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Plastic deformation of polycrystalline molybdenum: Experimental data and macroscopic model accounting for its anisotropy and tension–compression asymmetry

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ABSTRACT

In this paper a systematic experimental investigation of the room-temperature mechanical response of polycrystalline commercially pure molybdenum (Mo) is presented. It was established that the material has ductility in tension at 10^{-5}/s and that the failure strain is strongly dependent on the orientation. A specimen taken along the rolling direction sustains large axial strains (20%), while a specimen taken at an angle of 45° to the rolling direction could only sustain 5% strain. It was observed that irrespective of the loading orientation the yield stress in uniaxial compression is larger than in uniaxial tension. While in tension the material has a strong anisotropy in Lankford coefficients, in uniaxial compression it displays weak strain-anisotropy. An elastic-plastic orthotropic model that accounts for all the specificities of the plastic deformation of the material was developed. Validation of the model was done through comparison with data on notched specimens. Quantitative agreement with both global and local strain fields was obtained. In particular, the effect of loading orientation on the response was very well described.

1. Introduction

At present, the materials commonly used in high-temperature applications (e.g. gas-turbine engines), are the single-crystal nickel-based superalloys. Unfortunately, these materials have reached their technological limit (e.g. see Perepezko, 2009). Attention is increasingly turning towards refractory materials, in particular polycrystalline Molybdenum (Mo). Recently, experimental studies aimed at understanding the room-temperature tensile behavior of rolled polycrystalline Mo sheets and plates as well as their forming properties, have been undertaken (e.g. Walde, 2008; Oertel et al., 2008, etc.). However, the mechanical response in compression of polycrystalline Mo, and the influence of loading orientation on the tension–compression asymmetry have been largely unexplored. Test results in uniaxial tension and compression are available for single-crystal Mo, either bulk single crystals (of mm size) (e.g. Hollang et al., 2001; Seeger and Hollang, 2000) or micropillars (of nm size, e.g. Kim et al. 2012).

In this work, a comprehensive experimental and theoretical investigation of the quasi-static, room temperature, mechanical response of a commercial purity polycrystalline Mo material is presented. The structure of the paper is as follows. We begin by reporting the results of a series of monotonic tensile and compression tests, conducted to quantify the plastic anisotropy and the tension–compression asymmetry of the material (Section 2). In addition, uniaxial tension tests on notched specimens cut at different orientations in the plane of the plate are conducted.

To describe the observed behavior, an elastic/plastic modeling framework is adopted. Yielding is described using Cazacu et al. (2006) yield criterion that accounts for both anisotropy and strength differential effects. Identification of the model parameters is based on the results obtained on smooth specimens (Section 3). Model validation is provided through comparison between the simulations and data on notched specimens. Furthermore, detailed analysis of both the global and local strains acquired using digital image correlation (DIC) techniques for both smooth and notched specimens is presented (Section 4). A summary of the main findings and future perspectives is given in Section 5.

2. Experimental characterization

2.1. Material and testing procedures

The material used in this work was a high purity (99.98%) polycrystalline Molybdenum plate. The chemical composition, reported

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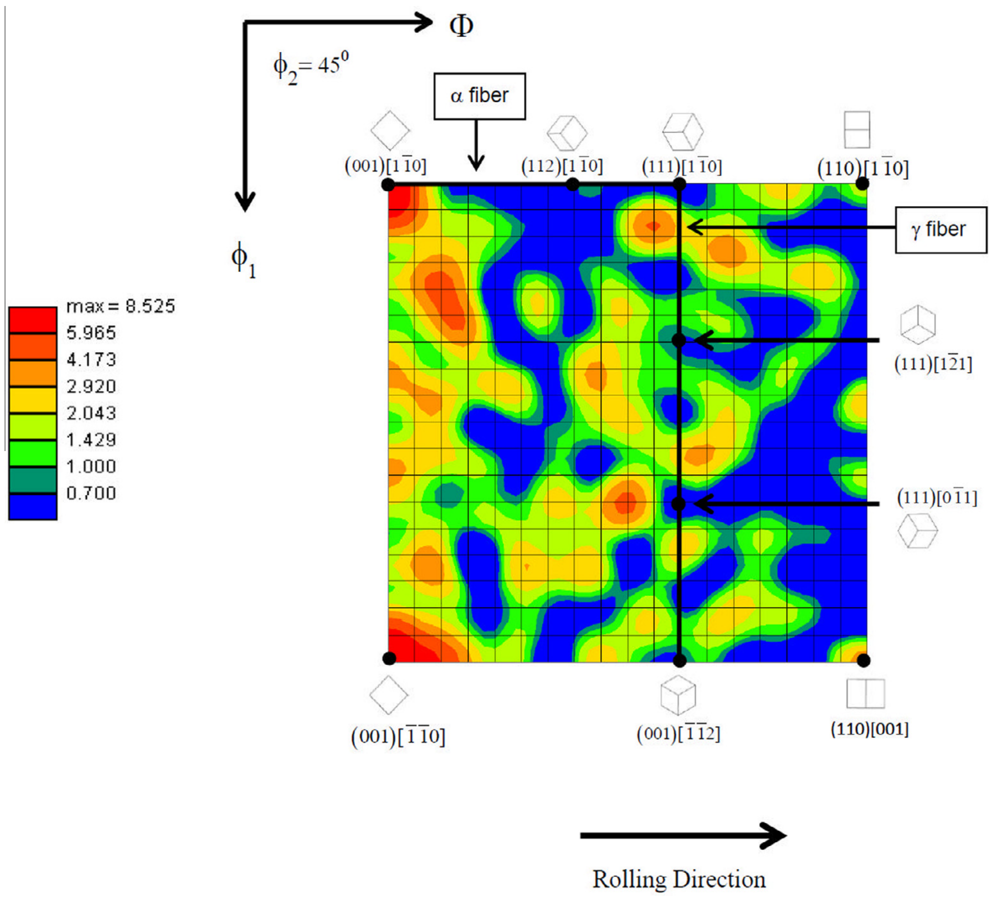

Fig. 1. Measured orientation distribution function (ODF) of the polycrystalline Mo plate.

in Table 1, was determined using a LECO combustion technique for carbon (C), oxygen (O), and nitrogen (N) content, and Glow Discharge Mass Spectrometry for the remaining elements. The maximum quantity for a non-reported element was 0.1 parts per million (ppm) and any other elements with ppm less than 4 were summed and listed as "Other".

To characterize the initial state of the material (texture, grain size), Electron Back Scattered Diffraction (EBSD) measurements were performed using a FEI Quanta 200 field emission gun. Multiple scans were conducted in various locations of the plate, with similar results. As an example, the orientation distribution function (ODF) $\phi_2 = 45°$ section of the center layer of the plate is shown in Fig. 1. The results are in agreement with the literature (see Oertel et al., 2008), showing that rolling produces an incomplete α-fiber with the peak located at the rotated cube component $(001)\langle 110\rangle$.

Grain characteristics such as diameter, aspect ratio, and orientation were also determined. The material has almost equiaxed grains, the average grain diameter being 60 μm. Most of the grains within the plane of the plate had an orientation within ±30° of the rolling direction (RD). For the grains along the normal direction (ND) to the plate, the orientation of their major axis was random.

In order to quantify the influence of the loading direction, and thereby texture, on the room-temperature mechanical response uniaxial tensile and compression tests on smooth specimens were conducted for different loading orientations according to ASTM E-8/E8M-09 and ASTM E9, respectively. The specimens were cut from the polycrystalline Mo plate by electro-discharge machining (EDM). For the tensile specimens, the rectangular cross-section within the gauge length was of 3.175 mm by 1.588 mm (see Fig. 2(a)). Tests were conducted on specimens taken along RD and six other in-plane orientations i.e. $\theta = 15°$, 30°, 45°, 60°, 75° and 90° to RD. Additionally, uniaxial tension tests on notched RD and transverse direction (TD) specimens were performed. The geometry of the notched specimens and the FE mesh used for simulations are shown in Fig. 2(b). The compression specimens were right circular cylinders (5.23 mm in diameter by 9.83 mm long) that were machined such that the axes of the cylinders were along RD and two other in-plane directions at 45°, and 90° (i.e. TD) with respect to RD. In addition, compression tests were also conducted on specimens with the axis along ND, the through-thickness direction of the plate (see Fig. 2(c)).

An Instron Model 1332 mechanical test frame in conjunction with an Instron Model 3156-115 load cell of capacity 22.7 kN was used to conduct all tests. The displacement was measured using a linear variable displacement transducer (LVDT) which has a resolution of 0.00254 mm of piston movement. The rate of displacement was continuously monitored using an electronic feedback loop to ensure the desired rate of displacement and specimen strain rate. The output for the load cell and LVDT was recorded using a 14bit Win600 Digital Oscilloscope with a resolution of approximately 1.2 mV for the load cell (approximately 0.5 N force resolution).

In addition, digital image correlation (DIC) measurements were taken in order to monitor the evolution of the local strains.

Table 1
Chemical composition of the polycrystalline Molybdenum plate investigated.

C	O	N	Si	K	Cr	Fe	Ni	W	Other
5	16	5	4.7	15	13	35	6.2	80	27.96