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Characterization and modeling of mechanical behavior of single crystal titanium deformed by split-Hopkinson pressure bar

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Single crystal titanium samples were dynamically loaded using split-Hopkinson pressure bar (SHPB) and the resulting microstructures were examined. Characterization of the twins and dislocations present in the microstructure was conducted to understand the pathway for observed mechanical behavior. Electron backscatter diffraction (EBSD) was used to measure textures and quantify twinning. Microstructures were profusely twinned after loading, and twin variants and corresponding textures were different as a function of initial orientation. Focused ion beam (FIB) foils were created to analyze dislocation content using transmission electron microscopy (TEM). Large amounts of dislocations were present, indicating that plasticity was achieved through slip and twinning together. Visco-plastic self-consistent (VPSC) modeling was used to confirm the complex order of operations during deformation. The activation of different mechanisms was highly dependent upon crystal orientation. For [0001] and $[10\bar{1}1]$-oriented crystals, compressive twinning was observed, followed by secondary tensile twinning. Dislocations, though prevalent in the microstructure, contributed to final texture far less than twinning.

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1. Introduction

Materials properties in extreme environments are of great interest for structural applications. Of particular importance is the mechanical response of these materials in the complex dynamic loading environments experienced in automotive, aerospace, nuclear energy and biomedical applications. Hexagonal close-packed (hcp) metals, such as titanium, magnesium, and zirconium, and their alloys are important for their role as structural materials in these applications. As such, it is essential to understand the mechanical response under extreme conditions to prevent unexpected engineering failures of structural components.

Split-Hopkinson pressure bar (SHPB) is a common technique for studying mechanical properties of materials subjected to dynamic loading, where strain rates can exceed $10^2\ s^{-1}$ (for a brief review, see (Kolsky, 1949; Gray, 2000; Ramesh, 2002)). The technique is well-suited for dynamic testing because it imparts a uniform, uniaxial load on a specimen. Much effort has been devoted to determining the predominant deformation mechanisms in hcp metals, notably titanium (Partridge, 1967;

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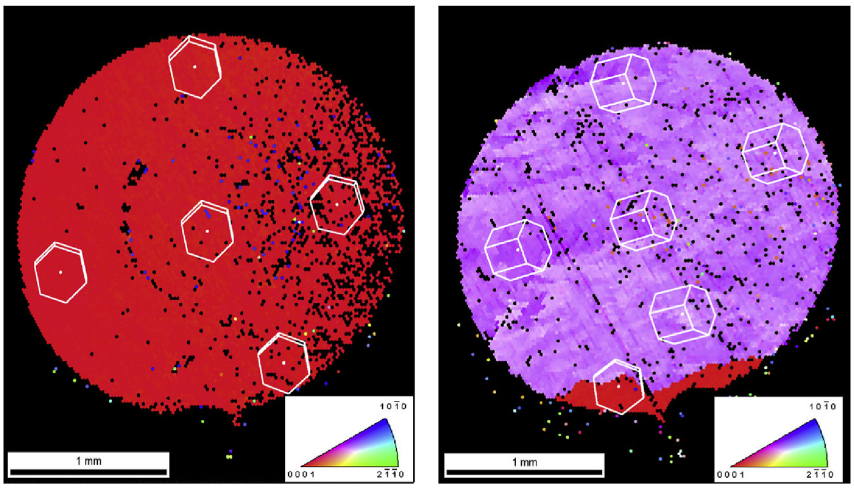
Christian and Mahajan, 1995; Nemat-Nasser et al., 1999; Meyers et al., 2001, 2002; Salem et al., 2003; Ungár et al., 2008; Moon et al., 2009; Xu et al., 2012), zirconium (Beyerlein and Tomé, 2008; McCabe et al., 2009; Morrow et al., 2013b; Niezgoda et al., 2014; Wang et al., 2013; Morrow et al., 2013a, 2014c), hafnium (Cerreta and Gray, 2004; Cerreta et al., 2007), and magnesium (Lou et al., 2007; El Kadiri et al., 2013; Morrow et al., 2014b,a, 2015) over a range of strain rates. Materials in this class tend to behave similarly, so for simplicity the current work focuses on titanium as a representative for ductile hcp materials. It is well known that both dislocation slip and twinning contribute significantly to the deformation behavior in polycrystalline hexagonal metals (Partridge, 1967; Christian and Mahajan, 1995), and that these mechanisms contribute differently depending on numerous conditions, including temperature, strain rate, grain size, polycrystalline texture, etc. The effects of strain rate, in particular, has proven challenging to predict. Several studies have observed the mechanical response of titanium under quasi-static (Nemat-Nasser et al., 1999; Salem et al., 2003; Zeng et al., 2009; Nixon et al., 2010) and dynamic loading (Meyers et al., 1994; Chichili et al., 1998; Nemat-Nasser et al., 1999; Cheng and Nemat-Nasser, 2000; Ramesh, 2002; Li et al., 2004; Huang et al., 2007; Xu et al., 2013; Sun et al., 2014). Existing dynamic mechanical test data, and, with it, understanding of active mechanisms in the dynamic loading regime is fairly limited. Because of this, few attempts have been made to predict the mechanical behavior of titanium under these extreme loading conditions. Additionally, most research to date has been performed on polycrystalline samples. Both twinning and slip, the mechanisms responsible for strength, occur predominately on the grain or single crystal length scale. It is therefore essential to understand plasticity in single crystals, which can then be used to inform polycrystalline strength models. Only a few works have dealt with the effect of crystallographic orientation on mechanical properties during quasi-static deformation in titanium (Battaini et al., 2007; Gong and Wilkinson, 2011). Generally, these studies are performed at strain rates below the dynamic regime, so the relative contributions and sensitivities of deformation mechanisms may differ from those observed at high rate.

The current work seeks to fill these gaps by studying titanium single crystals which have been deformed dynamically in compression using a SHPB technique. The resultant microstructure is characterized with respect to the basic deformation mechanisms: twinning and dislocation slip activity. Additionally, a viscoplastic self-consistent (VPSC) model is used to simulate deformation in these single crystal samples during plastic deformation and determine the likely deformation path based on experimentally observed mechanisms.

2. Material and methods

High-purity (99.99%) titanium multi-crystalline materials were used for this study. The oxygen impurity content is expected to be less than 300 ppm. Electron backscatter diffraction (EBSD) was used to triage crystallographic orientations within the multi-crystals and identify large grains from which single crystal specimens would be machined. Cylindrical specimens in two different single crystal orientations, 2.5 mm in diameter by 2.5 mm tall, were machined from the larger multi-crystalline samples using electrical discharge machining (EDM). The single crystal specimens were machined such that a single orientation was parallel to the center compression axis of the cylinder in each case. The orientation of each smaller sample was verified using EBSD prior to mechanical testing. Top and bottom surfaces of each cylinder were scanned to ensure consistency through the thickness of each specimen. Fig. 1 shows EBSD maps for [0001] and [$10\bar{1}1$] specimens in the untested condition. Samples were deformed in uniaxial compression using a split-Hopkinson pressure bar (SHPB) at room temperature and to 25–30% strain. The compression direction corresponds to the normal axis of the pole figures shown in Fig. 1. Strain



(a) [0001] (b) [$10\bar{1}1$]

Fig. 1. EBSD of compression surface of (a) [0001], and (b) [$10\bar{1}1$] specimens before loading.