Superelasticity of CoNiGa:Fe single crystals

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We have fabricated CoNiFeGa single crystals with excellent superelasticity. The superelastic strains of 4% and 6.7% in compression have been obtained along the [001] and [110] directions, respectively. These single crystals show strong anisotropy in strains, superelastic parameters, and even transformation path related to the different crystalline directions. A large superelastic strain up to 11% has been obtained in tension test. The perfect superelasticities have also displayed in bending and torsion tests. © 2005 American Institute of Physics. [DOI: 10.1063/1.2045563]

Since the discovery of Ni$_2$MnGa ferromagnetic shape memory alloy (FSMA), many new FSMA s such as FePt, NiFeGa, CoNiAl, and CoNiGa (see Refs. 5–8) have been subsequently developed. Polycrystalline CoNiGa had a superelastic strain of more than 4% in compression. Previous results also suggested that NiMnFeGa has better mechanical properties than those of ternary NiMnGa. It is therefore plausible to improve the mechanical properties by adding Fe to CoNiGa alloys. In this work, the superelasticities of CoNiFeGa single crystals have been investigated. Large superelasticities were obtained in various stress conditions including compression, tension, bending, and torsion. The direction dependence of superelasticities and the intermartensitic superelasticity have also been studied.

The Co$_{90}$Ni$_{32}$Ga$_{28}$:Fe$_x$ ($x=0,1.5,2,2.5$) single crystals were grown along the [001] direction using the Czochralski method. Metal elements Co, Ni, Fe, and Ga of 99.95% purity were used as starting materials. Single-crystal samples were cut into $1 \times 3 \times 5$ mm$^3$ pieces along the different directions for strain measurements. Similarly, $1 \times 1 \times 10$ mm$^3$ bar samples were used for bending and torsion experiments. Compression and tension tests were carried out in an extensometer.

Figure 1 shows the temperature dependence of the transformation strains ($\epsilon$) for the undoped and doped single crystals. The martensitic transformation temperature ($T_M$) is the highest for the undoped sample and decrease steadily with increasing Fe content. This implies that the Fe dopants tend to stabilize the parent phase. The addition of Fe slightly improves the transformation strains over the undoped sample, clearly indicating the existence of the preferential orientation of martensitic variants. From Fig. 1, one can also observe that the thermal hysteresis increases slightly with increasing Fe content. This result implies that the friction losses of phase boundary motion increase and more elastically stored energy is relaxed.

Figure 2 shows the stress-strain curves tested along the [001] and [110] directions of Co$_{90}$Ni$_{32}$Ga$_{28}$:Fe$_x$ ($x=0,1.5,2,2.5$) free single crystals.

![Figure 1. Temperature dependence of the strain measured along the [001] direction of Co$_{90}$Ni$_{32}$Ga$_{28}$:Fe$_x$ ($x=0,1.5,2,2.5$) free single crystals.]
Martensitic transformation occurred around 70 MPa. A plateau appeared in higher stress of about 100 MPa, suggesting an intermartensitic transformation occurred. Two sets of crossed martensitic variants were observed [the inset of Fig. 3(a)] using a metallographic method on the (001) polished surface stressed at 100 MPa. During unloading, two reversed transformations were also observed. Such multitransitional phenomena have often been observed in NiMnGa and other alloys.\textsuperscript{14–16} On the other hand, only a single transformation was observed in NiFeGa\textsuperscript{15} and NiMnGa\textsuperscript{16} in tension, but they are associated with intermartensitic transformations. In Co\textsubscript{50}Ni\textsubscript{22}Ga\textsubscript{28} :Fe\textsubscript{2} single crystal, the superelasticity is only from a complete single martensitic transformation.

Perfect superelastic strain up to 11\% with a low critical stress of 83 MPa has been obtained in tensile test in Co\textsubscript{50}Ni\textsubscript{22}Ga\textsubscript{28} :Fe\textsubscript{2} single crystal along the [001] direction, as shown in Fig. 4. The deformation was reversible with a small stress hysteresis of 45 MPa during unloading. Such superelasticity is much larger than that created in the compression test. This can be primarily attributed to the difference in the variants and the effect of detwinning. Along the [001] direction, the Co\textsubscript{50}Ni\textsubscript{22}Ga\textsubscript{28} :Fe\textsubscript{2} sample exhibits different martensitic elastic moduli of 22 GPa and 15 GPa in compression and tension, respectively, implying that different martensite or reorientation of variants might be induced under different stress conditions. Different variants have been observed using an in situ single-crystal x-ray diffraction method in NiMnGa single crystals under compression and tension.\textsuperscript{14} In addition, the detwinning can increase the strain under tensile loadings but no effect during compression.\textsuperscript{15} Large strains of more than 10\% have also been reported in NiFeGa\textsuperscript{15} and NiMnGa\textsuperscript{16} in tension, but they are associated with intermartensitic transformations. In Co\textsubscript{50}Ni\textsubscript{22}Ga\textsubscript{28} :Fe\textsubscript{2} single crystal, the superelasticity is only from a complete single martensitic transformation.

Finally, we performed two more complex superelastic experiments, bending and torsion, in Co\textsubscript{50}Ni\textsubscript{22}Ga\textsubscript{28} :Fe\textsubscript{2} single crystal. The $1 \times 1 \times 10$ mm\textsuperscript{3} bar sample recovered fully after being bent in a semicircle or twisted 90° (Fig. 5), showing more complicated superelastic properties. For CoNiGa samples, the superelasticities have also been observed in compression, but there are no reported results in tension, bending, or torsion tests. All these results indicate that Fe dopant can make the crystal lattice ductile but are difficult for slipping and dislocation to occur.

In summary, the superelasticity has been investigated in Fe-doped CoNiGa single crystals. The superelastic strains of 4\% and 6.7\% in compression have been obtained along the [001] and [110] directions, respectively. The strong aniso-

![FIG. 3. Compression stress-strain curves for Co\textsubscript{50}Ni\textsubscript{22}Ga\textsubscript{28} :Fe\textsubscript{1.5} single crystal along the [001] and [110] directions.](Image)

![FIG. 4. Tensile stress-strain curve for Co\textsubscript{50}Ni\textsubscript{22}Ga\textsubscript{28} :Fe\textsubscript{2} single crystal along the [001] direction.](Image)

TABLE I. The transformation strains $\varepsilon$, the Young’s modulus of parent phase $Y_p$, the elastic modulus of martensite $Y_m$, the critical stress $\sigma_c$, the critical energy density $E_c$, and the press hysteresis $\delta_o$ of Co\textsubscript{50}Ni\textsubscript{22}Ga\textsubscript{28} :Fe\textsubscript{2} single crystal.

<table>
<thead>
<tr>
<th>Direction</th>
<th>$\varepsilon$ (%)</th>
<th>$Y_p$ (GPa)</th>
<th>$Y_m$ (GPa)</th>
<th>$\sigma_c$ (MPa)</th>
<th>$E_c$ (erg/cm$^3$)</th>
<th>$\delta_o$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[001]</td>
<td>4.0</td>
<td>14</td>
<td>22</td>
<td>104</td>
<td>$4.6 \times 10^6$</td>
<td>70</td>
</tr>
<tr>
<td>[110]</td>
<td>6.7</td>
<td>6.2</td>
<td>15</td>
<td>147</td>
<td>$1.95 \times 10^3$</td>
<td>140</td>
</tr>
</tbody>
</table>
tropy of superelasticity and transition path have also been observed. A large superelastic strain up to 11% has been obtained in tension test. The perfect superelasticities have also been manifested in bending and torsion. These superelastic properties indicate that Fe dopant can significantly enhance the tensile tenacity.

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