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Work-hardening and twinning behaviors in a commercially pure titanium sheet under various loading paths

Takayuki Hama*, Hirotaka Nagao, Akihiro Kobuki, Hitoshi Fujimoto, Hirohiko Takuda

Department of Energy Science and Technology, Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto 606-8501, Japan

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ABSTRACT

In this study, the work-hardening and twinning behaviors in a commercially pure titanium sheet were examined under various loading paths including reverse loading. The yield stress was identical between tension and compression, while the work-hardening was slightly larger during compression than during tension. These tendencies were the same in both the rolling and transverse directions. When the sheet was subjected to reverse loading, the Bauschinger effect was observed during both tension–compression and compression–tension. The tendency in the Bauschinger effect was nearly independent of the strain path tested in the present study. Concerning the twinning, the activities of $\{10\bar{1}2\}$ tensile twinning, $\{11\bar{2}2\}$ compressive twinning, and $\{11\bar{2}1\}$ tensile twinning were observed during tension. Alternatively, during compression, the activity of $\{10\bar{1}2\}$ tensile twinning was observed and was much larger than that during tension. When the sheet was subjected to tension following compression, detwinning occurred. Although the trend in the activity of twinning was similar to that of a magnesium alloy sheet, the behavior observed in the stress–strain curves was quite different from that of a magnesium alloy sheet. Based on the results presented, the effect of twinning and detwinning activities on the work-hardening behavior was discussed.

1. Introduction

With properties such as low density, high corrosion resistance, and high heat resistance, commercially pure titanium (hereafter referred to as CP-Ti) is widely used in various applications such as chemical plants, heat exchangers, and chassis of mobile phone and computer [1–3]. CP-Ti sheets have high ductility at room temperature, therefore they are often manufactured at room temperature by press forming and bending.

Alternatively, it is also well known that rolled CP-Ti sheets demonstrate strong anisotropic deformation behavior. For instance, their Lankford value (r-value), i.e., the ratio between the width and thickness strains, is very high and it differs notably between the rolling direction (RD) and the transverse direction (TD) [2–4]. In addition, the work-hardening behavior exhibited by rolled CP-Ti sheets differs between tension and compression [3–7] as well as between the RD and the TD [3,4,6,8,9]. Among the previous examples, the high r-value is advantageous for press forming because this yields good deep drawability. Alternatively, because of the strong anisotropy observed between tension and compression and between the RD and the TD, it is recognized that press forming of CP-Ti sheets is quite difficult.

The strong anisotropy in CP-Ti sheets is because of the strong crystal anisotropy of the hexagonal close-packed (hereafter referred to as hcp) structure and the strong basal texture with c-axes tilted between 20° and 40° from the normal direction (ND) to the TD [2,3,6,7,9,10]. In CP-Ti sheets at room temperature, $\{10\bar{1}0\}\langle 11\bar{2}0\rangle$ prismatic slip is the easiest family to be activated, however $(0001)\langle 11\bar{2}0\rangle$ basal slip and $\{10\bar{1}1\}\langle 11\bar{2}0\rangle$ pyramidal slip are also active [10–16]. Alternatively, because there are only four independent slip systems in the three previously mentioned families, at least one other independent deformation mode is necessary to satisfy the von Mises criterion [17]. From earlier studies, it is known that $\{10\bar{1}1\}\langle 11\bar{2}3\rangle$ pyramidal slip, $\{11\bar{2}2\}\langle 11\bar{2}3\rangle$ pyramidal slip [18–22], or twinning [2,9,10,19,23–25] may act as the additional deformation mode.

In polycrystalline CP-Ti, the activity of several twin modes has been reported: $\{10\bar{1}2\}$, $\{11\bar{2}1\}$, and $\{11\bar{2}3\}$ tensile twinning, and $\{11\bar{2}2\}$, $\{10\bar{1}1\}$, and $\{11\bar{2}4\}$ compressive twinning [9,10,19]. Among them, at room temperature the activities of $\{10\bar{1}2\}$ tensile twinning and $\{11\bar{2}2\}$ compressive twinning are most common compared to the other twinning modes. Chun et al. [23] reported that $\{10\bar{1}1\}$ compressive twinning and $\{11\bar{2}1\}$ tensile twinning were difficult to activate because of a large shuffling parameter

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* Corresponding author. Tel.: +81 75 753 5418; fax: +81 75 753 5428.
E-mail address: hama@energy.kyoto-u.ac.jp (T. Hama).

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and high twinning shear strain, respectively. Paton et al. [19] also demonstrated that the activity of $\{10\bar{1}1\}$ compressive twinning was negligible at temperatures below 300 °C. Murayama et al. [24] concluded from their experiments that $\{10\bar{1}2\}$ tensile twinning and $\{11\bar{2}2\}$ compressive twinning were observed, whereas $\{11\bar{2}3\}$ tensile twinning and $\{11\bar{2}4\}$ compressive twinning were not observed under uniaxial tension at room temperature.

Mullins et al. [9] examined active twin modes during uniaxial, plane strain, and equibiaxial tension in a rolled CP-Ti sheet. Under uniaxial tension along the RD, $\{11\bar{2}2\}$ compressive twinning and $\{11\bar{2}4\}$ compressive twinning were active, whereas under uniaxial tension along the TD $\{10\bar{1}2\}$ tensile twinning was also active. These results were similar to those reported by Ishiyama et al. [2]. The active twin modes under plane strain and equibiaxial tension were also similar to those of uniaxial tension; however, the volume fraction of twinned area was much larger than that of uniaxial tension. Stanford et al. [26] conducted a compression test in a wire-drawn CP-Ti sample and depicted that $\{10\bar{1}2\}$ tensile twinning was the most active twin mode and $\{11\bar{2}2\}$ compressive twinning and $\{11\bar{2}1\}$ tensile twinning were also active. They also reported that $\{11\bar{2}2\}$ compressive twinning was very sensitive to grain size. Ghaderi and Barnett [27] also examined the sensitivity of twinning to grain size in CP-Ti. Bozzolo et al. [28] observed misorientations induced by twinning during cold rolling in CP-Ti and showed that $\{11\bar{2}2\}$ compressive twinning was very active and $\{10\bar{1}2\}$ tensile twinning and $\{11\bar{2}1\}$ tensile twinning were also active. Tirry et al. [29] carried out a monotonic simple shear test in a CP-Ti plate and presented that $\{10\bar{1}2\}$ tensile twinning could be activated easier than $\{11\bar{2}2\}$ compressive twinning. Deng et al. [30] reported a similar result. Wang et al. [31] investigated the activity of $\{11\bar{2}1\}$ tensile twinning under tension in a CP-Ti plate and reported that the activity of $\{11\bar{2}1\}$ tensile twinning was much less than that of $\{10\bar{1}2\}$ tensile twinning. Murasawa et al. [7] performed the uniaxial tensile test on a rolled CP-Ti sheet and found that the twinning nucleated and grew around the yield point. This successive twin nucleation around the yield point was pronounced when the angle between the tensile and rolling direction was smaller than 30°. Becker et al. [32] examined the work-hardening behavior under tension in a rolled CP-Ti sheet. The authors identified three different work-hardening stages depending on the work-hardening rate and explained the dominant mechanism as follows. Plastic deformation was dominated primarily by prismatic and basal slip and additionally by pyramidal $\langle a+c \rangle$ slip in the first stage, whereas $\{11\bar{2}2\}$ compressive twinning and $\{10\bar{1}2\}$ tensile twinning were active in the second and third stages, respectively. Mullins et al. [9] also reported that twinning was active only at the latter stage of deformation under tension.

As described earlier, extensive studies have been conducted to identify the twinning activity in CP-Ti sheets. Considering strong basal texture is generally developed in CP-Ti sheets, the active twin mode may be different between tension and compression. However, to the best of our knowledge, the identification of the twinning activity has been done under either tension or compression but a comparison between tension and compression has not yet been examined. Ishiyama et al. [2] investigated the activity of twinning under uniaxial tension and compression in the RD in a polycrystalline CP-Ti sheet theoretically. They depicted that $\{11\bar{2}2\}$ compressive twinning could be activated under tension, while $\{10\bar{1}2\}$ and $\{11\bar{2}1\}$ tensile twinning would be active under compression. However, their discussion was based only on the Schmid factor and was not verified experimentally.

In rolled magnesium (hereafter referred to as Mg) alloy sheets that also have the hcp structure, it is well known that $\{10\bar{1}2\}$ tensile twinning is active when the sheet is subjected to in-plane compression. That twinning activation occurs because of the strong basal texture of the Mg, however detwinning is easily activated when the loading direction is inverted to tension [33–43]. The activities of twinning and detwinning play important roles in deformation behavior such as work-hardening under reverse loading and the nonlinearity in the stress–strain curve during unloading; thus they have been investigated extensively both experimentally and theoretically [44–47]. Based on the large activity of twinning in CP-Ti sheets observed in the earlier parts of this study, it would be expected that the detwinning would also be active under reverse loading in CP-Ti sheets. Moreover, detwinning has been reported in Ti alloys with a body-centered cubic structure [48,49]. However, to the best of our knowledge, studies on the deformation behavior upon strain path changes in CP-Ti sheets are scarce; hence, the activity of detwinning upon strain path changes has not been observed. Shamsaei et al. [50] and Peng et al. [51] performed fatigue tests in CP-Ti and examined the stress–strain behavior and the fatigue life in detail. Alternatively, the activity of twinning was not investigated in their studies. Tritschler et al. [52] conducted a cyclic loading test in a Ti alloy sheet with hcp structure and modeled the work-hardening behavior. However, microstructure upon cyclic loading was not observed; hence, the occurrence of detwinning and the effect of twinning activity on the work-hardening behavior upon cyclic loading are not yet understood. Because sheets are often subjected to reverse loading such as bending–unbending in press forming, it is worth examining the occurrence of detwinning and the deformation behavior of CP-Ti sheets upon strain path changes.

The present study investigates the work-hardening and twinning behaviors in a CP-Ti sheet under in-plane tension, compression, compression followed by tension (hereafter referred to as compression–tension), and tension followed by compression (hereafter referred to as tension–compression). In particular, the occurrence of detwinning upon reverse loading is examined carefully. To this end, the stress–strain curves and the microstructure evolution using electron backscatter diffraction (hereafter referred to as EBSD) are investigated in detail.

2. Experimental details

2.1. Material

A cold rolled CP-Ti sheet (Kobe Steel, JIS grade 2) with 1 mm thickness was used in the present study. A specimen shown in Fig. 1 was machined parallel to the RD or the TD. A specimen cut parallel to the RD or the TD is hereafter referred to as the RD sample or the TD sample, respectively. The samples were annealed for approximately 1 h at 530 °C before testing. The average grain size was approximately 20 μm.

2.2. Experimental procedure

Testing was performed in in-plane monotonic tension, monotonic compression, compression–tension, and tension–compression.

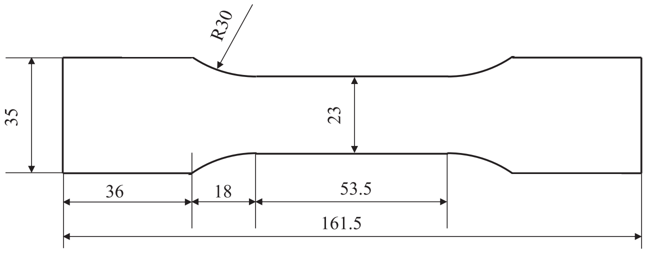

Fig. 1. Geometry of a specimen used in the experiment with measurements expressed in mm.