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THE INFLUENCE OF TEXTURE AND IMPURITIES ON THE MECHANICAL BEHAVIOR OF ZIRCONIUM

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Development of physically-based constitutive models capable of simultaneously describing slip, twinning, and anisotropy requires knowledge of the coincident influence of each on mechanical response. The effects of interstitial impurities and texture on twinning in zirconium (Zr), in addition to variations in strain rate and temperature are utilized to probe substructure evolution and mechanical behavior. The compressive yield response of high-purity crystal-bar and commercial-purity Zr was found to depend on the loading orientation relative to the h.c.p. c-axis, the applied strain rate, varied between 0.001 and 3500/s, and the test temperature, varied between 76 and 298K. The rate of strain hardening in Zr is seen to depend on the controlling defect storage mechanism as a function of texture, strain rate, and temperature. The substructure evolution of high-purity Zr was observed to depend on the applied strain rate and test temperature; the substructure of high-purity Zr was seen to display a greater incidence of deformation twinning when deformed at high strain rate or quasi-statically at 76K.

INTRODUCTION

Plastic deformation of metals may occur mainly by either of two mechanisms: dislocation slip or twinning. Whether slip or twinning is the dominant mechanism depends on which mechanism requires the least stress to initiate plastic deformation.

Knowledge of the influence of temperature, strain rate, microstructure, and chemistry on mechanical response is necessary for developing an accurate constitutive model. Previous studies have demonstrated the influence of temperature and strain rate on the slip and twinning behavior of zirconium (1). This study examines our ability to more accurately model the behavior of such low-symmetry metals by investigating the influence of texture and interstitial impurities on twinning deformation.

The goal of this study was to measure the stress-strain response of zirconium (Zr) over a wide range of temperatures and strain rates and to use microstructural evidence to identify dominant

deformation mechanisms. The mechanical response will be considered in terms of the initial yield behavior and strain-hardening rate. The strain-hardening behavior is generally the most important response for modeling constitutive behavior to large strains and is influenced by impurity level, grain size, and the extent of deformation twinning.

EXPERIMENTAL TECHNIQUES

This investigation utilized both high-purity zirconium obtained from Teledyne Wah Chang and commercial-purity (CP) zirconium supplied by the Naval Surface Warfare Center (NSWC). The high-purity material contained (wt. %) approximately 54 ppm Hf and 40 ppm O in contrast to impurity levels of 63 ppm Hf and 510 ppm O in the NSWC stock (referred to hereafter as commercial-purity). The high-purity Zr was cold-rolled at room temperature then annealed at 823K for 1 hour. This produced an equiaxed grain structure with strong

in-plane isotropic basal texture in the plate. The commercial-purity Zr was tested in the as-received recrystallized condition. It, too, has in-plane basal texture but exhibits some directionality which reflects that the plate was cross-rolled rather than clock-rolled. Both materials have a mean grain size of approximately 25 μm .

To examine the influence of loading orientation, and thereby texture, on the mechanical response of this strongly basal textured Zr-plate, compression samples were sectioned from both the through-thickness (TT) and in-plane (IP) plate directions. Cylindrical compression samples (5-mm diameter by 5-mm long) were first electro-discharge machined (EDM) normal to the plane of the plate; this orientation, relative to the plate texture, fixed the compression axis of the samples to be nominally 20 degrees to the c-axis orientations of the grains. Samples were also EDM machined in the in-plane plate direction to evaluate texture effects on constitutive behavior and substructure evolution. In-plane samples of high-purity Zr were machined at 0, 45, and 90 degrees orientations to an arbitrary direction in the plate. In-plane samples of commercial-purity Zr were cut at angles of 0 and 90 degrees relative to the rolling direction.

All mechanical tests were performed in compression at temperatures between 76 and 298K. Quasi-static compression tests were conducted at strain rates of 0.001 and 0.1/s using an Instron screw-drive load frame. Results of high-purity IP samples typically exhibited stress-strain curves parallel to one another with small variations in stress levels; ± 10 MPa about the mean value for a given set of conditions. Dynamic tests at strain rates from 1000 to 3500/s were conducted utilizing a Split-Hopkinson Pressure Bar. The inherent oscillations in the dynamic stress-strain curves and the lack of stress equilibrium in the specimens at low strains make the determination of yield inaccurate at high strain rates; data at strains less than 0.02 have been deleted.

Specimens for optical metallography were sectioned, parallel to the loading axis, from the as-recrystallized and deformed samples. The initial microstructure of both forms may be characterized as having equiaxed grains, a relatively broad grain size distribution, and few residual twinned grains. Specimens for analysis of the deformation

microstructures were deformed to a true strain of approximately 20%; selected samples were also deformed to a true strain of 5% to facilitate examination of the microstructure at different stages of deformation. Samples for optical metallographic examination were polished conventionally and etched using an acidic solution (10 ml H_2O , 10 ml HNO_3 , 10 ml HCl , and 5 ml HF).

RESULTS AND DISCUSSION

Preferred texture is significant because it results in orientation-dependent constitutive properties. Moderate axisymmetric (fiber) texture was observed in (0001) pole figure of clock-rolled high-purity Zr (Fig. 1a). Although the commercial-purity Zr also has a strong texture, the influence of cross-rolling is evident in the distribution of preferred orientations (Fig. 1b). Texture maxima of 5.63 and 3.64 m.r.d. (multiples of random distribution) were reported for the high-purity and commercial-purity, respectively.

The effects of the strong basal texture of the high-purity Zr (Fig. 1a) are demonstrated in the compressive stress-strain data displayed in Figure 2a. Peak flow stresses of quasi-static compression tests performed at room temperature are approximately 2.5 times greater for the TT samples compared to IP samples of the high-purity Zr. When tested at 76K, yield stresses of TT samples were 3 times greater than that of IP samples. The

FIGURE 1. (0001) pole figures of (a) clock-rolled, high-purity Zr and (b) cross-rolled, commercial-purity (CP) Zr.

stress-strain response of the TT sample tested under quasi-static conditions at low temperature has an especially sharp transition from elastic loading to nearly linear work hardening. This indicates the onset of twinning with little to no deformation by slip (1, 2).

The stress-strain response at quasi-static strain

FIGURE 2. a) Comparison of in-plane and through-thickness high-purity Zr tested in compression at 0.001/s. b) Results of through-thickness (TT) tests conducted over a range of rates (0.001 - 2500/s) and temperatures (76 - 298K). c) Results of in-plane (IP) compression tests performed over a range of rates (0.001 - 3500/s) and temperatures (76 - 298K).

rates at 298K (Fig. 2b) is consistent with previous observations (1): an increase in strain rate results in a slight shift of the curve but the characteristically continuous curvature is preserved.

Other effects of texture for the commercial-purity Zr are evident in Fig. 3a. The ratio of the yield stresses for TT and IP compression tests is

FIGURE 3. a) Comparison of in-plane and through-thickness commercial-purity Zr tested in compression at 0.001/s. b) Results of through-thickness tests conducted over a range of rates (0.001 - 2000/s) and temperatures (76 - 298K). c) Results of in-plane compression tests performed over a range of rates (0.001 - 3500/s) and temperatures (76 - 298K).

significantly less than for the case of the more strongly textured high-purity Zr. Data from IP tests (Figs. 3a and 3c) have a distinctive tendency to cross between strain values of 15 to 20 % due to mild texture anisotropy (Fig. 1b).

The contrasts between the IP and TT samples tested under quasi-static conditions (Figs. 2 and 3) are consistent with previously observed results for polycrystalline anisotropic materials (3, 4). The large variation in flow stresses is due to the number of active twinning and slip systems available and the stress levels required to activate them. Compressive loading perpendicular to the basal plane, as in the case of the TT samples, favors deformation twinning over prism, pyramidal, or basal slip. Compressive loading of the IP samples will have more favorable conditions, with respect to Schmidt factors, for activating slip, thus plastic flow is achieved with lower applied forces.

Strain rate sensitivity is observed to vary as a function of loading direction in both the high-purity and commercial-purity Zr (Figs. 2b, 2c, 3b, and 3c). Strain rate sensitivity is greatest in samples tested in the IP orientation. This too, is compatible with slip dominant deformation and the concept of dislocation motion controlled by Peierls forces (1).

Yield stress values are consistently greater for the commercial-purity Zr compared to samples of the high-purity Zr tested under similar conditions. Since the materials used in this study are of similar texture and grain size, the difference in flow stress may be attributed to differences in the interstitial impurities contents (5, 6). Interstitial impurities make twinning less thermodynamically favorable; hence deformation by slip becomes the dominant mechanism (6). In instances where the flow stress of twinning is greater than the flow stress of slip, the tendency to twin is suppressed and the required stress to deform the matrix increases.

Twins are present in the majority of grains after testing. Twins are observed to operate in several different systems in samples deformed at high rates and low temperatures. Hence, the strain-hardening and yield behavior differences between high and low strain rates are thought to be due to dislocation slip versus twinning dominated deformation mechanisms.

SUMMARY AND CONCLUSIONS

The effects of texture and interstitial impurities on the deformation behavior of a low-symmetry metal were demonstrated by comparing high-purity and commercial-purity Zr. The compressive stress-strain response of high-purity crystal-bar and commercial-purity Zr was found to depend on the loading orientation relative to the h.c.p. c-axis, the applied strain rate (varied between 0.001 and 3500 /s) and the test temperature (varied between 76 and 298K). The rate of strain hardening increases with increasing strain rate and decreasing temperature. The rate of strain hardening is also much greater when samples are loaded perpendicular to the c-axis in a slip-dominant orientation. The substructure evolution of high-purity Zr was observed to depend on the applied strain rate and test temperature; a greater incidence of deformation twinning was observed in samples deformed at high strain rate or quasi-statically at 76K. The rate of strain hardening in Zr is seen to depend on the controlling defect storage mechanism as a function of texture, strain rate, and temperature.

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