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Effect of interface diffusion on the strain and stress stability of particulate reinforced electrostrictive materials

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ABSTRACT

This paper presents an analytical method to solve the creep rate and stress relaxation behaviors of particle reinforced electrostrictive composites induced by the interface diffusion between particle and electrostrictive matrix, subjected to external electric fields. Based on the microstructures evolution theory and electroelastic theory of electrostrictive materials, the thermodynamic equations of creep rate and stress relaxation induced by the interface diffusion are, respectively, deduced and solved. The investigation results show that the strain and stress stabilities of particle reinforced electrostrictive materials can be enhanced by optimizing the shape, stiffness and volume fraction of reinforced particles.

1. Introduction

Electrostriction describes the phenomenon of mechanical deformation induced by electric field load exerted on a dielectric material. The good characteristics of smart devices and structures made by electrostrictive materials or particle reinforced electrostrictive composites depend on the strain and stress stabilities of the electrostrictive materials or particle reinforced electrostrictive composites. When electrostrictive materials and particle reinforced electrostrictive composites are subjected to an external electric field, cracks and particles in the electrostrictive materials may lead to destructive invalidation induced by creep rupture [1,2]. Therefore, it is important to investigate the creep and stress relaxation of particle reinforced electrostrictive composites under external electric field.

The electrostrictive theories are developed by many researchers [3,4]. Smith and Warren [4] discussed the problem of an elliptical hole and a rigid elliptical disk in electromagnetic material without considering Maxwell stress. From Maxwell's equations, Maxwell stress was introduced into the electrostrictive theory by Pao [5], but its expression is not the only one. The non-linearized variability theory was came up by McMeeking, Landis and Jimenez [6–8]. Jiang and Kuang [9,10] presented rational governing equations to calculate stress and electric field of two-dimensional electrostrictive material with an elliptical inhomogeneity and crack. By utilizing the equations, Gao et al. [11,12] solved the two-dimensional problem of cracks in electrostrictive materials subjected to the remote electric field load.

Generally, the mechanical behaviors of particle reinforced composites are composed of the matrix behaviors and the behavior induced by interface diffusion between reinforced particle and matrix [13–18]. In order to completely understand the mechanism of the real creep and stress relaxation of particle reinforced electrostrictive composites, the investigation on the creep characteristics and stress relaxation induced by the interface diffusion is necessary. In faith, the creep and stress relaxation induced by diffusion and slip along the interface between particle and matrix often appears in particle or fiber reinforced composites [19]. This problem has been widely noticed in the engineering application of reinforced composites. The creep rate and partial creep debonding at the interface are, respectively, predicted by utilizing semi-analytical method and finite element method [20]. The creep deformation behavior of short fiber composites was researched by Mondali and Abedian [21] based on an approximate analytical method. Researchers [22–25] have done a wide research on stress relaxation and creep behaviors of particulate composites of oxynitride glass matrix doped with SiC particles.

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Nomenclature

μ	thermodynamic potential
γ_i	interfacial energy per unit area
Ω	atom volume
κ	interface curvature
σ_n	normal stress
W	strain energy
J	atomic flux density
K	Boltz-mann's constant
T	absolute temperature
D_i	isotropic lattice diffusion coefficient
s	arc length of the interface
V_n	material accumulation or depletion rate along the normal of the interface
M	shape parameter
a and b	length of long and short axis of elliptical particle
λ and G	Lame constants
δ_{kl}	Kronecker delta
a_1 and a_2	isotropic electrostrictive coefficients
σ_{ij}	stress components
ε_{kl}	strain components
E_V	electric field intensity
$\alpha = G_p/G_m$	ratio of Lame constants between particle and material

This paper presents an analytical method to solve the creep rate and stress relaxation of particle reinforced electrostrictive composites induced by the interface diffusion between particle and electrostrictive matrix, where the creep in electrostrictive matrix is omitted. Therefore, the interface diffusion between particle and electrostrictive matrix is considered as a single independent variable of the problem. Based on a rigorous electroelastic coupling theory of electrostrictive composites containing reinforced particles, the stress field and strain energy in interface layer are obtained, which is the driven force for diffusing mass transport along the interface between particle and electrostrictive matrix. Utilizing the driven force obtained and the atomic migration principle in a diffuse interface layer between particle and electrostrictive matrix from regions of high chemical potential to those of low chemical potential along the interface layer, an analytical solution for the creep characteristics and stress relaxation of particle reinforced electrostrictive materials induced by the interface diffusion is presented. The results describe the effects of the external electric filed, and the material characteristic, shape parameter and volume fraction of reinforced particle on the creep characteristics and stress relaxation of particle reinforced electrostrictive materials, which may provide useful reference to understand the effect of reinforced particles on the strain and stress stabilities of particle reinforced electrostrictive materials, and to design an electrostrictive composites with higher strain and stress stabilities.

2. Analytical model and method

A unit cell as a periodical microstructure for particle reinforced electrostrictive films is described by a square with an elliptic particle located at the center of cell, as shown in Fig. 1. The volume ratio between the elliptic particle and the unit electrostrictive material cell is given by the volume fraction of particle in electrostrictive films. Effect of interface diffusion on the strain and stress stability of particulate reinforced electrostrictive materials is investigated by considering the creep and stress relaxation characteristics in the electrostrictive unit cell with an elliptic particle under electric field strength E_V. When the electrostrictive matrix reinforced by particle is subjected to external loads, the creep rate and stress relaxation of the electrostrictive cell with particle is induced by diffusion mass transport in the interface layer between particle and electrostrictive cell from the sides to the poles of the elliptic particle, where the main driving force is from the gradients of normal stress, strain energy and electric potential energy along the interface between particle and electrostrictive matrix. Inevitably, the strain and stress stability of electrostrictive matrix reinforced by particle will be weakened by the diffusion effect. Relative to crystal bulk diffusion, the interface diffusion between particle and electrostrictive matrix plays a leading role. Thus the interface diffusion effect is recognized as the fundamental mechanism influencing creep and stress relaxation of electrostrictive film reinforced by particles.

2.1. Thermodynamic potential and physical relations of electrostrictive materials

Under external loads, the thermodynamic potential driving mass migration in the interface diffusion layer between particle and electrostrictive matrix is written as

$$\mu = \mu_0 - \Omega\gamma_i\kappa - \Omega\sigma_n + \Omega W \tag{1}$$

where μ_0 is a reference value of the chemical potential and is a constant for a determined material, γ_i is the interfacial energy per unit area, Ω is the atom volume, κ is the interface curvature relating to the reinforced particle morphology, σ_n is the interfacial normal stress exerted on the interface layer, and W is the strain energy density in the interface diffusion layer.

The physical relations of electrostrictive material cell are expressed as [9]

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} = \begin{bmatrix} 2\mu+\lambda & \lambda & 0 \\ \lambda & 2\mu+\lambda & 0 \\ 0 & 0 & 2\mu \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{Bmatrix} - \frac{1}{2} \begin{bmatrix} a_1+a_2 & 0 & 0 \\ 0 & a_1+a_2 & 0 \\ 0 & 0 & a_1 \end{bmatrix} \begin{Bmatrix} E_x^2 \\ E_y^2 \\ E_xE_y \end{Bmatrix} \tag{2}$$

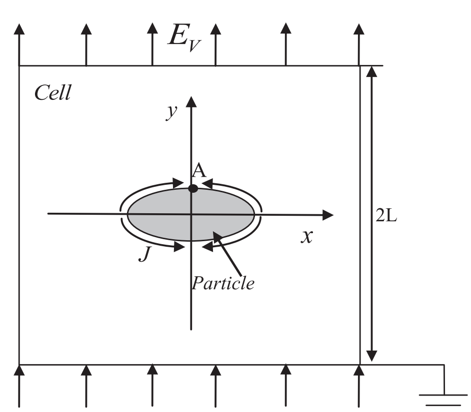

Fig. 1. The model of electrostrictive matrix doped with elliptical particle subjected to remote electric field in y direction, $E_y = E_V$.