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It is shown that tensile stress pulses generated by the reflection of compressive shock waves at a free surface induce martensitic transformation (from B2-CsCl to monoclinic structure), in equiatomic NiTi alloys. The transformation products are in the form of acicular needles with a micro-twined or dislocation substructure.

1. INTRODUCTION

Since 1954, shock waves have been used to study the high pressure (13 GPa) bcc-to-hcp martensitic transformation in iron and steel.[1] This is however, an example of transformation from the initial low density state to a final high density state, induced by solely compression stresses. Tensile-stress-pulse induced transformations in ferrous alloys have also been reported by several investigators.[2-5]

Equiatomic NiTi alloys undergo a martensitic transformation (from a high density B2-CsCl structure to a low density monoclinic structure) as well as a crystalline-to-amorphous phase (low density state) transformation. In the present study shock-impact generated tensile-stress pulses were used to induce such high-density to low-density transformations in NiTi alloys.

2. EXPERIMENTAL PROCEDURE

The chemical composition, grain size, and transformation temperatures of the two NiTi alloys are listed in Table I. The microstructures of the as-received NiTi alloys are shown in Figure 1 (a) and (b). In these micrographs a large number of $Ni_2Ti_4O_x$ precipitates (marked 'p') can be seen in the direction of rolling. I addition, since M_s of the NiTi-I alloy is close to room temperature, it also shows martensite phase with a "tweed"-like morphology (Figure 1(a)).

TABLE - I
Characteristics of As-Received Materials

ALLOY TYPE	CHEM. COMP.	GRAIN SIZE	TEMPERATURE* M_s	A_s
NiTi-I	54.71%Ni 45.8%Ti .048%Co .01%O	55 μm	+27°C	+48°C
NiTi-II	50.18%Ni 46.43%Ti 3.39%Fe <0.001%O	25 μm	-45°C	-51°C

* M_s - martensitic transformation start temperature; A_s - reverse transformation temperature.

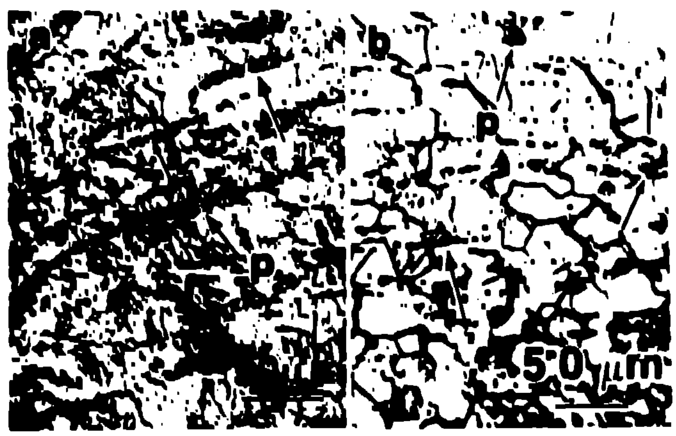

FIGURE 1
Optical micrographs of as-received (a) NiTi-I and (b) NiTi-II alloys.

The room temperature shock impact experiments were conducted using the CETR 6.35 mm diameter single-stage compressed-helium gas gun. The steel flyer plate (mounted at the head of the projectile) was always maintained at half the thickness of the NiTi target, such that the tensile stresses of maximum duration (0.4μs) were formed almost in the center of the target.[6] Details of the experimental conditions are tabulated in Table II.

TABLE - II
SHOCK EXPERIMENTAL CONDITIONS

SMPL #	ALLOY TYPE	START* PHASE	V m/s	P GPa
1.	NiTi-I	B2+M	120	2.0
2.	NiTi-I	B2+M	160	2.7
3.	NiTi-II	B2	245	4.1

* Starting phase prior to impact experiment; B2 - parent CsCl phase, M - martensite phase

3. RESULTS AND DISCUSSIONS

The recovered samples were cut longitudinally, along the direction of shock wave propagation. Optical microscopy was conducted on the cross-sectional surfaces, while x-ray diffraction (XRD) and transmission electron microscopy (TEM) analysis were conducted on various slices cut parallel to the shock plane.

Low magnification micrographs of typical cross-sections of shocked samples No. 1 and 3 are shown in Figure 2 (a) and (b), respectively. Fine needle-like features indicative of the transformation product can be seen in these photos, and more clearly in the adjacent higher magnification images (Figure 2 (c) and (d)). In the case of the NiTi-I alloy shocked close to M_s ($\simeq$ 27°C), the B2-to-monoclinic transformation products (martensite needles) are observed to be more copious in the central mid-plane region (Fig. 2(a)). The NiTi-II alloy (Sample #3) shocked above M_s (=-45°C), showed spalling in the central mid-plane region. In addition to the spall, fine martensite needle-like features were observed in regions adjacent to the spall (Figure 2(b) and (d). This localized transformation is caused by shear stresses generating around the spall.

The martensite formed in all of these shocked samples has an "acicular" needle-like morphology, which is quite different from the "tweed" morphology (Fig. 1(a)) of the thermally induced martensite formed in the NiTi-I alloy upon cooling below M_s.

Identification of transformation products was obtained by XRD analysis. The XRD analysis results for the NiTi-I alloy (Sample #1) are illustrated in Figure 3. Curve (a) is from the mid-plane region (where the tensile pulse has maximum duration), and the Curve (b) is from impact surface (where compressive wave is of maximum duration) of the same sample. It is apparent from this figure that the intensities of the ($1\bar{1}0$), (020), ($1\bar{1}1$) and (022) monoclinic martensite peaks are larger in Curve (a) than in Curve (b). The change in intensities is clearly discernible in Curve (c), which is the numerical difference between Curves (a) and (b). These results show that the NiTi-I alloy sample #1 has a larger amount of martensite at the central mid-plane region, than at the impact surface, thus illustrating that the monoclinic martensite needles are formed by tensile-stress pulses and not by compressive shock waves. Similar results were also observed for NiTi-I alloy Sample # 2 impacted at 160 m/s.

The NiTi-II alloy shocked at 245m/s (Sample # 3) underwent spalling in the central plane, and as shown in the optical micrograph of the sample cross-section, the

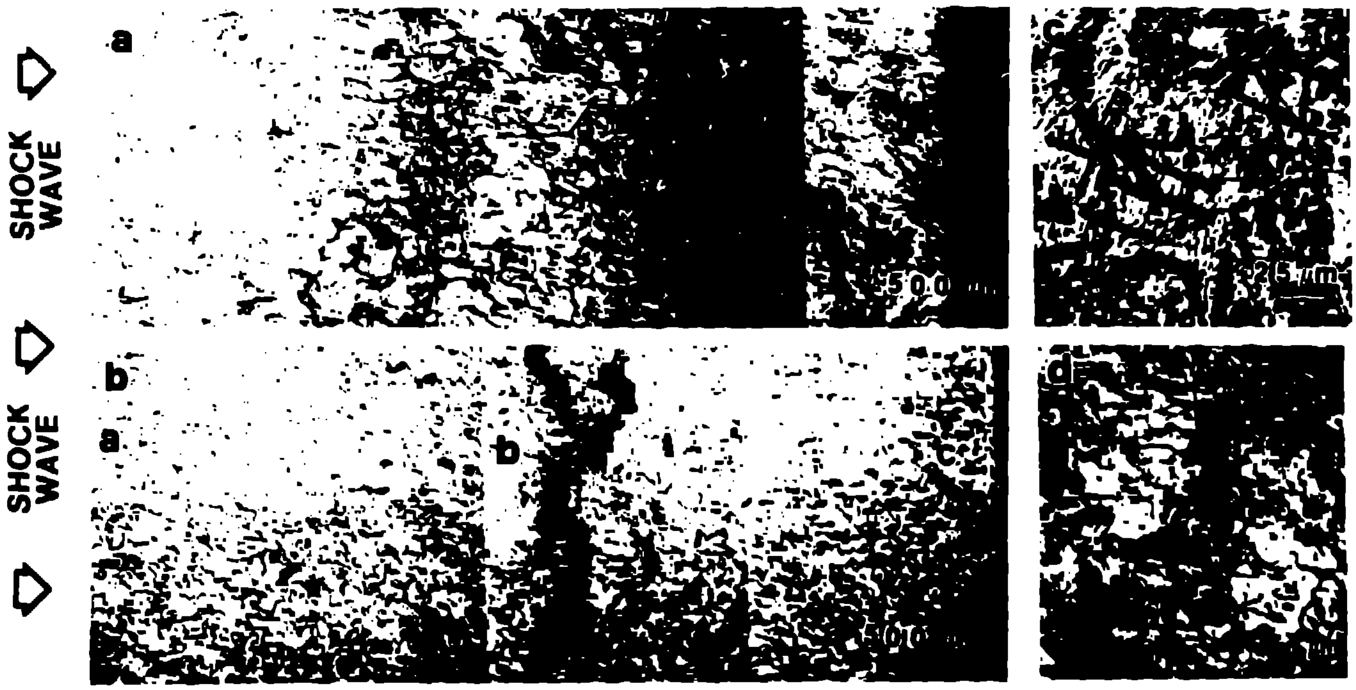

FIGURE 2
Cross-sections and high-mag views of shocked NiTi alloys; (a,c) Sample # 1; (b,d) Sample #3.

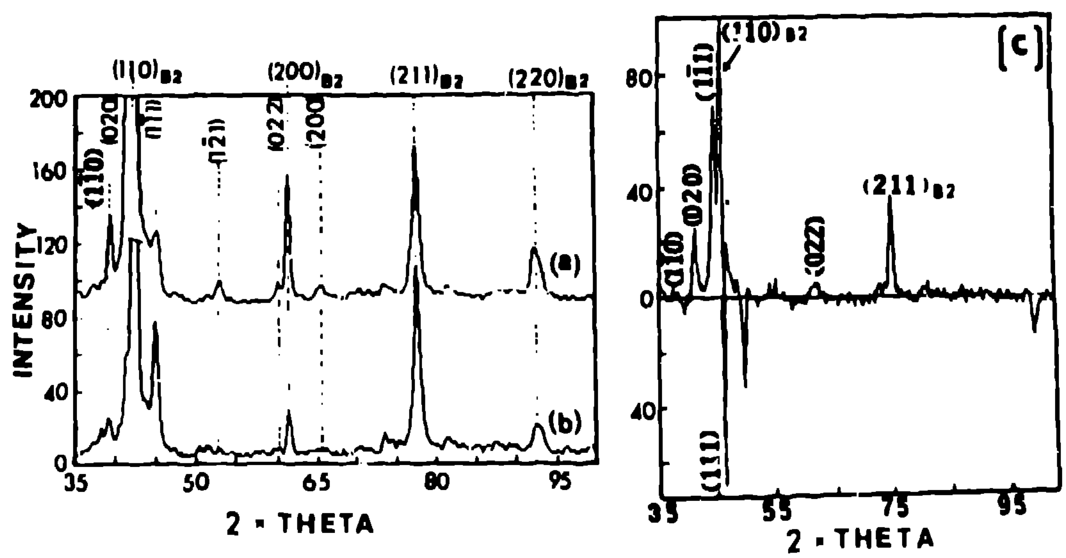

FIGURE 3
X-ray diffraction patterns of NiTi-I alloy Sample # 1 from (a) mid-plane region, and (b) impact surface; and (c) numerical difference of (a) and (b).

transformation was confined only in regions adjacent to spall. The extent of phase transformation in this sample was possibly below (10%), hence could not be detected by XRD analysis.

The TEM observations were also consistent with optical microscopy and XRD analysis results. Bright field TEM images of martensite needles from NiTi-I alloy, Sample #1 and #2 (taken from areas in the central mid-plane region) are shown in Fig. 4(a) and (b), respectively. The selected area diffraction patterns (SAD) confirm the monoclinic structure of the needles. These tensile-stress-pulse induced martensite needles contain a micro-twined substructure, characteristic of *stress-assisted* [3] martensite formed in samples deformed below the yield strength.

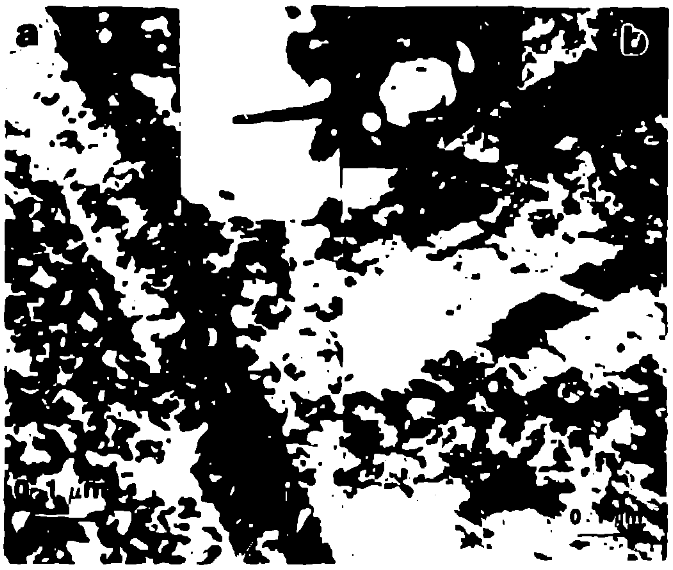

FIGURE 4
(a) and (b) TEM images of martensite needles in Samples # 1 and 2.

Figure 5 (a) and (b) are TEM images in NiTi-II showing the monoclinic martensite needles. Here, the martensite substructure contains predominantly dislocations. Martensites containing a dislocation substructure are characteristic of *strain-induced* [3] transformations, formed upon stressing above the yield strength of the material.

4. SUMMARY

Tensile-stress pulses induce B2-to-monoclinic martensitic transformation in equiatomic NiTi alloys. The transformation product is in the form of acicular needles with either a micro-twined or dislocated substructure depending on whether the alloy is deformed at temperatures close to M_s or temperatures way above M_s.

ACKNOWLEDGMENTS

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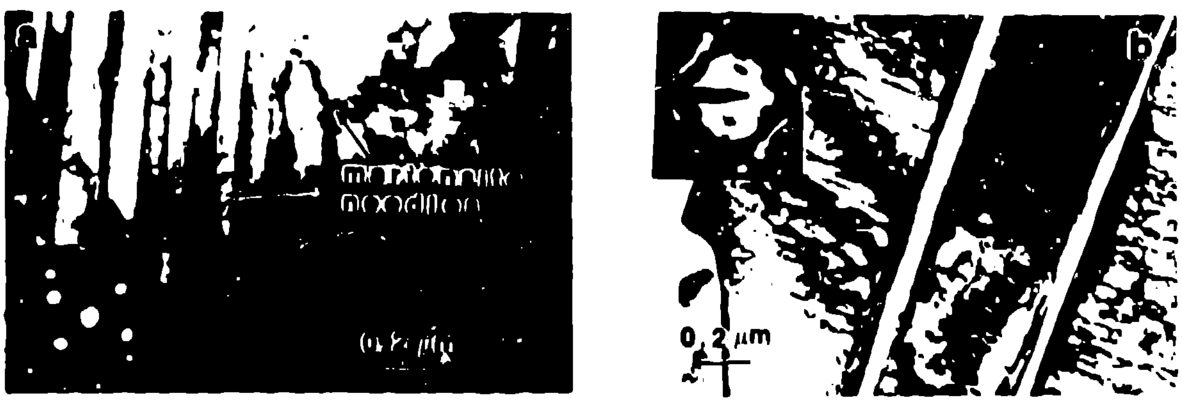

FIGURE 5
(a) and (b) TEM images showing martensite needles in NiTi-II alloy (Sample # 3)