MATERIALS CHARACTERIZATION 62 (2011) 651–660

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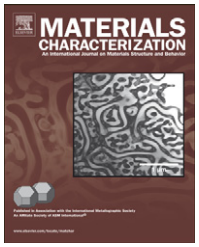

Grain-resolved elastic strains in deformed copper measured by three-dimensional X-ray diffraction

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ARTICLE DATA

Article history:
Received 16 November 2010
Received in revised form 7 April 2011
Accepted 27 April 2011

Keywords:
Synchrotron X-ray diffraction
Strain measurement
Bulk deformation
Crystal plasticity
Orientation relationships

ABSTRACT

This X-ray diffraction study reports the grain-resolved elastic strains in about 1000 randomly oriented grains embedded in a polycrystalline copper sample. Diffraction data were collected *in situ* in the undeformed state and at a plastic strain of 1.5% while the sample was under tensile load. For each grain the centre-of-mass position was determined with an accuracy of 10 μm, the volume with a relative error of 20%, the orientation to 0.05° and the axial strain to 10^{-4}. The elastic strain along the tensile direction exhibited a grain orientation dependence with grains within 20° of <100> carrying the largest strain. While the width of the strain distribution for all grains did not change upon plastic loading, the grain-resolved data show a significant widening of the distribution evaluated for small subsets of initially elastically similar grains. This widening appears independent of the grain orientation.

1. Introduction

Polycrystal plasticity models are widely used to predict both the evolution of deformation textures and the resulting mechanical properties, for example mechanical anisotropy. Historically, polycrystal plasticity modelling has relied on assumptions about the local stress/strain conditions at the level of individual grains, spanning from enforcement of the same strain on all grains in the Taylor [1] and Bishop-Hill [2] models, over consideration of the interaction between a grain and a homogenous medium with the average properties of all the other grains (self-consistent models, e.g. [3]), to detailed modelling of the interaction between neighbouring grains in models based on the finite element method (e.g. [4]) or Fourier transformations [5].

The verification and improvement of models have been impeded by the lack of experimental data on both the plastic deformation (plastic strain as well as the associated lattice rotation) and the elastic strains at the grain scale. Recently, measurements using neutrons or X-rays have progressed from probing bulk textures to providing the lattice rotations of a large number of individual grains deeply embedded in the bulk of the sample by means of the three-dimensional X-ray diffraction (3DXRD) technique [6–9].

Diffraction of neutrons [10] or X-rays [11,12] can also be used to measure elastic strains. Due to limited spatial resolution of

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doi:10.1016/j.matchar.2011.04.020

traditional set-ups such measurements have often been restricted to average values for the bulk of the sample, and the elastic strains have been monitored along certain directions corresponding to the largest spacing of the lattice planes. By means of high-energy X-rays it has become possible to measure elastic strain distribution functions which can be combined with orientation distributions to evaluate the elastic strain tensor for specific texture components [13]. This method, however, does not give spatial information and therefore not grain-resolved data. The polychromatic microdiffraction technique offers elastic strain and crystal orientation information with a spatial resolution of less than 1 μm, i.e. at the level of subgrains [14,15]. The microdiffraction technique is, however, only realistically applied to relatively small sample volumes due to a long data acquisition time and a limited penetration depth.

The 3DXRD technique, besides giving grain-resolved orientations, also allows elastic strain measurements at the scale of individual bulk grains [16–22]. So far such investigations have, however, been limited to a relatively low number (20 or less) of selected grains. Progress within the field of elastic strain analysis has improved both the number of grains that can be handled and the previous limitations on how these were selected to a point where grain-resolved maps of the elastic strain in a representative sample volume has become a reality as recently demonstrated for around 100 grains in an IF steel sample [23] in the elastic regime.

This paper presents the first grain-resolved elastic strain map covering about 1000 grains in a polycrystalline copper sample plastically deformed in tension to a small plastic strain. In contrast to the previously investigated IF steel, copper contains annealing twins, which add complexity to the diffraction analysis. The large number of investigated grains allows a statistical meaningful analysis involving not only the mean values of calculated quantities for subsets of special orientations, but also comparison of the variations within each subset (in the form of standard deviations). The analysis provides new insight in the relative effects of the crystallographic orientation of the grain and the interaction between neighbouring grains. Finally, future applications of the technique are discussed in relation to polycrystal plasticity modelling.

2. Material and Methods

2.1. *Material Examined*

The material used in this study was fully recrystallised copper with a grain size[2] of about 50 μm and an almost random texture; see the pole figure, Fig. 1, as obtained from the present X-ray diffraction measurement. Fig. 2 is a representative EBSD image of the undeformed material which clearly shows the presence of annealing twins, especially within the larger grains. The macroscopic stress-strain curve is given in Fig. 3. The measurement was done on a cylindrical (Ø=4 mm) specimen using an extensiometer in the laboratory. The tensile specimen for the diffraction experiment was spark cut into a cylindrical gauge section with a diameter of 1 mm and a length of 3 mm. Outside the gauge length the diameter

[2] See Section 2.4 for details.

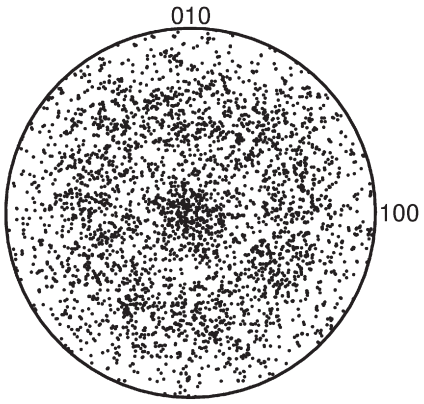

Fig. 1 – {111} stereographic pole figure showing the texture of the undeformed copper sample with the tensile axis in the centre.

of the cylinder was 4 mm and threaded for mounting in the tensile stress rig.

2.2. *Experimental Set-up*

The diffraction experiment was performed at beamline ID11 at the European Synchrotron Radiation Facility (ESRF) using a set-up similar to the one sketched in Fig. 4. The X-ray energy was 69.5085 keV (W edge). The beam was made monochromatic using a Laue-Laue set-up [24]. The dimensions of the beam were confined by slits to 100 μm and 1.2 mm in the vertical and horizontal directions, respectively, in order to illuminate the entire cross section of the sample in 100 μm high layers along the vertical tensile axis. The Frelon4M detector [25] with 2048×2048 pixels^2 of 50×50 μm^2 pixel size was placed a distance of 250 mm from the tensile sample, making the first six Debye–Scherrer rings of diffraction spots from individual grains of Cu fully visible on the detector as exemplified in Fig. 4. The sample was positioned in the stress

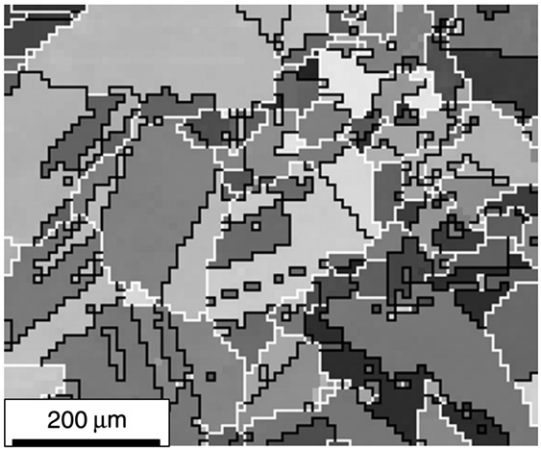

Fig. 2 – EBSD image showing a representative grain map of a 700×600 μm section perpendicular to the tensile axis. Different colours represent orientation, white lines are grain boundaries, while black lines are twin boundaries. Annealing twins are clearly visible.