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Indentation of pressurized viscoplastic polymer spherical shells

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ABSTRACT

The indentation response of polymer spherical shells is investigated. Finite deformation analyses are carried out with the polymer characterized as a viscoelastic/viscoplastic solid. Both pressurized and unpressurized shells are considered. Attention is restricted to axisymmetric deformations with a conical indenter. The response is analyzed for various values of the shell thickness to radius ratio and various values of the internal pressure. Two sets of material parameters are considered: one set having network stiffening at a moderate strain and the other having no network stiffening until very large strains are attained. The transition from an indentation type mode of deformation to a structural mode of deformation involving bending that occurs as the indentation depth increases is studied. The results show the effects of shell thickness, internal pressure and polymer constitutive characterization on this transition and on the deformation modes in each of these regimes.

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1. Introduction

There has recently been a great deal of interest in measuring mechanical properties by indentation of shells under internal pressure. Thus, Vella et al. (2012a) have studied both polymeric capsules and yeast cells, and Milani et al. (2011) have studied the cell wall in living shoot apical meristems (SAMs), which are highly organized structures that contain the plant stem cells. For the cells the experiments are based on microindentation techniques, using atomic force microscopy (AFM). Vella et al. (2012a) also analyze the relation between indentation depth, indenter force and internal pressure, using linear shallow shell theory, or nonlinear shell theory in cases where the indentation depth is much larger than the shell thickness. Kol et al. (2006) used indentation to investigate the mechanical properties of a leukemia virus particle and carried out elastic finite element calculations to use in conjunction with the experimental measurements to quantify virus particle stiffness. Zelenskaya et al. (2005) used atomic force microscopy together with indentation analyses to understand the mechanical behavior of cochlear hair cells.

Ogbonna and Needleman (2011) carried out a numerical study for indentation of thick-walled elastic spherical shells using finite strain elastic theory to be able to represent the geometry changes during bending, as well as the initial indentation response, where bending is not yet noticeable. A variety of studies have been carried out investigating the indentation of thin shells, e.g. Fitch and Budiansky (1970), Vaziri and Mahadevan (2008), Vella et al. (2012a,b), and Nasto and

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Reis (2014), with attention directed to the emergence of non-axisymmetric deformation mode and with the focus on elastic material response. Here, we focus on indentation of relatively thick spherical shell and confine attention to axisymmetric deformations. We carry out our analyses using full finite deformation kinematics and a material constitutive relation including viscoelastic and viscoplastic material response.

The constitutive relation used for the finite strain behavior of the polymers is mainly adopted from Wu and Van der Giessen (1996) and models proposed by Boyce et al. (1988) and Boyce and Arruda (1990). This material model was used by Tvergaard and Needleman (2011, 2012) in full 3D numerical analyses of indentation into a polymer half-space by conical and pyramidal indenters. The indentation analyses first considered material parameters that give a reasonable approximation of tensile tests for high-density polyethylene, and subsequently indentation was analyzed for a number of different parameter sets that represent other polymers. In the analyses the effect of viscoelasticity is modeled following discussions by Anand and Ames (2006).

For metals it is well known that the hardness is about three times the yield strength (Johnson, 1970, 1985), but such high hardness values are not found in the analyses of polymer indentation. Recently, Needleman et al. (2015) have studied indentation of elastically soft or plastically compressible solids, and these results show that a hardness around 1.1 times the yield stress is consistent with a polymer having Young's modulus around 19 times the yield stress. Plastic analyses of shell indentation aimed at structural applications have been carried out, including the work of Morris and Calladine (1971) on indentation of cylindrical shells using upper bound analyses. Analyses of shell plastic indentation aimed at structural applications include the work of Morris and Calladine (1971) on indentation of cylindrical shells. They used their results to delineate between an elasticity dominated regime where snap-through occurs and a plasticity dominated regime where it does not occur.

The indentation studies of Tvergaard and Needleman (2011, 2012) also considered the spherical cavity model, which was suggested by Bishop et al. (1945) as an alternative approach to elastic–plastic indentation, and later carefully discussed by Johnson (1970, 1985). It was found that also for the polymers this simpler 1D model with spherical symmetry gives a good approximation of the indentation hardness for indentation into a half-space.

A basic question for indentation into shells is the extent to which the indentation hardness (indentation force/some measure of contact area) provides a measure of a material property or reflects the overall structural response, including the shell geometry and the internal pressure (if any).

In the present paper we confine attention to the indentation of spherical shell by conical indenters. The cases analyzed include various thickness to radius ratios and various values of internal pressure. Also, two sets of the material parameters from Tvergaard and Needleman (2012) are used in the calculations: one, termed material G has network stiffening come into play at a strain of about 0.3 while the other termed material A does not undergo network stiffening until very large strains.

For sufficiently small indentation depths, we expect the indentation response to be the same as for a half-space. For larger indentation depths, the overall structural response of the shell, as well as the material response, comes into play. The effects of the two constitutive characterizations and of the value of the prescribed internal pressure on the indentation responses in these two regimes and the transition between them are investigated.

2. Constitutive relation

The constitutive relation used in the calculations is mainly adopted from Wu and Van der Giessen (1996) and is based on models proposed by Boyce and co-workers, see Boyce et al. (1988), Boyce and Arruda (1990), Arruda and Boyce (1993), and Mulliken and Boyce (2006). The specific formulation and implementation used in the calculations are those used in Tvergaard and Needleman (2011) where further details and additional references are given.

The rate of deformation tensor is written as

$$\boldsymbol{D} = \boldsymbol{D}^e + \boldsymbol{D}^{p1} + \boldsymbol{D}^{p2} \tag{1}$$

with

$$\boldsymbol{D}^e = \boldsymbol{K}^{-1}: \hat{\boldsymbol{\sigma}}, \quad \boldsymbol{D}^{p1} = \dot{\gamma}^{p1}\boldsymbol{p}^{p1}, \quad \boldsymbol{D}^{p2} = \dot{\gamma}^{p2}\boldsymbol{p}^{p2} \tag{2}$$

where $\boldsymbol{\sigma}$ is the Cauchy or true stress, a superposed $(\wedge)$ denotes the Jaumann rate and $\boldsymbol{K}$ is the isotropic tensor of moduli with elastic constants Young's modulus E and Poisson's ratio ν. The expression for $\boldsymbol{D}^e$ in Eq. (2) is a hypoelastic relation and is not, in general, a path independent hyperelastic relation. Attention here is confined to circumstances where the elastic strains remain relatively small.

The viscoplastic term, $\boldsymbol{D}^{p1}$, is given by

$$\boldsymbol{p}^{p1} = \frac{\boldsymbol{\sigma}' - \boldsymbol{b}'}{\sqrt{2}\,\tau}, \quad \tau = \sqrt{\frac{1}{2}(\boldsymbol{\sigma}' - \boldsymbol{b}'): (\boldsymbol{\sigma}' - \boldsymbol{b}')} \tag{3}$$

with $(\ )'$ denoting deviatoric quantities with, for example,

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