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Straining of NiMnGa by stress and magnetic fields

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Abstract

This paper shows that martensitic transformation in Ni_2MnGa strongly depends on stress but is insensitive to magnetic field up to 10 kG. However, stress caused by the force due to inhomogeneous magnetic field affects transformation and can induce large straining. © 2001 Published by Elsevier Science Ltd. on behalf of Acta Materialia Inc.

Keywords: Ferromagnetic shape memory alloy; NiMnGa; Stress-induced transformation; Magnetic field; Superelasticity

Introduction

Martensitic phase transformations are observed in ferromagnetic alloys such as NiMnGa [1], FePd [2,3] and FePt [4]. These alloys exhibit shape memory and small transformation hysteresis, and demonstrate superelastic deformation [5–9]. Purely magnetoelastic martensitic transformations have also been reported [10]. The present paper investigates the role of external magnetic fields in the transformation of a NiMnGa alloy. Unlike some Fe alloys [11,12], the NiMnGa alloys manifest relatively small hysteresis, and effects of magnetic and stress fields on equilibrium between the parent and martensite phases can be studied without the complication of nucleation phenomena.

Bending of small sample strips has been used as a convenient method to study transformation-induced deformation. While we were studying transformation in NiMnGa using this method to detect transformation in a magnetic field, we noticed that any direct magnetic effects on martensitic transformations, if present, were small. Rather, we have found appreciable stress-induced transformations in the material as a result of

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magnetic forces on the sample, the forces which are induced by a magnetic field gradient.

Alloy

Single crystal samples were supplied by AMES laboratory, Iowa. The nominal atomic composition was 50.3% Ni, 22.7% Mn, and 27.0% Ga. The orientation of the crystal growth direction, along which a specimen was cut, was $\langle 2\,2.6\,8\,\bar{1}\rangle$. The transformation temperature M_s varied throughout the sample because of segregation of the alloy constituents during crystal growth. We observed changes of M_s in excess of 10°C/mm along the growth direction. Consequently, an accurate determination of the strain response to stresses and magnetic fields for a known fixed alloy composition was not possible. Nevertheless, we could usefully observe the transformation-induced bending. The region covered by martensite in the present experiment was ferromagnetic in the parent phase at room temperature. An additional polycrystalline specimen having the same nominal composition was used to observe transformation of individual martensite plates. It was also ferromagnetic at room temperature.

Bending in a magnetic field and by external mechanical stress

A thin sheet specimen, 0.5 mm thick, 6 mm wide and 30 mm long, was placed between the two poles of a laboratory electromagnet. The normal of the top surface was $\langle 1\,0\,2\rangle$. One end of the specimen was clamped while the other end was free to move. A small Al sheet was glued to the free end. The applied field was normal to the (unbent) plane of the specimen, Fig. 1(a). The magnetic field (induction) of 10 kG was rapidly applied or removed during slow cooling. When the field was applied at 0°C, the sheet was bent as shown in Fig. 1(b). The relatively small pole-face gap limited the extent of bending. Analysis of the deformation observed in Fig. 1(b) gave an estimated maximum surface strain of the specimen of about 1.5%. When the field was removed, the displacement was only partially restored, as shown in Fig. 1(c). That is, the deformation induced by the application of the field was partially superelastic. A strain of 1.5% is far larger than elastic deformation in lattice – it was caused by martensitic transformation.

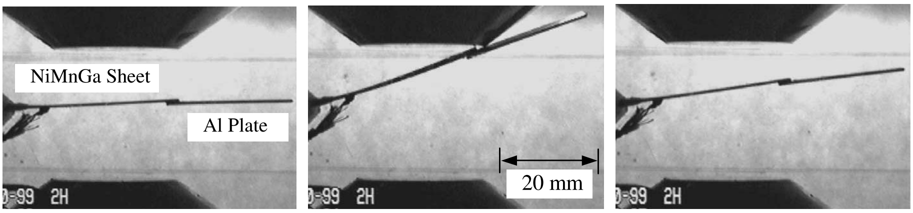

Fig. 1. Bending observed by the rapid application of a magnetic field of 10 kG at 0°C: (a) before the application of the field; (b) during the application; (c) after the removal of the field. The direction of the field is vertical.

We observed the temperature dependence of the bending effect by slowly cooling the sample under a constant field of 10 kG. The specimen started bending at 7°C and increased the bending gradually as the temperature was lowered. It suddenly bent to the limit at about 2.5°C.

We believe that the bending is caused primarily by magnetic forces on the ferromagnetic sample in the inhomogeneous field (i.e. magnetic field gradient). The bending moment induces mechanical stress, which causes or accelerates the martensitic transformation (stress-induced transformation). This conclusion is supported by the following observations: (1) There was a position near the center of the field, the position where very little bending was observed; (2) bending was always towards the nearer pole, when it occurred; (3) when bending occurred to a pole (e.g. pole A), the specimen was purposely moved to the other pole (e.g. pole B), while keeping the field unchanged. During the movement, unbending was observed and further bending occurred to the pole (pole B), to which the specimen was moved. The field is stronger near a pole than in the center. Under the assumption that a specimen is magnetically saturated, the magnetic force per unit volume is the magnetization times the gradient of the field, hence the well-known observation that ferromagnetic materials are attracted to regions of higher field. The substantial bending is achieved by transformation to martensite in response to the stress. Observations (1)–(3) are consistent with this picture. [1] Needless to say, the direction of bending, if observed, remained the same when the field was reversed.

Next, another sheet specimen of a single crystal was again placed between the magnetic poles in a new arrangement, in which a direct mechanical force (bending moment) could also be applied to the specimen by the following method. One end of the specimen was fixed and the other end was glued to an Al plate. A load could be applied to the free end of the Al plate to impose a prescribed bending moment to the specimen. This moment was around the axis parallel to the specimen surface and perpendicular to the specimen length direction. In this setup, the maximum bending was limited to 1.5% by an Al block with a constant curvature, which was placed under the sheet specimen. The block also served as a reference for focusing the optics. The applied magnetic field was approximately in the plane of the sample, perpendicular to the length direction. The mechanical moment produced by magnetic force was thus mostly normal to the sample plane. The specimen had large stiffness against this moment and no bending was visually observed. In the experiment, a small initial moment was applied using the method mentioned above. The maximum stress induced by this moment was about 4 MPa. The temperature was lowered, and a sharp boundary between the transformed and untransformed regions advanced from the clamped end, as shown in Fig. 2(a). (The clamped end had highest Ms.) At 1°C, a bending moment producing a maximum tensile stress of 92 MPa was applied by loading the free end of the Al plate. This caused the boundary to advance about 0.4 mm, Fig. 2(b). At the same time, martensite plates, having the same shape as those in the previously transformed region, appeared in front

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[1] In principle, if the magnetization of the sample is not parallel to the applied field due to shape or crystal anisotropy, a distributed torque acts on the sample in a homogeneous external field. This torque would appear as an effective force and would produce a similar bending effect.

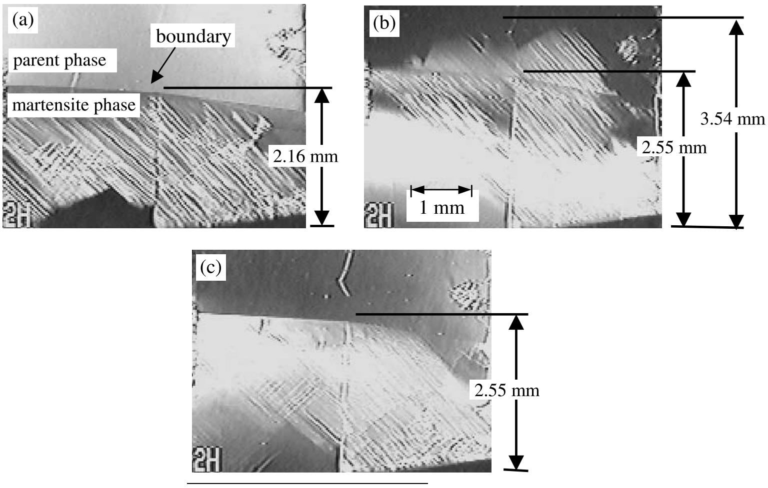

Fig. 2. Change in the surface structure due to forward and reverse transformation produced by the application of stress and its removal at 1°C: (a) before the application of stress; (b) during the application of stress; (c) after the removal of stress.

of the advancing boundary. The largest distance from the original boundary to the newly formed martensite plates was 1.4 mm, Fig. 2(b). When the external force was removed, the latter plates disappeared, but the advanced front remained in the same position, as shown in Fig. 2(c). Partial superelasticity, in addition to stress-induced transformation, was thus confirmed optically.

However, when a magnetic field of 10 kG was rapidly applied or removed, the boundary showed no detectable movement. (A small bending moment was applied to the specimen in this case, too, to make the specimen position stable.) Similar experiments were conducted to see the effect of the application of a 10 kG magnetic field on transformation, while the largest mechanical moment was being applied (stress: 92 MPa). No change in the transformation front or the structure in the transformed region was observed. The direct effect of a magnetic field, if present, was too small to be detected.

The following is a quantitative analysis of the above observations. The surface tensile stress, 92 MPa applied for the change from Fig. 2(a) and (b), supplied the work of 1.4×10^6 J/m^3. The work was calculated using the strain of 0.015. The enthalpy of the transformation was estimated to be 1.1×10^7 J/m^3, using the result of a differential thermal analysis conducted for a small polycrystalline sample. The estimation assumed the Dulong–Petit law and the metallographic estimation of the fraction of transformation. This result is only approximate, but the value is acceptable for the present purpose. Using the Clapeyron–Clausius formula, the increase in the transformation temperature by the application of 92 MPa was calculated to be 34°C. If we incorporate an enthalpy change of 4×10^7 J/m^3 for the transformation, as suggested in Ref. [5], a net transformation temperature increase of 11°C is calculated. The observed boundary movement of 1.4 mm corresponds to an increase in the transformation temperature of about 14°C. This agreement between the experimental observation and thermodynamic estimation is reasonable. Strain and, thus, stress in bending is not uniform. Thus, the above analysis is subject to certain ambiguity in a quantitative sense. However, the agreement between the calculation and observation is a sound confirmation of the applicability of the Clapeyron–Clausius formula to Ni_2MnGa.

The observation that a magnetic field of 10 kG does not influence transformation can also be understood. Since our knowledge of the magnetic characteristics of our specimens is incomplete, we make estimates for stoichiometric Ni_2MnGa [1]. The magnetization changes by 0.09 kG, when the transformation occurs under a magnetic field similar to that used in the present study. The Clapeyron–Clausius formula gives a change of 0.02°C in the transformation temperature for the field of 10 kG. (The enthalpy change of 1.1×10^7 J/m^3 is used in the calculation.) This corresponds to the movement of the transformation front of 2×10^{-2} mm, which is too small to detect, in agreement with the observation.

Metallographic determination of transformation temperature

Even in a small, arc-melted polycrystal NiMnGa sample, in which macroscopic solute segregation must be smaller than in single crystals, the transformation temperature varied with position. For example, a polycrystal, used for a differential thermal analysis, started transformation at 10°C but did not complete it even at −20°C. Further, within a small area, the transformation temperature depended on local martensite plates. However, individual plates appeared almost always at the same temperature. Thus, if plates are examined individually, we can better assess effects of the magnetic field on the transformation. To accomplish this, we used an optical fiber guided image. Resolution of the image was not good, but sufficient to detect appearance of martensite plates, as shown in Fig. 3(a). Four martensite plates were observed in this area during cooling in different magnetic fields. Transformation temperatures of the individual plates are plotted against magnetic field in Fig. 3(b). Changes in the transformation temperature by magnetic fields up to 10 kG were less than 0.5°C, within the measurement errors of our thermocouple method. We conclude that moderate magnetic fields, up to 10 kG, do not significantly affect martensitic transformation in this alloy.

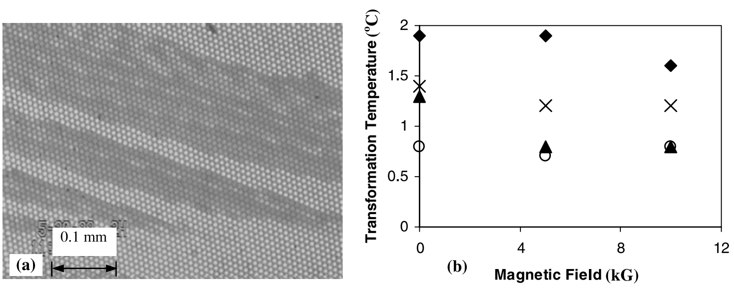

Fig. 3. (a) Optical fiber transmitted martensite plate image. (b) Transformation temperature of four martensite plates (◆, ×, ▲, ○) against magnetic field.

Concluding remarks

Moderate mechanical stress induces or promotes martensitic transformation in NiMnGa. This is because the transformation strain is large enough to produce strain in the order of 1.5% in the transformed domain. Mechanical work is readily available to accelerate transformation. On the other hand, applying a magnetic field alone using a conventional laboratory magnet does not significantly influence the transformation. This is because change in the magnetization in transformation is small in this alloy. The demonstration of the transformation by bending in magnetic field may be misleading. An inhomogeneous distribution of magnetic field associated with the geometry of a specimen assembly causes bending moment, which, in turn, causes stress-induced martensitic transformation. An experiment that addresses a role of magnetic field in transformation must eliminate or carefully examine magnetic force caused by non-uniformity of the field.

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