Tuning the austenite and martensite phase fraction in ferromagnetic shape memory alloy ribbons of Ni₄₅Co₅Mn₃₈Sn₁₂

Lakhani, Archana; Dash, S.; Banerjee, A.; Chaddah, P.; Chen, X.; Ramanujan, R. V.

2011

Lakhani, A., Dash, S., Banerjee, A., Chaddah, P., Chen, X., & Ramanujan, R. V. (2011). Tuning the austenite and martensite phase fraction in ferromagnetic shape memory alloy ribbons of Ni₄₅Co₅Mn₃₈Sn₁₂. *Applied physics letters*, 99(24), 242503-.

<https://hdl.handle.net/10356/105796>

<https://doi.org/10.1063/1.3669510>

© 2011 American Institute of Physics. This paper was published in *Applied Physics Letters* and is made available as an electronic reprint (preprint) with permission of American Institute of Physics. The paper can be found at the following official DOI: [<http://dx.doi.org/10.1063/1.3669510>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 16:40:10 SGT

Tuning the austenite and martensite phase fraction in ferromagnetic shape memory alloy ribbons of Ni₄₅Co₅Mn₃₈Sn₁₂

Archana Lakhani, S. Dash, A. Banerjee, P. Chaddah, X. Chen, and R. V. Ramanujan

Citation: [Applied Physics Letters](#) **99**, 242503 (2011); doi: 10.1063/1.3669510

View online: <http://dx.doi.org/10.1063/1.3669510>

View Table of Contents: <http://scitation.aip.org/content/aip/journal/apl/99/24?ver=pdfcov>

Published by the [AIP Publishing](#)

Articles you may be interested in

[Giant magnetic refrigeration capacity near room temperature in Ni₄₀Co₁₀Mn₄₀Sn₁₀ multifunctional alloy](#)

Appl. Phys. Lett. **104**, 132407 (2014); 10.1063/1.4870771

[Stress-induced transformations at low temperatures in a Ni₄₅Co₅Mn₃₆In₁₄ metamagnetic shape memory alloy](#)

Appl. Phys. Lett. **103**, 242406 (2013); 10.1063/1.4840336

[Peculiarity of magnetoresistance in high pressure annealed Ni₄₃Mn₄₁Co₅Sn₁₁ alloy](#)

Appl. Phys. Lett. **102**, 032407 (2013); 10.1063/1.4789514

[Martensitic and magnetic transformation in Mn₅₀Ni_{50-x}Sn_x ferromagnetic shape memory alloys](#)

J. Appl. Phys. **112**, 083902 (2012); 10.1063/1.4758180

[Magnetoresistance and its relation to magnetization in Ni₅₀Mn₃₅Sn₁₅ shape-memory epitaxial films](#)

Appl. Phys. Lett. **100**, 162403 (2012); 10.1063/1.4704562

Automate your set-up with
Miniature Linear Actuators

Affordable. Built-in controllers.
Easy to set up. Simple to use.

ZABER

www.zaber.com

Tuning the austenite and martensite phase fraction in ferromagnetic shape memory alloy ribbons of $\text{Ni}_{45}\text{Co}_5\text{Mn}_{38}\text{Sn}_{12}$

Archana Lakhani,^{1,a)} S. Dash,¹ A. Banerjee,¹ P. Chaddah,¹ X. Chen,² and R. V. Ramanujan²

¹UGC-DAE Consortium for Scientific Research, University Campus, Khandwa Road, Indore-452001, Madhya Pradesh, India

²School of Materials Science and Engineering, Nanyang Technological University, N4.1-01-18, 50 Nanyang Avenue, Singapore 639798

(Received 29 September 2011; accepted 18 November 2011; published online 13 December 2011)

The ferromagnetic shape memory alloy ribbons with composition $\text{Ni}_{45}\text{Co}_5\text{Mn}_{38}\text{Sn}_{12}$ are shown to have field induced kinetically arrested ferromagnetic austenite phase down to the low temperature due to hindered martensite transformation. This gives rise to the coexisting martensite and austenite phases in a wide range of temperature and field. Here, we show a systematic rise in arrested austenite phase with the reduction in martensite phase quantitatively by various magnetization measurements. The fraction of these coexisting phases can be tuned in “field-temperature” space. Further, we show that the “domain” of tunability varies with temperature. © 2011 American Institute of Physics. [doi:10.1063/1.3669510]

Magnetic field induced phenomena like colossal magnetoresistance, magnetocaloric, and magnetic shape memory effects have motivated the development of new technology. Ferromagnetic shape memory alloys (FSMAs) with general formula $\text{Ni}_{50}\text{Mn}_{50-y}\text{X}_y$ ($\text{X} = \text{In}, \text{Sn}, \text{and Sb}$) belong to the class of magnetic materials having interesting functional behavior associated with the application of magnetic field.¹⁻⁴ The functional performance of FSMAs as transducers, actuators, and switching devices is associated with the first order structural transition known as martensitic transition (MT). The high temperature phase is a ferromagnetic austenite (FM-A) phase, while the low temperature phase is low magnetization martensite (LM-M) phase, which could be either ferromagnetic or antiferromagnetic in nature. This magnetostructural transition is very sensitive to the field, pressure, and composition, which makes them a good candidate for multifunctional applications.⁵

In these alloys, the first order MT is influenced by disorder which gives rise to the coexisting austenite and martensite metastable states. Metastability associated with phase co-existence in a system is an interesting feature which introduces the possibility of tuning a particular phase fraction with the application of external parameters like temperature, field, and pressure. This quantitative manipulation is important in the development of first order phase transition materials towards the aim of practical applications like in magnetic refrigeration and switching devices,⁶ because the path followed in the field-temperature (HT) space is a crucial criterion in deciding the final state of the system.

In this letter, we emphasize the tuning of phase fraction in $\text{Ni}_{45}\text{Co}_5\text{Mn}_{38}\text{Sn}_{12}$ alloy ribbons by magnetization measurements. Use of magnetocaloric materials in the form of ribbons enhances the technical performance of refrigerators.⁴ The sample used in the present investigation is the same one used for our earlier study;⁷ therefore, preparation and characterization can be seen from this reference. Magnetization

measurements are carried out by using 14 T Physical Property Measurement System (PPMS)- Vibrating Sample Magnetometer (VSM) from Quantum Design, USA.

Figure 1(a) shows magnetization as a function of temperature while field cooled cooling (FCC) and field cooled warming (FCW) in various constant fields ranging from 0.05 T to 9 T marked on the respective curves. This data were reported in our earlier paper⁷ and is reproduced here for completeness. At 0.05 T, on decreasing the temperature, we observe a broad first order transition from FM-A to LM-M at martensitic transformation temperature (T_m), while on heating a reverse MT to the FM-A phase takes place. The characteristic temperatures for the onset and finish of martensite (M_s and M_f) and austenite transition (A_s and A_f) are marked on the 0.05 T curve of Figure 1(a). For 0.05 T, the phase co-existence region lies between ~ 210 K to ~ 70 K during cooling and heating cycles. This broadening of first order transition is due to the disorder induced by chemical inhomogeneities.^{8,9} On increasing the field, the hysteresis suppresses and T_m decreases gradually. Here, T_m is defined as $T_m = [(M_s + M_f)/2 + (A_s + A_f)/2]/2$. Variation of T_m with increasing field is shown in the inset of Figure 1(a). The observed average shift in T_m is ~ 4 K/T which demonstrates the high sensitivity of this alloy with field. This definition of T_m is different from the T_c defined as the temperature of the peak magnetization in our earlier study,⁷ and this is the cause of the lower value of dT_m/dH quoted here in comparison to dT_c/dH .

At low field ~ 0.05 T, the transition is broad and the magnetization at 5 K and 350 K is nearly same indicating almost a complete transformation from austenite to martensite-phase while cooling. At higher fields, this difference of magnetization at 350 K and 5 K increases, which is seen by a gradual rise in the value of magnetization at 5 K, indicating the gradual inhibition of martensitic transformation, and at 9 T, the MT is almost hindered. Hence, we see that the high temperature FM-A fraction remains frozen on increasing the magnetic field and we get coexisting phases of

^{a)}Electronic mail: archnalakhani@csr.res.in.

FIG. 1. (Color online) (a) Temperature dependent magnetization for $\text{Ni}_{45}\text{Co}_5\text{Mn}_{38}\text{Sn}_{12}$ at various fields as shown on the respective curves (reproduced from Ref. 7). Inset shows the variation of T_m with field. (b) Arrested (FM-A) and transformed (LM-M) phase fraction as a function of field at 5 K. Inset (taken from Ref. 7): Field dependent magnetization at 5 K after cooling in zero field.

metastable FM-A and equilibrium LM-M states at low temperature. The amount of ferromagnetic fraction depends on the magnetic field applied. At 9 T, we get maximum FM-A fraction mixed with equilibrium martensite phase. Similar arrested kinetics of MT induced by field have been observed for NiMnX ($X = \text{In, Sn, and Sb}$) alloys and their Cobalt derivatives^{10–16} which confirm the metastable regions with varying H and T but there are no studies which quantify the transformed and arrested phase fraction on varying temperature and fields. Here, we make an attempt to estimate the transformed martensite and arrested austenite phases with the application of field at various temperatures.

It is apparent from the $M(T)$ curves shown in Figure 1(a) that the magnetization across the MT differs significantly with the change in field, for example, the difference in magnetization at M_s and A_s , i.e., $\Delta M_{(A_s-M_s)}$ at 0.05 T is ~ 41 emu/gm, while at 9 T, it is ~ 7 emu/gm indicating the reduction in the transformed martensite fraction with rise in field. Since on cooling in zero field down to 5 K yields a LM-M state as seen by the zero field cooled (ZFC) $M(H)$ curve at 5 K,⁷ shown in the inset of Figure 1(b), we can estimate the arrested FM-A fraction by comparing the ZFC magnetization and FC magnetization values from $M(T)$ curves at low temperature. The difference in magnetization from FC- $M(T)$ curves and from ZFC-MH at 5 K increases as we increase the magnetic field. This divergence of M values (ΔM at 5 K = $M_{\text{FC-MT}} - M_{\text{ZFC-MH}}$) at various fields would give the arrested ferromagnetic fraction. Considering the sum of $\Delta M_{(A_s-M_s)}$ and ΔM at 5 K and 0.05 T as the 100% transformed martensite fraction and at 9 T as the 100% arrested FM-A fraction, we can have a quantitative estimate of the transformed LM-M and arrested FM-A phase fraction as a function of cooling field shown in Figure 1(b). The normalized arrested fraction with increase in magnetic field is shown by the full circles. This signifies the gradual reduction in the transformed martensitic phase fraction at 5 K, with increase in the FM-A phase which is getting freezed with rise in field. The triangles in the Figure 1(b) show the normalized martensite phase fraction at 5 K. At 0.05 T, we have maximum transformed martensite fraction, while at 9 T, the transformation to martensite phase is negligible due to maximum arrested phase. Hence, as the cooling field increases, the martensite fraction across the transition decreases and

arrested fraction increases giving rise to co-existing FM-A and LM-M states. The two curves are in very good one to one correspondence with each other as the sum of the transformed and arrested fraction at each field is $\sim 100\%$. At 4 T, austenite and martensite fraction is almost equal across the transition.

To elucidate the arrested kinetics in magnetic systems, an unusual and now established measurement protocol in which cooling and heating in unequal fields (CHUFs) is performed. This protocol facilitates identifying glass like arrested state in various functional magnetic systems known as “magnetic glasses” by heating in different fields than the cooling fields by showing the evidence of de-arrest.^{7,17} Normally, there are two threshold field values H_1 and H_2 which decide the state of material at low temperature while cooling above and below these fields.^{18,19} In this case, since the low temperature state is a LM-M state, cooling above H_2 (~ 8 T) results in the maximum arrested phase, while cooling below H_1 (~ 1 T) results in the maximum transformed phase. The best field values for CHUF measurements are between H_1 and H_2 , which give varying coexisting phase fractions when cooled in various fields above and below these values. We have performed various magnetization measurements in a range of measured fields after cooling in various fields; here as an example, we show $M(T)$ measurements at 4 T, in Figure 2, after cooling in various fields $H_{\text{cool}} = 0, 1, 2, 3, 4, 5, 6, 7$, and 8 T. In each case, the sample is cooled from 350 K down to 5 K in field, and then field is changed isothermally to 4 T at 5 K. At 4 T, austenite and martensite phase fraction is 50% each, as seen from Figure 1(b). When $H_{\text{cool}} \leq 4$ T, only one transition is seen, this corresponds to reverse MT at ~ 200 K. On the other hand, for $H_{\text{cool}} > 4$ T, there are two transitions, one indicated by sharp fall in magnetization while heating and the other by rise in magnetization at ~ 200 K. The sharp fall in magnetization after cooling in lower fields signifies the de-arrest of arrested FM-A fraction, while the rise in magnetization indicates the reverse martensite transformation to FM-A state.

The magnetization value at 5 K increases gradually on increasing the cooling fields, indicating the larger arrested fraction at low temperature on cooling in higher fields. Taking the sum of arrested and transformed fraction at 9 T as

FIG. 2. (Color online) Magnetization w.r.t T , while warming in 4 T after cooling in different fields from 0–8 T. Data are reproduced from Ref. 7. Inset shows the arrested phase fraction as a function of cooling field at 4 T.

FIG. 3. (Color online) (a)–(d) Arrested fraction as a function of measuring field at 5, 25, 50, and 75 K, respectively. Colored area corresponds to the domain of tunable phase fraction in the HT space.

100% arrested FM-A fraction from FC-M(T) measurements as above, we have calculated the corresponding arrested phase fraction as a function of cooling field from CHUF magnetization data at 4 T, which is shown in the inset of Figure 2. The arrested fraction increases up to 90% at 4 T on increasing the cooling field to 8 T. It shows that the field induced state has the memory of last field experienced. This is a paradigm of magnetic memory effect seen in these alloys where a variety of coexisting phase combinations can be shaped by varying the values of cooling fields. Similarly, at various measuring fields, the arrested fraction increases on increasing the cooling fields as shown by the vertical lines in Figure 3(a). The rectangular area represents the domain of arrested phase fraction at 5 K. In the same way, we have calculated the arrested phase fraction as a function of measuring field after cooling in various fields at 25 K, 50 K, and 75 K shown in Figures 3(b)–3(d), respectively. Evidently, the area representing the arrested fraction decreases with increase in temperature from 5 to 75 K indicating that the “domain” of tunability of phase fraction in a range of field depends on temperature. Hence, for FSMAs, we can tune the austenite and martensite phases in the HT space. This feature can be utilized for the device applications.

Since phase co-existence is the key parameter for associated functionalities in metamagnetic materials, the understanding of path dependence in the phase space defined in terms of controlled variables like magnetic field and temperature can be helpful in understanding the use of these sensitive functional alloys as potential magnetic refrigerants and switching devices.^{6,20}

We acknowledge Kranti Kumar for help in magnetization measurements. CX and RVR acknowledge support from National Research Foundation, Singapore through the CREATE program on Nanomaterials for Energy and Water Management.

- ¹Y. Sutou, Y. Imano, N. Koeda, T. Omori, R. Kainuma, K. Ishida, and K. Oikawa, *Appl. Phys. Lett.* **85**, 4358 (2004).
- ²R. Kainuma, K. Oikawa, W. Ito, Y. Sutou, T. Kanomata, and K. Ishida, *J. Mater. Chem.* **18**, 1837 (2008).
- ³R. Kainuma, Y. Imano, W. Ito, Y. Sutou, H. Morito, S. Okamoto, O. Kitakami, K. Oikawa, A. Fujita, T. Kanomata *et al.*, *Nature* **439**, 957 (2006).
- ⁴A. M. Aliev, A. B. Batdalov, I. K. Kamilov, V. V. Koledov, V. G. Shavrov, V. D. Buchelnikov, J. Garca, V. M. Prida, and B. Hernando, *Appl. Phys. Lett.* **97**, 212505 (2010).
- ⁵A. K. Nayak, K. G. Suresh, and A. K. Nigam, *J. Appl. Phys.* **108**, 063915 (2010).
- ⁶P. J. Shamberger and F. S. Ohuchi, *Phys. Rev. B* **79**, 144407 (2009).
- ⁷A. Banerjee, S. Dash, A. Lakhani, P. Chaddah, X. Chen, and R. V. Ramanujan, *Solid State Commun.* **151**, 971 (2011).
- ⁸Y. Imry and M. Wortis, *Phys. Rev. B* **19**, 3580 (1979).
- ⁹P. Chaddah, *Pramana- J. Phys.* **67**, 113 (2006).
- ¹⁰V. K. Sharma, M. K. Chattopadhyay, and S. B. Roy, *Phys. Rev. B* **76**, 140401(R) (2007).
- ¹¹B. M. Wang, L. Wang, Y. Liu, B. C. Zhao, Y. Yang, and H. Zhang, *J. Appl. Phys.* **106**, 063909 (2009).
- ¹²W. Ito, K. Ito, R. Y. Umetsu, R. Kainuma, K. Koyama, K. Watanabe, A. Fujita, K. Oikawa, K. Ishida, and T. Kanomata, *Appl. Phys. Lett.* **92**, 021908 (2008).
- ¹³J. L. Sanchez Llamazares, B. Hernando, J. J. Sunol, C. Garcia, and C. A. Ross, *J. Appl. Phys.* **107**, 09A956 (2010).
- ¹⁴R. Y. Umetsu, W. Ito, K. Ito, K. Koyama, A. Fujita, K. Oikawa, T. Kanomata, R. Kainuma, and K. Ishida, *Scr. Mater.* **60**, 25 (2009).
- ¹⁵S. Chatterjee, S. Giri, S. Majumdar, and S. K. De, *Phys. Rev. B* **77**, 224440 (2008).
- ¹⁶S. Chatterjee, S. Giri, S. Majumdar, and S. K. De, *Phys. Rev. B* **77**, 012404 (2008).
- ¹⁷A. Banerjee, K. Kumar, and P. Chaddah, *J. Phys. Condens. Matter* **20**, 255245 (2008).
- ¹⁸A. Banerjee, A. K. Pramanik, K. Kumar, and P. Chaddah, *J. Phys. Condens. Matter* **18**, L605 (2006).
- ¹⁹K. Kumar, A. K. Pramanik, A. Banerjee, P. Chaddah, S. B. Roy, S. Park, C. L. Zhang, and S. W. Cheong, *Phys. Rev. B* **73**, 184435 (2006).
- ²⁰P. Chaddah, K. Kumar, and A. Banerjee, *Phys. Rev. B* **77**, 100402(R) (2008).