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Numerical and experimental indentation tests considering size effects

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ABSTRACT

A series of nanoindentation experiments with maximum depths varying from 1200 to 2500 nm were conducted to study indentation size effects on copper, aluminium alloy and nickel. As expected, results from classical plasticity simulation deviate significantly from experimental data for indentation at micron and submicron levels. C^0 continuity finite element analysis incorporating the conventional theory of mechanism-based strain-gradient (CMSG) plasticity has been carried out to simulate spherical and Berkovich indentation tests at micron level where size effect is observed. The results from both numerical and actual spherical and Berkovich indentation tests demonstrate that materials are significantly strengthened for deformation at this level and the proposed approach is able to provide reasonably accurate results.

1. Introduction

Material characterization using instrumented indentation tests has been extended to new applications as a result of technological advances in microelectronics and nano-technology. Not only hardness of material but also other mechanical properties such as Young's modulus, yield strength and strain hardening exponent can be deduced from load–displacement indentation curves. Most of indentation tests have been intensively conducted at indentation depths from micron down to submicron levels to accommodate the needs of material properties of small volumes in the fields of MEMS and NEMS. In many of these applications, material properties are shown to be inconsistent with those provided by classical plasticity approach, exhibiting a strong size effect.

Gains in strength at such small deformation comparable to the material length scales have been reported for many tests on metallic materials. Numerous experiments (micro- and nano-indentation tests (see e.g. Atkinson, 1995; Ma and Clarke, 1995; Nix, 1989; Stelmashenko et al., 1993); twisting of copper wires of micron diameters by Fleck et al. (1994) micro-bend tests by Haque and Saif (2003)) have shown significant size-dependent effects when the material and deformation length scales are of the same order at micron and submicron levels. Finite element simulations employing classical plasticity theories are unable to capture these size-dependent effects. The size effects cannot be simulated via classical plasticity theories as no material length scale is introduced. Fleck et al. (1994) proposed the theory of strain gradient plasticity requiring additional higher-order stress and consequently leading to significantly greater formulation and computational efforts. Gao et al. (1999) and Huang et al. (2000) proposed the mechanism-based strain gradient (MSG) plasticity guided by the Taylor dislocation concept to model the indentation size effect. Huang et al. (2004) further developed the conventional mechanism-based strain gradient (CMSG) plasticity theory confining the presence of the strain gradient plasticity in the material constitutive equation without involving the higher-order stress components. Adopting this approach, Swaddiwudhipong et al. (2005, 2006) formulated C^0 continuity solid, plane and axisymmetric finite elements incorporating strain gradient plasticity to simulate various indentation tests and other physical problems involving deformation at micron and submicron levels. Alternatively, the strain gradient plasticity may also be determined via the differences in numerical values of the plastic at various locations. The formulation was derived based on the classical continuum plasticity framework taking into consideration Taylor dislocation model. Higher order variables and consequently higher-order continuity conditions are not required and the direct application of conventional plasticity algorithms in finite element modelling is applicable.

Indentation size effect (ISE) has been studied extensively for both sharp and spherical indentation tests. The measured hardness of metallic materials increases with decreasing indentation depth for conical and Berkovich tips (McElhaney et al., 1998; Nix and Gao, 1998; Oliver and Pharr, 1992; Stelmashenko et al., 1993;

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