Microstructural Evolution and Deformation Micromechanism of Cold-Deformed TiNi-Based Alloys

L.C. Zhao, W. Cai and Y.F. Zheng

School of Materials Science and Engineering, Harbin Institute of Technology, PO Box 433, Harbin 150001, China

Keywords: Deformation, Martensite, Microstructure, TiNi-Based Alloy

Abstract. The microstructural evolution and deformation micromechanism of cold-deformed TiNi based alloys, both in the martensite and parent phase conditions, have been reviewed in the present paper. The emphasis is placed on the modification of the microstructure proceed through atomic migration such as the coalescence and rearrangement of martensite variants and the adjustment and development of internal twinnings. The atomic configuration at the preexisting twinning boundaries after deformation have been revealed. The corresponding deformation micromechanisms were discussed.

Introduction

Twining orientation relationships are the prevailing feature of martensites, both thermally induced[1-3] and stress induced[4-7], in TiNi based shape memory alloys. These glissile movements of various twinning interfaces allow the recovery of the predeformation microstructure and the macroscopic shape upon unloading or heating, which correspond to the superelasticity and shape memory effect, respectively. Thus, an understanding of the microstructural evolution with the cold deformation strain and corresponding twinning interface structures is essential.

Microstructural Evolution of Thermal Martensite during Deformation

Electron microscopic observations[8-10] on the Ti-49.8at.%Ni alloy specimen subjected to 5% thickness reduction indicate that the martensite variants in the favorable stress direction accommodate the deformation strain by consuming the neighboring variants in the unfavorable stress direction during the slightly cold-rolled deformation stage. The (100) compound twinning intervariant boundaries become curved and irregular. Meanwhile the width of the internal <011> Type II twinning substructural bands inside each martensite variant shows no obvious change. When the thickness reduction reaches 8%, both the intervariant boundary and the substructural boundary of the martensite variants become confused and blurred. Electron diffraction results indicate that the substructure of martensite variant is still dominantly the <011> Type II twinning.

With the further increase of the thickness reduction to 16%, the substructural bands in the Ti-49.8at.%Ni alloy specimen are found to adjust partially its orientation by the rearrangement of its internal twinning structure, at the same time, some needle-like plates, as the subunit smaller than the <011> Type II twin related unit, appear obviously inside some substructural bands of martensite variants. Fig.1(a) shows the typical morphological feature of the newly generated twinning subunits in the specimen under this condition. Each substructural band has been divided into several segments by these small “fill-in” structures. The newly formed martensite plates are found to be (001) compound twin related with the matrix part they developed from, as indicated by the corresponding
micro-diffraction patterns Fig.1(b). The formation of these microtwins is obviously due to the existence of immobile intervariant boundaries. From Fig.1(c), it could be also noticed that the conjunct near-identical oriented martensite variants begin to merge into each other. The $\{11\bar{1}\}$ Type I twinning plates are found to adapt the further cold-rolled deformation condition better than the $<011>$ Type II twinning bands, since the number of observations for $\{11\bar{1}\}$ Type I twinning mode increases, as indicated by Fig.1(d). Fig.1(e) depicts a newly-formed $(011)$ Type I twinning plate inside a coalesced substructural band, with the corresponding micro-diffraction pattern illustrated in Fig.1(f).

Fig.1 (a) Bright field image of deformed martensite; (b) Corresponding EDPs to area A in (a); (c) Bright field image; (d) Corresponding EDPs to area B in (c); (e) Bright field image of deformed martensite; (f) Corresponding EDPs to area C in (e) of the deformed martensite in the Ti-49.8at.%Ni specimen subjected to 16% thickness reduction.

HREM observation of the Ti-49.8at.%Ni alloy specimen subjected to 16% thickness reduction indicate that the $(11\bar{1})$ Type I twinning interface is relatively straight, with locally one-atomic-height step existing at the boundary, whereas the $<011>$ Type II twinning interface is clearly distorted and partly lose its coherency. The $(001)$ compound subtwinning interface is relatively straight with one
atomic-layer-height step existing at the boundary, whereas the newly-formed (011) Type I subtwinning interface is also relatively straight, despite stepped at local positions. Fig.2 depicts the HREM image of the residual intervariant (100) compound twinning boundary in the 16% deformed specimen, from which it can be seen that the (001) compound twin related substructure develops inside each martensite variant. It causes the atomic combination at the intervariant interface complex and leads to a wavy interfacial structure.

![HREM image of deformed martensite](image)

Fig.2 HREM image of deformed martensite in the specimen subjected to 16% thickness reduction showing the (100) compound twinning boundary, electron beam // [010]_MT.

In the Ti-49.8at.%Ni alloy specimen subjected to 22% thickness reduction, the (111) Type I twinning bands inside different martensite variants are found to merge gradually into each other and replace most of the original neighboring <011> Type II twinning bands. At the same time, the appearance of secondary subtwinning plates inside the substructure of martensite variants also become more obvious. Several kinds of microtwinning structures are found to form inside the substructural bands, they are (001) compound, (011) Type I and (111) Type I modes. HREM observation indicates that the (111) Type I twinning interface in the 22% thickness reduced specimen exhibits a wavy feature.

When the thickness reduction is about 30%, the gradually curved martensite substructural bands with different orientations become the dominant microstructural feature inside the Ti-49.8at.%Ni alloy specimen. It is difficult to find out the original intervariant boundaries, which indicates that the substructural bands completely merged into each other. The separated unit inside the heavily cold-rolled martensite substructural band with a single orientation is very fine and has been characterized as “nanocrystals” by Koike et al.[11]. Lattice distortion happens violently in some areas and at local region the amorphous bands emerge in the specimen.

**Microstructural Evolution of Stress Induced Martensite during Deformation**

In the Ti_{46.3}Ni_{44.7}Nb_{9} alloy specimen strained to 8% at room temperature, a majority of SIM variants with self-accommodating morphology is found[12]. The substructure of the SIM variant is dominantly to be (111) Type I twin, though a few (001) compound twins[13], antiphase domain boundaries[13] and (111) Type I twins[14] were occasionally observed. The orientation relationship
between neighboring variants is (100) compound twin related. The (100) compound twinning boundary between SIM variants has been found to be pinned by numerous dislocations in the 16% deformed Ti$_{46.3}$Ni$_{44.7}$Nb$_9$ alloy specimen, which impede the further deformation through variant coalescence[14].

Inside the 16% deformed Ti$_{46.3}$Ni$_{44.7}$Nb$_9$ alloy specimen, secondary deformation microtwinnings happen along several directions inside the (111) Type I twinning SIM variants, as indicated by single arrows, double arrows and triple arrows, respectively in Fig.3(a)-(d). All the (111) twinning planes in Fig.3 are nearly perfect Bragg condition, the included angle between the secondary twinning plane and (111) plane could be approximately measured to be 70°, 0° and 20°~30°. Correspondingly they were turned out to be (001) compound, <011> Type II /or (011) Type I and (111) Type I twinning plates. The high magnification image will be presented separately to show the details on the atomic scale in the following.

Fig.3 (a) Typical bright field electron micrograph of moderately deformed SIM; (b) Enlarged image of the area marked by A in (a); (c) Another typical bright field micrograph of moderately deformed SIM; (d) Enlarged image of the area marked by B in (c) in the 16% deformed Ti$_{46.3}$Ni$_{44.7}$Nb$_9$ alloy specimen.

Adjustment from (111) Type I Twinning Mode to <011> Type II Twinning Mode. The
Type II twinning, as the widely recognized lattice invariant shear of the martensite in Ti-Ni alloys, has not been observed experimentally in the 8% deformed Ti$_{46.3}$Ni$_{44.7}$Nb$_{9}$ alloy specimen, yet it was found to appear inside the deformed SIM variants as a newly formed deformation twinning instead of the transformation twinning and confirmed to be developed from the (111) Type I twinning, as shown in Fig. 4. A portion of “Twin 1” is found to transform into “Twin 2”. Correspondingly its twinning relationship with the “matrix” changes from (111) Type I to <011> Type II and the interfacial feature changes from the straight one to the gradually and randomly curved one. The dashed lines in Fig. 4 represent the boundaries between the residual untransformed (111) Type I SIM twin part and the newly formed <011> Type II SIM twin part. Despite the boundaries are very ragged, no obvious lattice distortion could be detected along them.

**Development of (001) Compound Twinning Plates inside the (111) Type I Twinning Bands.**

Fig. 5 illustrates a HREM image of the microstructure inside the 16% deformed Ti$_{46.3}$Ni$_{44.7}$Nb$_{9}$ alloy specimen in which the (001) compound twinning plates coexist with the (111) Type I twinning bands. It could be found that (001) compound twinning plates are mainly generated inside the substructural bands. The interfacial steps along the (001) twinning boundary correspond to the twinning dislocations, which glide and thus can cause one twin orientation to grow at the expense of the other. This feature is consistent with that reported by Knowels[1]. From Fig. 5, it can be suggested that the coalescence of the (111) Type I twinning substructural bands could be realized by the nucleation and growth-up of (001) compound twins.

![Fig.4 HREM image showing the development from (111) Type I twin to <011> Type II twin inside the 16% deformed Ti$_{46.3}$Ni$_{44.7}$Nb$_{9}$ alloy specimen.](image)

**Introduction of Foreign (111) Type I Twinning Plate into (111) Type I Twinning Bands.**

{111} Type I twinning mode is not equivalent to the {111} Type I twinning mode in the monoclinic Ti-Ni martensite. In the Ti$_{46.3}$Ni$_{44.7}$Nb$_{9}$ alloy specimen, wedge-like (111) Type I twinning plate is frequently observed in the deformed SIM and supposed to correspond most likely to the injection of foreign variants from other groups, being akin to the observations for the “cross-hatch” structure in Ti-Ni alloy[7]. The introduction of SIM variants of different plate groups could cancel the shape deformation and relax the shear stress inside the matrix variant. HREM observation indicates that the
(111) Type I twinning boundary shows wavy interfacial feature.

**Formation of (011) Type I Twinning Plates inside (111) Type I Twinning Bands.** The (011) Type I twinning plates would be formed inside the (111) Type I twinning bands of the moderately deformed SIM in Ti46.3Ni44.7Nb9 alloy specimen. Its morphology under TEM is found to be similar to that of the <011> Type II twin. This could be easily understood since (011) Type I and <011> Type II twinning modes are conjugated. HREM examinations showed that irregular ledges exist in the (011) twinning interface in the 16% deformed specimen[14]. Whereas the HREM image of the (011) Type I twinning boundary in the 24% deformed specimen showed that the interface is confused and its coherence is partly damaged after further deformation. Akin to that of <011> Type II twin, the appearance of (011) Type I twinning plates is also regarded as a result of the reorientation of SIM variants.

Fig.5 HREM image showing the twinning development from (111) Type I mode to (001) compound mode in the 16% deformed Ti46.3Ni44.7Nb9 alloy specimen, electron beam // [110]M.T.

**In-situ TEM Observation of Deformation Behavior of Cold-drawn Martensite**

In-situ TEM observation of the Ti-49.8at.%Ni alloy specimen subjected to 14% area reduction deformed in tension has been carried out to illustrate the variation of the microstructure under different deformation conditions, as shown in Fig.6[8]. The TEM image after unloading is omitted since it is almost identical to Fig.6(a). The structural change during the loading and unloading sequentially can be deduced as follows: the applied stress induces the formation of strait (001) twinning martensite plate inside the martensite in the favorable orientation at the beginning, then these new-formed (001) twinning martensite strips broaden associated with the formation of other (001) twinning strips with the increase of the applied stress, during the unloading these needle-like (001) twinning martensite plates shrink back and return to its original micro-structure mostly when the load is zero. These results suggest that the unusual superelastic behavior of the cold drawn TiNi alloy is associated with the appearance and disappearance of (001) deformation microtwin upon loading and unloading, respectively.
Fig. 6 TEM in situ observations showing the microstructural changes with the applied stress in the 14% cold-deformed Ti-49.8at.%Ni alloy specimen at 20°C: (a) Bright field image before tensile deformation; (b) EDPS taken from the framed area in (a), electron beam // [110]_{M,T}/[10\bar{1}]_{T}; (c) Bright field image corresponding to a strain of approximately 0.8%; (d) Bright field image corresponding to a strain of approximately 1.8%; (e) Bright field image corresponding to a strain of approximately 2.5%; (f) EDPS derived from the area A in (e), electron beam // [110]_{M,T}.

Summary

1. With the increase of the thickness reduction, the following phenomena happen in cold deformed TiNi alloys: The dominant deformation mechanism changes from the coalescence of the martensite variants to the coalescence of the substructural bands and the introduction of the secondary twinning plates; The quantities of the (100) compound and <01\bar{1}> Type II twinning plates are reduced, with the increase of (111) Type I, (001) compound and (011) Type I twinning bands and the introduction of (111) Type I twinning plates; The (100) intervariant boundary gradually loses its mobility and becomes wavy, the <01\bar{1}> Type II twinning boundary changes
from the gradually and randomly curved one to the distorted one, the (111) Type I, (001) compound and (011) Type I twinning boundaries become stepped, and the (111) Type I twinning boundary exhibits wavy feature.

2. Besides the ordinary slip, the adjustment and development of the internal secondary twinning from (111) Type I twin to <011> Type II /or (011) Type I twin, (001) compound twin and (111) Type I twin happen concurrently or in combination inside the SIM variants with the further deformation in Ti-Ni-Nb alloy. The corresponding deformation mechanisms include stress induced reorientation of SIM substructural bands by the most favorably oriented twin system, stress induced migration of SIM substructural boundary through internal twinning and stress induced injection of foreign SIM variant to the preexisting substructural bands.

3. The intrinsic reason for the linear superelasticity of the moderately cold drawn TiNi alloy was confirmed to be associated with the appearance and disappearance of (001) microtwinning inside the <011> Type II substructural bands.

References