Magnetic and Martensitic Phase Transformations in a Ni_{54}Ga_{27}Fe_{19} Alloy

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The martensitic and magnetic transitions of Ni_{54}Ga_{27}Fe_{19} alloy were investigated by differential scanning calorimetry and X-ray powder diffraction with a vibrating sample magnetometer. The alloy is martensitically transformed from a L2₁ to a martensite phase with a 14M (7R) structure. The ferromagnetic transition is also accompanied by the martensitic transformation from a paramagnetic parent phase to a ferromagnetic martensite phase in the temperature interval between \( T_f (= 293 \text{ K}) \) and \( T_r (= 274 \text{ K}) \). The Ni–Ga–Fe system is promising as a ferromagnetic shape memory alloy.

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1. Introduction

Ferromagnetic shape memory alloys (FSMAs) showing the displacive magnetic transformation in the ferromagnetic state have a possibility of inducing the thermoelastic martensite transformation and rearrangement of martensite variants by applying the external magnetic field. Since a large magnetically induced strain was confirmed in Ni₂MnGa Heusler alloys, extensive studies have been conducted to develop new ferromagnetic shape memory alloys, such as Fe–Pd, Fe₃Pt alloys, Ni₂MnAl, and CoNiGa alloys.

Recently, the present authors have developed new ductile FSMAs with a \( \beta \) phase in Co–Ni–Al and Co–Ni–Ga ternary alloy systems. Since the composition range of the \( \beta \) phase alloy having the FSM is located near the \( \beta/\beta + \gamma \) phase boundary, the \( \gamma \) (A1: disordered fcc) phase which results in the significant improvement of ductility can be introduced in the \( \beta \)-based alloys by suitable choices of the alloy composition and the annealing condition.

The martensite starting temperature \( (M_s) \) of the \( \beta \) phase in the Co–Ni–Al and Co–Ni–Ga systems decreases with increasing Co and Al or Ga content, whereas the Curie temperature and the spontaneous magnetization increase with increasing Co content and with decreasing Al or Ga content. It is considered that the ferromagnetism of these alloys is closely correlated with Co antistructure atoms on the Al or Ga sites.

In the Fe–Ga binary system, the \( \beta \) and \( \gamma \) phases appear in a wide range of composition at temperatures over 892 K. Since the NiGa B₂ phase is stable in wide regions of temperature and composition, the solid solution of (Ni, Fe)Ga B₂ phase is formed at a high temperature. Furthermore, a doping of Fe to the Ni-rich NiGa \( \beta \) phase alloys is expected not only to induce the ferromagnetism in a similar manner as an Fe doped Ni₃Ga L1₂ phase but also to exhibit the thermoelastic martensitic transformation just as Co–Ni–Ga B₂ alloys. The present study has been undertaken to investigate the magnetic transition and the martensitic transformation of a Ni_{54}Ga_{27}Fe_{19} \( \beta \) phase alloy.

2. Experiment

Ni_{54}Ga_{27}Fe_{19} (at%) alloy weighing about 20 g was prepared by a cold crucible levitation melting method, and was cast into a copper mold. Some small pieces of the specimen were taken from the ingot and sealed in a quartz capsule filled with an argon gas. The solution heat treatment was conducted at 1473 K for 10.8 ks and quenched into ice water. The microstructure of the specimen was examined by optical microscopy. The Curie temperature \( T_C \) and the magnetization \( M \) were measured with a vibrating sample magnetometer (VSM), and the martensitic transformation temperatures were determined by differential scanning calorimetry (DSC) with the cooling and heating rates of 10 K/min.

Phase identification and characterization were carried out by X-ray powder diffraction (XRD) using Cu–Kα radiation. The solution treated powder was sealed in a quartz capsule and heat treated at 1473 K for 0.9 ks. After heat treatment, the capsule was dropped into ice water.

3. Results and Discussion

3.1 Microstructures and martensitic transformation temperatures

The optical micrograph at room temperature is shown in Fig. 1. A typical twinned martensitic structure is observed in some regions. This result implies that the transformation temperatures are located in the vicinity of room temperature. Figure 2 shows the DSC curves, where the endothermic and exothermic reactions corresponding to the martensitic transformations were observed upon heating and cooling processes, respectively. The martensitic temperatures \( (M_s = 293, M_f = 274, A_s = 292 \text{ and } A_f = 308 \text{ K}) \) were defined as the cross points of the base line and the tangent of the maximum or minimum inclination in the DSC curves as given in Fig. 2. Since the transformation hysteresis \( (T_h, A_f - M_s = 15 \text{ K}) \) is very small, the transformation is expected to be thermoelastic, exhibiting a shape memory effect. Both the transformation enthalpy and the entropy determined from the DSC curves are about \( \Delta H = 340.28 \text{ J/mol} \)
and $\Delta S = 1.13$ J/mol K, respectively.

Figure 3 are the XRD patterns obtained at room temperature and at 203 K. The spectrum peaks of the parent phase obtained at room temperature are identified well as a BCC structure as indexed in Fig. 3. No extra characteristic peaks of the ordered structures, such as B2, D03 existing in the Fe–Ga and Ni–Ga binary systems, were clearly confirmed from the XRD result, because the atomic scattering factors of Fe, Ni and Ga are close one another. The crystal structure of the parent phase at room temperature was identified as the L2$_1$ Heusler type by transmission electron microscopic (TEM) examination. Furthermore, the dark field image taken from the (111)$_{L2_1}$ super-lattice reflection showed small anti-phase domains (APDs) with several decades nanometer in diameter, while no APD structure was observed in that from the (200)$_{L2_1}$ reflection. This fact suggests that the parent phase with the B2 structure at the annealing temperature of 1473 K transforms to the L2$_1$ structure during quenching. Details of the TEM examination will be presented in the separate paper. Weak spectra matched with those of disordered fcc ($\gamma$) phase were also observed, although no $\gamma$ phase was confirmed in the bulk sample by the optical microscopic observation. The $\gamma$ phase probably precipitates during the cooling process, because the cooling rate from the heat treatment temperature of the powder without breaking the quartz tube is slower than that of the quenched bulk sample. The X-ray diffraction lines at 203 K for the martensite phase are identified well as a 14M (7R) structure as indexed in Fig. 3. The lattice parameters have been determined for the martensite phase as $a_{14M} = 0.427$ nm, $b_{14M} = 0.270$ nm, $c_{14M} = 2.930$ nm and $\beta_{14M} = 86.6^{\circ}$. The 14M martensite phase was observed in NiAl $\beta$ phase binary and its ternary alloys. According to the corresponding lattice constants between the L1$_0$ and 14M structures, the $c/a_{L1_0}$ of the L1$_0$ structure is given by $c/a_{L1_0} = \sqrt{2} = 1.414$. The ratio of $c/a_{14M}$ calculated from $a_{14M} = 0.865$ of Ni$_{57}$Al$_{25}$Fe$_{18}$ alloy.

### 3.2 Magnetic transition

Figure 4(a) shows the thermomagnetization curves in a magnetic field of 0.04 MAm$^{-1}$ on heating and cooling process for Ni$_{54}$Ga$_{27}$Fe$_{19}$ alloy. The curves exhibit a clear hysteresis, implying that this ferromagnetic transition is of a first-order transition. Figure 4(b) shows the temperature derivative of magnetization, $\partial M/\partial T$, for the thermomagnetization curve in Fig. 4(a). When the transition temperatures are defined as the cross point of the base line and the tangent of the maximum inclination as shown in Fig. 4(b), the transition temperatures ($M_s = 289$, $M_f = 278$, $A_s = 291$ and $A_f = 303$ K) are almost coincident with the values determined from the DSC curves. The magnetization curves of the martensite phase at 263 K and the parent phase at 309 K are shown in Fig. 5. The martensite phase shows typical magnetization curve of the ferromagnetism, while that of the parent phase is likely the paramagnetism. It is confirmed that the parent phase dose not show spontaneous magnetization from the Arrott plots for the data in Fig. 5, namely, the parent phase is the paramagnetism. These results mean that the magnetic transition is caused by the martensitic transformation from the paramagnetic parent phase to the ferromagnetic martensite phase in analogy with a Co$_{35}$Ni$_{53}$Al$_{30}$ (B2) and Ni$_{54.75}$Mg$_{20.25}$Ga$_{25}$ (L2$_1$) Heusler alloys. The saturation magnetization $M_s$ and the high-field susceptibility $\chi_M$ of the martensite phase at 263 K are esti-
Fig. 4 Temperature dependences of the magnetic properties in a magnetic field of 0.04 MAm$^{-1}$ for Ni$_{54}$Ga$_{27}$Fe$_{19}$ alloy. (a) magnetizations $M$ of heating and cooling processes, (b) temperature derivative of magnetization, $\partial M/\partial T$.

Fig. 5 Magnetization curves of the martensite phase at 263 K and the parent phase at 309 K for Ni$_{54}$Ga$_{27}$Fe$_{19}$ alloy. $M_s = 29.5$ Am$^2$/kg and $\chi_{hf} = 3.45 \cdot 10^{-6}$ m$^3$/kg. These values are larger than those of the Co$_{35}$Ni$_{35}$Al$_{30}$ alloy in the martensite phase near $A_s$ temperature evaluated as $M_s = 25.0$ Am$^2$/kg and $\chi_{hf} = 2.60 \cdot 10^{-6}$ m$^3$/kg at 233 K. These results suggest that the martensitic transformation in the Ni$_{54}$Ga$_{27}$Fe$_{19}$ alloy is expected to be induced by lower magnetic field than that of the Co$_{35}$Ni$_{35}$Al$_{30}$ alloy.

4. Conclusion

The martensitic and magnetic transitions of Ni$_{54}$Ga$_{27}$Fe$_{19}$ alloy have been investigated. This alloy martensitically transforms from a L2$_1$ parent phase to a 14M martensite phase. The ferromagnetic transition is caused by the martensitic transformation from a paramagnetic parent phase to a ferromagnetic martensite phase. The present Ni–Ga–Fe system is promising as a new ferromagnetic shape memory alloy.

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