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A linear elastic $Ni_{50}Mn_{25}Ga_9Cu_{16}$ martensitic alloy

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Abstract The linear elasticity was studied in a martensitic alloy $Ni_{50}Mn_{25}Ga_9Cu_{16}$. A 0.4 % linear elastic strain is obtained in the polycrystalline sample under compressive stress of 745 MPa. The elastic modulus is 186 GPa. The obtained linear elastic strain and elastic modulus are much higher than that of ternary Ni–Mn–Ga martensitic alloys.

Keywords Ni–Mn–Ga; Linear elasticity; Elastic modulus; Martensite

1 Introduction

Ni–Mn–Ga alloys are a recently developed ferromagnetic shape memory alloy (FSMA) system. Giant magnetostrain and magnetic-field-induced shape memory effect were widely studied in Ni–Mn–Ga FSMAs [1–6]. Like most shape memory alloys, such as Ni–Ti [7, 8], Cu–Zn–Al [9], and Fe–Pt alloys [10], Ni–Mn–Ga alloys also exhibit large pseudoelasticity, a nonlinear stress–strain behavior caused by the stress-induced martensitic transformation [11–13]. Also, there is another mode of elasticity deformation in Ni–Mn–Ga alloys, i.e., the linear elasticity, which generally takes place in all materials. It is well known that the linear elasticity is with narrow-hysteresis feature, which is quite different from the pseudoelasticity. Thus, exploring the linear elasticity may extend the applications of Ni–Mn–Ga alloys in sensors and actuators. However, compared with the intensively studied magnetostrain and pseudoelasticity, the linear elasticity of Ni–Mn–Ga alloys has been overlooked for a long time. To date, only limited studies have been addressed on this issue. Obvious elastic modulus changes were monitored in single crystals during the martensitic transformation [14, 15]. Recently, large linear elastic strain was observed in Ni–Mn–Ga single crystals under the compressive stress ~100 MPa [16]. Recently, we have reported that Cu addition can effectively improve the ductility and strength of Ni–Mn–Ga alloys [17]. This gives rise to the opportunity of investigating the linear elasticity of the polycrystalline samples. In this paper, we report a polycrystalline martensitic alloy $Ni_{50}Mn_{25}Ga_9Cu_{16}$ with 0.4 % linear elastic strain under the stress of 745 MPa, and the elastic modulus of 186 GPa. This may extend the applications of Ni–Mn–Ga alloys in sensors and actuators, especially under high stresses.

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2 Experimental

High-purity starting elements nickel, manganese, gallium, and copper with the purity of 99.9, 99.7, 99.99, and 99.99 %, respectively, were remelted four times by arc melting under argon protection. The button ingots were then cast into chilled copper mold to obtain a $Ni_{50}Mn_{25}Ga_9Cu_{16}$ master rod with the size of Φ7 × 100 mm. The rods were sealed under vacuum in quartz tubes and annealed at 900 °C for 48 h, followed by water quenching. Cylindrical samples of Φ7 × 20 mm were cut from the rod for the compression tests. The micromorphology was observed at room temperature by optical microscope (Olympus BX51M), after etching the samples in a solution of 4 g copper sulfate, 20 mL hydrochloric acid, and 20 mL water. The martensitic transformation temperatures were

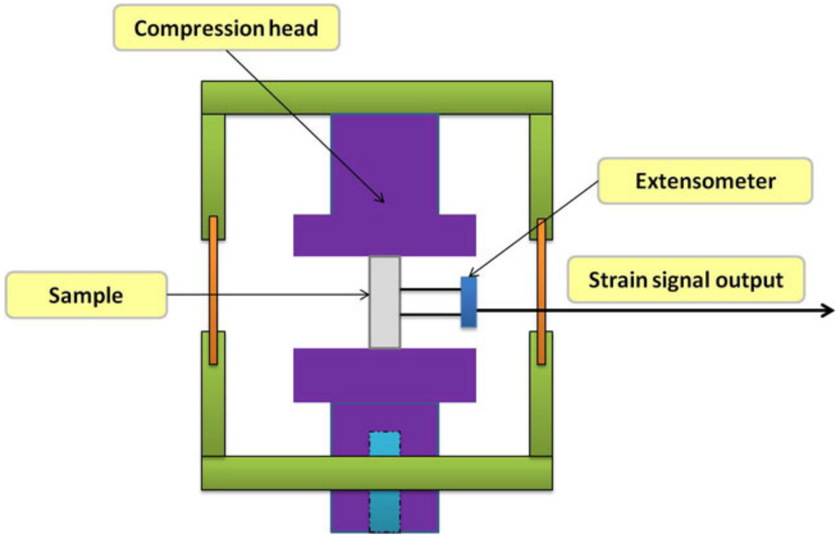

Fig. 1 Schematic diagram of the compression tests. An extensometer is directly fixed on the sample to detect the strain purely from the sample deformation

determined by differential scanning calorimetry (DSC Perkin-Elmer) with heating and cooling rates of 20 K·min^{-1}. The linear elasticity was checked by testing the compressive stress–strain curves on the Instron 8801 mechanical testing machine, with loading and unloading strain rates of 0.05 mm·mm^{-1}. During the strain tests, in order to avoid the influence of the machine, an extensometer was directly linked to the sample to detect the deformation strain purely from the sample, as schematically shown in Fig. 1.

3 Results and discussion

Figure 2a shows the DSC curves of $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy. The exothermic and endothermic peaks monitored on heating and cooling cycles are due to the forward and reverse martensitic transformation, respectively. The forward martensitic transformation start, peak, and finish temperatures, M_s, M_p, and M_f are 640, 630, and 613 °C, respectively. The reverse martensitic transformation start, peak, and finish temperatures, A_s, A_p, and A_f are 665, 680, and 708 °C, respectively. The transformation hysteresis is $A_s - M_s = 25$ °C, exhibiting typical thermoelastic features of the martensitic transformation. Figure 2b shows the optical morphology observed for $Ni_{50}Mn_{25}Ga_9Cu_{16}$ at room temperature. The typical self-accommodated twinning morphology confirms the detected martensitic transformation. Thus, the present $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy is in the martensite state at room temperature.

Figure 3 shows the compressive stress–strain curves of the polycrystalline $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy tested at room temperature. Two cylindrical samples with the size of

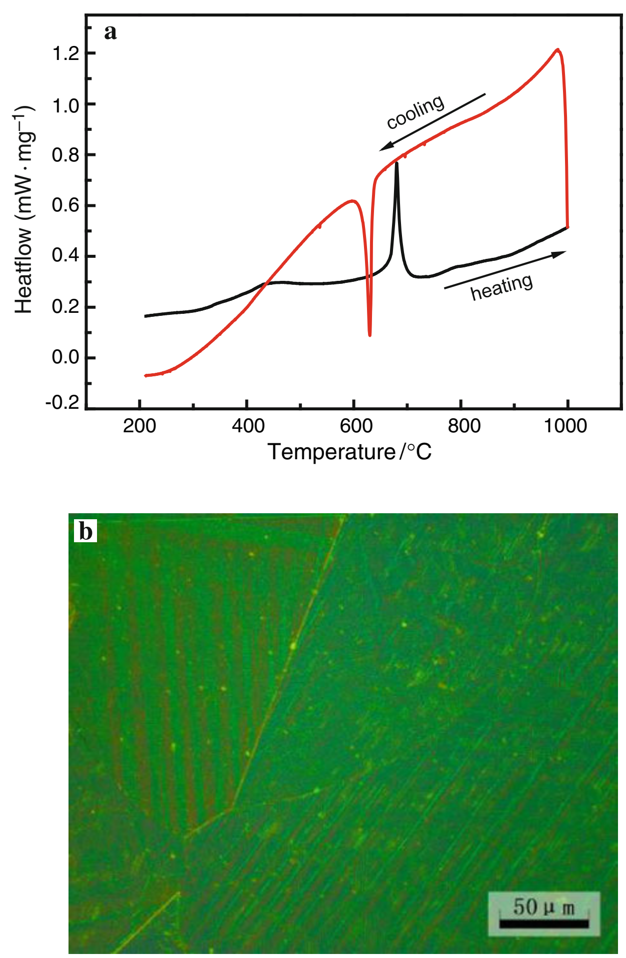

Fig. 2 DSC curves (**a**) and optical micrograph (**b**) $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy

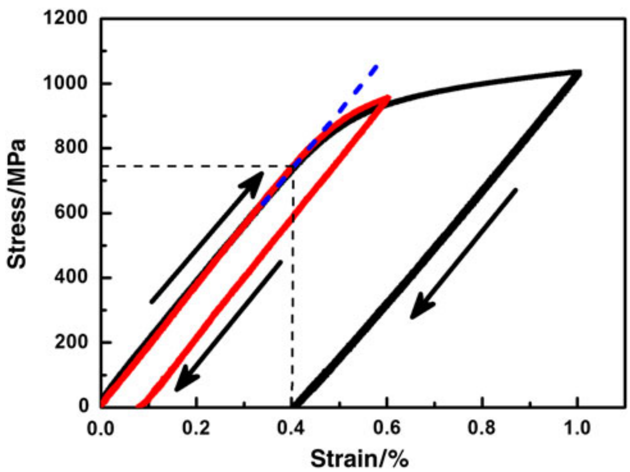

Fig. 3 Stress vs Strain curves of $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy

$\Phi 7 \times 20$ mm were precompressed to $\varepsilon_{pre} = 0.6$ %, and $\varepsilon_{pre} = 1.0$ %, respectively, and then unloaded. As described in the experimental methods section, the tested compressive strain is purely from the deformation of the sample. Two stages of different deformation features are observed on the curves, i.e., the elasticity and plasticity. Taking the curve with prestrain of $\varepsilon_{pre} = 1.0$ % as an example, at the first stage, the strain gradually increases linearly with the increasing stress, indicating the linear elastic deformation feature. When the sample is strained to 0.4 %, the curve deviates from the linear stage. The sample begins to yield and plastic deformation occurs. The yield stress is 745 MPa. During unloading, 0.6 % recovery strain and 0.4 % residual strain are monitored. The linear feature of the unloading curve indicates that the 0.4 % elastic strain during loading is fully recovered. On the other hand, the fact that the recovery strain is higher than the elastic strain observed during the loading process implies that the yield of the sample is the co-occurrence of the elastic and plastic deformation. The 0.4 % residual strain is due to the plastic deformation. For the smaller prestrain of $\varepsilon_{pre} = 0.6$ %, the stress–strain curve is similar to that of $\varepsilon_{pre} = 1.0$ % except that a smaller plastic deformation strain is observed. It is worth noting that both curves are fully overlapped at the linear stage on loading. Therefore, the present polycrystalline $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy possesses a linear elastic strain limit of 0.4 %, which is higher than the general linear elastic limit strain of 0.2 % for most alloys.

As well as the elastic limit strain there is another important parameter of the linear elasticity, i.e., the elastic modulus E_c. Generally the elastic modulus is defined as the slope of the linear stage of the stress–strain curves, i.e., $E_c = \sigma/\varepsilon$. In Fig. 3, the elastic modulus is calculated to be $E_c = 186$ GPa. Previously, large linear elasticity was obtained in the single-variant single crystal of Ni–Mn–Ga alloys [16]. According to Ref. [16], the elastic modulus of the single variant was calculated to be $E_c = 0.6$ GPa. Here, it obtained much higher elastic modulus allows the alloys to be used under high stresses. This may extend the applications of the linear elasticity of Ni–Mn–Ga alloys under high stresses.

Furthermore, a comparison on the compressive stress–strain behavior is addressed between the present $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy and the other two martensitic alloys, $Ni_{50}Mn_{28}Ga_{22}$ and $Ni_{50}Mn_{25}Ga_{22}Cu_3$ [17]. Figure 4 shows the compressive stress–strain curves of all the polycrystalline alloys strained to 0.6 %. For the convenience of comparison, the stress–strain curves of $Ni_{50}Mn_{28}Ga_{22}$ and $Ni_{50}Mn_{25}Ga_{22}Cu_3$ are enlarged and shown in the inset in Fig. 4. No obvious linear elastic deformation is observed on the stress–strain curves of $Ni_{50}Mn_{28}Ga_{22}$ and $Ni_{50}Mn_{25}Ga_{22}Cu_3$ alloys. The recovered strain and the residual strain after unloading indicate that the nonlinear loading curves are the mixture of elastic and plastic deformations. Comparably, obvious linear elastic deformation feature is observed on the stress–strain curves of $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy. Moreover, the yield stress is much higher than that of $Ni_{50}Mn_{28}Ga_{22}$ and $Ni_{50}Mn_{25}Ga_{22}Cu_3$ alloys. Previously, we have confirmed that at room temperature, $Ni_{50}Mn_{28}Ga_{22}$ and $Ni_{50}Mn_{25}Ga_{22}Cu_3$ alloys possess single martensite phase with body-centered tetragonal structure, while $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy possesses single martensite phase with face-centered tetragonal structure. Thus, the observed obvious linear elasticity in $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy may be related with the face-centered tetragonal (fct) structure of the martensite. More detailed in situ studies, including optical morphology, X-ray, and neutron diffractions under stress, will be performed in the next step to understand the observed linear elasticity.

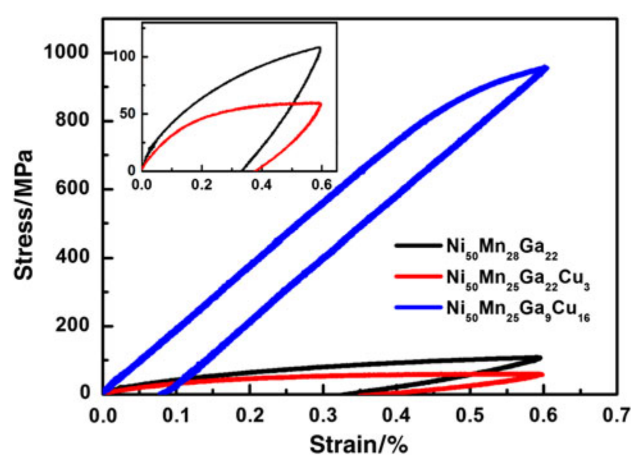

Fig. 4 Compressive stress-strain curves of $Ni_{50}Mn_{28}Ga_{22}$, $Ni_{50}Mn_{25}Ga_{22}Cu_3$ and $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloys

As for the linear elasticity of the present $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy, three features should be noted. First, the 0.4 % linear elastic strain obtained in the polycrystalline $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy is much higher than the linear elastic strain limit of 0.2 % for most metals and alloys. Higher linear elastic strain is expected in preferentially oriented polycrystals or single crystals. Second, the elastic modulus and yield stress of $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy is much higher than that of Ni–Mn–Ga alloys. Third, the stress inducing the linear elasticity in the $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy is much higher than that (generally about 200 MPa or less) inducing the nonlinear pseudoelasticity. Thus, the presently obtained large linear elastic strain and high elastic modulus in $Ni_{50}Mn_{25}Ga_9Cu_{16}$ alloy may allow Ni–Mn–Ga–Cu alloys to be used in sensors and actuators under high stresses.

4 Conclusion

In summary, 0.4 % linear elastic strain was obtained in the polycrystalline martensitic alloy $Ni_{50}Mn_{25}Ga_9Cu_{16}$, with the elastic modulus of 186 GPa and yield stress of 745 MPa. The linear elastic strain and elastic modulus are much higher than that of ternary Ni–Mn–Ga alloys.

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