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Non-classical $\{3\,3\,4\}_{\beta}$ type of twinned α' martensite in a Ti–5.26 wt.% Cr alloy

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Abstract

Some uncommon crystallographic features of α' martensite were characterized in the martensitic transformation in a water-quenched Ti–5.26 wt.% Cr alloy. A pair of martensite plates, type K and type M, sit side-by-side and share a $\{3\,3\,4\}_{\beta}$ habit plane. However, they have different habit planes in terms of the hexagonal close-packed lattice. While the classical phenomenological theory of martensite crystallography (PTMC) is unable to explain the habit plane of type K martensite even though they contain $\{1\,\bar{1}\,0\,\bar{1}\}$ internal twins, application of the edge-to-edge matching (E2EM) model succeeded in accounting for both the orientation relationship and the habit plane orientation of the two types of martensite. The elastic strain energy as a function of the thickness of type K martensite plates was calculated, and the result supports the preference of the E2EM model over PTMC in explaining this type of martensite. In addition, a self-accommodation mechanism for strain was proposed to maintain the macroscopic invariant plane, and reduce the overall elastic strain energy of the adjacent pair of martensite plates. The application of the E2EM model plus this self-accommodation mechanism provides a new perspective on understanding martensitic transformations and providing a link between the crystallography of displacive and diffusional transformations.

Keywords: Crystallography; Martensitic transformations; Strain energy; Edge-to-edge matching; Ti alloys

1. Introduction

The martensitic transformation from body-centered cubic (bcc) β phase to hexagonal close-packed (hcp) α' phase in Ti and its alloys has been studied extensively from 1950 onwards [1–6]. Two distinctive morphologies of α' martensite, i.e. plate-like martensite with flat parallel interfaces (type M [4]) and another plate-like martensite with a zig-zag interface associated with internal twinning (type K [4]), were reproducibly observed by transmission electron microscopy (TEM). Type M martensite is always characterized by its habit plane of $\{3\,3\,4\}_{\beta}$, which is perpendicular to the hcp basal plane, i.e. perpendicular to $(0\,0\,0\,1)_{\alpha'}$, which is approximately parallel to $(0\,\bar{1}\,1)_{\beta}$, while type K martensite always has a $\{3\,4\,4\}_{\beta}$ habit plane that is not perpendicular to $(0\,0\,0\,1)_{\alpha'}$ and contains $\{1\,\bar{1}\,0\,1\}_{\alpha'}$ twins. By incorporating these internal twins as the inhomogeneous lattice invariant shear (LIS), the $\{3\,4\,4\}_{\beta}$ habit plane, as well as the near Burgers orientation relationship (OR) was reasonably well explained [3,4,7] by the phenomenological theory of martensite crystallography (PTMC), proposed by Bowles and Mackenzie [8,9] and Wechsler et al. [10]. However, there is still some controversy regarding these PTMC solutions. First, there is no evidence of any slip or internal twining inside the type M martensites. In this case, a small-scale dilatation was introduced to rationalize the $\{3\,3\,4\}_{\beta}$ habit plane [2], and the physical meaning of this dilatation is still debatable [3]. Second, some type M martensite plates can change to type K along their length,

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with each local facet of the zig-zag interface parallel to $\{334\}_\beta$ [2,3]. A question then arises: if $\{334\}_\beta$ is already a macroscopic invariant plane, why does it still require internal twins to produce an overall invariant plane with $\{344\}_\beta$ as predicted by PTMC? Third, in ferrous alloys, such as high carbon steels [11] and Fe–Ni alloys [12] where the {259} and {3 10 15} habit plane can be adequately explained by the PTMC, the martensite plates consists of a dense arrangement of very thin twins (~10 nm). By comparison, the twins in type K martensite in Ti–Mn and Ti–Mo alloys are relatively wide (30–50 nm) and widely spaced (100–300 nm). The resultant local facets are far away from the average habit plane, and therefore it is doubtful that such big twins are responsible for producing a macroscopic invariant plane strain. These issues imply that the PTMC is not entirely satisfactory in explaining the crystallography of α′ martensite in Ti alloys, even though it appears plausible at first sight. Further experimental and theoretical investigations are required to resolve this puzzle.

In addition to the PTMC, other attempts have already been made to understand the crystallographic features in martensitic transformations. These include minimizing the Burgers vector content of the interface [4], the topological model (TM) [13–15] and the O-lattice model [16]. A long-range strain-free interface between martensite and the parent phase is always pursued, no matter which model is applied. Without violating the requirement of a macroscopic invariant habit plane, the present paper aims to present a new perspective on the crystallography of α′ martensite based on the edge-to-edge matching (E2EM) model [17–19] originally developed to predict the OR and habit planes in diffusion-controlled phase transformations. The preference of the E2EM solutions over conventional PTMC solutions is justified by the resulting minimization of strain energy associated with the formation of twinned martensite. The long-range strain accommodation mechanism is also discussed.

2. Experimental procedures

A Ti–5.26 wt.% Cr alloy was selected for the current study. A button ingot of Ti–Cr alloy was hot-rolled into a 3.5-mm-thick slab in a stainless sheath at 1273 K. After encapsulation in a quartz tube under vacuum, the slab was homogenized for 3 days at 1273 K, followed by water quenching. The slab was cut into rectangular blocks 6 mm by 4 mm in size. A layer of Ta foil was used to wrap each block, to minimize surface vaporization of alloying elements at high temperatures. These Ta-wrapped blocks were again encapsulated in quartz tubes, annealed at 1273 K for 30 min in the single β phase region, and then quenched into water at room temperature to trigger the martensitic transformation. For TEM sample preparation, slices 0.6 mm thick were cut from the as-quenched rectangular blocks and ground to a sheet 100 μm thick. Disks 3 mm in diameter were punched from the sheet and further thinned to 50 μm. The disks were then twin-jet polished in a Struers A3 electrolyte consisting of 50 ml of perchloric acid, 300 ml of butyl cellosolve and 500 ml of methanol at −35 °C with a voltage of 15 V. All the thin foils were then examined by TEM in a JEOL 2100 microscope.

3. Experimental results

An optical micrograph of the as-quenched Ti–5.26 wt.% Cr alloy is shown in Fig. 1. The microstructure consists of retained β matrix and a number of thin martensite plates up to hundreds of microns in length. These martensite plates exhibit typical "lightning-bolt" morphology [2] associated with the coexistence of different variants. More detailed morphological features of such thin plate martensite are shown in the scanning TEM (STEM) bright-field (BF) image of Fig. 2a. A pair of side-by-side martensite plates, with edge-on habit planes and different morphologies are visible in the field of view. Following Smith and Knowles [4], the present authors term the left-hand side martensite with the zig-zag interface "type K" and the one with the flat interface "type M". This STEM BF image was taken with the electron beam parallel to a $\langle 1\,\bar{1}\,0\rangle_\beta$ zone axis of the matrix. The selected area diffraction pattern (SADP) of the matrix is shown in Fig. 2b. It contains strong reflections from the dispersed ω phase at $n/3$ periodicity relative to the bcc reflections. Correlating the habit plane trace in the BF image with the SADP of the matrix, it appears that both types of martensite plate have a $\{334\}_\beta$ type habit plane. However, their habit plane orientation in terms of the hcp lattice is not the same, as will be described in the following section.

The SADP of the plate martensite were taken at the same specimen orientation. Fig. 2c shows the SADP from the type M martensite with the zone axis along $[0001]_M$. The subscripts "M" and "K" denote the type M and untwinned matrix of type K martensite, respectively, and these subscripts are subsequently used to indicate which plate is being referred to. Overlapping the SADP in Fig. 2b and c, one can express the OR between the type M plate and its β phase matrix as a near Burgers OR, denoted as OR I, namely

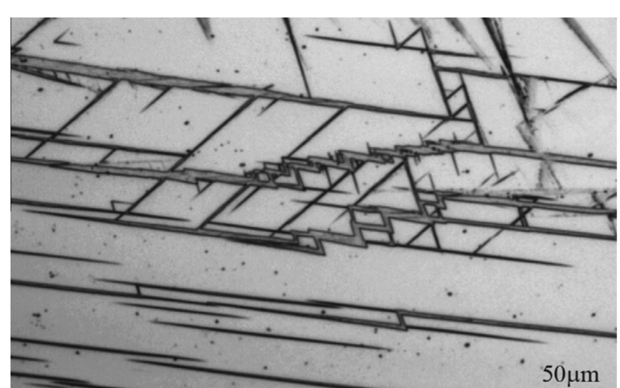

Fig. 1. Optical micrograph of plate martensite in the as-quenched Ti–5.26 wt.% Cr alloy.