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High strain-rate plastic deformation of molybdenum: Experimental investigation, constitutive modeling and validation using impact tests

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A B S T R A C T

In this paper, an experimental study on the quasi-static behavior and dynamic behavior of a polycrystalline molybdenum material is presented. Due to the material's limited tensile ductility, successfully acquiring data for impact conditions is very challenging. For the first time, Taylor impact tests were successfully conducted on this material for impact velocities in the range of 140–165 m/s. For impact velocities beyond this range, the very high tensile pressures generated in the specimen immediately after impact lead to failure. A constitutive model accounting for the key features of the Mo plastic behavior, i.e. its tension–compression asymmetry and plastic anisotropy was developed. An implicit solver was used to simulate the impact deformation. A good agreement was obtained between predictions and experimental outlines of the specimens. Furthermore, it was shown that the model can be used to gain understanding of the dynamic deformation process in terms of time evolution of the pressure, the extent of the plastically deformed zone, distribution of the local plastic strain rates, and when the transition to quasi-stable deformation occurs.

1. Introduction

The high-temperature stability and creep resistance of refractory materials, and in particular of molybdenum (Mo), make them very attractive for high-temperature applications (e.g. turbines). However, of major concern is the limited ductility of Mo at room-temperature. Recently, experimental studies devoted to the investigation of the room-temperature response in tension and the forming properties of polycrystalline Mo were reported (e.g. Walde [1], Oertel et al. [2]). However, the tension–compression asymmetry in yield and flow stresses and its hardening directionality were not documented.

Of particular importance is the investigation of the mechanical response of Mo under impact where the strain-rates experienced are very high. Such strain rates (of the order of 10^4–10^5 s^{-1}, Nicholas [3]; Wilkins and Guinan [4]; Cerreta et al. [5]) can be achieved in a Taylor impact test, which consists of launching a solid cylindrical specimen at high velocity of the order of 100–300 m/s against a stationary rigid anvil (see Taylor [6]; Cristescu [7]; Wilkins and Guinan [4]). When the specimen impacts the rigid stationary anvil, an elastic compressive wave that is generated at the impact interface, travels through the specimen in the axial direction with a speed equal to the sound speed in the respective material. When this compressive wave reaches the other end of the specimen, it is reflected as a tensile wave. For a sufficiently high impact velocity, for which the magnitude of the compressive wave reaches the yield stress of the material, the impacted end undergoes plastic deformation. The plastic front with maximum stress magnitude equal to this yield/flow stress starts propagating from the impact interface at a much lower speed than the elastic wave. The travelling plastic front interacts with the reflected precursor elastic wave at some intermediate point along the length of the specimen. The elastic wave then gets reflected at the elastic–plastic interface and travels toward the free end of the specimen. This back and forth movement of the elastic wave results in deceleration of the specimen. For more details about wave propagation during an impact event, the reader is referred to the seminal books of Rakhmatulin and Demyanov [8] and Cristescu [7].

Taylor [6] developed a one-dimensional wave propagation analysis to estimate from this test the dynamic yield strength of a given material. Later on, semi-analytical models have been proposed to determine the yield strength as a function of density, impact velocity, initial and final length, and length of the un-deformed region of the recovered specimen (see for example, Gilmore et al. [9]; Lu et al. [10]; Wang et al. [11]). Currently, the Taylor test is used more as a means of validating plasticity models and codes for the simulation of dynamic deformation (see Holt et al. [12]; Zerilli and Armstrong [13]; Maudlin et al. [14]; etc.).

It is also important to note that Taylor impact test data have been reported only for materials that exhibit large tensile ductility at

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room-temperature (e.g. for iron, see Zerilli and Armstrong [13]; for tantalum, see Zerilli and Armstrong [15]; Maudlin et al. [14]; for titanium, see Revil-Baudard et al. [16]). Recently, Taylor impact tests on copper and aluminum alloys have been performed and numerical studies on damage evolution during such tests have been conducted (e.g. for aluminum alloys, see Rakvåg et al. [17]; Moćko et al. [18]; for copper alloys, see Wei et al. [19]; Borodin and Mayer [20]). Concerning the very high strain rate deformation of refractory metals, the literature is very limited. For spall tests on such materials, the reader is referred to Chhabildas et al. [21], while for shock testing, see Kleiser et al. [22].

For a polycrystalline high-purity molybdenum material, which shows no ductility for quasi-static strain rates of order of 10^{-2}/s, even the feasibility of a Taylor test is questionable. This is because the very large tensile stresses generated at impact would result in immediate fracture with disintegration of the specimen. To the best of the authors' knowledge, Taylor impact test results on molybdenum have not been reported.

In this paper, we present an experimental investigation and a new three-dimensional model that was developed in order to account simultaneously for the anisotropy, tension–compression asymmetry and strain-rate sensitivity of the plastic deformation of a high purity polycrystalline molybdenum. Furthermore, Taylor impact tests conducted on the same material are reported. The results of these tests will serve to assess the predictive capabilities of the model.

The outline of the paper is as follows. Section 2 presents the polycrystalline material, and the experimental tests that were conducted. Section 3 presents the elastic/viscoplastic modeling framework adopted. Finite-element (FE) simulations of the dynamic Taylor impact tests using this model and a dynamic implicit solver are presented in Section 4. The model predictions are compared with the measurements of the deformation of the impacted specimens. Discussion of the capabilities of the model and its potential to be used for "virtual testing" for high-rate application is also given. The summary of the main findings and conclusions are given in Section 5.

2. Experimental characterization

2.1. Material and mechanical tests

The material used in this work was a high purity (99.98%) polycrystalline molybdenum rolled plate. The chemical composition, reported 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 element with ppm less than 4 were summed and listed "as other".

In order to quantify the influence of the loading direction, and thereby the texture, on the mechanical response room-temperature quasi-static (nominal strain rate of 10^{-5} s^{-1}) uniaxial compression tests and uniaxial tension tests were conducted. Many factors influence the ductility of molybdenum based materials in uniaxial tension at room temperature. These include alloy composition and impurity content, strain rate, surface defects in the sample, and thermo-mechanical processing (see Lement and Kreder [23]). For the commercially pure polycrystalline Mo material studied, first we conducted a uniaxial tensile test along the rolling direction (RD) at a strain rate of 10^{-2}/s. At this strain-rate, the elongation at failure is less than 1% (for more details about the quasi-static deformation of Mo, the reader is referred to Kleiser et al. [24]). Given the strain-rate sensitivity of the brittle-to-ductile transition of refractory metals, uniaxial tension tests at a strain rate of 10^{-5}/s (i.e. three order of magnitude lower) were also conducted. Note that for this strain rate the specimen exhibited ductile behavior, the failure strain being of 22%. To investigate the effect of the loading orientation on the mechanical response a systematic investigation was conducted. All the quasi-static tests were conducted at 10^{-5}/s. The tensile specimens are of rectangular cross-section (3.175 mm by 1.588 mm), the gauge length being of 25.4 mm. Tests were conducted on specimens taken along RD and six other in-plane orientations i.e. θ = 15°, 30°, 45°, 60°, 75° and 90° (TD) to RD. On the basis of all tests, it can be concluded that the material displays anisotropy in tensile yield stresses, the largest yield stress corresponding to θ = 60° ($\sigma_T|_{\theta=60} = 349.6$ MPa), while the lowest yield stress is along RD ($\sigma_T|_{\theta=0} = 308.6$ MPa). For θ < 45° the yield stress is increasing with the angle θ ($\sigma_T|_{\theta=45} = 347.6$ MPa) and then remains almost constant for 45° < θ < 90° ($\sigma_T|_{\theta=90} = 347.5$ MPa). Lankford coefficients, defined as the ratio of the width to thickness plastic strain increments, were measured in the uniaxial tension tests along RD, 45°, and TD, respectively. It was found that the r-value at 45° to the RD is the lowest one ($r|_{\theta=45} = 0.665$), the r-value along RD being 0.75 while the r-value along TD is almost 1 ($r|_{\theta=90} = 0.93$).

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. In uniaxial compression, the polycrystalline Mo exhibits anisotropy in yield stresses, the largest yield stress being for the 45° orientation ($\sigma_C|_{\theta=45} = 384$ MPa) and the lowest yield stress being along RD ($\sigma_C|_{\theta=0} = 318$ MPa), while along TD direction, $\sigma_C|_{\theta=90} = 372$ MPa. The yield stress in compression along ND is of 341 MPa. Due to the material's anisotropy, any specimen cross-section, which was initially circular, becomes slightly elliptical, the ellipticity ratio (ratio of the minor over major axes) varying between 0.94 for the compression specimen taken at 45° to the RD and 0.99 for the TD specimen (for more details concerning the material's anisotropy revealed by the quasi-static tests performed for various intermediate orientations and specimen geometry, the reader is referred to Kleiser et al. [24]).

As an example, a comparison between the experimental stress–strain curves in uniaxial tension and compression along RD and along TD directions, respectively, are shown in Fig. 1. Note that the material is harder in compression than in tension. Furthermore, the tension–compression asymmetry ratio depends on the loading orientation, being the lowest along RD and the largest for the specimen loaded at an angle of 45° to RD.

High-strain rate compression tests were conducted using a split-Hopkinson pressure bar (SHPB) pressure bar technique to characterize the strain-rate sensitivity of the material. The SHPB system used has nickel-based alloy Inconel pressure bars with diameters of 15.9 mm and the lengths of the striker, incident, and transmitted rods are 1.37 m, 6.53 m, and 3.27 m, respectively. The specimens used for the SHPB compression tests were cylinders 5.08 mm in diameter by 5.08 mm long (0.2 inches). A small film of $MoSi_2$ industrial lubricant was used between ends to minimize frictional effects during radial expansion. The striker bar was accelerated using a torsion spring. The loading durations for the SHPB experiments were nominally 560 μs. The average strain rates for compression experiments were around 400 s^{-1}. Strain gages were placed 1.6 m from each specimen interface and sampled every 2 μs using a Win600 digital oscilloscope. Compressive SHPB tests were conducted for specimens

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