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Author

Mohamed, H.A.

Publication Date

1976-02-01

Submitted to Metallurgical Transactions

LBL-4597
Preprint c. |

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H. A. Mohamed and J. Washburn

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Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

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ON THE MECHANISM OF THE SHAPE MEMORY EFFECT IN Ni-Ti ALLOY

H. A. Mohamed and J. Washburn

Department of Materials Science and Engineering, College of Engineering
and Materials and Molecular Research Division of Lawrence Berkeley
Laboratory, University of California, Berkeley, California 94720

Several alloys have been known to exhibit a mechanical shape memory effect associated with a thermoelastic martensitic-type phase transformation⁽¹⁻⁶⁾. Of particular interest is the alloy NiTi near the equiatomic composition.

The purpose of this paper is to present experimental results on the deformation modes in the early stages of 55.4wt%Ni (50.3 at%) alloy in a partially transformed state. Wires from this same batch of material have been put through more than 10^7 cycles of shape recovery in a new type of heat engine⁽⁷⁾.

Specimens in the form of sheets (0.037 inch thick) were encapsulated in quartz tubes ($\sim 10^{-6}$ torr in argon atmosphere), solution treated at 1000°C for 24 hours and then quenched in ice water. Chemical analysis was done after such treatment and showed the oxygen content to be ~ 350 ppm and the nitrogen content < 10 ppm.

The initial M_s temperature as determined from the peak of the electrical resistivity vs. temperature diagram⁽⁸⁾ was found to be $\sim 55^\circ\text{C}$.

Transmission electron microscopy and diffraction showed the martensite to be internally twinned as reported for similar alloys by some other investigators^(9,10). Fig. (1a) shows a bright-field image of a twinned martensite plate observed at room temperature. The same area was reobserved under the same diffraction conditions after the foil had been slightly bent outside the microscope at room temperature as shown in Fig. (1b). The image of (b) was printed such that it was the mirror

image of (a) and then both images were cut along the same line. It can be seen by comparing the two images that one of the two sets of twin-related domains has grown at the expense of the other. It should be pointed out that because of the fine scale this deformation mode cannot be observed in the optical microscope as in the case of Cu-Al-Ni⁽¹¹⁾, Au-Cd⁽¹²⁾ and In-Tl⁽¹³⁾ alloys. Fig. (2) shows a sequence of light optical micrographs of the surface of a tensile specimen, initially polished, un-etched and then deformed in tension at room temperature with a calibrated small tensile device while under observation. The parallel bands which can be seen to develop with progressive straining within the recoverable range (<6% elongation at room temperature) are believed to arise from stress-induced growth of favorably oriented martensite plates as would be expected. Notice also that no new bands have developed with progressive straining. Fig. (3) shows an optical micrograph of another area after 4% elongation at room temperature. Note that the grain boundaries have been revealed. These results suggest that, in a partially transformed material, deformation in the early stages occurs by at least two modes (i) stress-induced twin boundary migration within the martensite and (ii) stress-induced growth of the most favorably oriented existing martensite plates in each grain. It would be expected that the strain associated with these two modes would be reversed when the martensite reverts to the high temperature phase since both modes are associated with the transformation. Further, it was observed that if a virgin specimen (not cycled) was bent at room temperature and then cooled further, it continued to bend spontaneously in the same direction as illustrated schematically in Fig. (4). Heating the specimen to above

$\sim 62^{\circ}\text{C}$ then caused the specimen to completely recover its original shape. Further cooling in the absence of the initial bending did not cause any macroscopic shape change. This behaviour is different from the reversible or two-way shape memory effect^(14,15,16,17,18), which seems to require the recoverable strain limit ($\sim 6\%$ elongation in the present case) to be exceeded^(15,16,17), or several hundred transformation-deformation cycles⁽⁷⁾.

The spontaneous strain observed in the present case is believed to be related to the above deformation modes in the following way. Since further cooling causes the martensite plates to grow, after bending those sets which have been already preferentially developed by the initial bending would make the major contribution to the new thermally transformed volume. This would contribute to the observed macroscopic strain. Also further growth of martensite plates in which one set of twins had been widened at the expense of the other set by the initial strain would contribute to additional macroscopic strain. These processes are illustrated schematically in Fig. (5). It is suggested that the sum of these two strains is the cause of the observed spontaneous strain.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation and the U.S. Energy Research Development Administration through the Materials and Molecular Research Division of the Lawrence Berkeley Laboratory.

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FIGURE CAPTIONS

Fig. (1) Bright-field transmission electron micrographs showing the effect of external deformation on the widths of the twin-related domains in a martensite plate. (a) Undeformed (b) after bending at room temperature.

Fig. (2) Light optical micrographs showing surface relief effects associated with stress-induced growth of favorably oriented martensite plates. (a) 1%, (b) 2%, (c) 3% elongation at room temperature.

Fig. (3) Light optical micrographs of a specimen given 4% elongation at room temperature showing surface-relief effects and grain boundaries of the parent phase.

Fig. (4) Schematic illustration showing the spontaneous bending observed during further cooling of a specimen bent slightly at room temperature. (a) original shape and shape after bending at room temperature (b) and (c) change in shape which occurs with progressive cooling.

Fig. (5) Schematic interpretation of the effect illustrated in Fig. (4). (a) favorably and unfavorably oriented martensite plates before (dashed lines) and after (solid lines) bending, (b) change in size of the plates shown in (a) after further cooling, (c) martensite plates 1) before and 2) after bending showing growth of one set of twins at the expense of the other, (d) further growth of the martensite shown in (c-2) due to further cooling.

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Fig. 1

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Fig. 2

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Fig. 3

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Fig. 4

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Fig. 5

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