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Quantifying the mesoscopic shear strains in plane strain compressed polycrystalline zirconium

N. Keskar [a,c], S. Mukherjee [a,b], K.V. Mani Krishna [c], D. Srivastava [c], G.K. Dey [c], P. Pant [a], R.D. Doherty [a,d], I. Samajdar [a,*]

[a] *Department of Metallurgical Engineering and Materials Science, IIT Bombay, Mumbai 400076, India*
[b] *Department of Mechanical Engineering, McGill University, Montreal H3A 2KH, Canada*
[c] *Materials Science Division, Bhabha Atomic Research Center, Mumbai, India*
[d] *Department of Materials Science and Engineering, Drexel University, Philadelphia, PA 19104, USA*

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Abstract

An algorithm is used to estimate mesoscopic strains in a deformed polycrystalline material. This requires comparison of microstructures before and after imposed macroscopic plastic deformations, in order to estimate the local/mesoscopic strains from the displacements of identifiable grain boundary segments. The algorithm was applied to lightly plane strain compressed (PSC) polycrystalline zirconium. Very large (up to 1.2) near-boundary mesoscopic shear strains were estimated. These were well above the estimated measurement uncertainties and remarkably larger than the extremely small (0.01–0.04) PSC strains imposed. Opposing local shears, on both sides of a grain boundary, appeared to compensate each other. Direct correlations were noted, in the same grain, between mesoscopic shear strains and (i) in-grain misorientations and (ii) subsequent grain fragmentation.

Keywords: Shear strain; Plastic deformation; Zirconium; Digital image correlation (DIC); Electron backscattered diffraction (EBSD)

1. Introduction

Deformation in polycrystalline metallic materials can be viewed from the tenets of classical plasticity and/or microstructural developments. In Taylor theory [1,2], the local deformation/strain is assumed to match the global values. The assumption of strain homogeneity is, however, questionable from the observations on microstructural developments [3–9]. Microstructural observations have always revealed the presence of heterogeneities: both between different grains and within the same grain [4,5,9–18]. The continuity across grain boundaries is thought to be maintained through relative activation of slip systems in different regions [5]. The actual physics can be approximated through numerically intensive solutions, like the crystal plasticity finite element method [19–24]. For experimental comparison, however, the model requires knowledge of the local 3-D grain arrangements and orientations – knowledge that is almost never available. Another alternative is to capture mechanics of grain interactions through suitable model assumptions. This may include two- or multi-grain models [25–27], or models attempting to address creation of geometrically necessary dislocations [28–30]. It is best to complete this discussion by referring to a recently published article [29] that highlights the differences between model predictions and experimental observations in polycrystalline aluminum. It was reported that deviations between the models happen under complex strain mode: classical Taylor-type models ignore the aspects of near-boundary shear.

* Corresponding author. Tel.: +91 22 2576 8621.
E-mail addresses: indra@iitb.ac.in, isamajdar@gmail.com (I. Samajdar).

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During plastic deformation in polycrystalline material, near-boundary gradients of orientation/misorientation have been reported [31–36]. Such zones, generalized as near boundary gradient zone (NBGZ), appear to depend on the strain mode [31] and on the plasticity of the neighboring grain [32]. Though the phenomenon of NBGZ appears to be potentially very important in crystal plasticity, there has not been a direct experimental attempt to relate NBGZ with mesoscopic or in-grain strains. Such strains can be quantified through digital image correlation (DIC). For example, images before and after plastic deformation can be compared digitally, based on the displacement of identifiable markers, and displacement fields or strains estimated.

Starting from the initial days [37], where laser speckles were used to identify displacement and/or deformation, the subject of DIC has evolved [38–45] remarkably. Efforts were/are made to measure microscale strains, even employing elegant corrections [38] for drift and distortion associated with scanning electron microscope (SEM) imaging. It is, however, important to note that there are certain intrinsic 'limitations'. DIC-based strain calculations depend on the pixel subset size and step size. The subset size needs to be carefully chosen to obtain continuity of deformation and hence must approximate distinguishable microstructural features or externally imposed markers. For in-grain strain measurements, the challenge is to put numerous, small, permanent and passive markers around the grain boundary [43,45]. A high number of measurements is important to resolve local strains, while grain interior measurements demand smaller sizes. The marker also needs to be permanent and passive, so that it does not get altered or affect the deformation-induced microstructure developments. For the latter, using electron backscattered diffraction (EBSD) is a natural development [41–43]. However, placing appropriate markers and measuring local strains and subsequent EBSD of the same region are nontrivial [41–45]. Furthermore, the commercial packages usually do not have the ability to consider appropriate/flexible user-defined inputs (UDI), thus restricting the use of microstructural features as markers for strain estimation. In this study a new DIC model/algorithm was developed. The algorithm, described in the Appendix, estimates near boundary in-plane strains: both the expected/imposed normal strains and any additional or redundant local shear strains. These are estimated from displacements of identifiable grain boundary segments. Estimated mesoscopic shear strain values were then correlated with different aspects of the deformed microstructures.

Table 1
Chemical composition of Zircaloy-4 used in this study.

Element	Sn	Fe	Cr	Ni	Hf	Zr
Content	1.5%	0.22%	0.1%	<0.007%	<0.02%	Balance

2. Experimental details

To explore the use of the proposed algorithm (see Appendix), predominantly single-phase fully recrystallized Zircaloy-4 (chemical composition listed in Table 1) was selected. The selected material was then precision machined to provide split channel die samples (see Fig. 1). In this technique, described in greater detail elsewhere [46–49], effectively internal regions of a material were subjected to plane strain compression (PSC) and the same grains were observed before and after progressive plastic deformations.

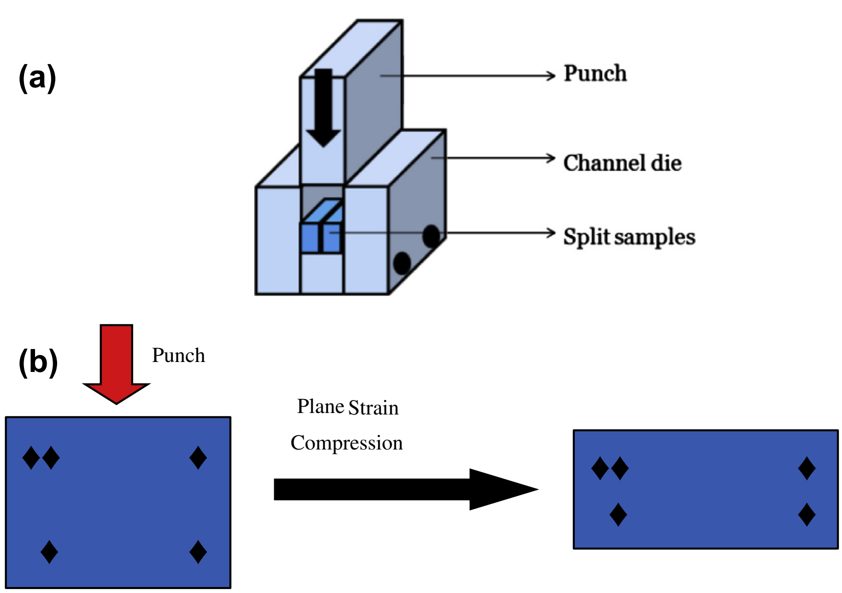

Fig. 1. (a) Schematic of a split-channel plane strain compression set-up. (b) The surfaces of the split samples are marked by microhardness indentations, to enable measurements of the same area before and after PSC. Displacements of the indents can be used (Table 2) for macroscopic strain estimates. Further details about the split channel die technique can also be found elsewhere [46–49].