European Journal of Mechanics A/Solids 45 (2014) 41–58

Contents lists available at ScienceDirect

European Journal of Mechanics A/Solids

journal homepage: www.elsevier.com/locate/ejmsol

Viscous interfaces as source for material creep: A continuum micromechanics approach ☆

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ARTICLE INFO

Article history:
Received 2 November 2012
Accepted 2 November 2013
Available online 15 November 2013

Keywords:
Multiscale creep model
Liquid crystals
Viscous interfaces

ABSTRACT

It is generally agreed upon that fluids may play a major role in the creep behavior of materials comprising heterogeneous microstructures and fluid-filled porosities at small length scales. In more detail, nano-confined fluid-filled interfaces are typically considered to act as a lubricants, once electrically charged solid surfaces start to glide along fluid sheets, with the fluid being typically in a liquid crystal state, which refers to an "adsorbed", "ice-like", or "glassy" structure of fluid molecules. Here, we aim at translating this interface behavior into apparent creep laws at the continuum scale of materials consisting of one non-creeping solid matrix with embedded fluid-filled interfaces. To this end, we consider a linear relationship between (i) average interface dislocations and (ii) corresponding interface tractions, with an interface viscosity as the proportionality constant. Homogenization schemes for eigenstressed heterogeneous materials are used to upscale this interface behavior to the much larger observation scale of a matrix-inclusion composite comprising an isotropic and linear elastic solid matrix, as well as interacting parallel interfaces of circular shape, which are embedded in the aforementioned matrix. This results in exponentially decaying macroscopic viscoelastic phenomena, with both creep and relaxation times increasing with increasing interface size and viscosity, as well as with decreasing elastic stiffness of the solid matrix; while only the relaxation time decreases with increasing interface density. Accordingly, non-asymptotic creep of hydrated (quasi-) crystalline materials at higher load intensities may be readily explained through non-stationarity, i.e. spreading, of liquid crystal interfaces throughout solid elastic matrices.

1. Introduction

It is generally agreed upon that water may play a major role in the creep behavior of materials comprising heterogeneous microstructures with water being embedded into those; as is encountered, among others, in the realm of geophysics (Morrow et al., 2000; Stipp et al., 2006; Tullis and Yund, 1991), in cementitious materials like concrete (Bažant et al., 1997; Alizadeh et al., 2010; Kalinichev et al., 2007; Vlahinić et al., 2012; Youssef et al., 2011), in alcohol-based surfactant-water system (Németh et al., 1998; Cordobés et al., 1997), or in hard biomedical materials like bone or bone cements (Vlahinić et al., 2012; Eberhardsteiner et al., 2012; Arnold and Venditti, 2001). Hence, creep increases with increasing water content, as described for bone in Sasaki et al. (1993). Water layers in a somewhat ice-like structured (or "glassy" (Lombardo et al., 2009)) state qualify as "liquid crystals". The latter term refers to matter which is right in between the long-range positional and orientational order found in solids and the long-range disorder found in liquids. The creep phenomena in liquid crystal systems have been extensively studied also beyond the presence of water, e.g. for polymers (Berghausen et al., 1997; Brostow et al., 1999; Colby et al., 2001) or ferroelectrics (Jezewski et al., 2008). More specifically, the intimate bounding of water molecules to electrically charged solid surfaces as well as the "lubricant effect" of the fluid once the solid surfaces start to glide along the water sheets are thought of as the origins of the creep process, as is supported by various experimental and computational chemistry studies (Alizadeh et al., 2010; Kalinichev et al., 2007; Vlahinić et al., 2012; Manzano et al., 2012). What is somehow lacking in this respect, is the explicit mathematical consideration of how the lubrication effect of water on 2D interfaces results in creep properties of a bulk of material hosting such surfaces. As a contribution to this somehow open problem, the present paper describes a micromechanical framework which allows for translation of creep laws for interfaces, into the resulting creep laws at the continuum scale of materials

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http://dx.doi.org/10.1016/j.euromechsol.2013.11.001

Nomenclature

a	radius of an oblate spheroid
$\underline{\underline{\underline{\underline{A}}}}_i$	fourth-order strain concentration tensor of oblate inclusion phase
$\underline{\underline{\underline{\underline{A}}}}_s$	fourth-order strain concentration tensor of solid
$\underline{\underline{\underline{\underline{A}}}}_i^{\infty}$	fourth-order strain concentration tensor of oblate inclusion phase in Eshelby-type matrix-inclusion problem
$\underline{\underline{\underline{\underline{A}}}}_i^{\lim}$	limit of $\underline{\underline{\underline{\underline{A}}}}_i$ for flat interfaces
$\underline{\underline{\underline{A}}}_i^{\lim}$	third-order strain concentration tensor describing the influence of macroscopic strain on the average displacement jump of flat interfaces
$\underline{\underline{\underline{A}}}_i^{\Sigma,\lim}$	third-order strain concentration tensor describing the influence of macroscopic stress on the average displacement jump of flat interfaces
$A_{i,jkm}^{\lim}$	jkm − th component of $\underline{\underline{\underline{A}}}_i^{\lim}$; $j, k, m \in \{x, y, z\}$
$A_{i,jkm}^{\Sigma,\lim}$	jkm − th component of $\underline{\underline{\underline{A}}}_i^{\Sigma,\lim}$; $j, k, m \in \{x, y, z\}$
$\underline{\underline{\underline{B}}}_i^{\lim}$	third-order influence tensor describing the influence of interfacial eigentractions of flat interfaces on the macroscopic stress
$\underline{\underline{\underline{B}}}_i^{\Sigma,\lim}$	third-order influence tensor describing the influence of interfacial eigentractions on the macroscopic strain
$B_{i,jkm}^{\lim}$	jkm − th component of $\underline{\underline{\underline{B}}}_i^{\lim}$; $j, k, m \in \{x, y, z\}$
$B_{i,jkm}^{\Sigma,\lim}$	jkm −th component of $\underline{\underline{\underline{B}}}_i^{\Sigma,\lim}$; $j, k, m \in \{x, y, z\}$
c	half opening of an oblate spheroid
$\underline{\underline{\underline{\underline{C}}}}_i$	fourth-order stiffness tensor of oblate inclusion phase
$\underline{\underline{\underline{\underline{C}}}}_s$	fourth-order stiffness tensor of solid
$\underline{\underline{\underline{\underline{C}}}}_{\mathrm{hom}}$	fourth-order homogenized stiffness tensor
$\underline{\underline{\underline{\underline{C}}}}_{\mathrm{hom}}^{\lim}$	limit case of $\underline{\underline{\underline{\underline{C}}}}_{\mathrm{hom}}$ for flat interfaces
$(\underline{\underline{\underline{\underline{C}}}}_{\mathrm{hom}}^{\lim})^{-1}$	inverse of $\underline{\underline{\underline{\underline{C}}}}_{\mathrm{hom}}^{\lim}$, i.e. homogenized compliance tensor for flat interfaces
d	interface density parameter
$\mathrm{d}r$	differential of r
$\mathrm{d}u$	differential of u
$\mathrm{d}\Omega$	differential volume
$\underline{\underline{\underline{\underline{D}}}}_{ii}$	fourth-order influence tensor describing the influence of eigenstresses in oblate inclusion phase on its total strains
$\underline{\underline{\underline{\underline{D}}}}_{ii}^{\lim}$	fourth-order limit of $\underline{\underline{\underline{\underline{D}}}}_{ii}$ for flat interfaces
$\underline{\underline{D}}_{ii}^{\lim}$	second-order influence tensor describing the influence of interfacial eigentraction on the average displacement jump
$\underline{\underline{D}}_{ii}^{\Sigma,\lim}$	second-order influence tensor describing the influence of interfacial eigentraction on the average displacement jump
$\underline{\underline{\underline{\underline{D}}}}_{si}$	fourth-order influence tensor describing the influence of eigenstresses in oblate inclusion phase on the total solid phase strains
$D_{ii,jkmn}^{\lim}$	$jkmn$ − th component of $\underline{\underline{\underline{\underline{D}}}}_{ii}^{\lim}$; $j, k, m, n \in \{x, y, z\}$
$D_{ii,jk}^{\lim}$	jk − th component of $\underline{\underline{D}}_{ii}^{\lim}$; $j, k \in \{x, y, z\}$
$D_{ii,jk}^{\Sigma,\lim}$	jk − th component of $\underline{\underline{D}}_{ii}^{\Sigma,\lim}$; $j, k \in \{x, y, z\}$
$\underline{e}_x, \underline{e}_y, \underline{e}_z$	unit base vectors of Cartesian coordinate system
$\underline{\underline{E}}$	macroscopic strain tensor
$\underline{\underline{E}}_{\infty}$	remote strain tensor of Eshelby-type matrix-inclusion problem
$\underline{\underline{E}}_I$	$\underline{\underline{E}}$ in first load case
$\underline{\underline{E}}_{II}$	$\underline{\underline{E}}$ in second load case
E_s	Young's modulus of the solid phase
E_{jk}	jk − th component of $\underline{\underline{E}}$; $j, k \in \{\alpha, x, y, z\}$
$E_{\alpha z}^0$	initial macroscopic shear strains in a creep experiment
$\Delta E_{\alpha z}^{\infty}$	asymptotically reached increment of creeping shear strains
f_i	volume fraction of inclusion phase
f_s	volume fraction of solid phase
i	index for inclusion and interface phases
$\underline{\underline{\underline{\underline{I}}}}$	symmetric fourth-order identity tensor
$\underline{\underline{\underline{\underline{I}}}}_{\mathrm{dev}}$	deviatoric part of $\underline{\underline{\underline{\underline{I}}}}$
$\underline{\underline{\underline{\underline{I}}}}_{\mathrm{vol}}$	volumetric part of $\underline{\underline{\underline{\underline{I}}}}$
$\underline{\underline{1}}$	second-order identity tensor
j	index $j \in \{x, y, z\}$
$\underline{\underline{\underline{\underline{J}}}}$	fourth-order creep tensor
J_{ijkl}	$ijkl$ − th components of $\underline{\underline{\underline{\underline{J}}}}$
k	index $k \in \{x, y, z\}$
k_s	bulk modulus of solid phase
ℓ	characteristic size of RVE
m	index $m \in \{x, y, z\}$
n	index $n \in \{x, y, z\}$
$\mathscr{N}$	number of interfaces inside the RVE, making up the interface phase
$\underline{\underline{\underline{\underline{P}}}}$	fourth-order Hill tensor, accounting for inclusion shape
$\underline{\underline{\underline{\underline{P}}}}_i$	fourth-order Hill tensor of oblate inclusion phase
r	radial coordinate of a cylindrical coordinate system
RVE	Representative Volume Element
$\underline{\underline{\underline{\underline{R}}}}$	fourth-order relaxation tensor
R_{ijkl}	$ijkl$ − th components of $\underline{\underline{\underline{\underline{R}}}}$
s	index for solid phase
$\underline{\underline{\underline{\underline{S}}}}_i$	fourth-order Eshelby tensor of oblate inclusion phase
$S_{i,jkmn}$	$jkmn$ − th component of $\underline{\underline{\underline{\underline{S}}}}_i$; $j, k, m, n \in \{x, y, z\}$
$\underline{\underline{\underline{\underline{T}}}}_i$	fourth-order morphology tensor for flat inclusions; abbreviation for $\lim_{\omega \to 0} \omega \underline{\underline{\underline{\underline{A}}}}_i^{\infty}$
$T_{i,jkmn}$	$jkmn$ − th component of $\underline{\underline{\underline{\underline{T}}}}_i$; $j, k, m, n \in \{x, y, z\}$
$\underline{T}_i^E$	viscous eigentraction vector of interface phase
$T_{i,j}^E$	j-th component of $\underline{T}_i^E$; $j \in \{\alpha, z\}$
u	integration variable
x, y, z	Cartesian coordinates
$\underline{x}$	position vector
$\underline{x}^+$	position vector labeling geometrical points at upper boundary of the spheroidal oblate inclusion
$\underline{x}^-$	position vector labeling geometrical points at lower boundary of the spheroidal oblate inclusion
$z(r)$	half opening of an oblate spheroid, measured relative to the midplane of the oblate spheroid, at a distance r from the center on the long axis ($z(0) = c$)
α	index $\alpha \in \{x, y\}$
δ	Kronecker delta
$\underline{\underline{\varepsilon}}$	microscopic strain tensor
$\underline{\underline{\varepsilon}}_i$	average strains of the oblate inclusion phase