Mechanical Twinning and Plasticity in Ti-Ni-Fe (3%)

Moberly, Duerig, Proft, Sinclair

Martensitic Transformation II
(ed.) B.C. Muddle
Materials Science Forum Vols. 56-58
pp. 759-764

1990

Materials Science Forum Vols. 56 - 58 (1990) pp. 759-764

MECHANICAL TWINNING AND PLASTICITY IN Ti-Ni-Fe (3%)

W.J. Moberly (a), T.W. Duerig (b), J.L. Proft (b) and
R. Sinclair (a)
(a) Dept. of Materials Science & Engineering, Stanford University
Stanford, CA 94305, USA
(b) Raychem Corporation, Menlo Park, CA 94025, USA

ABSTRACT

Like most intermetallics $Ti_{50}Ni_{47}Fe_3$ has insufficient independent (dislocation) slip systems for compatible polycrystalline plastic deformation. However, the presence of complex {114} mechanical twinning in conjunction with [100] dislocation slip provide this B2 intermetallic with > 40% room temperature ductility. The mechanical twinning is determined to be macroscopically "strain-controlled" as mechanical twinning and dislocation slip also occur together during warm working. Greater cold working results in higher dislocation densities and twin densities, although the individual size of the twins is limited to less than 200 nm. Moreover, this intermetallic is thermo-mechanically strengthened by annealing the cold worked structure. Subgrains form which are limited to the size of the twins. Greater cold working produces a finer twin spacing, which results in a finer subgrain size after annealing and a corresponding improvement in the combined mechanical properties of yield strength and ductility.

1. INTRODUCTION

Mechanical twinning has been observed in the intermetallic B2 structure of $Ti_{50}Ni_{47}Fe_3$ [1-4]. Many authors [5-9], including those of this conference, have discussed the stress-induced martensitic transformation that may occur in this shape memory alloy, but little attention has been given to the stress-induced mechanical twinning which retains the B2 structure after twinning. Transmission electron microscopy is utilized to observe and analyze the mechanical twinning. An evaluation of the other mode of deformation in this intermetallic, dislocation slip, indicates why deformation twinning does occur. The interaction of dislocation slip and twinning, which occur concurrently, provide this intermetallic with significant room temperature ductility. Additionally, thermo-mechanical processing provides a means of strengthening the intermetallic while retaining room temperature ductility. Again the strengthening is determined to be a result of dislocation and twin interaction.

2. EXPERIMENTAL PROCEDURES

The substitution of 3% Fe for Ni in the binary TiNi shape memory alloy suppresses the martensitic transformation to cryogenic temperatures, such that the B19' martensite structure may not be stress-induced during room temperature deformation. Fully annealed stock was processed (as indicated in reference [4]) with different extents of cold working via swaging (10%, 30% and 40%) followed by various recovery annealing times and temperatures. The processed material was observed by transmission electron microscopy (TEM) with a Philips EM400 and was tensile-tested using an MTS model #810 to determine the mechanical properties. Procedures and results have been further discussed by these authors in reference [4].

3. RESULTS AND DISCUSSIONS

The fully annealed material has room temperature ductility of 40% elongation or more. TEM observations of material having undergone 1% plastic strain reveals the Burgers vector to be of the **b=<100>** type, as previously observed by Pelton [10]. The <100> type dislocations provide for only 3 independent slip systems, whereas 5 ISS are required for compatible plastic deformation of polycrystalline material [11].

After 10% plastic strain, as well as a significant increase in dislocation density, some grains are observed to have a few mechanical twins in them. A longitudinal section of the swaged bar observed by TEM (figure 1), indicates the twinned region to have the same B2 structure as the matrix. Thus a new structure has not been stress- induced. Additionally, electron diffraction (figure 1b) determines the twinning plane to be of the {114} type, as has been observed by Goo [1] in this alloy. Goo has provided a model for this complex twinning mode whereby the atoms shear on the {114} planes in the <22$\bar{1}$> direction, followed by half the atoms shuffling on {110} planes. The twinning plane is also determined to be at ~ 43° to the swaging direction, indicating the shearing step of the complex twinning to be occurring on the planes of maximum resolved shear stress.

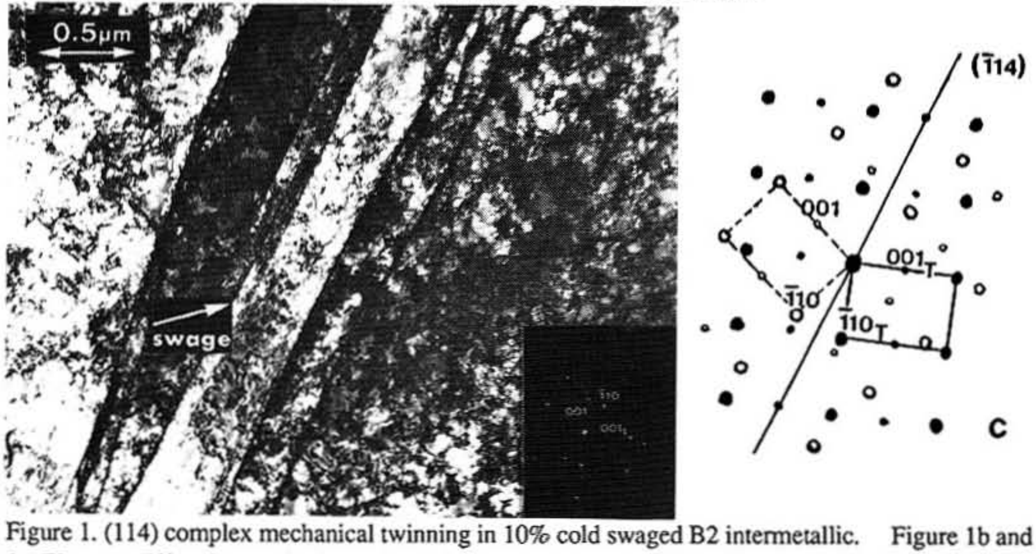

Figure 1. (114) complex mechanical twinning in 10% cold swaged B2 intermetallic. Figure 1b and 1c. Electron diffraction, and schematic, of (114) twin plane at ~ 43° to the swaging axis.

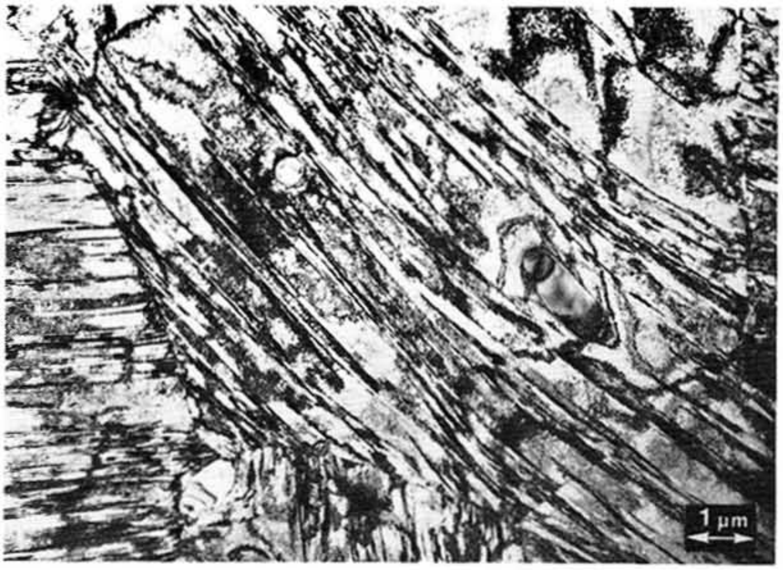

Figure 2a. Transverse section of mechanical twinning in 30% cold swaged bar.

When 30% plastic strain is incurred (figure 2a), a still higher dislocation density is observed than existed for the 10% cold worked material. However, the more prominent feature in the microstructure of figure 2a is the increased twin density. Most grains exhibit twins throughout the grain, with the twin thicknesses being ~ 100 nm or less. Although the twin density increases upon further deformation (40% cold swaging), the majority of the deformation in the 10%, 30%, and 40% cold worked material is determined to be due to dislocation motion. The strain associated with the twinned material accounts for less than half the total plastic strain. It is noted though that both mechanical twinning and dislocation slip are occurring concurrently. The dislocations apparently do not hinder the occurrence of mechanical twinning and may actually assist in the formation of the complex {114} twins.

As previously stated, the <100> dislocations allow for only 3 ISS. Thus the additional slip systems required for plastic deformation of polycrystalline material dictate the necessity of additional modes of deformation shearing, which are accounted for by the occurrence of deformation twinning. Although mechanical twinning differs from dislocation slip in that all atoms have to shear in unison, it would be possible to obtain arbitrary shape changes via mechanical twinning from a combination of different twin systems. Goo [12] has determined that 6 independent (twinning) slip systems would be required for compatible plastic deformation. In the grains of material that have experienced significant twinning (30% and 40% cold swaging), only one set of parallel twinning planes is observed. This would imply that only one ISS is provided by the mechanical twinning. Added to the three ISS due to <100> dislocation slip, this still leaves the material apparently with insufficient ISS to satisfy the Von Mises criterion. This discrepancy seems to be accounted for in the fact that the regions of twinned material will have three different (new) <100> directions and therefore can have three different slip systems from those of the 3 ISS in the matrix. With fine twin spacing, this provides submicron regimes with the required 5 ISS for compatible plastic deformation of polycrystalline material.

The presence of mechanical twinning in this intermetallic is a consequence of the necessity to have sufficient slip systems for compatible shape changes in a polycrystalline material. This alloy has also been shown to exhibit mechanical twinning, in conjunction with dislocation slip, during warm working at 500°C [4,13]. Thus the mechanical twinning is determined to be "strain-controlled" as suggested by R.W. Cahn [14]. If the twinning had been stress-controlled, upon reaching a stress sufficient to initiate twinning one would expected continued twinning without additional dislocation slip and work hardening.

An additional consequence of the presence of twins and dislocations is to provide a means of strengthening this intermetallic. As expected, cold working results in an increase in yield strength and a decrease in ductility. Subsequent annealing can improve the ductility, in some cases without sacrificing all the improved yield strength. The annealing conditions and resultant mechanical properties have been reported in [4]. When the 10% cold swaged material, which had exhibited only dislocations in most grains, is annealed, recovery occurs via annihilation of dislocations and no stable, fine subgrain structure develops. Thus the mechanical strength decreases with subsequent annealing to a level comparable to that of the initial fully annealed material. However, upon annealing the 30% cold swaged material, which had exhibited twins throughout most grains, (figures 2b and 2c), a fine subgrain structure does develop and most of the high mechanical strength is retained. During the initial stages of the recovery anneal, many dislocations annihilate while others line up within the twins. The twin boundaries, however, remain straight and intact (figure 2b). With longer annealing (figure 2c), the twin boundaries become obscure as fine subgrains develop. The subgrains are stable upon further annealing. The size of the subgrains is apparently limited by the spacing of the twin boundaries. Material that had more and finer twins in it would develop a finer subgrain

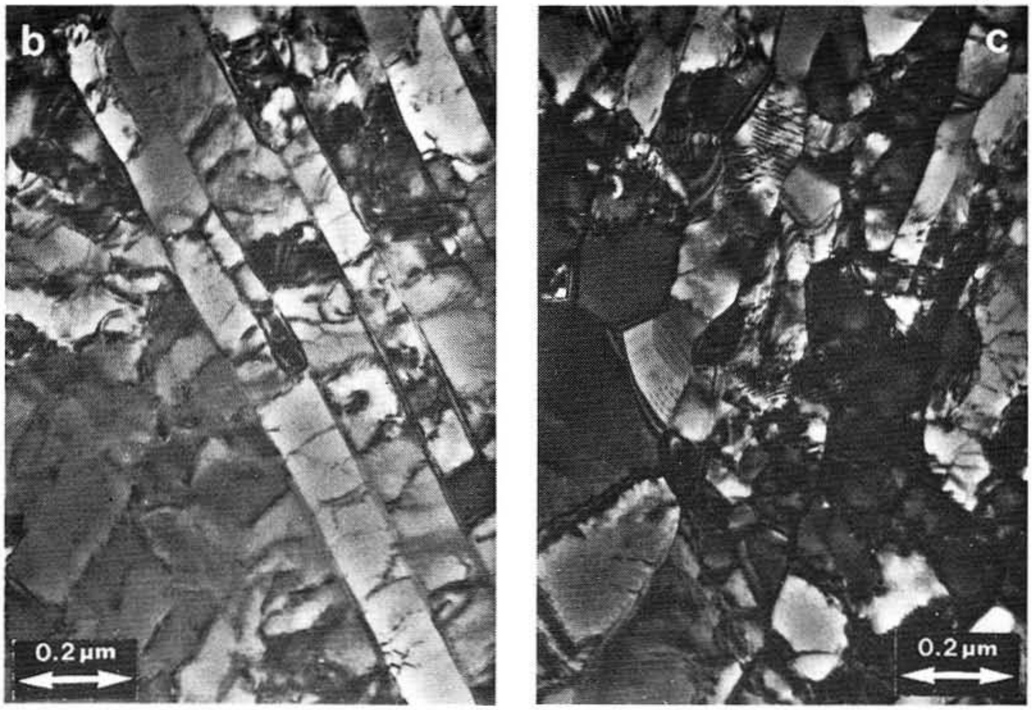

Figure 2b and 2c. 30% cold swaging, followed by annealing 10 min. and 1000 min. @ 500°C.

structure. Thus when comparing the 30% and 40% cold worked material, the mechanical strength of the 40% cold worked material after the recovery anneal is greater than that of the 30% cold worked material. More cold working results in a higher twin density, which in turns reduces the size of the subgrains that form within the twins upon annealing and provides the final thermo-mechanically processed material with a higher strength/ductility combination.

4. CONCLUSIONS

1) Although <100> dislocations provide $Ti_{50}Ni_{47}Fe_3$ with only three independent slip systems, the concurrence of {114} complex mechanical twinning results in significant (> 40%) room temperature ductility.

2) Joint mechanical twinning and dislocation slip during warm working further substantiate that the mechanical twinning is "strain- controlled".

3) Short recovery anneals after cold working provide a means to thermo-mechanically strengthen this intermetallic and retain significant ductility. This occurs due to the development of a fine, stable subgrain structure with a size limited to that of the twin spacing. Greater cold working results in a finer mechanical twin spacing, which upon annealing results in a finer subgrain size and improved mechanical (strength/ductility) properties.

REFERENCES

1. Goo,E., Duerig,T., Melton, K. and Sinclair,R.: Acta Metall., 1985, 33, 1725.
2. Goo,E.: Scripta Met., 1988, 22, 1079.
3. Moberly,W.J.: accepted by Ultramicroscopy.
4. Moberly, W.J., Proft,J.L., Duerig,T.W. and Sinclair,R.: to be submitted to Acta Metall.
5. Miyazaki,S., Imai,T., Igo,Y., and Otsuka, K.: Met Trans., 1986, 17A, 115.
6. Stachowiak,G.B. and McCormick, P.G.: Scripta Met., 1987, 21, 403.
7. DeLaey,L., Krishnan,R.V., Tas, H. and Warlimont, H.: J. Mat. Sci., 1974,9, 1521.
8. Otsuka,K., Wayman, C.M., Nakai,K., Sakamoto, H. and Shimizu, K.: Acat Metall., 1976, 24, 207.
9. Otsuka,K. and Shimizu, K.: Intl. Met. Rev., 1986, 31, 93.
10. Pelton,A.R., Moine, P., Sinclair, R. and Noack, M.A.: to be submitted to Acta Metall.
11. Von Mises,R.: Z. Ang. Math. Mech., 1928, 8, 161.
12. Goo,E. and Park, K.T.: submitted to Scripta Met.
13. Moberly, W.J., Proft,J.L., Duerig, T.W. andSinclair, R.: in preparation.
14. Cahn, R.W.: Deformation Twinning (Reed-Hill, ed.), (Gordon and Breach Science Publishers, New York), 1968, p.17.