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Thermal shock damage behavior of CVD ZnS by oxygen propane flame: A numerical and experimental study

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Abstract Chemical vapor deposition zinc sulfide (CVD ZnS) is widely used as an infrared window material to transmit infrared signals, keep the aerodynamic shape and protect its imaging system, which often suffers high temperature and complicated thermal stresses. The purpose of this paper is to investigate the thermal shock damage of CVD ZnS through a finite element method and oxygen propane flame experiments. The finite element model is developed to simulate the temperature and thermal stress fields by an oxygen propane flame. Then, the thermal shock experiments are performed to investigate the thermal shock damage behavior. The results show that the temperature rising rate of the shock surface is fast during the initial heating stage resulting in high thermal stress. After the thermal shock experiment, the scanning electron microscope (SEM) photographs shows that the shock surface of the specimen becomes rough and the microcracks occur in the thermal shock zone. Good agreements are achieved between the numerical solutions and the experimental results.

1. Introduction

Chemical vapor deposition zinc sulfide (CVD ZnS) is widely used as an infrared window material to transmit infrared signals, keep the aerodynamic shape and protect its imaging system, which often suffers high temperature and complicated thermal stresses. Therefore, it is very important to understand the thermal shock resistance of CVD ZnS.

The main methods to evaluate the thermal shock resistance of materials are experiment and numerical simulation. Experimental methods for determining thermal shock damage are numerous. The main experimental methods are hardening,[1–5] flame striking,[6,7] plasma arc heating,[8,9] arc-heated tunnel,[10,11] laser shocking[12] and so on. The main test facilities for thermal shock resistance are wind tunnels, but the experiments are very costly. The thermal shock tests on the ground are usually used to reduce the cost and give out a primary evaluation of the materials. The oxygen propane flame as a kind of simulation thermal shock method is extensively used due to its low cost and easy operation.

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Dai et al.[13] investigated the thermal shock resistance of Tungsten through finite element method and laser irradiation experiments and concluded that the critical power density curves could be measured to evaluate the thermal shock resistance of Tungsten. Shen et al.[14] tested the ablation of zirconium carbide (ZrC) modified carbon/carbon (C/C) composites by oxyacetylene torch and showed that the formation of zirconia form the oxidation of ZrC improved the ablation resistance of the C/C composites. Jeong et al.[15] proposed a new damage criterion to predict the thermal shock damage resistance of the brittle materials under a dynamic loading. However, there is less experimental research for the thermal shock damage of CVD ZnS.

The aim of this work is to study the thermal shock behavior of CVD ZnS. A finite element model is developed to simulate the temperature and thermal stress fields by an oxygen propane flame. A brief description of the experimental system is first given in Section 2. Numerical method and simulation conditions are described in Section 3. Numerical and experiment results are presented and discussed in Section 4. Finally, a summary of the main conclusions is given in Section 5. In addition, the thermal shock experiments are performed to investigate the thermal shock damage behavior. Temperature will be measured and microscope pictures will be observed to evaluate the damage of CVD ZnS. To compare the simulation with experimental results, the geometry of the specimen and thermal condition used in the simulation will be the same as that used in the experiment.

2. Thermal shock test

In this study, the oxygen propane thermal shock facility includes a thermal shock system and a set of temperatures detecting system (see Fig. 1). The thermal shock system includes a specimen holder made of graphite and an oxygen propane gun, and the detecting system includes an infrared thermometer used for measuring the shock surface temperature and a thermocouple employed to measure the back surface temperature during the heating process. The error scales of the thermocouple and infrared thermometer are $\pm 0.75\% T$ and $\pm 0.3\% T \pm 1$ °C (T is the measured temperature), respectively. The schematic of the CVD ZnS specimen and graphite holder in this test is shown in Fig. 2. A circular specimen ($OACD$) with radius AC (R) 10 mm and thickness OA (δ) 3 mm is set on a graphite holder ($DCEFGH$). r is the radial direction and the y axis is the symmetry axis. The inner radius AE (R_1), outer radius OH (R_2) and thickness EF (δ_1) of the graphite holder are 20 mm, 8 mm and 10 mm, respectively.

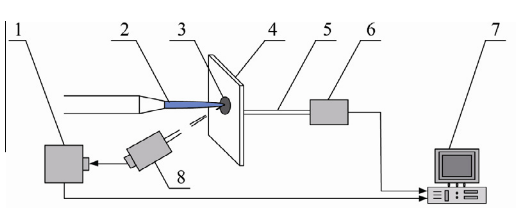

Fig. 1 Schematic of oxygen–propane experiment.

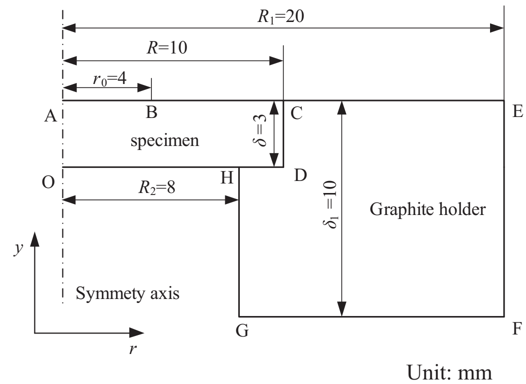

Fig. 2 Schematic of CVD ZnS specimen in thermal shock test.

The thermal shock resistance of the specimen is tested with an oxygen propane torch, and the oxygen propane flame is parallel to the axial orientation of specimen. The circle of radius AB (r_0 = 4 mm) is the central regions of flame strike. The fluxes of oxygen and propane are 2.5 m^3·h^{-1} and 1.0 m^3·h^{-1}, respectively. After calibration, the heat flux on the specimen received from the flame is 563.8 kW·m^{-2}. The inner diameter of the nozzle is 2 mm. The distance between the nozzle tip and the specimen is 300 mm. The heating process lasts 10 s.

3. Numerical simulation

3.1. Mathematical and physical model

The modeling is based on the thermal shock experiment. According to the characteristics of the problem, an axisymmetric model is used in the following simulation. The heat transfer model is presented in Fig. 3. h_0, $h_0(r)$ and h_1 are the heat transfer coefficients of the central regions of flame strike (AB), edge regions of the specimen (BC), and graphite holder and rear surface of the specimen (CE, EF, FG, GH and OH).

The temperature distribution can be extracted by solving the classical heat equation for the axisymmetric problem as[16,17]

$$\rho c \frac{\partial T}{\partial t} = \lambda_r \left(\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} \right) + \lambda_y \frac{\partial^2 T}{\partial y^2} + \frac{\partial \lambda_y}{\partial T}\left(\frac{\partial T}{\partial y}\right)^2 \quad (1)$$

where ρ is the density, kg·m^{-3}; c is the specific heat, kJ·(kg·K)$^{-1}$; T is the temperature, K; t is the time, s; λ is the thermal conductivity, W·(m·K)$^{-1}$.

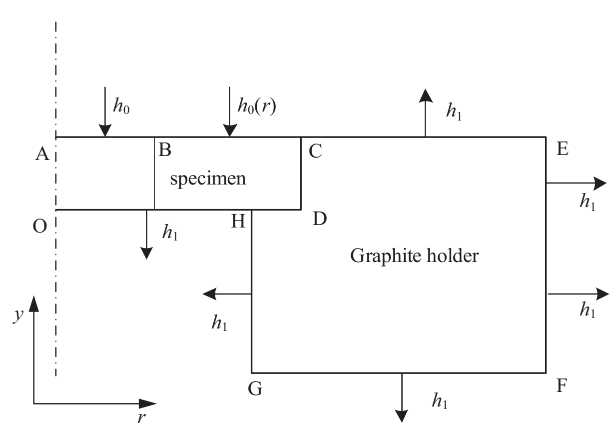

Fig. 3 Illustration of heat transfer model.