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Modelling wave propagation through creep damaged material

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ABSTRACT

In this paper, a creep-damaged material is modelled as a two-phase composite material comprising a matrix containing a distribution of clustered spherical voids. The voids are dispersed uniformly within oblate ellipsoidal regions that represent preferred regions of voiding that can form close to grain boundaries orthogonal to the loading. In turn, the ellipsoidal regions have a preferred direction of alignment and are distributed randomly in the matrix. A double composite model based on coherent elastic wave propagation is used to determine the effective dynamic stiffness of the two-phase material. As the creep progresses, the ellipsoidal elements are sparsely scattered in the matrix, but they continue to grow in volume, containing progressively more voids within them. This evolution results in an anisotropy increase due to the preferential void formation within the ellipsoid elements and alignment of the ellipsoids. The model predicts elastic softening and the development of anisotropy, providing bulk-average information pertinent to the assessment of creep damage. The predicted velocity evolution is in satisfactory agreement with the observations of Morishita and Hirao.

1. Introduction

Problems involving the modelling of wave propagation in particulate composites are generally recognised as being impractical to solve analytically. This is because infinite orders of rescattering have to be considered along with the need to satisfy the continuity conditions for stresses and displacements across each of the scatterer boundaries when, in many cases, the exact location of each of the scatterers (with respect to some chosen origin) is unknown. Often, however, the analysis can be simplified by replacing the scattering medium by a homogeneous *effective* medium that can be characterised by appropriate choice of effective static and dynamic parameters (e.g., wavenumber, elastic moduli, density, etc.). For a low concentration of sparsely distributed scatterers, when multiple scattering effects are negligible, single scattering approaches can often be used reliably. If the dimensions of the scatterers are sufficiently small so that their resonant frequencies lie outside the frequency band of interest, then homogenisation schemes that lead to effective elastic properties of particulate composites can be used (see e.g., [1–5]). For higher concentrations of scatterers, multiple scattering approaches must be used, for example, that of Waterman and Truell [6], which accounts for the first order of rescattering, or that developed more exactly by Varadan et al. [7] in which the effective wavenumbers in the low frequency limit are obtained from simple dispersion relations.

In effect, all of these models provide a means of obtaining a set of frequency-dependent estimates of effective parameters (e.g., wavenumber, elastic moduli, density, etc.) as a function of the material properties of the constituent media, the dimensions of the scatterers and their volume fraction.

The present paper is concerned only with the modelling of elastic wave propagation through the various types of void-filled media in the low-frequency limit. An enhancement to allow modelling in higher frequency regions is the subject of on-going research. Further, since effective medium techniques are now well established for simple shaped and uniformly distributed cavities and elastic inclusions, the work concentrates on their application to modelling the multi-scale nature of creep-damaged materials. Recent reviews of the extensive literature on creep damage can be found in Maharaj et al. [8] and Sposito et al. [9]. It is widely recognised that in many engineering materials, micro-voids, created by the nucleation of cavities due to dislocations, tend to align orthogonally with respect to the direction of the applied stress [10,11], subsequently coalescing into microcracks that eventually lead to fracture [12]. During this process, the mass density and the overall (static and dynamic) elastic moduli are changed, which induces a potentially measurable decrease of the ultrasonic velocities (where the velocity depends on the propagation and polarisation directions). This paper aims to develop models to predict velocity variations as creep progresses. This link between the velocities and the morphology of the creep process can then be used to further optimisation of the *in-situ* ultrasonic measurement of creep.

The outline of the paper is as follows. Section 2 describes the creep-damage scattering model and the calculation procedure for

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effective velocities of the coherent elastic waves. The model is based on *a priori* damage morphology observed by photomicrography. As a result, a two-phase composite material comprising a distribution of clustered spherical voids in a matrix material is considered. In Section 3 the effective properties of a porous material are derived from simple dispersion relations. Accordingly, the clustered regions are modelled as homogeneous effective inclusions. A subsequent use of these material properties in the two-phase material allows the calculation of the effective velocities as shown in Section 4. A comparison between the model and the measurements from the literature is presented in Section 5.

2. Creep damage material

2.1. Preliminary observations

Photomicrographic observations of polycrystalline materials subjected to an intergranular creep process suggest that voids are often not randomly positioned [10,11,13–15]. They tend to gather preferentially on the grain boundaries orthogonal to the creep axis. The oriented growth of voids makes the material transversely isotropic about the stress axis.

The damage morphology observed by photomicrography motivates us to consider a double composite modelling that captures the non-random positions of spherical voids. A sketch of this idea is illustrated in Fig. 1. Based on these observations, the overall progression of the creep damage can be described as follows. The spherical voids nucleate and grow preferentially on the grain boundaries mostly in areas orthogonal to the applied stress direction. As the creep progresses, the voids form into clusters and the void volume fraction increases. In this paper, the clustered regions are modelled as oblate ellipsoids.

2.2. Creep damage scattering morphology

We consider creep damage in a metal to result in a two-phase double composite material comprising an isotropic matrix and spherical voids. The voids are assumed to be dispersed uniformly within oblate ellipsoidal regions (or volume elements). The volume elements are randomly distributed in the matrix. The calculation procedure with this model consists of two steps. First, spherical voids are assumed to be randomly and uniformly distributed in a matrix, as illustrated in Fig. 2. We calculate the effective stiffness and the overall density of the *porous material*. Second, the oblate ellipsoidal inclusions, whose density and stiffness are known from the previous step, are distributed randomly in the matrix with the minor axes parallel to the stress direction, and the new effective stiffness is obtained. This model allows us to determine the effective velocities of the coherent elastic waves propagating and polarised in the principal directions of the resultant transverse isotropy. The present treatment draws much on previous work by many researchers, especially of Ledbetter et al. [14] and Jeong and Kim [10]. For simplicity, we assume that the effective velocities are affected only by the creep voids and other texture effects are neglected.

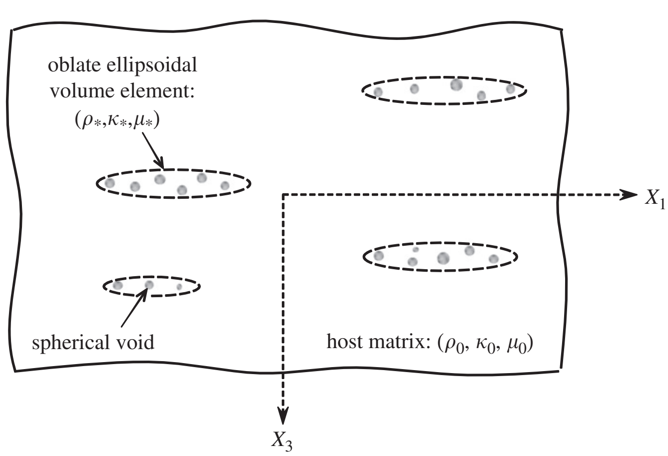

Fig. 1. Two-dimensional sketch of double composite modelling for intergranular creep process.

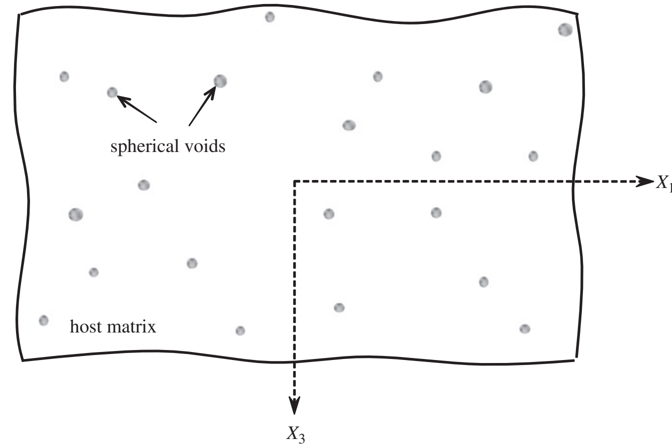

Fig. 2. Random and uniform distribution of spherical voids in a solid material.

3. Porous material

Suppose that identical spherical cavities of radius a are distributed randomly and uniformly in an isotropic homogeneous elastic solid. The volume fraction of cavities is denoted by ϕ_0. In view of the coherent elastic wave propagation with frequency ω, the given medium may be seen as isotropic homogeneous made up of some effective material. Let ρ_0, κ_0 and μ_0 denote, respectively, the mass density, the bulk modulus and the shear stiffness of the matrix material. The density ρ_*, the bulk modulus κ_* and the shear stiffness μ_* of the effective material depend on the concentration ϕ_0 and on the scattering dispersion parameter:

$$\tilde{\omega}_w = k_w a, \quad w = L,T, \tag{1}$$

where

$$k_L = \omega\sqrt{\frac{\rho_0}{\kappa_0+\frac{4}{3}\mu_0}} \text{ and } k_T = \omega\sqrt{\frac{\rho_0}{\mu_0}} \tag{2}$$

are the longitudinal and shear wavenumbers in the host material, respectively.

In the reminder of this section, we summarise the predictions of the effective wavenumbers obtained using the dispersion relations obtained in [16] and [7] for the propagation constants of a solid filled with spherical scatterers. From this, we obtain the corresponding effective medium properties.

3.1. Dispersion relations

When dealing with multiple scattering by a random distribution of cavities in a solid, one tries to evaluate the effective wavenumber γ of the ensemble-averaged scattered plane wave. The imaginary part of γ accounts for loss due to scattering in all directions, while the real part determines the velocity of the coherent wave. In general, the exact calculation of the effective wavenumber is intractable, but various approximations have been widely used. Most of them originate from the work of Foldy [17]. Here, we consider a multiple scattering theory involving