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Functionally graded hollow cylinder under pressure and thermal loading: Effect of material parameters on stress and temperature distributions

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ABSTRACT

This study presents an analytical solution of stresses and displacements in a long functionally graded (FGM) hollow cylinder subjected to uniform heat generation and internal pressure. Thermo-elastic material properties of FGM cylinder continuously vary in radial direction along the thickness with a power function. The temperature distribution is assumed to vary as a function of the radial coordinate and in steady state. Stress formulation approach is employed using the Airy stress function to derive the analytical solution. In the failure analysis of FGM cylinder, Coulomb-Mohr theory is applied for the ceramic phase whereas Tresca yield criterion is used for the metal phase. The stress analysis reveals that stresses in FGM cylinder decrease considerably, compared to the homogenous one, for a particular interval of material parameters. Radial displacement analysis in FGM cylinder supports the results obtained from stress analysis.

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1. Introduction

Functionally Graded Materials (FGM) are designed to have improved thermo-mechanical properties that cannot be achieved by homogenous materials or conventional composite materials (Koizumi, 1997; Li & Hu, 2016). The material properties are described by introducing proper material functions such that these properties vary from one material to another with a specific gradient (Golak & Dolata, 2016; Kiani, 2016; Li & Hu, 2016; Salehipour, Shahidi, & Nahvi, 2015). Three phases of FGMs (Ceramic/Metal, Ceramic/Ceramic, Metal/Metal) can be properly designed to avoid the problems related to the presence of an interface in the material, mismatch of elastic and thermal properties and stress concentrations. The use of ceramics and metals together in a composite structure by varying the microstructure from ceramic to metal with a specific gradient enables the FGM to have properties of high thermal and corrosion resistance coupled with high toughness (Erdogan & Ozturk, 1995; Jabbari, Shahryari, Haghighat, & Eslami, 2014).

Materials capable of tolerating material properties with spatial dimensions offer reliable engineering solutions for industrial applications involving severe thermal and mechanical loading as in the case of tribology, combustion processes, aerospace structures and high temperature technologies. FGM cylinders are designed to fulfill specific and specialized functions in a variety of engineering applications such as high-performance cylinder-piston mechanisms of combustion engines and lightweight, wear resistant gun barrels. The material tailoring in the FGMs enables a compromising solution which

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Nomenclature

a	inner radius
A, B, C	constants of particular solution of the nonhomogeneous differential equation
b	outer radius
C_1, C_2	constants of homogenous differential equation for the stress function
C_{1t}, C_{2t}	constants of integration for temperature distribution in the radial coordinate
c_p	specific heat
E	modulus of elasticity
E_o	constant of modulus of elasticity
P	pressure
$\overline{P_i}, \overline{P_o}$	dimensionless pressure terms
r	radial coordinate
$\bar{r}$	dimensionless radial coordinate
Q	inner to outer radius ratio
q	heat generation for per unit time and per unit volume
$\bar{q}$	dimensionless heat generation
t	time
T	temperature distribution
T_o	outer surface temperature
$\bar{T}$	dimensionless temperature
u	radial displacement
$\bar{u}$	normalized radial displacement
z	axial coordinate
α_0	constant of thermal expansion coefficient
β_1	power low exponent of thermal expansion coefficient
β_2	power low exponent of modulus of elasticity
β_3	power low exponent of thermal conductivity coefficient
β_4	power low exponent of yield stress
θ	circumferential coordinate
$\emptyset$	stress function
λ_0	constant of thermal conductivity coefficient
ε	strain
ε_0	constant value of axial strain
ρ	density
σ	stress
σ_0	constant of yield stress
$\bar{\sigma}_r, \bar{\sigma}_\theta, \bar{\sigma}_z$	dimensionless stress components
ν	Poisson's ratio

Subscripts

c	complementary
i	inner
o	outer
p	particular
r	radial
θ	circumferential
z	axial

optimally satisfies the design requirements (Li, Li, & Hu, 2016). The heat conduction problem and thermal stress distribution of FGM cylinder were analyzed by introducing theory of laminated composite cylinder model as one of a theoretical approximation. Shao (2005), analyzed FGM hollow cylinder with finite length subjected to thermal/mechanical loads using the theory of laminated composites and derived the solutions of temperature, displacements and stresses. Besides the studies using theory of "laminated composite" model (Ootao, Akai, & Tanigawa, 1995; Ootao, Fukuda, & Tanigawa, 1989; Ootao, Tanigawa, & Fukuda, 1991; Shao, 2005; Tanigawa, Oka, Akai, & Kawamura, 1997), there are other studies making use of "continuously variable material properties" model to analyze the thermal and mechanical stresses for thick walled FGM cylinders under different thermal and mechanical boundary conditions (Jabbari, Sohrabpour, & Eslami, 2002; Ozturk, & Gulgec, 2011; Praveen, Chin, & Reddy, 2001; Tarn, 2001; Tutuncu & Ozturk, 2001; Yang, 2000). Whereas the laminated composite model assumes FGM cylinder to consist of homogenous sub-layers, the model with continuously variable material properties defines material properties such as elastic moduli, coefficients of thermal conductivity and thermal expansion as

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