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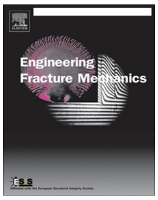

Crack development and deformation mechanisms of carbon-fiber-reinforced plastics at elevated temperatures

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ABSTRACT

Cracks that induce deformation in ablators reinforced with Kynol-based carbon fibers during pyrolysis reactions are assessed using experimental observations and theoretical estimation of tensile stress. Tensile stress in the transverse direction is produced by mismatch strain between the fiber and matrix during pyrolysis reactions and subsequently generates cracks. Observations and theoretical estimations of tensile stress using a model showed that cracking triggers buckling of fiber bundles, which consequently expands the ablator in the thickness direction. When large pores exist in the matrix, cracking relaxes the mismatch strain when tensile stress is low, thereby suppressing the buckling.

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1. Introduction

Knowledge of surface recession and material properties is important in the design of ablators used for thermal protection systems for re-entry capsules. When a capsule is exposed to extremely high temperatures, the surface suffers wear caused by chemical reactions and mechanical erosion during heating [1–3]. Surface recession by this wear is an important consideration in ablator thickness design [4–6] and has been measured by comparing the thicknesses before and after heating. Another consideration in the design of ablators is the temperature distribution within the ablator during heating. This distribution has been estimated using numerical methods [7–9]. For such estimates to be reliable, the temperature must be calculated using material properties that will necessarily change during heating. However, the measurement of surface recession and the prediction of material properties are complicated by crack generation that occurs during heating. When carbon-fiber-reinforced plastic (CFRP), the material most commonly used for ablators, is heated to extremely high temperatures, the CFRP is damaged, producing numerous cracks [1–3,10,11] that often expand the CFRP [12,13]. This expansion, which is not negligibly small compared to the recession, is included in the measurement of the recession. Consequently, the true recession has not been precisely evaluated. Furthermore, although cracks in the CFRP drastically alter material properties, such as thermal conductivity and density, the material properties used for the numerical modeling do not reflect information related to the cracks. To overcome these difficulties, we investigated crack formation and deformation mechanisms in CFRP during heating.

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Nomenclature

a	half of spacing between adjacent transverse cracks
C	function of E_{90}
D	transverse crack density
E_0	Young's modulus of 0° layer in x-axis direction
$E_0^{T_c}$	E_0 at T_c
E_{90}	Young's modulus of 90° layer in x-axis direction
$E_{90}^{T_c}$	E_{90} at T_c
E_{fL}	longitudinal Young's modulus of carbon fiber
E_{fT}	Young's modulus of carbon fiber in plane of isotropy
E_m	Young's modulus of phenolic resin with pores
$\ddot{E}_m$	Young's modulus of phenolic resin without pores
E_p	Young's modulus of pores
g_{mc}	fracture toughness of matrix
$g_{mc}^{T_c}$	g_{mc} at T_c
G_0	shear modulus of 0° layer in x–z plane
$G_0^{T_c}$	G_0 at T_c
G_{90}	shear modulus of 90° layer in x–z plane
$G_{90}^{T_c}$	G_{90} at T_c
G_{fLT}	shear modulus of carbon fibers in plane of isotropy
$\ddot{G}_{LT}$	shear modulus of unidirectional carbon-fiber-reinforced plastic (CFRP) in plane of isotropy
G_m	shear modulus of matrix
$G_m^{T_r}$	G_m at T_r
k_m	function of E_0, E_{90}, and t
t	half of thickness of a layer
T_c	onset temperature of cracking
T_g	glass transition temperature
T_p	onset temperature of pyrolysis reaction
T_r	room temperature
V_f	volume fraction of fibers
V_p	volume fraction of pores
$Y(D)$	function of D, E_0, E_{90}, G_0, and G_{90}
α	function of V_f, $\ddot{G}_{LT}$, and G_m
σ_1	theoretical tensile stress that induces first transverse crack
$\sigma_1^{T_c}$	σ_1 at T_c
σ_2	experimental tensile stress produced by mismatch strain between fiber and matrix
$\sigma_2^{T_c}$	σ_2 at T_c
ε	strain difference in a matrix between T_p and T_c
η	function of E_p and $\ddot{E}_m$
ν	Poisson's ratio
ν_0	Poisson's ratio of 0° layer in x–z plane
ν_{90}	Poisson's ratio of 90° layer in x–z plane
υ_p	Poisson's ratio of phenolic resin
υ_g	Poisson's ratio of graphite

Several researchers have studied crack development mechanisms in CFRPs under static heating conditions [14–16]. Schulte-Fischedick et al. [14,15] and Wittel et al. [16] investigated the cracking mechanisms during heating of 0/90°-laminated CFRP reinforced with polyacrylonitrile (PAN)-based carbon fiber. Fig. 1 shows that tensile stress perpendicular to the fiber and compressive stress parallel to the fiber are generated when the matrix undergoes carbonization because the fiber bundle prevents matrix shrinkage caused by pyrolysis reactions. When the tensile stress becomes sufficiently high, transverse cracks are formed, as illustrated in Fig. 1. When the remaining tensile stress is increased by further carbonization, delaminations tend to extend from the edges of the transverse cracks.

In our previous research, we investigated crack development and deformation in an ablator reinforced with Kynol-based carbon fiber [17,18]. Kynol-based carbon fiber and rayon-based carbon fiber have often been used for ablator reinforcement because of their low density and low thermal conductivity [19]. The microstructure of Kynol-based carbon fiber-reinforced composite greatly differs from that of PAN-based carbon fiber-reinforced composite. The Kynol-based carbon fiber material

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