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Deformation field evolution in indentation of a porous brittle solid

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ABSTRACT

An experimental study of plane strain wedge indentation of a model porous brittle solid has been made to understand the effect of indentation parameters on the evolution of the deformation field and the accompanying volume change. A series of high-speed, high-resolution images of the indentation region and simultaneous measurements of load response were captured through the progression of the indentation process. Particle image velocimetry analysis of the images facilitated *in situ* measurement of the evolution of the resulting plastic zone in terms of incremental material displacement (velocity), strain rate, strain and volume change (e.g., local pore collapse). These measurements revealed initiation and propagation of flow localizations and fractures, as well as enabled estimate of volume changes occurring in the deformation zone. The results were directly compared with theoretical estimates of indentation pressure and deformation zone geometry and were used to validate a modified cavity expansion solution that incorporates effects of volume changes in the plastic zone.

1. Introduction

Drilling of geomaterials to extract hydrocarbons is among the most critical of activities involved in the production of petroleum in offshore and onshore processing environments. The design and operation of extraction platforms must factor in a host of safety and economic considerations that are intrinsically related to the thermomechanical loading and micromechanical material response (e.g., strain, strain rate, volume change, fracture) occurring in the vicinity of the interface of a drill and a porous brittle solid. For example, specific (drilling) energy is often used to estimate equipment power requirements and drill life through empirical correlations to operating variables including, but not limited to, rotational speed, thrust load, and material constitutive parameters. While aggregate metrics such as this provide for convenience in macro-scale process design and evaluation, local material response in the drill zone is ultimately dependent on the resulting strain, strain rate and fracture during loading. An understanding of the deformation and fracture of porous brittle solids at the tool interface, such as the extent and evolution of the plastic zone, must be established to facilitate higher fidelity process models.

Improvements in the design of geological drilling systems have been facilitated by consideration of the underlying mechanics of the drilling process. Fixed cutter bits or drag bits, which are standard tooling for drilling in many classes of geomaterials, are an agglomeration of individual drill heads made of polycrystalline diamond compacts. The overall action of these drag bits can be understood by considering the unit actions of a single cutter, modeled using both indentation-type and cutting-type mechanisms (Fairhurst and Lacabanne, 1957; Detournay and Defourny, 1992; Besson et al., 2000). While such model frameworks have been used to describe the performance of drag bit tools in geomaterials, relatively little progress has been made to experimentally calibrate the deformation fields underlying indentation and cutting in this class of solids. Calibration of these unit models is an important step toward establishing the effectiveness of indentation-cutting models to predict the operative stress and strain fields in the drill zone.

Understanding of indentation response in porous solids is relatively nascent due to significant volume change and oft-brittle behavior that add substantial complexity to plastic deformation in these material systems. Models with varying simplifying assumptions have been proposed to describe indentation response, most of which are based on models for metals or glasses with appropriate modifications to more closely match behavior of porous brittle solids. The cavity expansion class of models (Alehossein et al., 2000), wherein the deformation caused by a blunt indenter is approximated as an expanding cavity, have been used to estimate the pressure and the size of the plastic zone. Experimental calibration of cavity expansion models can be made by comparisons with measurements of load response and post-mortem characterization of deformation fields. While loading data is widely accessible,

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estimates of the kinematics are not trivial due to simultaneously operative mechanisms such as severe plastic deformation, volume change and fracture. In this regard, relatively few reports are available to describe the evolving kinematics during indentation for the broad set of porous solids.

In contrast, the mechanics (especially the kinematics) of indentation in metallic solids has received significantly greater attention. The deformation occurring in indentation of metals has been examined through indirect post-mortem assessments of strain-induced effects (Tabor, 1951), and more recently, the development of image based measurement techniques such as particle image velocimetry (PIV) and particle tracking velocimetry (PTV) has added a new dimension to experimental studies on the mechanics of indentation in metals (Murthy et al., 2008, 2012; Sundaram et al., 2012). These image-based techniques have provided useful qualitative and quantitative insights into the evolution of deformation in indentation. The present work aims to experimentally study the mechanics of indentation in a model porous brittle solid using image based deformation measurements. A series of quasi-static indentation experiments are conducted under plane strain conditions with different indenter geometries. The mechanics of deformation during the progress of the indentation is measured using image based analysis techniques. Insights into localization of deformation and the development of the plastic zone are brought to fore. These results are compared to analytical solutions of cavity expansion in a rigid perfectly plastic solid and a pressure dependent solid.

2. Background

Prior experimental research on indentation, especially on metals has predominantly been carried out using post indentation observation. Indirect estimation of strain by analyzing deformed microstructure revealed through metallographic etching (Samuels and Mulhearn, 1957), physical grid distortion (Hill et al., 1947; Atkins and Tabor, 1965) and secondary-phase distortion (Chaudhri, 1993) have all been traditionally used to understand the deformation in a metal around a wedge indenter. More recently, experimental techniques based on high-speed image analysis have provided further insight into the evolution of the deformation during indentation (Murthy et al., 2008, 2014) and have enabled direct comparisons of the ensuing strain fields to microstructure and texture evolution. These prior studies have provided requisite background capability for exploring deformation response of more complex materials such as porous solids (e.g., soft rocks) that exhibit both ductile and brittle behavior (Huang and Detournay, 2012; Lin et al., 2012; Alehossein et al., 2000).

The inherent anisotropy, porosity, and complexity in microstructure of rocks and other porous solids present challenges in studies on large strain deformation. Studies on fracture of model materials such as glass have played a pivotal role in establishing a framework for theories of deformation for porous brittle solids. Inorganic glasses have the distinct advantage of being transparent, homogeneous and isotropic, and have been used as model materials to study the mechanics of deformation in brittle solids. Swain and Lawn (1976) conducted a series of experiments on westerly granite and silicate glass and examined fracture patterns underneath the indenter post-mortem. Based on detailed measurements of crack size changes with indentation load, a series of similarity equations were established to correlate the mechanics of indentation in glass and rocks. Extensive discussion on the initiation and propagation of fracture in brittle solids under a myriad of boundary conditions was presented in Lawn (1993), especially noteworthy are the distinctions identified between the mechanics of indentation for sharp and blunt indenters using linear elastic fracture mechanics. Two types of cracks (e.g., cone, median) of penny shape were observed in indentation of brittle solids during loading, followed by crack closure during unloading. Further, it was found that residual stresses present in the deformed material cause formation of lateral cracks that lead to eventual failure (Lawn, 1993, 1983; Lawn and Marshal, 1984).

Theoretical constructs such as the blister field and cavity expansion have been used to study plastic response in indentation of porous solids. During indentation, the deformation zone underneath the indenter can be modeled as the expansion of a cylindrical or spherical cavity in an elastic–plastic material, dependent on indenter angle. The indentation pressure during the expansion of this cavity is related to the ratio (E/Y) where E is Young's modulus and Y is the yield strength (Marsh, 1964; Johnson, 1970). Similar analytical solutions have been extended to porous solids and have incorporated dependence of hydrostatic stress (or I_1) on the cavity expansion solution (Alehossein et al., 2000). These solutions were also benchmarked against experimental response in Harcourt granite loaded with a spherical indenter. Using sintered steel as a model material, Fleck et al. (1992) studied the effects of porosity on indentation using finite element (FE) analysis and experiment. The effects of porosity were modeled using the constitutive models of Gurson and FKM in the FE analysis. Indentation pressure computed from the FE simulations was found to be 20–30% less than that calculated by the traditional analytical solution using cavity expansion, but showed good agreement with experimental results. Huang and Detournay (2012) used DEM simulations wherein the solid was simulated by allowing cohesion to pervade through inter-particle contacts with packing generating the porous structure. The ductile mode associated with the development of the deformation zone below the indenter and the brittle fracture zones were identified through the simulations.

Indentation of porous rocks has also been studied experimentally, this providing insight into several important aspects of the problem. Wedge indentation of porous brittle solids, including sandstone and granite, was conducted by Chen and Labuz (2006). Acoustic emission was used to study the initiation and propagation of fractures during indentation, as well as cavity pressure and the size of the deformation zone. While acoustic emission enabled experimental study of the indentation process, it did not provide direct measurement of the evolving flow fields. In this regard, image-based methods (e.g., PIV, PTV) for assessing deformation parameters can offer an ideal alternative to study the mechanics of indentation in porous brittle solids. The PIV and PTV techniques allow *in situ* quantification of the extent and characteristics of the plastic zone underneath the indenter. In the ensuing, the evolution of the deformation field and effect of wedge angle on plane strain indentation in a porous brittle solid is studied. These measurements provide a detailed characterization of changing material structure, such as estimates of volume change due to pore collapse and damage. Further, the present results are used to understand the efficacy of various theoretical constructs to describe plastic response in indentation. Such validations are critical to develop a fundamental understanding of the mechanics of indentation in porous brittle solids, which has direct relevance to topics ranging from hardness testing, cutting, and drilling of geological materials (Detournay and Defourny, 1992).

3. Experimental

Plane strain indentation experiments on a model porous brittle solid, gypsum, was carried out in the present study. Gypsum is a porous brittle solid with fracture properties in resemblance to many naturally occurring rocks (Vekinis et al., 1993; Bobet and