Size Effects in Plasticity: From the Basic Concepts of Mindlin to Mechanism-Based Strain Gradient Plasticity

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ABSTRACT

This paper presents an overview of the current understanding of size effects in plasticity. Starting with the original work of Mindlin, phenomenological theories of size effects are described along with the length scales that have been proposed to characterize them. Experimental techniques are also presented for the measurement of the length scales proposed by Hutchinson and Fleck in their recent phenomenological theories. These include rotational and stretch length scale parameters that are measured using bending, torsional and indentation experiments. The implications of such measurements are discussed for the constitutive modeling of plasticity at the micron- and sub-micron scales. Subsequently, mechanism-based strain gradient plasticity models are presented. These include the original ideas by Ashby, and more recent work by Gao, Huang and Nix, and Ma and Clark. These concepts are shown to provide physical insights into the underlying mechanisms of deformation at the micron- and sub-micron scales. However, they involve continuum assumptions that do not necessarily capture the discrete nature of deformation at the nanoscale, where deformation becomes dislocation source limited. Examples of such "dislocation starved" scenarios are presented using results from nanoindentation and compression pillar experiments. These are shown to give rise to much greater hardness values and yield stresses, even in the absence of externally applied gradients. Finally, a multi-scale modeling framework is presented for the modeling of deformation between the nano and micron-scales. This includes the use of atomistic, discrete dislocations and strain gradient plasticity theories in the modeling of contact-induced deformation and plasticity compression loading.