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Composites Science and Technology 66 (2006) 1409–1417

COMPOSITES SCIENCE AND TECHNOLOGY

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A flow through porous media model for pore pressure during heating of polymer–matrix composites

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Received 27 April 2005; received in revised form 14 August 2005; accepted 14 September 2005
Available online 25 October 2005

Abstract

During heating of moisture saturated polymer composites that are damaged and has an interconnected pore network, the water from the damaged composite evaporates into the interconnected pore network and induces pore vapor pressure as it escapes out of the material. The model proposed by Sullivan and Stokes [A model for the effusion of water in carbon phenolic composites. Mech Mater 1997;26:197–207] is adopted to study the evolution of pore pressure in such a composite and is applied to study the pore pressure generated in a moisture saturated plate exposed to dry air and subjected to various heating rates. It is shown that the maximum pore vapor pressure, which occurs at the center of the plate for isothermal heating conditions, depends only on two dimensionless parameters; the porosity ϕ and the normalized heating rate $\tau = \dot{T}L^2\mu(T_0)/(T_0kp_0)$, where $\dot{T}$ is the heating rate, L is the plate thickness, T_0 is the initial temperature, k is the material permeability, $\mu(T_0)$ and p_0 are the vapor viscosity and saturated vapor pressure at the initial temperature, respectively. An exact self-similar solution of the non-linear equation is obtained for the special case of rapid heating of a thick plate. This solution is useful in understanding the short time behavior of pore pressure evolution and is used to check our numerical results.

Keywords: A. Polymer–matrix composites; B. Hygrothermal effect; B. Porosity; C. Finite element analysis; Pore vapor pressure

1. Introduction

Polymer–matrix composites exposed to humid air can absorb moisture in excess of 3% by weight. Absorbed moisture can lead to failure or extensive internal damage in the form of micro-cracks, blisters and steam-induced delamination during rapid heating. Of particular relevance are graphite fiber/polyimide matrix composites. These composites represent an important class of materials for use in airframe (wings and control surfaces), cryotanks and propulsion systems as well as other secondary support structures in future space transport due to their high specific stiffness and strength properties at temperatures in excess of 300 °C. This has led to many studies on blister formation and growth in high temperature resins and composites: see Bowman et al. [1], Price et al. [2], Rice and Lee [3].

Until recently, little attention was given to micromechanical modeling of blister formation and the evolution of internal damage due to moisture transport. The phenomenological aspect of moisture induced damage can be found in the works of Loos and Springer [4]; Shirrel [5]; Whitney and Browning [6]. These authors have conducted experiments that demonstrate that internal damage occurs when the composite is exposed to moist air with high relative humidity and high ambient temperatures [4–6]. Damage occurs even at zero heating rates with no applied mechanical load. There is considerable experimental evidence that suggest that moisture transport is coupled to internal damage (Shirrel [5]), although the exact nature of this coupling has not been quantified. To model this

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doi:10.1016/j.compscitech.2005.09.004

Nomenclature

T_0, T_f	initial and final temperature, respectively
$\dot{T}$	heating rate
ϕ	volumetric porosity
ρ_{wp}, ρ_{ws}	density of water in the pore volume and solid phase, respectively
$\vec{v}_w$	velocity of water vapor through the pore network
p	pore vapor pressure
$p_w(T)$	saturation vapor pressure of water at temperature T
p_0	initial pressure
p^*, p_w^*	pore and saturation vapor pressure normalized by p_0
c_w	mass fraction of water in the mixture
k	material permeability
μ	viscosity of water vapor
L	plate thickness
τ	normalized heating rate, $\tau = \frac{\dot{T}L^2\mu(T_0)}{T_0 k p_0}$
t^*	normalized time, $t^* = \frac{tkp_0}{L^2\mu(T_0)}$

phenomenon, it is necessary to develop a model for moisture transport. An example of such an approach is given by the work of Sullivan and Stokes [7], abbreviated as SS henceforth. They modeled the damaged composite as a porous media. The flow of water vapor (assumed to be an ideal gas) is assumed to obey Darcy's law and mass conservation is used to obtain a single partial differential equation governing the evolution of pore pressure. Their approach is adopted in this work.

Recently, Hui et al. [8] studied the build up of steam pressure inside an isolated cavity in a moisture-saturated composite subjected to rapid heating by assuming that the chemical potential is continuous across the cavity/composite interface. Exact closed form solutions were obtained for the evolution of steam pressure inside a ‘‘crack-like’’ cavity under *infinitely* fast heating in a plate. Since this infinite heating rate solution provides an upper bound for the steam pressure, it may be too conservative for optimal design. Hence, the above paper was extended to study the effect of heating rate on the maximum steam pressure (Muralidharan and Hui [9]). In these works, the micromechanics of the diffusion process is studied and the model can be used to calculate the pressure developed in an isolated cavity. This could then be used to find the pressure developed in an array of non-interacting cavities in the polymer sample. The advantage of such a model is that it can be used to study damage evolution in a composite with a large number of cavities. One of the disadvantages of this model is that it is valid only in the low damage regime where the cavities are sufficiently far apart so that they do not form an interconnected pore network.

An alternate approach to study moisture diffusion in composites is to use mixture theory. A comprehensive review on the use of mixture theory to study the problem of diffusion in rubbery polymers undergoing large deformations can be found in Rajagopal [10]. Though the theory is well developed, there are many difficulties with the boundary conditions as pointed out by Rajagopal [10] and hence the theory is not widely used in practice. For fiber reinforced composites, the deformation is typically very small until the onset of failure and hence, a large deformation description is not needed. Weitsman [11] considered the general formulation for moisture diffusion under hygro-thermo-mechanical loading conditions but it is difficult to apply his theory due to the large number of material parameters needed to be determined by experiments.

The plan of this paper is as follows. In Section 2, the approach of SS is summarized. We then consider the problem of pore pressure generated during heating of a moisture-saturated plate and the corresponding normalization scheme used is given in Section 3. Section 4 considers the special case of rapid heating of a thick plate after which the numerical results are discussed in Section 5. The summary of the main results and future extensions of the present work are discussed in Section 6.

2. Problem formulation

As in SS, we consider a porous solid in which water exists in both the solid sites and in the pores as water vapor. The material is assumed to be sufficiently damaged so that the pores in the material form an interconnected network through which water vapor flows. Initially, the composite is in thermal equilibrium with its environment, which is held at temperature T_0. Without loss in generality, we assume that the composite is initially fully saturated, that is, the relative humidity inside the cavity is 100%. The composite is subjected to the following thermal history:

$$T(t) = \begin{cases} T_0 + \dot{T}t, & 0 \leqslant t \leqslant t_f, \\ T_f, & t \geqslant t_f, \end{cases} \tag{1}$$

where $\dot{T}$ is the heating rate and t_f is the time taken to reach the temperature T_f. The solid phase is also assumed rigid so that the effect of stress on moisture transport can be neglected. This assumption will slightly overestimate the rate of pressure increase in the cavity. We expect the effect of cavity deformation on moisture transport to be small, since the maximum steam pressure is on the order of 12 MPa, which is significantly less than the elastic modulus of the composite. As in SS, it is assumed that thermal equilibrium is achieved much faster than moisture equilibrium; this is a reasonable