A new method to rapidly and accurately assess the mechanical properties of geologically
relevant materials

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Abstract

A new indentation-based method was developed that will impact and facilitate the elastic property measurements of rocks and minerals, especially those possessing unusual deformation behavior, including brittle materials and those with complex architectures. The novel feature employed is a metallic film that uniformly transfers the load from the indenter tip to the sample. The film also absorbs the damage caused by the penetrating indenter, shielding the material from highly localized deformation that can impact its response to loading. Many geologically relevant materials have resisted traditional indentation testing because they are either brittle in nature or possess highly anisotropic architectures, such as layered or lamellar structures. In both cases, the highly localized deformation from direct indentation significantly affects the indenter unloading stiffness, from which the elastic properties are determined. The indirect indentation method developed here has demonstrated accurate determination of the elastic properties of many common geological materials as well as materials that have resisted elastic characterization such as galena and talc.

Keywords: Indentation, elastic properties, lamellar structure, highly localized deformation

Introduction

The elastic properties of rocks and minerals have long been central to understanding and predicting the mechanical behavior of the Earth from a regional to a planetary scale. Recent decades have seen the development of many skillful techniques capable of measuring elastic properties, including their dependence on temperature and/or pressures relevant from the Earth’s crust to its core. These include electromagnetic radiation, acoustic emission, micro-seismic, and many others; see Angel et al. (2009) for a recent review. Given these significant advances, the accuracy of deformation models continues to depend on accurate property inputs, which should be reflective of the regional rocks and minerals relevant to the model. In this regard, the local environmental conditions that these materials form and exist in can influence their properties as a function of composition, structure, hydration, and other characteristics (Ersoy and Waller 1995; Na et al. 2017; Raisanen 2004; Sun et al. 2017; Tandon and Gupta 2013). Thus, the mechanical behavior of many geologic relevant materials can vary appreciably from region to region (Atkinson 1976; Blackman et al. 2002; King Hubbert 1951; Meyers and Chawla 2009; Riecker 1984), warranting the need for simple, rapid and accurate tests to provide this information. Indentation has long been a popular technique to carry out elastic property measurements due to the minimal sample preparation and the rapid collection of numerous data points, important to robust statistical analyses (Oliver and Pharr 1992, 2004). It also enables unrivaled spatial mapping of elastic properties to ascertain variations in sample composition, microstructure, and phases (Constantinides et al. 2006; Randall et al. 2009). An additional benefit is that indentation does not require specific expertise or access to special facilities and can be performed at most universities and research institutions. The basic premise involves pressing a sharp diamond tip of well-known geometry into the material while independently recording the load and indentation depth. The resistance to penetration is represented by hardness (H), while the elastic behavior (E) is related to the slope of the unloading curve, the unloading stiffness (S), as described by the following relations (Oliver and Pharr 1992):

\[
H = \frac{P}{a} \quad \text{and} \quad S = \frac{dP}{dh} = E \frac{2}{\sqrt{\pi}} \sqrt{a}
\]

where P is the applied indenter load, a is the contact area between the indenter and sample, h is the indenter displacement into the sample surface, and E is the elastic modulus of the sample. By oscillating the indenter tip during penetration, both properties can be monitored continuously as a function of depth, termed continuous stiffness (Pharr et al. 2009). The typical indentation test ranges from the nanometer to micrometer scale and can infer local variations in elastic behavior, including; compositional and structural changes, different material phases, interfaces, and many other varying characteristics. (Hintsala et al. 2018).

The extraction of the elastic modulus from indentation can be problematic for materials that are brittle or that possess unusual deformation behavior (Chen et al. 2018; Pharr and Bolshakov 2002), which many rocks and minerals do. For example, brittle materials that cannot plastically strain in response to indenter penetration instead generate cracks or other defects. These form during the loading cycle and dissipate energy through the creation of new surface. They have a significant effect on the unloading stiffness (S) as they consume stored elastic energy that would normally push back on the indenter as it is withdrawn.

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