Chapter

Multiple Matrix Cracking of Fiber-Reinforced Ceramic-Matrix Composites during Operation

Chengzheng Zhu

Abstract

In the field of civil aviation, the most important factor is safety quality. Improving aircraft performance can increase flight safety factor in some degree. To improve the thrust-to-weight ratio of aircraft engines and reduce fuel consumption, the fundamental measure is to increase the turbine inlet temperature of engines, while hot-section components is directly related to the maximum allowable operating temperature. Ceramic-matrix composite (CMC) material is one of the important candidate materials for aeroengine. To improve CMCs in aircraft engine application, it is necessary to investigate the failure mechanism of CMCs and also failure models. However, during operation, matrix multiple cracking occurs with fiber debonding and fracture, which affects the flight safety and failure risk. In this chapter, the multiple matrix cracking of fiber-reinforced CMCs is investigated using energy balance approach.

Keywords: ceramic-matrix composites (CMCs), failure mechanism, matrix cracking, evolution, energy balance approach

1. Introduction

Ceramic matrix composites (CMCs) have high specific stiffness, specific strength, high temperature resistance, corrosion resistance and other excellent properties [1–6]. However, CMCs also have inherent weaknesses. Due to the low failure strain of the matrix, cracking of the matrix occurs before the failure of the fiber. Matrix multiple cracking affects the reliability and safety of CMCs during operation. In this chapter, based on the failure model of CMCs, the matrix cracking problem CMCs is investigated.

2. The matrix cracking of unidirectional CMCs

A partial fiber/matrix interface debonding model is used in this chapter. The problem of multiple cracking of unidirectional brittle composites was first analyzed by Aveston [7]. The fiber and matrix are simulated as concentric cylinders with radius r_o and R respectively. The composite material consists of a series of repeating units connected by the fiber, as shown in **Figure 1**. When matrix cracking occurs, the interfacial shear stress tends to concentrate near the matrix crack, which may lead to fiber/matrix debonding in these areas. Crack spacing is denoted by L and

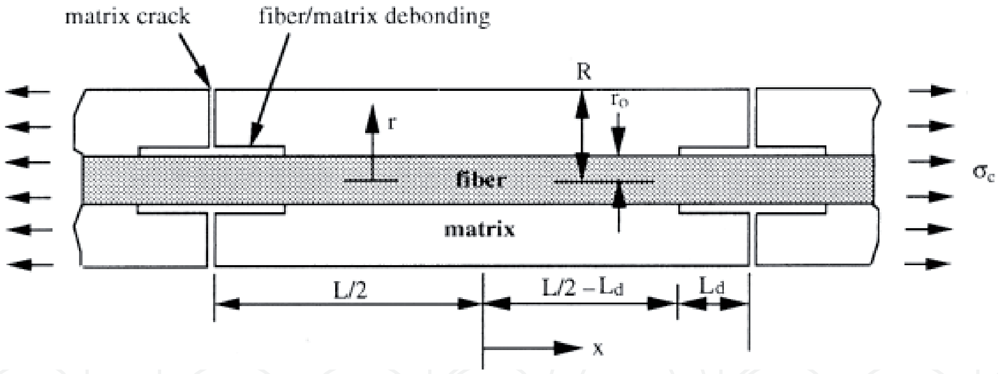

Figure 1.
Partial interfacial debonding model for unidirectional composites.

stripping length by L_d.X represents the displacement of the center of the composite. By changing L and L_d, the model can include: (1) complete bonding, (2) partial debonding/sliding, and (3) complete debonding/sliding. Because the fiber failure strain in most ceramic matrix composites is much higher than that in matrix, it is assumed that the fiber is intact during matrix cracking.

By using the energy method, the critical stress of matrix cracking is determined considering the energy balance between the undamaged state and the cracked state. The energy terms involved in the generation of matrix crack include matrix surface energy, fiber/matrix debonding energy, energy consumed by friction fiber sliding, strain energy change and work done by external load. According to the shear-lag model, the stress distribution of the fiber, the matrix and the interface before and after crack propagation was obtained, and the initial cracking stress of the matrix was obtained by combining with the energy balance equation. When matrix cracking and interface debonding occur, the composite strain is,

$$\varepsilon_c = \begin{cases} \dfrac{\sigma}{V_f E_f}\eta - \dfrac{\tau_i}{E_f}\dfrac{l_d}{r_f}\eta + \dfrac{\sigma_{fo}}{E_f}(1-\eta) - \dfrac{2}{\rho E_f}\left(\dfrac{V_m}{V_f}\dfrac{r_f}{l_c}\sigma_{mo} - \eta\tau_i\right) \\ \times\left[\exp\left(-\dfrac{\rho}{2}\dfrac{l_c}{r_f}(1-\eta)\right)-1\right] - (\alpha_c - \alpha_f)\Delta T, \eta < 1 \\ \dfrac{\sigma}{V_f E_f} - \dfrac{1}{2}\dfrac{\tau_i}{E_f}\dfrac{l_c}{r_f} - (\alpha_c - \alpha_f)\Delta T, \eta = 1 \end{cases} \quad (1)$$

where V_f is the fiber volume, V_m is the matrix volume, E_f is the fiber elastic modulus, η is the interface debonding ratio, τ_i is the interface shear stress, r_f is the fiber radius, l_c is the matrix crack spacing.

The composite tangent modulus is defined as:

$$E_p = \frac{d\sigma}{d\varepsilon} \quad (2)$$

Figure 2 shows the evolution of the composite tangent modulus versus the composite strain for different matrix crack spacing. The initial composite tangent modulus is about 310 GPa, with increasing composite strain, the tangent modulus decreases rapidly during the stage of matrix cracking and interface debonding, and slowly at the stage of the fiber failure.

Figure 3 shows the evolution of the composite tangent modulus versus the composite strain for different fiber volume. When the fiber volume increases, the composite tangent modulus increases.

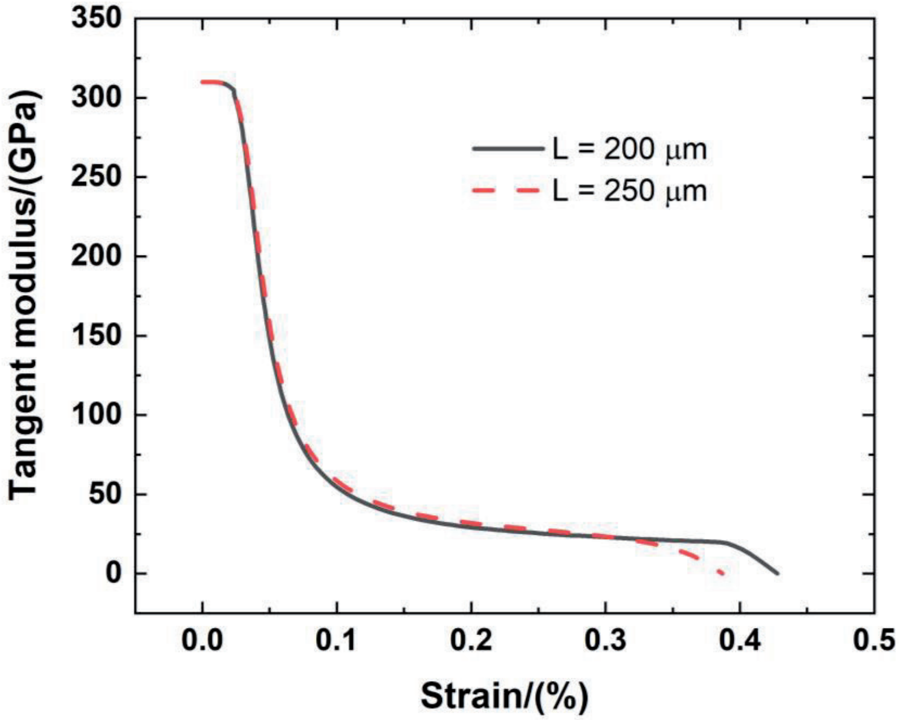

Figure 2.
The tangent modulus versus composite strain of C/SiC composite for different matrix crack spacing.

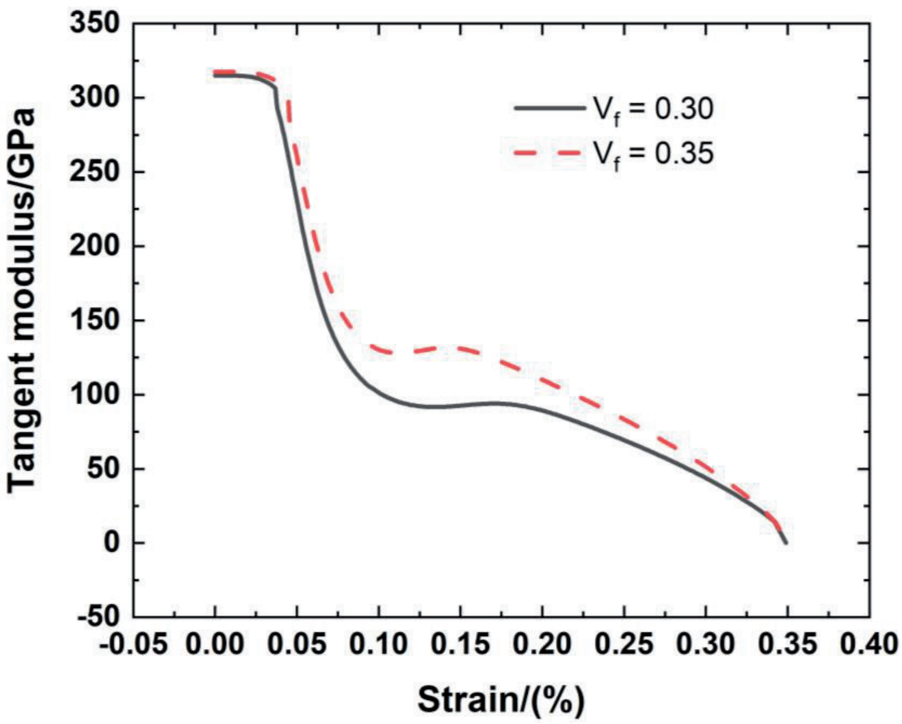

Figure 3.
The tangent modulus versus composite strain of C/SiC composite for different fiber volume.

3. Results and discussion

In this section, the effect of interface shear stress and interface debonding energy on the evolution of the matrix cracking is analyzed. **Figure 4** shows the effect of interface shear stress on the matrix cracking evolution of CMCs with the interface shear stress of τ_i = 25, 30 MPa. When the interface shear stress increases, the first matrix cracking stress increases, and the saturation matrix cracking stress also increases, however, the saturation matrix cracking density may decrease. **Figure 5**

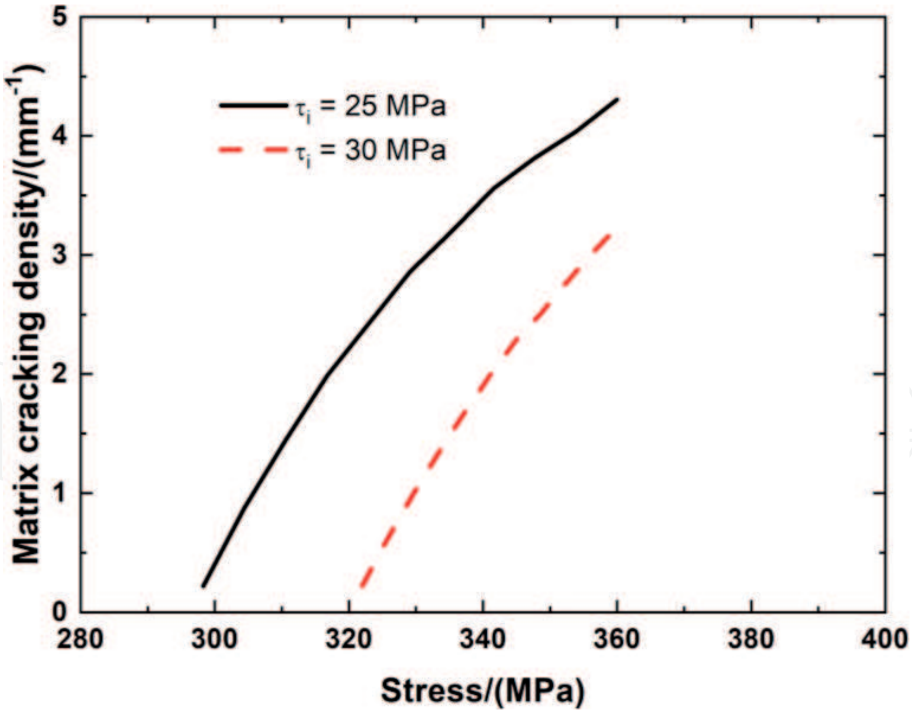

Figure 4.
The matrix cracking evolution of CMCs with different interface shear stress.

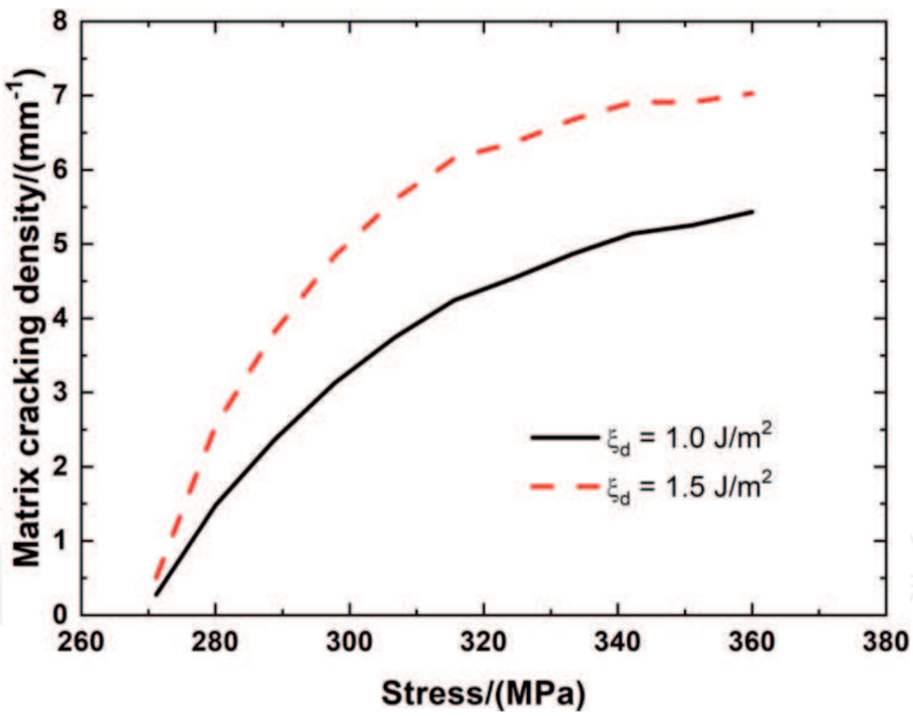

Figure 5.
The matrix cracking evolution of CMCs with different interface debonding energy.

shows the effect of interface debonding energy on the matrix cracking evolution of CMCs with the interface debonding energy of 1.0 and 1.5 J/m^2. When the interface debonding energy increases, the saturation matrix cracking density increases.

4. Experimental comparisons

Based on the energy balance approach, the experimental and predicted matrix cracking density of SiC/SiC composite is shown in **Figure 6**. When the applied

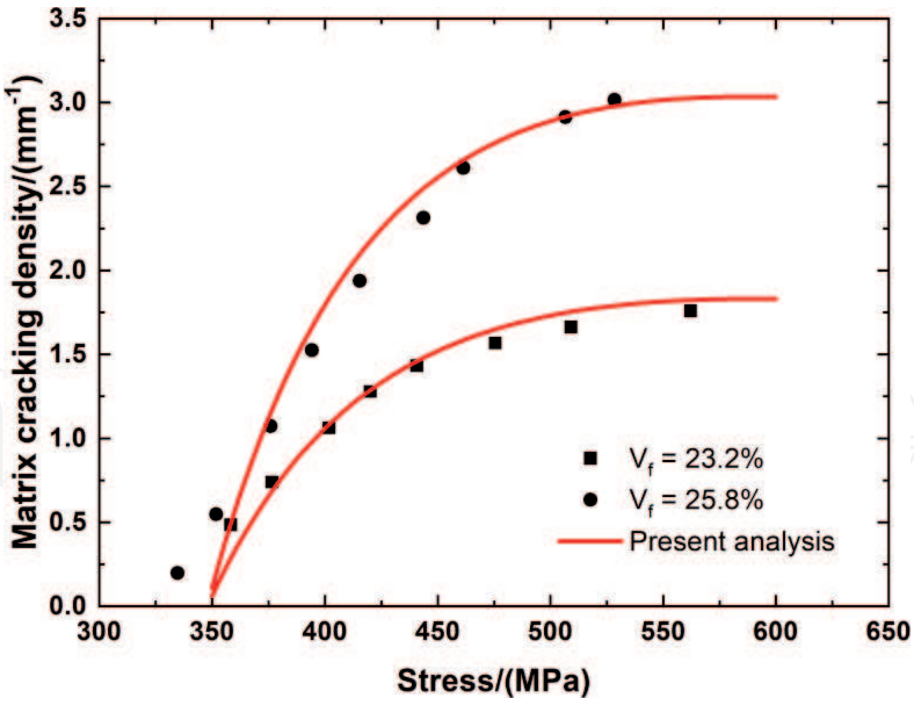

Figure 6.
Experimental and predicted matrix cracking density versus the applied stress curves of SiC/SiC composite.

stress increases, the matrix cracking density increases and approaches saturation. When the fiber volume is V_f = 23.2%, the matrix cracking starts at the applied stress of 350 MPa, and approaches saturation at 590 MPa with the saturation matrix cracking density of 1.83/mm; and when the fiber volume is V_f = 25.8%, the matrix cracking starts at the applied stress of 334 MPa, and approaches saturation at 550 MPa with the saturation matrix cracking density of 3.03/mm. When the fiber volume increases, the stress transfer between the fiber and the matrix increases, leading to the increase of the saturation matrix cracking density and saturation matrix cracking stress.

5. Conclusions

In this chapter, the multiple matrix cracking of CMCs is investigated. During multiple matrix cracking, the composite tangent modulus decreases with increasing stress, and the evolution of the tangent modulus with composite strain can be divided into several stages, due to the damage mechanisms of the matrix cracking, interface debonding and fiber failure. The effects of the fiber volume and the matrix crack spacing on the evolution of the composite tangent modulus are analyzed. The effects of the interface shear stress and interface debonding energy on the multiple matrix cracking evolution of CMCs are also analyzed. The experimental matrix cracking density versus the applied stress of SiC/SiC composite is predicted using the present analysis.

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