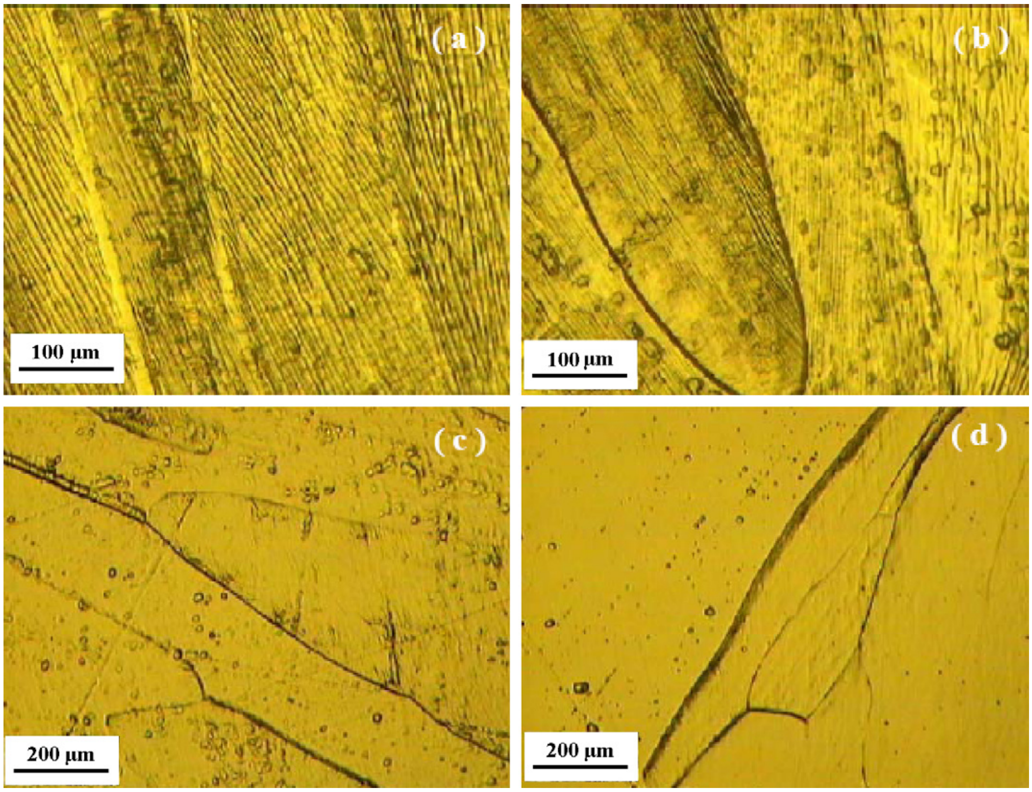

Fig. 1. Optical microscope photographs of $Ni_{56.5-x}Fe_{17}Ga_{26.5}Ge_x$ $x = 0$ (a), $x = 0.5$ (b), $x = 1.0$ (c) and $x = 2.0$ (d) alloys at room temperature.

0.5, 1, 2), and $Ni_{56.5}Fe_{17}Ga_{26.5-z}Ge_z$ ($z = 0$, 1, 2, 3) with weight of ~10 g were prepared using a suck-casting method. These alloys were fabricated by melting four times in a non-consumed vacuum arc furnace under an argon atmosphere using appropriate quantities of Ni (99.99% purity), Fe (99.99% purity), Ga (99.99% purity) and Ge (99.999% purity). The obtained button ingots were re-melted and suction-cast into a cylindrical copper mold set at the bottom furnace to prepare a rod with diameter of ~3 mm.

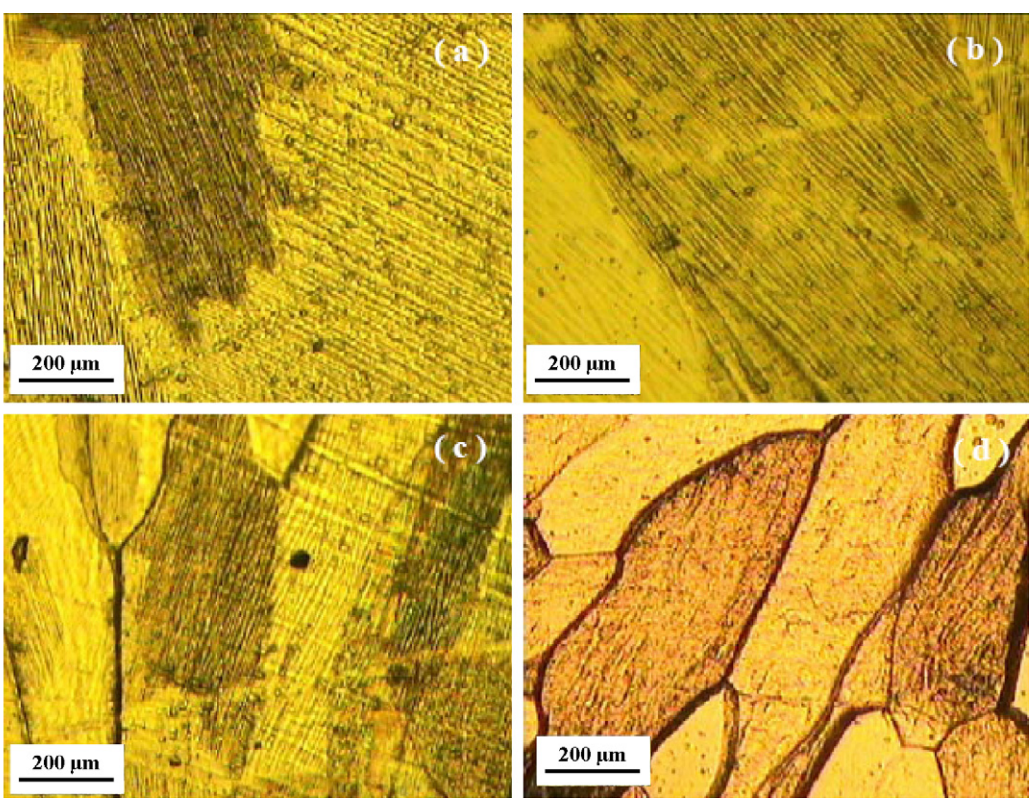

Fig. 2. Optical microscope photographs of $Ni_{56.5}Fe_{17}$ $Ga_{26.5-z}Ge_z$ $z = 1.0$ (a), $z = 2.0$ (b), $z = 3.0$ (c) and $z = 5.0$ (d) alloys at room temperature.