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Effect of crystallographic texture on ratcheting response of commercially pure titanium

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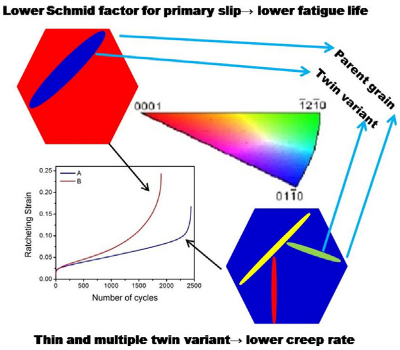
HIGHLIGHTS

- Orientation with high Schmid factor for prism slip gives higher ratcheting life.
- Anisotropy in strain hardening is not manifested in anisotropy in ratcheting response.
- Suppression of anisotropy in ratcheting response due to pronounced twin activity.
- Higher the number of twin variants lower is the cyclic creep rate.

GRAPHICAL ABSTRACT



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ABSTRACT

The effect of crystallographic texture on ratcheting behavior of cold rolled and annealed plate of commercially pure titanium has been investigated. Flat fatigue test specimens of two different orientations along rolling and transverse direction have been machined to obtain distinct texture with crystallographic direction close to $\langle 10\bar{1}0\rangle$–$\langle 11\bar{2}0\rangle$ and $\langle 0001\rangle \parallel$ loading direction for sample A and B respectively. The microstructure, texture and grain boundary characteristics of tested specimens have been analyzed using electron backscatter diffraction data. The significant anisotropy in strain hardening for monotonic loading is not manifested in anisotropy in ratcheting response and shows only 20% lower fatigue life in orientation B compared to A under same stress cycle condition. The anisotropy in ratcheting response has been attributed to the unique combination of dislocation activity and twin variant selection in orientation A and B. Orientation A with higher Schmid factor for prism slip efficiently partitions the accumulated backstress by activating prism slip and detwinning of thin multiple twin variants which causes slow accumulation of ratcheting strain for higher number of cycle. While in orientation B prism slip is restricted and detwinning is difficult due to formation of thick single variant extension twins that causes its early failure.

1. Introduction

Commercially pure titanium is an excellent material for various aerospace applications because of its high strength to weight ratio, ease of fabricability and superior fracture toughness [1]. In addition, it exhibits excellent corrosion resistance which lowers maintenance cost

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of titanium components. Hence, it is becoming a material of choice to replace components made of stainless steel in chemical and petrochemical industries for tubing, piping, heat exchangers etc. However, for materials to be used in above mentioned application it is essential to evaluate the endurance of the material under repeated cyclic loading condition which gives its fatigue life. Hence, in applications like pressure vessels operating at high temperature and pressure where proportional asymmetric cyclic loading is most prevalent, the study of ratcheting behavior of commercially pure titanium is of great significance. Moreover, due to inherent anisotropic nature of material, it is expected that there will be anisotropy in its ratcheting response also. Hence, the study of anisotropy in ratcheting behavior is essential for failure analysis of the component material which is often subjected to multi-axial loading during service.

The factors affecting anisotropy in mechanical properties are crystal structure, texture, mode of deformation and strain hardening coefficient. The extent of anisotropy of body centered cubic (bcc) and face centered cubic (fcc) crystal is not significant but has been found to be appreciable in case of hexagonal close packed (hcp) metal under monotonic loading. However, the anisotropy in fatigue life in some industrially important materials having cubic crystal structure e.g. bcc interstitial free (IF) steel and fcc stainless steel (SS 316) has been found to be significant. Cyclic loading along 45° to rolling direction resulted in fatigue life of one-fourth and half that of 0° sample in IF steel [2] and SS 316 [3] respectively. This observed anisotropy in ratcheting response in cubic system has been attributed to the number of active slip system which mainly controls the distribution of backstress and the rate of transition from planar to wavy slip [3]. With increase in strain the phenomenon of twinning-detwinning supplements relaxation of backstress when both the modes of deformation are activated. A thorough understanding of effect of texture in terms of in-plane anisotropy in tension [4] and compression [5] and also normal plane [6] anisotropy in tensile properties for rolled sheets of hcp CP-Ti is established whereas the anisotropy in cyclic deformation behavior is still unexplored. This anisotropic deformation behavior under monotonic tension and compression has been attributed to the polar nature of deformation twinning in hcp metals. Hence, it is expected that the asymmetric hysteresis loops arising due to distortion in the twinning-induced region during cyclic deformation of hcp metals will also lead to anisotropy in ratcheting response.

In the last decade, considerable studies have been carried out on the cyclic deformation behavior of hcp magnesium and its alloys especially AZ31 and AZ91. Extensive investigations have been carried out on low cycle fatigue behavior under both strain controlled [7–11,17,18] and stress controlled asymmetric cyclic loading or ratcheting behavior [12–16,19,20]. The presence of residual twins cause asymmetry in cyclic hardening response between tension and compression loading which increases the stress concentration due to dislocation/twin boundary interaction and inevitably influences the fatigue property [7]. The contribution of twinning to asymmetry has been challenged by reduction of asymmetry in hysteresis loop and improvement in fatigue life of magnesium alloy by pre-twinning treatment of rolled alloy [10–11]. Wu et al. [11] explained that the improvement results from the prolonged detwinning process and inhibited dislocation slip during reverse tension leading to development of compressive mean stress in the cycle resulting in more symmetric shape of stress-strain hysteresis loop. On the other hand, uniaxial ratcheting behavior of magnesium alloy has been studied to determine the influence of mean stress and stress amplitude on fatigue life [12–14]. In addition, new stress based [15] and improved crystal plasticity based [16] fatigue life prediction model has been developed for single-step and multistep asymmetric stress-controlled cyclic loading for AZ31B magnesium alloy.

It has also been recently reported that Mg alloys exhibit anisotropic fatigue resistance behavior [17–20]. Strain controlled cyclic loading carried out on extruded Mg alloy by Lv et al.. [17] found shorter fatigue lifetime of the extrusion direction (ED) sample compared to transverse direction (TD) sample. Meanwhile, Wu et al. [18] showed that fatigue life along the normal direction (ND) to the processing plane is significantly lower compared to the RD (or ED) strain controlled mode. The orientation of c-axis with respect to loading direction i.e., RD (or ED), TD and ND influence the activation of extension twin and its variant selection which in turn controls fatigue life in different orientation [21].

Compared to magnesium, low cycle fatigue behavior of CP-Ti has been studied sparsely in the literature [22–25]. Very limited studies have been carried out on the ratcheting response of commercially pure titanium except one by Peng et al.. [26]. This study is focused on the influence of stress amplitude on the fatigue and ratcheting response of CP-Ti in order to develop model based on the relationship between hardening coefficient of material and energy consumed per cycle for more robust prediction of fatigue life and hence does not involve micro-mechanistic approach of modeling of ratcheting response in CP-Ti. Nevertheless there is no study carried out on anisotropy in ratcheting response in hcp titanium. This is of particular scientific relevance as unlike magnesium where only basal slip and extension twinning is operative micro-mechanism of deformation, titanium is characterized by deformation by prismatic, pyramidal slip $<c + a>$ as well as extension and contraction twinning which makes it more difficult to predict the evolution of ratcheting strain and fatigue life in titanium. In the present investigation, two different combinations of stress amplitude and mean stress have been employed to decipher the micro-mechanisms of ratcheting behavior in differently oriented CP-Ti samples using Electron backscatter diffraction (EBSD) technique.

2. Experimental

Cold rolled and annealed plates of Grade 2 titanium with nominal chemical composition given in Table 1 were used in the present investigation. Flat specimens of dimension following ASTM Standard E606 [27] were machined from the plate of two different orientation designated as sample A and B. Sample A was machined with loading direction parallel to RD from the RD-TD plane and sample B was machined with loading direction along TD from TD-ND plane of the rolled plate. Fig. 1a shows the schematic of specimen orientation and Fig. 1b shows the E606 specimen dimension.

All the experiments were conducted on the above specimens at room temperature using BiSS Nano Plug 'n' Play servo-hydraulic universal test machine of 25 kN capacity. Tensile tests were carried out on the above specimens at constant strain rate of $5 \times 10^{-2}\ \mathrm{s}^{-1}$ to obtain mechanical properties of the material. Engineering stress controlled uniaxial asymmetrical stress cycling was imposed on the specimens. Two different combination of stress amplitude/yield stress (σ_a/σ_y) and mean stress/yield stress (σ_m/σ_y) used are given in Table 2. A sinusoidal waveform was used to perform the tests and the cyclic frequency was kept at 0.2 Hz for all the tests. Tests were continued till failure and stress–strain data acquired throughout the test to obtain 200 data points per stress cycle. Tests were conducted under software control running on a computer interfaced to the control system of the testing machine.

Bulk texture measurement was carried out using Rigaku four circle diffractometer Ultima with Cu K-alpha radiation. Five incomplete pole figures 0002, $10\bar{1}0$, $10\bar{1}1$, $10\bar{1}2$ and $11\bar{2}0$ were obtained from X-ray texture measurement using Schulz reflection geometry. Orientation distribution function was calculated from the incomplete pole figures and recalculated complete 0002 and $10\bar{1}0$ pole figures were plotted using Resmat software [28]. The tested specimens close to fracture region was electropolished using A3 electrolyte and then subjected to micro-

Table 1
Chemical composition of as-received commercially pure titanium.

Element (wt%)	Ti	Fe	O	C	Rest
CP Grade 2 Ti	99.5	0.2	0.06	0.04	0.2