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Thermal cycling response behavior of ceramic matrix composites under load and displacement constraints

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Abstract

Thermal cycling response of a two-dimensional carbon fiber reinforced SiC matrix composite (2D C/SiC) to load constraint (LC) and to displacement constraint (DC) in an oxidizing environment was investigated. During thermal cycling between 700 and 1200 °C, a constraint strain with a 0.208% range and a constraint stress with a 180 MPa range were, respectively, generated on the composites in LC and DC. It was found that with increasing cycles, the constraint strain increased in LC and the constraint stress decreased in DC. After 50 cycles, in contrast to the as-received composite materials, the as-cycled composites suffered greater loss in mechanical properties: the residual strength and failure strain are 204 MPa and 0.49% for the LC tested samples, and 223 MPa and 0.64% for the DC tested samples, respectively. Microstructural observations indicated that the LC could develop thermal microcracks and assist in oxidizing the internal fibers, whereas the DC reduced crack propagations and fiber oxidation because of decreasing tensile and increasing compressive stresses.

Keywords: Carbon fiber; Ceramic matrix composites; Thermal cycling; Constraints; Microstructure

1. Introduction

Among the first applications under consideration for fiber reinforced ceramic matrix composites (CMCs) are components for aerospace shuttles and jet engines which will be subject to high temperatures and temperature gradients but low mechanical loads [1]. On the one hand, the large difference in coefficient of thermal expansion (CTE) between the matrix and reinforcement gives rise to internal stresses, which can stimulate various stress relaxation phenomena leading to mechanical degradation and irreversible dimensional changes [2–3]. Therefore, there is considerable interest in the investigation of thermal shock/cycling behavior of CMCs in order to understand their behavior in the temperature variation environments with free expansion, and a large number of such studies are reported in the literature [4–8]. On the other hand, the thermal expansion property of the composites plays an important role in determining the macro-thermal strain or thermal stress where the rigid constraints are applied. There are two kinds of significant constraints in the engineering fields: one is load constraint (LC) and the other is displacement constraint (DC). The tight connection between the constraint types and thermal expansion behaviors motivates the study in this paper.

Earlier work on this general problem was mainly devoted to studies of thermal cycling response of metals and their composites (MMCs) by using either a dilatometry technique or a strain/stress-controlled method [9,10]. In this regard, Chawla and co-workers have an initial attempt to experimentally obtain the constraint thermal strain and stress curves of fiber reinforced MMCs at lower temperatures (below 500 °C). Recently, studies by Mei et al. [11,12] have demonstrated some preliminary efforts to investigate the influence of the constraint conditions on the damage behaviors of a CMC material (C/SiC) during thermal cycles. Nevertheless, no more detailed description and/or comprehensive comparison involving thermal cycling response of the CMCs in constraints can be found in recent literature. Thermal cycling is a complex phenomenon requiring further research efforts. The results obtained so far are not possible and enough to provide a complete general interpretation for damage mechanism and process resulting from the constrained thermal cycling.

The work reported in this paper is part of a larger effort aimed at comprehensive understanding thermal cycling response mechanisms of a typical CMC (i.e., 2D C/SiC) when subjected,

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respectively, to load and displacement constraints in oxidizing atmosphere. Under the above two constraints, the experimentally observed macro-response results, i.e., constraint strain and constraint stress, were presented and then systematically analyzed and compared. Residual mechanical properties of the composites after 50 cycles were characterized and the fractured surfaces were observed.

2. Experimental procedures

As described in [13], the same isothermal CVI process was employed to fabricate the 2D C/SiC composites at ∼1000 °C, whose preforms were laminated with the 1K T-300 carbon fiber fabrics ([0°/90°], see Fig. 1a in [13]). The virgin properties of the as-received dog-bone samples were listed in Table 1 in [13]. Thermal cycling experiments were conducted in an oxygen/argon mixture of 10 vol.% O_2/90 vol.% Ar using a newly developed integrated system, which was described in detail in Fig. 2 of [14]. Thermal cycling was carried out between temperatures of $T_{lower} \approx 700$ °C and $T_{upper} \approx 1200$ °C over a period of 210 s, whose temperature range ΔT was about 500 °C. The LC tests involved free expansion of the sample with a constant stress of 100 MPa during thermal cycles. The strain induced by the thermal expansion of the material was measured by a contact extensometer (model A1452-1001B). The DC tests involved cycling the temperature of the sample while the sample positions were kept constant, i.e., *position-controlled* mode. The constraint stress produced was recorded directly by Instron tester. After 50 cycles, both LC and DC tests were terminated to obtain residual strengths of the samples by the tension tests with a loading rate of 0.001 mm/s. Microstructures were observed with a scanning electron microscope (SEM, Hitachi S-4700).

3. Results and discussion

3.1. Thermal cycling response curves

Fig. 1 presents response curves of 2D C/SiC composites to thermal cycling in LC (Fig. 1a) and DC (Fig. 1b). Fig. 1c and d are their close-up observations within several cycles from Nos. 28th to 31th. In Fig. 1a, the effects of the initial thermal expansion and mechanical strain on the response curves were eliminated by first holding the temperature at 700 °C for 2 min and then loading the sample to 100 MPa and rezeroing the extensometer. Thus, the constraint strain curves obtained in this test were slightly different from that illustrated in Fig. 4a in [11].

In the presence of LC (fixed stress), as shown in Fig. 1a, the constraint strain could be obtained automatically. It was apparent that the measured strain was cycled with the cyclic temperatures on a progressively increasing baseline strain, which is termed Thermal Cycle Creep (TCC) strain [14]. It was believed that the increase in TCC strain resulted from damage accumulation of the 2D C/SiC composites during thermal cycles in the terms of matrix cracking induced by thermal stress and of reduced

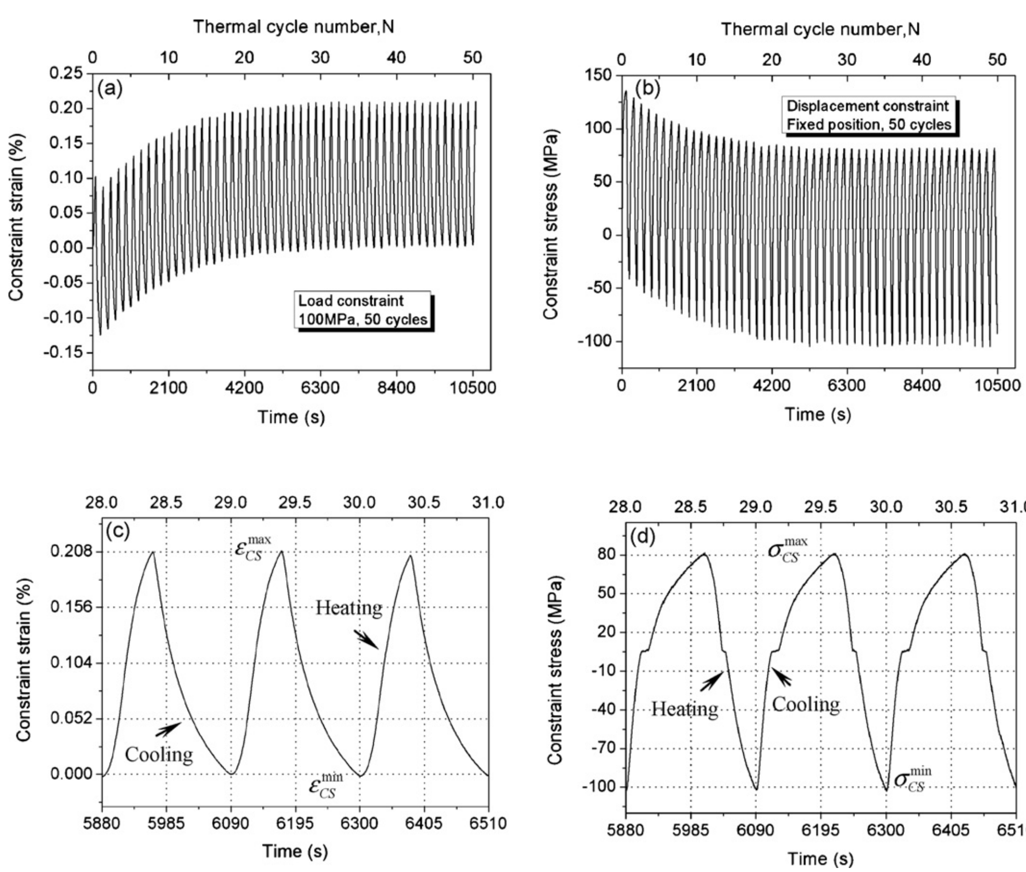

Fig. 1. Response curves of 2D C/SiC composites to thermal cycling in (a) load constraint and (b) displacement constraint. (c and d) Their close-up observations within several thermal cycles.