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Role of twinning in the hardening response of zirconium during temperature reloads

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Abstract

We aim to elucidate the interaction between twinning and slip in clock-rolled zirconium plate, and the role that it plays in the hardening response. Compression samples were deformed at liquid nitrogen temperature along the through-thickness and the in-plane direction of the plate to create compressive or tensile twins, respectively. The same samples were reloaded at room temperature and large differences in stress–strain response were observed with respect to samples loaded at room temperature from the beginning. Mechanical tests were complemented with texture analysis by neutron diffraction and orientation imaging microscopy, and also by polycrystal modeling. We show that twins influence the reload behavior by either reorienting material for easy slip or by providing barriers to slip.

Keywords: Zirconium; Twinning; Hexagonal close packing; Strain path changes; Neutron texture

1. Introduction

The work presented here is part of a systematic experimental characterization of slip and twin mechanisms in Zr as a function of temperature and loading direction, with the ultimate objective of developing polycrystal constitutive laws capable of addressing texture and hardening evolution associated with complex deformation histories. Motivated by observations and the conviction that changes in loading history provide the most demanding test of constitutive descriptions, we have devised a set of experiments that interrupt the mechanical deformation path and change either the test temperature or the orientation of the sample with respect to the loading direction. In this paper, we present the results of compression tests that maintain the loading direction and change the temperature. We first load at 76 K, then reload at 300 K, either along the in-plane or the through-thickness direction of a clock-rolled plate. In separate papers we report results for strain path changes [1,2].

In Zr, as in all hexagonal close-packed (hcp) materials, twinning is an important deformation mode under most deformation conditions. The twinning activity and the associated creation of twin domains inside grains lead to rapid texture evolution and to a characteristic increase in hardening rate. We consider Zr as a model hcp material for exploring the interplay of slip and deformation twinning. As we and others have previously shown [3–9], the operative deformation mechanisms in Zr are dependent on a plethora of variables including – but not limited to – grain size, orientation of the aggregate relative to the loading direction, temperature, strain rate, and interstitial impurities. In this study we concentrate on the effect of temperature changes. Specifically, we explore the interaction at room temperature between dislocations and twins formed under prior cryogenic deformation conditions. Depending on the direction of straining, twins are shown either to act as effective barriers to dislocation motion or to create regions of preferential slip.

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Deformation of Zr at low temperature takes place via a mixture of twinning and slip. As shown in previous work [1,2], and here in Figs. 1 and 2, the resulting deformation textures and microstructures introduce a large plastic anisotropy in the mechanical response. For samples loaded in compression at quasi-static strain rates the yield strength in the through-thickness (TT) direction is much greater than that in the in-plane (IP) direction. Using the viscoplastic self-consistent (VPSC) model, Tomé et al. [10] explained such a response in terms of the relative activity of the various slip and twinning modes in this material, depending on loading orientation and temperature. In a companion work [11], this polycrystal model was incorporated into a finite element code and validated by four-point beam tests performed at room and liquid nitrogen temperatures.

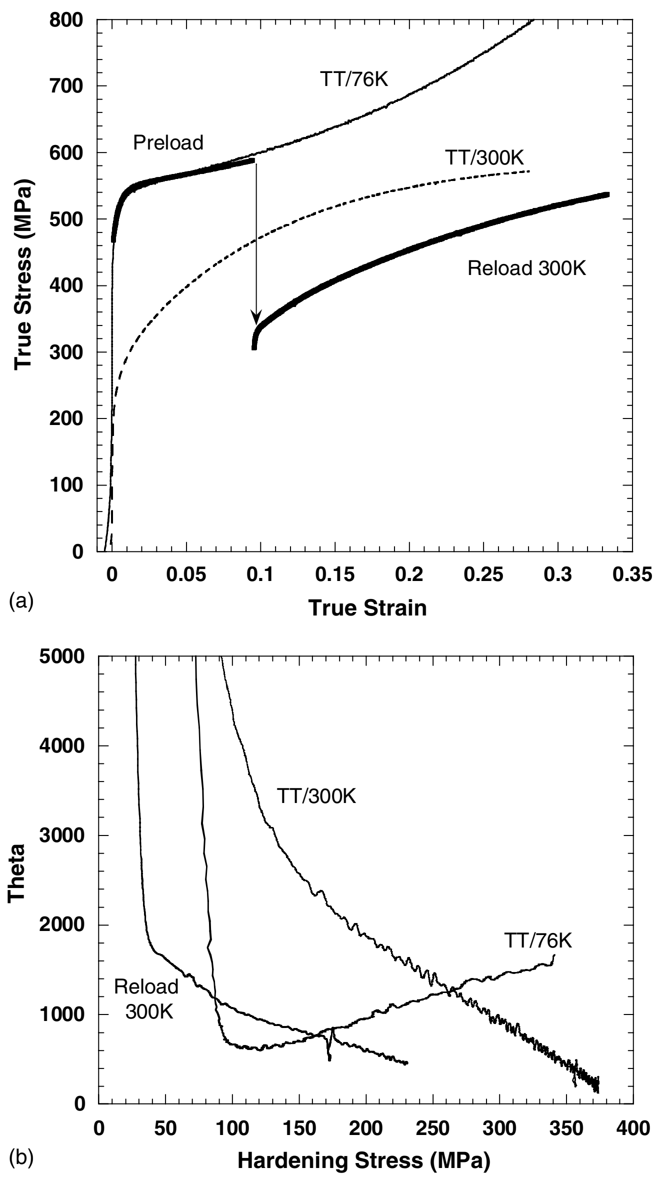

Fig. 1. TT compression response of clock-rolled Zr. Comparison of temperature change test with monotonic reference curves obtained at 76 and 300 K. (a) Stress vs. strain. (b) Hardening ($\partial\sigma/\partial\varepsilon$) vs. hardening stress ($\sigma - \sigma_y$).

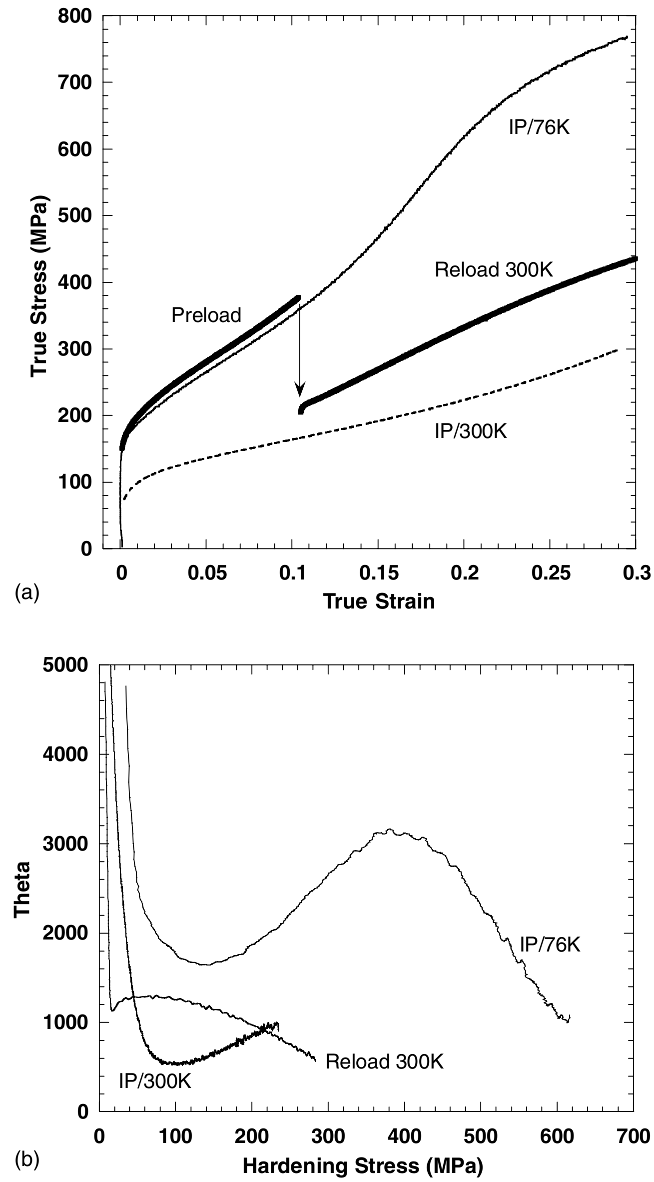

Fig. 2. IP compression response of clock-rolled Zr. Comparison of temperature change test with monotonic reference curves obtained at 76 and 300 K. (a) Stress vs. strain. (b) Hardening ($\partial\sigma/\partial\varepsilon$) vs. hardening stress ($\sigma - \sigma_y$).

In this work we use the high-pressure preferred orientation (HIPPO) neutron diffractometer at the Los Alamos Neutron Science Center (LANSCE) to characterize texture and estimate twin volume in deformed polycrystalline samples. The neutron measurements are nondestructive and evaluate the entire volume of a sample, making this technique particularly attractive for acquiring textures at each stage of deformation for each sample. We also use orientation imaging microscopy (OIM) combined with electron backscatter diffraction to characterize the twinned microstructure and to identify unambiguously the active twin systems by their characteristic misorientations across the twin boundaries [12]. The hardening response and texture evolution are interpreted here using a polycrystal constitutive