Engineering Fracture Mechanics 162 (2016) 309–323

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Non-Fourier effect and inertia effect analysis of a strip with an induced crack under thermal shock loading

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ARTICLE INFO

Article history:
Received 19 October 2015
Received in revised form 13 January 2016
Accepted 7 February 2016
Available online 9 April 2016

Keywords:
Crack
Inertia effect
Hyperbolic heat conduction
Fourier transform
Singular integral equations

ABSTRACT

In this paper, the transient temperature fields and the dynamic stress intensity factors of a thermo-elastic strip containing an inner crack parallel to the heated surface under thermal shock are studied. The Biot number of the crack gap, hyperbolic heat conduction theory and equation of motion are considered to investigate the behavior of the temperature fields around the crack and the stress intensity factors. Fourier transform and Laplace transform are used to reduce this mixed boundary value problem. Numerical methods are used to solved the singular integrate equations. Finally, the numerical results are presented illustrating the influence of Biot number, non-Fourier effect and inertia effect on temperature field and stress intensity factors. It is found that the Biot number strongly affect the uniformity of the temperature field and the magnitude of the stress intensity factors. The stress intensity factors have higher amplitude and an oscillating feature comparing to those obtained under conventional Fourier thermal conduction condition and quasi-static hypothesis, which can help to better understand the crack behaviors of advanced materials under thermal impact loading.

1. Introduction

Engineering thermo-mechanical structure components are widely used in server thermal loading such as extremely powerful laser impact or thermal barrier coatings (TBCs) used in gas-turbine engines [1,2]. When materials function in the presence of thermal gradients and high heat flux, they are susceptible to submit delamination and fracture. Many articles have studied the failure of such materials after suffering thermal loading [1–5]. In general, authors pay more attention on the cracks parallel to the heating surface (we call it CPHS in short), which play a key role in the spallation failure of materials. Most existing studies about CPHS are based on thermal expansion mismatch between the two different types of the materials or microgeometry defects of materials [2,3,6], both of which rely on the presence of interface. However, CPHS are found not only near the interface of coating materials but also in the coatings far from the interface and non-layered materials [1,7]. There is no doubt that we need an in-depth study to find the source and magnitude of the force which leading to the CPHS.

Classical thermos-elastic stress analysis in a homogeneous body cannot provide tensile stress leading to fractures parallel to the heating surfaces. Therefore, additional driving forces should be considered to explain this class of failures. These driving forces may include the non-Fourier thermal conduction effect [8–10] or the inertia force effect [11–13]. Moreover, the

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http://dx.doi.org/10.1016/j.engfracmech.2016.02.056
0013-7944/

Nomenclature

a	thermal diffusivity
$\mathbf{A}_{i,j}$	function defined in Eq. (A2)
Bi	Biot number
B_j	function defined in Eq. (39)
C_p	specific heat capacity
C_i	unknown coefficients
D_i	unknown coefficients
e	mathematical constant
E	Young's modulus
f_1, f_2	dislocation function
h	heat transfer coefficient
i	imaginary unit
i, j	subscript
k	thermal conductivity
$k()$	function defined in Eq. (24)
$K_{i,j}$	function defined in Eq. (A4)
l_a, l_b	distance between the crack and the boundary
La, Lb	dimensionless distance between the crack and the boundary
m	variable defined in Eq. (18)
m_0	variable defined in Eq. (22)
p	Laplace variable
$\vec{q}$	heat flux vector
r	crack length
t	time
T	temperature
T_0	initial temperature
T_∞	temperature of the surrounding external environment of the strip
u, v	displacement
$\bar{u}$, $\bar{v}$	displacement in Laplace space
$\tilde{\bar{u}}$, $\tilde{\bar{v}}$	displacement in Laplace–Fourier space
V	elastic wave velocity
W_i	function defined in Eq. (A4)
x, y	coordinate
X, Y	dimensionless coordinate
∇	Laplace operator

Greek symbols

α	coefficient of linear thermal expansion
β_i	function defined in Eq. (34)
γ_j	function defined in Eq. (A2)
$\delta()$	Dirac delta function
ε	strain
η	integral variable
θ	dimensionless temperature
λ_i	function defined in Eq. (37)
ν	Poisson's ratio
ξ	Fourier variable
π	circumference ratio
ρ	density
σ_x, σ_y	normal stress
τ	dimensionless time
τ_0	thermal relaxation time
τ_1	Fourier factor
τ_2	inertia factor
τ_{xy}	shear stress
$\varphi()$	dislocation density function
$\Phi()$	function defined in Eq. 25
ω_i	function defined in Eq. (A1)