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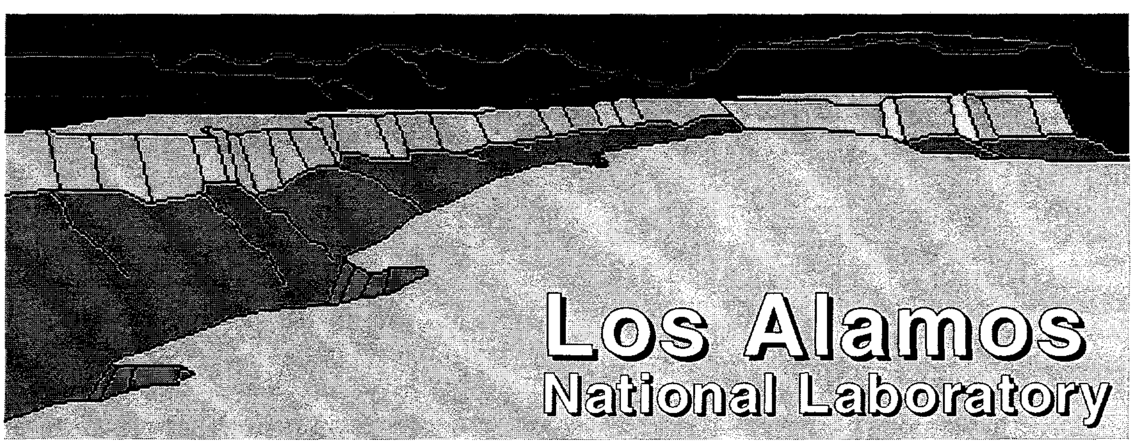

Some New Perspectives on the Strength and Fracture of Nicalon Fibers

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Introduction

Nicalon™ SiC fibers are attractive reinforcing materials for high-temperature structural composites due to their high strength, high stiffness, and excellent resistance to oxidation. These fibers are processed via melt-spinning techniques which have been shown to yield a broad distribution of fiber diameters within a given tow of fibers.[1-4] Previous studies characterizing the mechanical response of Nicalon fibers have identified a volume-based dependence of strength [2-4], but have failed to examine the effects of varying fiber diameter on the fracture behavior and the statistical strength distribution of the fibers. This study seeks to identify those effects by recourse to extensive fractographic analysis performed on individual Nicalon fibers, ranging in diameter from 8 to 22 μm, which have been fractured under tensile loading.

Experimental

Individual fibers of 10, 25 and 50mm gauge lengths were fractured in mineral oil to permit recovery of the fractured ends for evaluation on a SEM. Maximum load to failure was recorded, and tensile strength was calculated using fiber area from diameter measurements made on fractured samples. Fractographic studies included analysis of mirror size, critical flaw size, and relative flaw location (defined as the distance of the critical flaw from the fiber center divided by the fiber radius), when possible, on all fractured fibers.

Results and Discussion

Nicalon fibers fracture in a brittle fashion and therefore can be described by the classic Griffith-Orowan-Irwin relation

$$\sigma_f \sqrt{a_c}\, Y = K_{1c} \qquad (1)$$

where σ_f is the fracture strength, a_c is the critical flaw size, Y is the geometry factor and K_{1c} is the apparent fracture toughness of the material. Y is dependent on the specimen configuration and the critical flaw size and location, and can be characterized as a function of the flaw-to-fiber-size ratio (a_c/r) and the flaw location (ρ): $Y \equiv f[a_c/r, \rho]$. A linear relationship exists between critical flaw size and fracture mirror radius (r_m) for Nicalon fibers [4], so that Eq. 1 can be rewritten as

$$\sigma_f \sqrt{r_m}\, Y' = K_{1c} \qquad (2)$$

where Y′ is now a function of r_m/r and ρ.

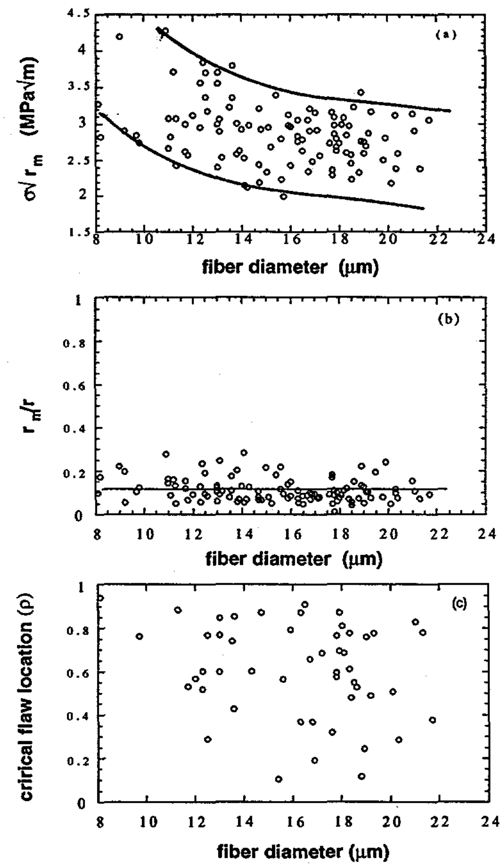

Figure 1. Plots of (a) mirror constant, (b) mirror-to-fiber size ratio, and (c) critical flaw location versus fiber diameter.

Figure 1a is a plot of $\sigma_f \sqrt{r_m}$ (also known as the mirror constant, A_m) versus fiber diameter, showing a modest trend for A_m to decrease with increasing diameter. Figure 1b is a plot of r_m/r versus fiber diameter showing this ratio essentially remains constant with changing diameter. In Figure 1c, the critical flaw location (ρ) is seen to be randomly distributed with fiber diameter. Figures 1b and 1c suggest that Y′ is effectively constant with diameter in this study. Thus, observing the trends in Figure 1, and invoking the relationship in Eq. 2, the apparent fiber fracture toughness appears to increase with decreasing fiber diameter.

The large scatter observed in Figure 1a likely stems from an inability to account for different flaw populations, variations in critical flaw location, and varying fiber gauge lengths in the data, all of which can affect mirror constant values. Similarly, the scatter observed in Figure 1b is attributed to the fact that flaws do not occupy a fixed location, nor do they conform to a fixed geometry. Furthermore, deviations from circular cross-sections in the Nicalon fibers result in a variety of different effective specimen geometries which further contribute to the scatter observed in Figures 1a and 1b.

Flaw location is also observed to play a prominent role in the fracture of individual fibers, as it can influence Y′ values, and consequently tensile strength values, as shown in Figure 2.

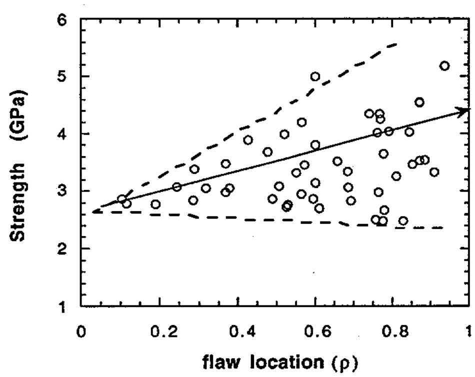

Figure 2. Strength versus critical flaw location.

Strength and strength variation are both seen to increase as the critical flaw location moves further away from the fiber center (ρ=0). The variation in strength is due to competing flaw populations which are observed to co-exist closer to the fiber surface (ρ=1), causing significant variation in the strength values in this region. Near the fiber center, however, only one type of flaw (individual pore) has been observed to cause fracture, and therefore strength values tend to be more consistent at low (<0.2) values of ρ.

Strength Characterization

The Weibull distribution, which is often used to characterize the statistical strength of ceramic fibers, is invalid for characterizing the strength of fibers over a broad range of diameters since it does not take into account the variation of K_{Ic} with varying diameter and the possible variation of flaw density with varying diameter. A modified Weibull distribution has been recently proposed for characterizing ceramic fibers with varying diameters [5]:

$$F(\sigma) = 1 - \exp\left(-\alpha\sigma^{\beta} L d^{n}\right) \qquad (3)$$

where α, β and n are constant, and L and d are fiber length and diameter, respectively. The average fiber strength can be described as: [5]

$$\bar{\sigma} = \alpha^{-1/\beta}\Gamma(1+1/\beta)L^{-1/\beta}d^{-n/\beta} \qquad (4)$$

α, β and n can be obtained by fitting the experimental data into Eq. 4 and the following equation.

$$\ln\ln\frac{1}{1-F(\sigma)} - \ln Ld^{h} = \ln\alpha + \beta\ln\sigma \qquad (5)$$

A value of n of 3.875 is obtained from fitting the experimental data for Nicalon fibers, while the β value is found to be 6.7 (see Fig. 3).

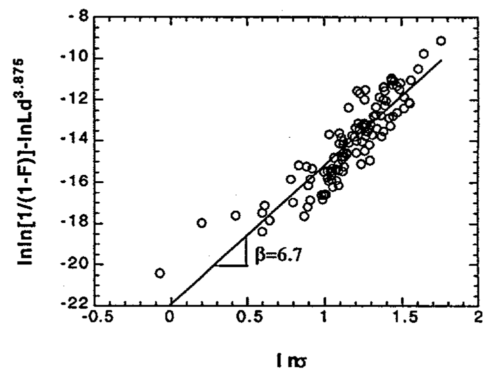

Figure 3. Fitting of Eq. 5 to experimental data.

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