



High temperature thermomechanical behavior of silica-phenolic composite exposed to heat flux environments



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ABSTRACT

The thermomechanical behavior of polymer matrix thermoprotective material during chemical decomposition can be recognized as the coupled temperature–diffusion–deformation problem of porous elastomers under high temperatures. A coupled solution model for the problem was developed to analyze the thermal and mechanical responses of a silica-phenolic composite exposed to heat flux environments. In the model, the coupling heat-transfer process, generation of pyrolysis gases and their subsequent diffusion process and thermal deformation were taken into account. The governing equations were established and further modified using the finite element method to obtain the effective element stiffness equation for each triangular element. The decomposition degree, displacement, thermal strain and stress distribution were calculated using the coupled solution model. Additionally, a two-dimensional digital image correlation (2D DIC) method was applied to measure the high-temperature deformation and strain of each specimen. The accuracy of the model was further assessed by comparing predicted and experimental depths of heat affected zones.

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1. Introduction

Silica fiber reinforced phenolic resin matrix composites are favored in thermal protection structures of numerous vehicle and nozzles of solid rocket motor, due to their superior insulating and erosion resistant qualities [1,2]. These composites undergo thermochemical decomposition and irreversible changes of thermomechanical properties under high temperatures which adversely affect the structural integrity and reliability of the composite. Therefore, it is necessary to study the thermomechanical behavior for further research on the failure and structure design of the thermoprotective composite under high temperatures. When silica-phenolic composite is subjected to heat flux environments, the solid matrix degrades to form carbonaceous char and gaseous products which may cause internal high pore pressure. As pyrolysis reactions proceed, the porosity and permeability of the material become sufficiently large to allow the gas flow. The heat–mass transfer processes and thermal blockade phenomena are generally associated with the pyrolysis reactions of phenolic resin. In addition, the thermal expansion coefficients difference of the composite matrix and the second phase can lead to high thermal stress. In spite of their complexity and coupling, the dynamic processes have significant effect on the calculation of deformation and thermal stress field. In order to predict the

thermomechanical properties of the composite, the effects of the as-mentioned processes must be considered in the formulation of an accurate model.

The sequential methods [3–7] and fully-coupled solution methods [8–12] are generally adopted to analyze the thermomechanical behavior of composite materials. The materials were exposed to the constant temperature [5], internal heat source [8,9], heat flux [3,4,10–12] and fire [6,13–16] as boundary conditions. Sullivan et al. [8–10] proposed a finite element method to study the thermochemical decomposition of polymeric materials. A similar model was introduced by Matsuura et al. [11,12]. The numerical results of temperature and strain of silica-phenolic ablator under high heating rates showed good agreements with the data of three typical experiments, named as restrained thermal growth (RTG) tests, free thermal expansion (FTE) tests and laser heating tests. A different method was presented by Mcmanus et al. [3,4] and Wu and Katsube [5]. The average compressive stress and longitudinal strain of decomposing composites were predicted by thermochemical decomposition and thermomechanical deformation analysis. However, the fully-coupled model for polymer matrix composites (PMCs) subjected to heat flux environments which actually closer to the real service environments of materials and the high-temperature deformation measurement have been rarely reported so far.

This study developed a fully-coupled model to predict the thermomechanical behavior of silica-phenolic composites during chemical decomposition. In addition, the 2D digital image correla-

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tion (DIC) technique was used to measure the high-temperature deformation and strain.

2. Experimental procedure

2.1. Materials

The phenolic impregnated silica fiber composite (Aerospace Research Institute of Materials and Processing Technology, Beijing, China) was selected and characterized, in which the silica fibers were regularly woven within the fiber plane and the fiber plane was oriented perpendicular to the longitudinal axis of the cuboid specimens ($10 \times 10 \times 40$ mm). The geometrical model and boundary conditions are illustrated in Fig. 1. It is assumed that material in the fiber plane (y - z plane shown in Fig. 1) exhibits isotropic. The subscripts L and T indicate properties of solid phase in the fiber plane and in the perpendicular direction (x direction shown in Fig. 1), respectively. In this experiment, the radiant heat flux was applied perpendicular to the fiber plane and the surface convection constant was taken as $5 \text{ W}/(\text{m}^2 \text{ } ^\circ\text{C})$.

The basic material properties, temperature-dependent thermal and transport properties of silica-phenolic composite material are summarized in Table 1. Based on the properties of virgin and char material listed in Table 1, the properties of the solid material can be calculated as a weighted function of the degree of decomposition c of the pyrolysis reaction [1,17]. The degradation of material stiffness will occur under high temperatures. Unfortunately, there is no available material stiffness degradation data of the silica-phenolic composite on hand. Therefore, the temperature-dependent stiffness property of E-glass/vinyl ester composite in Ref. [18] was also used in this paper.

2.2. Experimental

The 2D DIC method has been widely accepted and commonly used as a powerful and flexible tool for surface deformation measurement [19]. Nevertheless, the application of DIC method in high-temperature deformation measurement is limited due to the complexity of thermal environment. In this paper, the 2D DIC technique is used to measure the high-temperature deformation and strain of silica-phenolic composite subjected to one-sided heating.

Fig. 2a represents the high-temperature deformation measurement platform. The DIC testing system (VIC-3D, American Correlated Solutions Inc., US) includes CCD camera (1624×1224 pixel), white light source and computer system to process the acquired images. A cylindrical block of ultra-high temperature ceramics (UHTCs) material was heated using oxyacetylene flame and the rear temperature profile was measured using thermocouples (Ni-Cr). Furthermore, the radiant and convective heat transfer

of the UHTCs block in the hot state could form the thermal environment, which, in turn, heated the silica-phenolic specimen. The mounted location of UHTCs block and graphite fixture is shown in Fig. 2b. To ensure the specimen surface was exposed to a radiant thermal environment, the distance between UHTCs block and specimen was set as 2 mm. The cold wall heat flux, q_{cw} , is determined as follows:

$$q_{cw} = \varepsilon \lambda T_{\text{rear}}^4 + \alpha_T (T_{\text{rear}} - T_a) \quad (1)$$

where ε is emissivity of UHTCs material and is taken as 0.8 in this paper, λ is Stefan-Boltzmann constant. T_{rear} and α_T represent the rear temperature and surface convection constant of the UHTCs block, respectively. T_a is ambient temperature. The cold wall heat flux exposing silica-phenolic specimen was calculated using measured rear temperature profile of UHTCs block and plotted in Fig. 3.

The speckle pattern of specimen surface was artificially made by spraying black and white paints before testing, as shown in Fig. 2c. An insulation slice was mounted to ensure the one-sided heating of specimen, as shown in Fig. 2d. To obtain the internal parameters of the CCD camera, a calibration process was conducted firstly. Then, the images carried the deformation information of specimen were captured each second. Finally, these images were used as input data to the computer program and further processed to obtain full-field deformations and strains of desire locations [19].

3. Formulation for the coupled temperature-diffusion-deformation problem

The thermomechanical behavior of PMCs during chemical decomposition can be recognized as the coupled temperature-diffusion-deformation (TDD) problem of porous elastomers under high temperatures. In the present study, the governing differential equations for the coupled TDD problem which involve energy conservation equation, mass conservation equation of gas phase and motion equation of solid phase were established in the plane strain state.

3.1. Energy conservation equation

The rate of decomposition of the solid material depends on temperature and activation energy, expressed by a modified Arrhenius kinetic reaction equation.

$$\frac{dc}{dt} = -A_0 c^n \exp\left(-\frac{E_a}{RT}\right) \quad (2)$$

where c is the degree of decomposition, A_0 , n and E_a obtained by the thermogravimetric analysis (TGA) are the reaction rate constant, order of reaction and activation energy, respectively. The accuracy

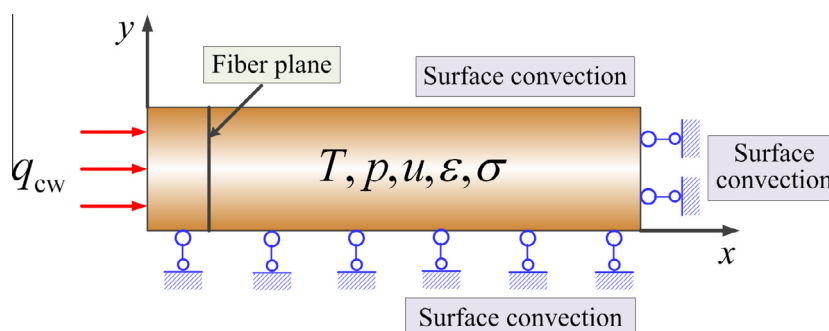


Fig. 1. The geometry model and boundary conditions.

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