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On couple-stress elasto-plastic constitutive frameworks for glassy polymers

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Abstract

Various experimental studies have revealed length scale dependent deformation of different materials at micron and sub-micron length scales. In metals, such length scale dependent deformations are considered to be associated with geometrically necessary dislocations arising from an increase in strain gradients related to non-uniform plastic deformation. Recent experiments, however, have shown that the nature of length scale dependent deformation in polymers is quite different from metals as in polymers size effects have been observed in pure elastic as well as in elasto-plastic deformation. It is shown in this study that similar to metals, size effects in polymers can be associated with an increase in higher order displacement gradients with decreasing length scale. However, the experimental results discussed here reveals that, in contrast to metals, these higher order displacement gradients are mainly of elastic nature even when glassy polymers deform elasto-plastically. Taking the effects of these elastic higher order displacement gradients into account, a couple-stress theory is developed to predict size effect in glassy polymers with elasto-plastic deformation.

Keywords: Length scale dependent deformation; Glassy polymers; Couple-stress; Elasto-plasticity

1. Introduction

Polymeric materials at small dimensions have found widespread technical applications in sensors, optical/electronic devices, etc. Subsequently, a great effort has been directed toward the understanding of the deformation mechanisms of polymers at nano- to micrometer length scales where the deformation characteristics of some polymers can be very different in comparison to bulk deformation behavior. As in metals (Nix & Gao, 1998; Ma & Clarke, 1995; Fleck et al., 1994; Liu et al., 2013; Swadener et al., 2002; Motz et al., 2005), length scale dependent behavior has been also experimentally observed in polymers (Han, 2010; Alisafaei & Han, 2015) at micron to submicron length scales by beam bending testing (Lam et al., 2003; McFarland & Colton, 2005), nanoindentation (Briscoe et al., 1998; Chong & Lam, 1999; Alisafaei et al., 2013; 2014) and bending test of nanofibers (Sun et al., 2008; Arinstein et al., 2007). Various polymers exhibited such length scale dependent deformation including epoxy (Chong & Lam, 1999; Lam & Chong, 1999; 2000; 2001; Lam et al., 2003; Alisafaei et al., 2014; Dutta et al., 2004; Sanchez et al., 2011), polycarbonate (PC) (Briscoe et al., 1998; Chong & Lam, 1999; Balta Calleja et al., 2004), polydimethylsiloxane (PDMS) (Charitidis, 2011; Alisafaei et al., 2013; Wrucke et al., 2013; Han et al., 2015; Lim & Chaudhri, 2006; Koumoulos et al., 2014), polystyrene (PS) (Briscoe et al., 1998; Balta Calleja et al., 2004; Tjernlund et al., 2004), silicone rubber/elastomer (Zhang & Xu, 2002; Xu et al., 2005;

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