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Origin of Plasticity Length-Scale Effects in Fracture and Deformation

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Engineering design of essentially all metallic components used in structural applications relies heavily on the framework of continuum plasticity. However, many experiments now show that the plastic flow stress in metals increases in micron-scale material volumes, i.e. "smaller is stronger". The failure of conventional plasticity is particularly manifest at a crack tip, where infinite toughness can be predicted. Phenomenological strain-gradient plasticity models and discrete-dislocation models have emerged to handle size effects but there is no clear physical identification of material length scales controlling size-dependence, in spite of wide speculation. Here, we use a new discrete-dislocation/cohesive-zone model to unambiguously demonstrate that the spacing between obstacles to dislocation motion is one dominant material length scale controlling the fracture toughness of plastically deforming metals. With this insight, we propose a new "stress gradient plasticity" concept based on the behavior of dislocations in a "pile-up" at an obstacle under a stress gradient, which (i) rationalizes our fracture results and (ii) predicts size-effects under other loading conditions (bending, torsion, indentation). Quantitative agreement between theory and experiments is then demonstrated in several cases.

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