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Life Limiting Phenomenon and Modeling of CMC in Interlaminar Shear at Elevated Temperatures

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Summary

Life limiting phenomenon in interlaminar shear was determined in stress rupture at 1316 °C in air for a mi sic/sic ceramic matrix composite. The results were described using a power-law type of crack growth model in mode II. The model was verified by additional life prediction test data obtained under a time-varying loading configuration.

Introduction

Most of efforts regarding the assessments of life limiting properties of ceramic matrix composites (CMCs) have been made for in-plane direction. Few studies have been done on the issue of life limiting of CMCs in interlaminar shear at elevated temperatures. In a previous study [1], life limiting properties of a cross-plied glass ceramic composite (Hi-Nicalon™ SiC fiber-reinforced barium strontium aluminosilicate matrix composite, SiC/BSAS) were evaluated in shear at 1100 °C in air by using double-notch shear test specimens subjected to constant shear stress-rate loading. The life limiting phenomenon in shear was modeled using a power-law, SCG process of a crack situated at fiber-matrix interfaces. This model has been applied to other CMCs such as SiC/SiCs, SiC/MAS (magnesium aluminosilicate), and C/SiC [2].

This paper describes the life limiting phenomenon of a commercial, gas-turbine grade, melt-infiltrated (MI) Hi-Nicalon™ SiC fiber-reinforced SiC ceramic matrix composite (designated Hi-Nic SiC/SiC) in interlaminar shear at 1316 °C in air. Life limiting phenomenon of the composite was analyzed using a power-law type of phenomenological life prediction model [1,2].

Experimental Procedures

Material

A 2-D woven Hi-Nicalon™ SiC fiber-reinforced SiC ceramic matrix composite (Hi-Nic SiC/SiC), fabricated by GE Power System Composites (Newark, DL; vintage '02), was used in this work. Detailed descriptions of the composite and its processing can be found elsewhere [3]. Briefly, Hi-Nic SiC fibers, produced in tow, were woven into 2-D 5 harness-satin cloth. The cloth preforms were cut into 200 mm x 150 mm, 8 ply-stacked, and chemically vapor infiltrated (CVI) with a thin BN-based interface coating followed by SiC matrix over-coating. Remaining matrix porosity was filled with SiC particulates and then with molten silicon at 1400 °C, a process termed slurry casting and melt infiltration (MI). The MI SiC/SiC

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composite was composed of about 39 vol% fibers. The nominal dimensions of the composite panels fabricated were about 200 mm by 150 mm with a thickness of about 2.0 mm.

Stress rupture testing

Stress rupture testing for the Hi-Nic SiC/SiC composite was conducted in interlaminar shear at 1316 °C in air. The double-notch-shear (DNS) test specimens were machined from the composite panels. Test specimens were 12.7 mm wide (W) and 30 mm long (L). The thickness of test specimens corresponded to the nominal thickness (=2 mm) of the composite. Two notches, 0.3 mm wide (h) and 6 mm (L_n) away from each other, were made into each test specimen such that the two notches were extended to the middle of the specimen so that shear failure occurred on the plane between the notch tips. Test fixtures were all made of α-SiC. A specially designed, tubular type of anti-buckling guides was also used. A total of 22 test specimens were tested over a total of five different levels of applied shear stresses ranging from 8 to 17.8 MPa. Test specimen configurations were followed in accordance with ASTM C 1425 [4]. Testing was carried out using an electromechanical test frame (Model 8562, Instron, Canton, MA). Interlaminar shear stress, i.e., the average nominal shear stress, was calculated using the following relation

$$\tau = \frac{P}{WL_n} \tag{1}$$

where τ is the applied shear stress, P is the applied load in compression, and W and L_n are the specimen width and the distance between the two notches, respectively.

Constant shear stress-rate testing

Additional interlaminar shear testing was also conducted using constant shear stress-rate testing. Each test specimen was subjected to a given applied shear stress-rate until it failed. A total of three different shear stress rates ranging from 5 to 0.005 MPa/s were employed with a total of five specimens tested at each applied shear stress rate. Test fixtures, test temperature, test specimen configuration, and test frame were the same as those used in stress rupture testing. The purpose of this supplementary testing was to determine life limiting behavior in constant stress-rate loading and to compare it with that in stress rupture, with which the phenomenological life prediction model can be validated. Applied shear stress rate ($\dot{\tau}$) was calculated using the relation

$$\dot{\tau} = \frac{d\tau}{dt} = \frac{\dot{P}}{WL_n} \tag{2}$$

where $\dot{P}$ is the applied load rate in compression, employed directly to test specimens via a test frame in load control.

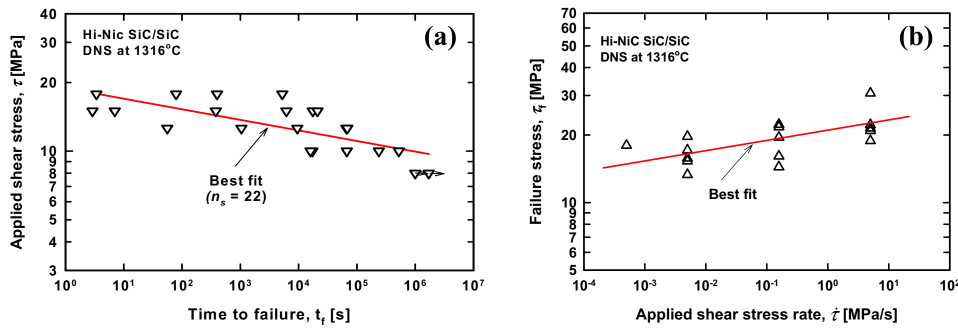

Figure 1: Results of (a) stress rupture testing and (b) constant stress-rate testing for Hi-Nic SiC/SiC composite in interlaminar shear (double notch shear, DNS) at 1316 °C in air. The solid lines represent the best fit.

Results and Discussion

Stress rupture

All specimens tested in stress rupture at 1316 °C failed in typical shear mode along their respective interlaminar shear planes. The results of stress rupture testing are presented in Figure 1(a), where time to failure was plotted as a function of applied shear stress. The data show an evidence of life limiting phenomenon, where time to failure decreased with increasing applied shear stress rate. The solid line represents the best-fit based on the log (*time to failure*) vs. log (*applied interlaminar shear stress*) relation, which will be discussed later. A relatively large scatter in time to failure is noted, similar to the feature shown in many CMCs and advanced monolithic ceramics subjected to stress rupture or cyclic fatigue in tension or flexure at ambient or elevated temperatures.

Constant stress-rate test

Without exception, all specimens tested in constant stress-rate loading failed via interlaminar shear. The results of constant stress-rate testing are presented in Figure 1(b), where interlaminar shear strength was plotted as a function of applied shear stress rate in a log-log scheme. The solid line represents the best fit. Despite some scatter in the data, the overall interlaminar shear strength decreased with decreasing applied shear stress rates. This phenomenon of strength degradation with decreasing test rate, often called slow crack growth or dynamic fatigue when referred to monolithic brittle materials in tension or flexure [5,6], is an evidence of slow crack growth or damage accumulation occurring at the fiber-matrix interfaces along a respective shear plane under loading. This type of life limiting behavior, associated with strength degradation in interlaminar shear at elevated tempeartures, was also observed for other CMCs including SiC/SiCs, SiC/MAS, C/SiC, and SiC/BSAS [1,2]. These will be discussed separately at the presentation. Based on the results of Figure 1, it can be stated that life limiting behavior of the composite took place in interlaminar shear, either in constant loading (stress rupture) or in time varying loading (constant stress rate).

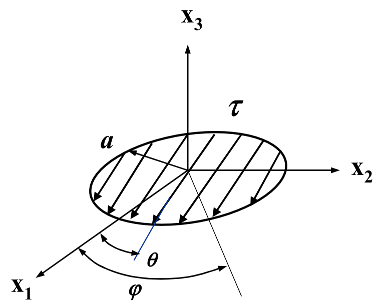

Figure 2: An assumed penny-shaped crack arbitrarily located at fiber-matrix interfaces in ceramic matrix composites, subjected to equal and opposite interlaminar shear stresses τ acting on both surfaces of a crack.

Assessment of life limiting parameters in stress rupture

A phenomenological slow crack growth (SCG) model proposed previously [1,2] will be applied to the stress rupture data determined for the Hi-Nic SiC/SiC composite. The proposed life model in mode II is similar in expression to the power-law relation in mode I loading and takes the following, empirical formulation

$$v_s = \frac{da}{dt} = \alpha_s (K_{II}/K_{IIc})^{n_s} \tag{3}$$

where v_s, a, t, K_{II}, and K_{IIc} are crack-growth rate in interlaminar shear, crack size, time, mode II stress intensity factor, and mode II fracture toughness, respectively. α_s and n_s are life limiting parameters in interlaminar shear.

The generalized expression of K_{II} along the crack front of a penny- or half-penny shaped crack subjected to shear loading either on crack planes or on remote material body (Figure 2) is [7]

$$K_{II} = Y_s \tau a^{1/2} f(\theta, \varphi) \tag{4}$$

where Y_s is a crack geometry factor related to a function of $f(\theta,\ \varphi)$ with the angles θ and φ being related to load and a particular point of the crack front, see Figure 2. Using Eqs. (3) and (4) together with some mathematical manipulations, one can obtain time to failure (t_f) as a function of applied shear stress, as done for brittle materials in mode I loading [8]

$$t_f = D_s[\tau]^{-n_s} \tag{5}$$

where

$$D_s = B_s[\tau_i]^{n_s-2} \tag{6}$$

where $B_s = 2K_{IIc}\left[\alpha_s[Y_s f(\theta,\varphi)]^2(n_s-2)\right]$ and τ_i is the inert shear strength. The geometry function may be simplified as $f(\theta,\varphi) = 1$ in the case of double-notch shear loading for an infinite material body. Equation (5) can be expressed in a convenient form by taking logarithms of both sides

$$\log t_f = -n_s \log\tau + \log D_s \tag{7}$$

Life limiting parameters n_s and D_s in interlaminar shear can be determined based on Eq. (7), respectively, from the slope and the intercept of a linear regression analysis of the log (*individual time to failure with unit of second*) vs. log (*individual applied interlaminar shear stress with units of MPa*) data, Figure 1(a):

$$n_s = 21.5 \text{ and } \log D_s = 27.5$$

with the coefficient of correlation of curve fit of r_{coef} = 0.7303. The best fit was indicated as a solid line in the figure. As seen from the figure, statistically good agreement exists between the model and the data, although the data scatter in time to failure was in a few orders of magnitude, which is typical of most brittle materials in stress rupture or in cyclic fatigue.

Verification

The proposed crack growth formulation, Eq. (3), indicates that for a given material/environmental condition, crack velocity depends on K_{II} so that in principle the life limiting parameters can be determined in any loading configuration which is either static, cyclic, or any time varying. Therefore, it should be possible to make a life prediction from one loading configuration to another provided that the same failure mechanism is operative. In this section, the life limiting parameters that were determined in stress rupture will be used to predict the strength degradation behavior in constant stress-rate loading and to thus validate the proposed crack growth model. Using Eqs. (5) and (6) with some mathematical stipulations, a relationship between interlaminar shear strength (τ_f) and applied shear stress rate ($\dot{\tau}$) can be derived as follows:

$$\tau_f = D_d[\dot{\tau}]^{\frac{1}{n_s+1}} \tag{8}$$

where

$$D_d = [D_s(n_s+1)]^{\frac{1}{n_s+1}} \tag{9}$$

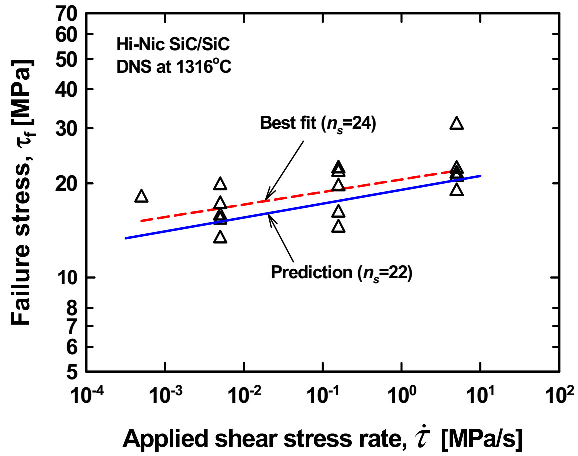

Figure 3: Comparison in interlaminar shear strength between the predicted and the actual data for Hi-Nic SiC/SiC composite in interlaminar shear tested at 1316 °C in air.

The resulting prediction of interlaminar shear strength, based on Eq. (8) with the estimated parameters n_s and D_s, is presented as a solid line (in log-log scheme) in Figure 3. Despite some scatters in shear strength, the prediction was in good agreement with the best fit of the experimental data. The discrepancy in shear strength between the prediction and the data was only 6 to 9 %. Particularly, the life limiting parameter of $n_s = 22$ estimated from stress rupture was in excellent agreement with $n_s = 24$ that was evaluated from the constant stress-rate data by a regression analysis of $\log(\tau_f)$-vs.-$\log(\dot{\tau})$. The parameter D_d was also in good agreement with log D_d=27.5 and 31.4, estimated from the stress rupture and the constant stress-rate data, respectively. Statistically, the prediction made above represents a failure probability of approximately 50 %. Of course, different levels of failure probability in shear strength can be made if reliable Weibull strength data are available.

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