Materials and Design 101 (2016) 66–71

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Strength model of the matrix element in SiC/SiC composites

Sheng Zhang [a], Xiguang Gao [a,*], Jing Chen [a], Hongnian Dong [a], Yingdong Song [a,b]

[a] Jiangsu Province Key Laboratory of Aerospace Power System, College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, PR China
[b] State Key Laboratory of Mechanics and Control Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, PR China

ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form 30 March 2016
Accepted 31 March 2016
Available online 6 April 2016

Keywords:
Ceramic matrix composite
Minicomposite
Matrix crack
Micro-mechanics

ABSTRACT

A strength model of the matrix element is developed for SiC/SiC composites to predict the matrix cracking process. A strength formula of the matrix element is presented. Modeling results using the previously introduced critical matrix strain energy criterion and the probabilistic-statistical approach are also examined. To verify these models, real-time matrix crack detection and a macroscopic tensile test are performed on SiC/SiC minicomposites. A comparison between the predicted and experimentally obtained results shows that the present strength model is better than the two above methods.

1. Introduction

SiC/SiC composites exhibit a high strength and modulus at elevated temperatures and also overcome the issue of ceramic brittleness. These features make them the materials with the highest potential for use in high-temperature parts of aeronautical vehicles [1,2].

When the composites are under loading, the SiC matrix will crack first due to its brittleness, followed by the fiber/matrix interfacial debonding [3]. According to the shear-lag model, the fiber/matrix interface will be divided into the debonded region and the bonded region following the cracking of the matrix. The distributions of the fiber and matrix normal stresses in these two regions are shown in Fig. 1 and are described by Eqs. (1)–(2).

$$\sigma_{\mathrm{f}}(x)=\begin{cases}\sigma/v_{\mathrm{f}}+2\tau/r_{\mathrm{f}}(|x|-L/2), & d\le|x|\le L/2\\ \sigma_{\mathrm{f0}}, & |x|\le d\end{cases} \tag{1}$$

$$\sigma_{\mathrm{m}}(x)=\begin{cases}\dfrac{-2v_{\mathrm{f}}\tau}{v_{\mathrm{m}}r_{\mathrm{f}}}(|x|-L/2), & d\le|x|\le L/2\\ \sigma_{\mathrm{m0}}, & |x|\le d\end{cases} \tag{2}$$

where subscripts f and m denote the fiber and matrix, respectively. σ_{f0} and σ_{m0} are the normal stresses if the composite is undamaged. Additionally, v is the volume fraction, r is the diameter of the SiC fiber and τ is the interfacial shear stress. The length of the debonded region d is:

$$d=\frac{r_{\mathrm{f}}}{2\tau}(\sigma/v_{\mathrm{f}}-\sigma_{\mathrm{f0}})\ . \tag{3}$$

The matrix spacing L is determined by the matrix cracking process, which is a significant damage mechanism for the ceramic matrix composites. The nonlinearity of the constitutive behavior is mainly caused by matrix cracking. Therefore, it is important to study and model matrix cracking to better understand and predict the mechanical behavior of SiC/SiC composites.

Four dominant failure criterions are presented in the literature for modeling the matrix cracking process: the maximum stress theory, the classical fracture mechanics approach, the critical matrix strain energy (CMSE) criterion and the probabilistic-statistical approach.

The maximum stress theory [4–6] assumes that a new matrix crack will form whenever the matrix stress exceeds the single-valued ultimate strength of the matrix and that new cracks form at the midspans of the existing cracks. The classical fracture mechanics approaches [3,7–12] include both the energy balance approach and the classical stress intensity factor approach.

Solti et al. [13] have stated that the maximum stress theory results in a rapid saturation of matrix cracking, while the classical fracture mechanics approach complicates the modeling process, especially for fatigue involving thousands or millions of cycles. Therefore, they proposed the CMSE criterion. According to this criterion [13–17], the crack spacing is uniform in the composite and a critical value of the strain energy exists for the matrix between two adjacent cracks, beyond which the matrix will be unable to support any extra load.

* Corresponding author at: College of Energy and Power, 29 Yudao St., Nanjing 210016, PR China.
E-mail address: gaoxiguang@nuaa.edu.cn (X. Gao).

http://dx.doi.org/10.1016/j.matdes.2016.03.166
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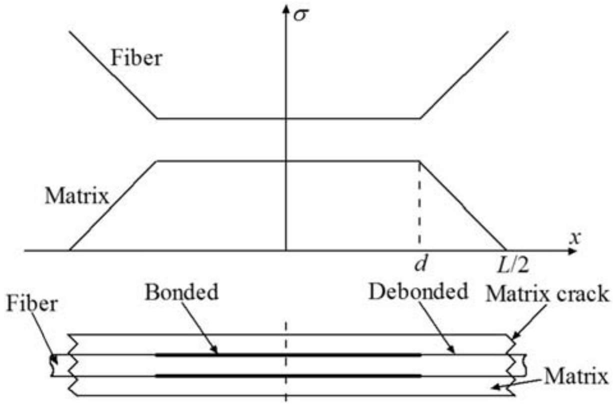

Fig. 1. Stress distributions in the debonded and bonded regions.

Subsequently, new cracks form so that the strain energy of the matrix between two adjacent cracks remains constant.

Other researchers have considered matrix cracking to be a random phenomenon resulting from the randomly distributed flaws in the brittle matrix. The probabilistic-statistical approach [18–20] was used in these studies to describe the matrix cracking process. According to this approach, the probability for the formation of a new crack in the matrix obeys the Weibull distribution.

In the present study, the CMSE criterion and the probabilistic-statistical approach were evaluated. To avoid the shortcomings of these criteria, a new matrix cracking model was developed. The strength formula of the matrix element was presented. Furthermore, real-time matrix cracks detection and the macroscopic tensile test were performed to obtain the matrix cracking data and the stress-strain response. The results predicted by the present model and the experimental data are in good agreement.

2. Models of matrix cracking

2.1. CMSE criterion

According to the CMSE criterion [13–17], the matrix crack spacing is uniform. There is a critical value of strain energy U_{cr} for the matrix between two adjacent cracks, beyond which the matrix will be unable to support an extra load as more energy is placed into the composites. Subsequently, new cracks form so that the matrix strain energy U_m remains constant. The CMSE criterion is expressed by

$$U_m = U_{cr} \tag{4}$$

Table 1
Material properties of SiC/SiC minicomposites.

Item	Value	Item	Value
E_f/GPa	160	E_m/GPa	190
v_f	0.23	v_m	0.77
$\alpha_f/\times10^{-6}/°C$	3.1	$\alpha_m/\times10^{-6}/°C$	4.6
r_f/μm	6.5	ΔT/°C	−1000
τ/MPa	15		

where

$$U_m = \int_V \int_\varepsilon \sigma_m(x) d\varepsilon dV \ . \tag{5}$$

Using Eqs. (2) and (5), the expression for U_m is obtained.

$$U_m = \frac{A_m}{v_m^2 r_f^2 E_m}\left[\frac{1}{2}(v_m r_f \sigma_{m0})^2 (L-2d) + \frac{4}{3}(\tau v_f d)^2 d\right] \tag{6}$$

As the applied stress increases, the crack density or crack spacing can be determined by ensuring that $U_m = U_{cr}$.

2.2. Probabilistic-statistical approach

According to the probabilistic-statistical approach [18–20], new matrix cracks form randomly in the bonded region because the matrix stress in the bonded region is uniform and is higher than that in the deboned region (see Fig. 1 and Eq. (2)). The probability P for the formation of a new crack in the matrix obeys the Weibull distribution. A two-parameter Weibull distribution is given by

$$P(\sigma) = 1 - \exp\left[-L_b/L_0(\sigma/\sigma_0)^m\right] \tag{7}$$

where m and σ_0 are the statistical parameters, L_b is the length of the bonded region and L_0 is the reference length taken to be 1 m.

To determine whether a new matrix crack will form under stress, a random number is first generated computationally. If the random number is less than the probability P, then a new matrix forms.

2.3. Present model

Due to the randomly distributed flaws in the brittle matrix, cracking is random (the cracking probability is described by Eq. (7)). However, the mean value of the stresses at which the matrix cracks is known. The mean stress is

$$\overline{\sigma} = \int_0^\infty sP(s)ds = (L_b/L_0)^{-1/m}\sigma_0\Gamma(1+1/m) \tag{8}$$

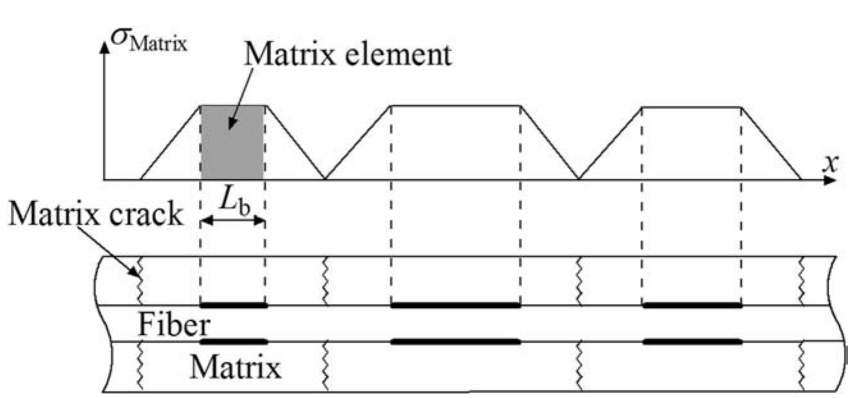

Fig. 2. Matrix element.