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# Transformation induced crack deflection in a metastable titanium alloy and implications on transformation toughening

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ABSTRACT

The deflection of cracks in grain interior was observed in a metastable $\beta$-phase Ti alloy (Ti-24Nb-4Zr-7.9Sn) with transmission electron microscopy during high cycle fatigue. This peculiar phenomenon is induced by the $\beta \rightarrow \alpha''$ martensitic transformation in front of crack tips in grain interior when cracks propagate along the $\{011\}_\beta$ slip planes with acute angles between $\alpha''$ lamellae and cracks approximately of 45°. The $\alpha''$ product phase has lattice dilation and contraction along two main transformation directions, thus introduces compressive and tensile strains perpendicular and parallel to crack propagating planes, respectively. This exerts beneficial effect on the crack deflection during the subsequent cyclic-loading.

## 1. Introduction

Extensive researches [1–3] have been focused on the crack deflection in metallic materials attributed to its significant role on improving the fatigue fracture toughness of materials. Generally, the crack deflection takes place in grain interior and at grain boundaries. It is well documented that crack deflection at grain boundaries is strongly related to the grain orientation [4,5]. Nevertheless, for crack deflection in grain interior, although load excursion [6], variation of slip planes [1,7] and local microstructure discontinuity (e.g. second phase [8,9] and martensitic transformation [10]) were proposed as possible mechanisms, direct experiment evidences are scarce especially for the transformation mechanism. Indirect methods, such as optical micrograph [11], X-ray diffraction [12] and scanning electron microscope (SEM) [1], are generally applied to investigate martensitic transformations in metals at millimeter to micrometer scale during fatigue, but rare direct evidences, particularly at the vicinity of cracks, have been obtained. Therefore, a direct experimental investigation in micrometer to atomic scale is desired to understand the relationship of phase transformation to crack propagation. In addition, a number of essential requirements for transformation toughening in ceramics are generally also applicable to metals and alloys. For example, volume expansion of martensites has been observed in transformation toughening of nanocrystalline aluminum [13], transformation-induced plasticity steel [14], $\gamma$-titanium aluminide [15], and Ti-1023 alloy [10]. However, whether these requirements are mandated for all the transformation toughening in metals and alloys is still subject to experimental investigations.

In this work, transmission electron microscopy (TEM) has been conducted on the crack deflection in a newly developed metastable $\beta$-phase Ti alloy Ti-24Nb-4Zr-7.9Sn [16,17] (termed as Ti2448 alloy), under fatigue deformation. The alloy exhibits extraordinary mechanical properties, e.g. a low Poisson's ratio of 0.14 [16], remarkable nonlinear elastic deformation behavior with ~3% recoverable strain [18,19], low bulk modulus of ~23 GPa [16] and Young's modulus of ~55 GPa [20], and has become a promising biomedical material [16] attributed to its excellent mechanical properties and biochemical compatibilities. With advances in contemporary medical research and improving longevity of human life, the expected longevity of orthopedic implants increases accordingly. The Ti2448 alloy demonstrates excellent fracture toughness, such as obvious bifurcating and tortuous propagation path of cracks for three-point bending fatigue and tensile-tensile fatigue, thus benefits the high longevities of the biomedical alloy subject to cyclic loading [21]. Here, we reveal that the fracture toughening of the Ti alloy is associated with a $\beta \rightarrow \alpha''$ single variant martensitic transformation in front of crack tips in grain interior when cracks propagate along the $\{011\}_\beta$ slip planes under fatigue deformation. This is attributed to the lattice dilation of $\alpha''$ martensite

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perpendicular to the crack propagation plane and the lattice contraction in the $\langle 200 \rangle_\beta$ direction, which lies in the crack propagation plane.

## 2. Experimental

### 2.1. Sample preparation

The studied Ti2448 alloy [22] consists of single $\beta$ phase with a chemical composition of 24.4Nb, 3.75Zr, 8.09Sn, 0.11O (wt%), and balance Ti. Bulk samples were cut parallel to the rolling direction (RD) into dimensions of 40 × 8.0 × 2.0 $mm^3$ and the notch is 1.0 mm. Sinusoidal cyclic fatigue tests were performed with a tensile stress of 200 MPa, a stress ratios $R$ of 0.1 and a frequency of 30 Hz. TEM [23] specimens were cut parallel either to the rolling direction (RD) or the transverse direction (TD) depending on designation, and then thinned by conventional grinding, polishing and ion-milling. Here, the exactly same locations of TEM specimens were investigated before and after the fatigue test, thus a direct comparison can be applied to resolve the evolution of cracks. The microstructure of TEM samples (such as grain boundaries and cracks) was registered by TEM bright field (BF) image before the fatigue test. The TEM specimens were then fixed on Ti alloy substrates and experienced high-cycle fatigue deformation with the substrates. After that, cracks formed during the fatigue deformation were then investigated as presented in Fig. 1. In order to avoid possible damage on the observation areas during the fatigue test, the TEM specimens were glued onto thin rings, and then mounted on substrates through these rings. A sinusoidal load was employed with a stress of 100 MPa, a stress ratio $R$ of 0.1, an oscillation frequency of 30 Hz and a fatigue cycle of $10^6$. The loading direction of RD specimens was set parallel to the rolling direction. The fatigue test was conducted in the ambient environment.

### 2.2. Microstructure characterization

Dark field (DF), bright field (BF) images and selected-area electron diffraction (SAED) patterns were taken with a JEM-2100 transmission electron microscope, operating at 200 kV. High-resolution TEM images and high-angle annular-dark-field scanning transmission electron microscopy (HAADF-STEM) images were recorded using an aberration-corrected transmission electron microscope (Titan$^3$ G2 60–300) and a Tecnai G2 F30 TEM both operating at 300 kV.

### 2.3. Finite element simulation

Finite element method (FEM) was used to analyze the strain distribution around an $\alpha''$ lamella and a crack tip during fatigue tensile loading. The plane strain distribution around an $\alpha''$ lamella was simulated according to experimental setups. A Ti2448 matrix and a load-bearing substrate (with the same physical properties of $\alpha''$ martensitic) were fixed together by an $\alpha''$ lamella. The lattice strain in the Ti2448 matrix around the $\alpha''$ lamella along the $[100]_{\alpha''}$ direction and the $[010]_{\alpha''}$ direction of the $\alpha''$ lamella, corresponding to the $[100]_\beta(\varepsilon_1)$ direction and the $[011]_\beta$ $(\varepsilon_2)$ direction of the $\beta$-Ti2448 alloy, was introduced by compressive and tensile strain on the load-bearing substrate, respectively. The rotation strain was released by free rotation of the Ti2448 matrix during loading. The elastic modulus of ~55 GPa [20] was used for the Ti2448 alloy and ~74 GPa [20] for the $\alpha''$ phase along $\varepsilon_1$ and $\varepsilon_2$ directions during the FEM simulation. The stress at a crack tip was simulated with the elastic modulus of 55 GPa, a Poisson's ratio of 0.14 and a strain of 0.2%.

## 3. Results

### 3.1. Crack deflection during high-cycle fatigue

Large angle deflection and bifurcation of cracks are observed in the bulk Ti2448 alloy during high-cycle fatigue as shown in Fig. 2a–b. TEM experiment was employed to analyze the mechanism of crack deflection during the fatigue. Based on significant amount of experiments, we observe that cracks are deflected in large angles in grain interior (e.g. Fig. 2c). These observations are conducted in both TEM samples cut along the RD direction (Fig. 2d) and the TD direction (Fig. 2e), although it seems that there is fewer deflected cracks in grain interior in the latter. This large angle crack deflection is in contrast to cracks observed in tensile deformed samples, where the cracks are mostly running straight with only few slight (small angle) deflection (Fig. 2f).

### 3.2. Transformation induced crack deflection in grain interior

Fig. 3a presents a typical crack deflection in grain interior in a TEM sample cut along the rolling direction. Bundles of $\alpha''$ lamellae

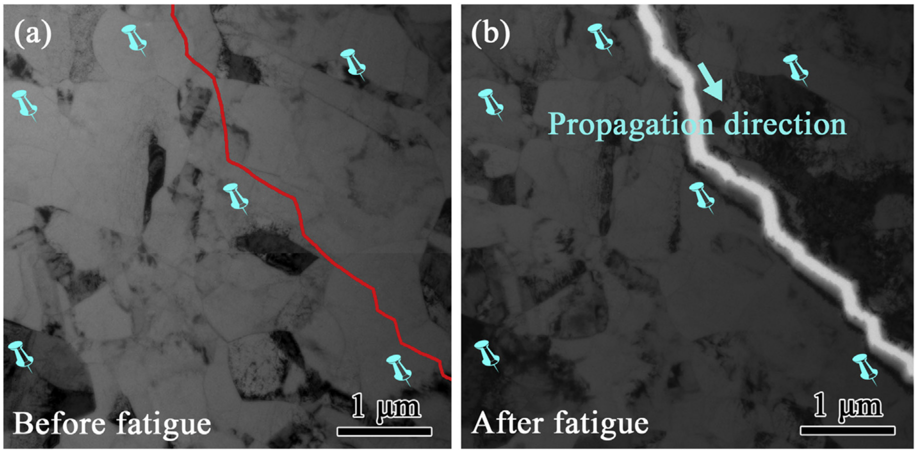

**Fig. 1.** (a) Registered sample information before fatigue deformation. (b) Deflection of a fatigue crack during the fatigue test corresponding to the same region in (a). Red solid line in (a) shows the crack propagation path in (b). Cyan marks in (a) and (b) are used to determine corresponding positions in the sample. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)