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Material modeling of the CVI-infiltrated carbon felt I: Basic formulae, theory and numerical experiments

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Abstract

A material model for predicting the unknown elastic properties of the chemical vapor infiltrated carbon felts is proposed. Representative volume element of the studied material includes pyrolytic carbon matrix, randomly distributed carbon fibers (carbon felt) and pores. The homogenization procedure for this composite consists of two steps: (1) homogenization of material response without pores, i.e., homogenization of a media consisting of carbon fibers randomly distributed in an isotropic pyrolytic carbon matrix; (2) homogenization of material response with presence of pores, i.e., homogenization of a media consisting of three-dimensional pores embedded in the homogenized matrix from the previous step. The proposed model constitutes a theoretical basis for the numerical analysis of various carbon/carbon material systems that will be presented in the consecutive publications.

Keywords: A. Carbon–carbon composites; B. Modelling; B. Microstructure; C. Elastic properties; E. Chemical vapour infiltration (CVI)

1. Introduction

Isothermal, isobaric chemical vapor infiltration (I-CVI) is widely used to produce carbon/carbon (C/C) composites for high tech applications such as in aeronautical and space industries [1]. Understanding of the relationship between the complex microstructure of these materials (distribution of the carbon fibers and that of the pores, texture of the deposited pyrocarbon matrix [2]) and their mechanical properties is essential in order to assess their full performance potential for more advanced service applications. However, micromechanical modelling of I-CVI densified carbon/carbon composites presents several challenges. Firstly, the constituents in the composite have different length scales: the diameter of fibers used in such composites is on the order of 10 μm while some pores reach up to hundreds of microns in dimensions. Secondly, pores are of irregular shapes, and cannot be easily analysed using available elasticity solutions. And finally, the distribution of pores and the texture and, consequently, the mechanical properties of the pyrolytic carbon matrix are highly dependent on the manufacturing parameters (pressure and temperature distribution during infiltration).

To overcome these difficulties, this paper proposes a homogenization procedure which consists of two steps: (1) homogenization of material response without pores, i.e., homogenization of a media consisting of carbon fibers randomly distributed in an isotropic pyrolytic carbon matrix; (2) homogenization of material response with presence of pores, i.e., homogenization of a media consisting of three-dimensional pores embedded in the homogenized matrix from the previous step.

The paper is organized as follows. Section 2 gives more details on the CVI technology and provides typical examples of the microstructure of carbon fiber felt composites

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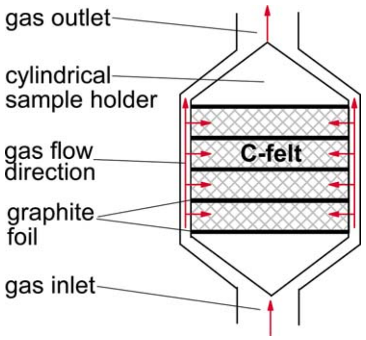

Fig. 1. Experimental setup.

(CFCs). Section 3 presents the theory of micromechanical modeling of these composites indicating all the assumptions and approximations made to obtain the closed form predictions of the effective elastic properties. The numerical simulation results for two types of CFCs are presented in Section 4. Several possible pore distributions are computer generated using a random number generator, and the influence of pore shapes on the overall properties is discussed.

2. Typical microstructures of I-CVI densified C/C composites

The investigated samples are carbon fiber felts (CCKF 1001, Sintec, Germany) with initial relative porosity of 88 vol.% infiltrated by means of the I-CVI process at a temperature of 1100 °C. The infiltration was carried out by the group of Prof. Hüttinger at the Institute for Chemical Technology of the University of Karlsruhe, Germany. Fig. 1 shows the experimental setup used. Further details on the infiltration procedure are given elsewhere [3,4].

The PAN-fibers forming the felts have a typical diameter of 12 μm and are randomly oriented (Fig. 2a). The felt infiltrated at 1095 °C, using pure methane at a total pressure of 10 kPa during 150 h is presented on Fig. 2b and felt infiltrated at 1070 °C, at 30 kPa methane pressure during 120 h is presented on Fig. 2c.

3. Material modelling

To predict the effective elastic properties of CVI CFCs we generalize the two-step homogenization procedure initially proposed in [5] for unidirectional carbon/carbon composites. We first homogenize the material consisting of pyrolytic carbon matrix with randomly distributed carbon fibers, and then account for contribution of pores as described below.

3.1. Non-interaction and Mori–Tanaka homogenization procedures for pyrolytic carbon matrix with randomly distributed fibers

Firstly, we homogenize material consisting of pyrolytic carbon matrix and randomly distributed carbon fibers. For this homogenizations step, carbon fibers are approximated by randomly oriented needle-shaped inclusions. Several micromechanical schemes have been proposed in literature to model such materials, see, for example, [6]. They differ, mostly, by how interaction between individual fibers is taken into account. However, as shown in [7], predictions of several most popular schemes can be readily obtained if the non-interaction approximation of the effective elastic properties is known. In this paper, we provide the non-interaction and Mori–Tanaka predictions of the overall material properties. The non-interaction approximation of the compliance tensor of the material is given by [7]:

$$D_{ijkl}^{\mathrm{MF}} = D_{ijkl}^{M} + \frac{f_I}{100}\left[h_1\delta_{ij}\delta_{kl} + h_2\left(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk} - \frac{2}{3}\delta_{ij}\delta_{kl}\right)\right], \tag{1}$$

where

$$h_1 = \frac{(k_M - k_I)[\mu_M(4k_I - k_M) + k_M(3k_I + \mu_I)]}{9k_I k_M^2(3k_I + \mu_I + 3\mu_M)} \text{ and}$$

$$h_2 = \frac{\mu_M - \mu_I}{5\mu_M}\left[\frac{2}{\mu_M + \mu_I} + \frac{6k_M + 8\mu_M}{3k_M\mu_I + 7\mu_I\mu_M + 3k_M\mu_M + \mu_M^2} - \frac{4\mu_I + k_I}{4\mu_I^2} + \frac{(3k_I + 4\mu_I)(k_I + \mu_I)}{4\mu_I^2(3k_i + \mu_I + 3\mu_M)}\right]$$

If the Mori–Tanaka micromechanical scheme for interacting fibers is used [8,9], then

$$D_{ijkl}^{\mathrm{MF}} = D_{ijkl}^{M} + \frac{f_I}{100}\left[h_3\delta_{ij}\delta_{kl} + h_4\left(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk} - \frac{2}{3}\delta_{ij}\delta_{kl}\right)\right], \tag{2}$$

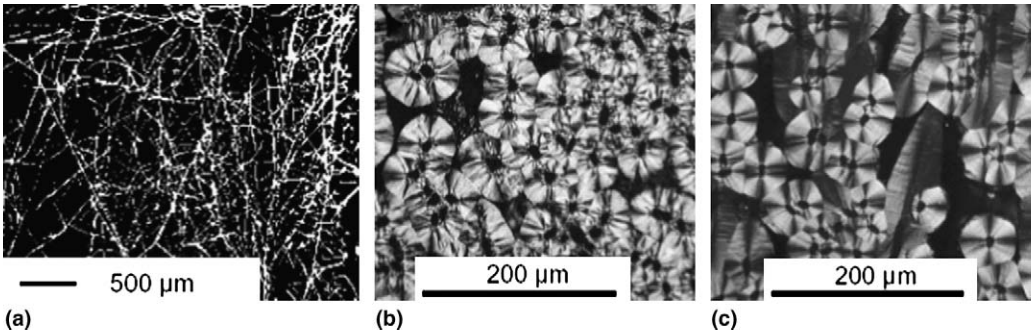

Fig. 2. (a) SEM micrograph of the carbon fiber felt as received (b) and (c) PLM micrographs of the investigated samples.