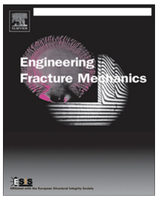
Engineering Fracture Mechanics 177 (2017) 167–179

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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



Double edge thermal crack problem for an interpenetrating phase composite: Application of a matricity-based thermal conductivity model

Z.-H. Jin [a,*], K. Tohgo [b], T. Fujii [b], Y. Shimamura [b]

[a] Department of Mechanical Engineering, University of Maine, Orono, ME 04469, USA
[b] Department of Mechanical Engineering, Shizuoka University, Hamamatsu, Shizuoka 432-8561, Japan

ARTICLE INFO

Article history:
Received 4 October 2016
Received in revised form 19 March 2017
Accepted 21 March 2017
Available online 27 March 2017

Keywords:
Interpenetrating phase composite
Effective thermal conductivity
Thermal shock
Thermal stress intensity factor

ABSTRACT

In this paper a matricity-based thermal conductivity model for interpenetrating phase composites (IPCs) is first developed. The model employs the formulas of effective thermal conductivities for particulate composites together with the so-called matricities of the constituent phases. The model is then applied to investigate a double edge cracked plate of a ceramic/metal IPC under a thermal shock. The numerical results for an Al_2O_3/aluminum IPC show that both the peak tensile thermal stress and the peak thermal stress intensity factor (TSIF) are significantly lower than those for the corresponding aluminum particulate Al_2O_3-matrix composite.

1. Introduction

Ceramic/metal interpenetrating phase composites (IPCs) are composite materials with three-dimensional, interconnected microstructural networks of the ceramic and metal phases [1]. Ceramic/metal IPCs exploit the corrosion, oxidation and wear resistance typical of ceramics, and the strength and toughness properties typical of metals. Mechanical behavior of IPCs such as stress-strain behavior, strength, fatigue, and fracture toughness has been studied by a number of researchers. For example, Prielipp et al. [2] experimentally investigated an Al_2O_3/aluminum IPC. Compared with the corresponding Al_2O_3 particulate reinforced aluminum (Al) matrix composite, they observed that both fracture toughness and fracture strength of the IPC could be improved. Agrawal and Sun [3] investigated fracture mechanisms and analyzed crack extension in Al_2O_3/Cu and Al_2O_3/Al IPCs. They found that thermal residual stresses play an important role in crack growth behavior in the composites. Moon et al. [4] evaluated the crack tip stress field and measured the crack growth resistance for an Al_2O_3/Al IPC. Hoffman et al. [5] investigated thermal residual stresses in an Al_2O_3/Al IPC. Agrawal et al. [6] measured and simulated thermal residual stresses in Al_2O_3/Cu and Al_2O_3/Al IPCs. Periasamy and Tippur [7] conducted experimental and numerical studies on the dynamic compression response of an interpenetrating phase composite foam. Lee et al. [8] experimentally investigated the energy absorption capability of an interpenetrating phase nanocomposite. Harris and Marquis [9] investigated failure in a glass-metal IPC system. Cheng et al. [10] analyzed the elastic-plastic response of a stainless steel/bronze IPC. They also computed the effective Young's modulus and coefficient of thermal expansion. Wang et al. [11] studied damage evolution in a SiC/Al IPC bar under dynamic compressive loads using both a finite element method and an experimental technique.

---

[*] Corresponding author.
E-mail address: zhihe.jin@maine.edu (Z.-H. Jin).

http://dx.doi.org/10.1016/j.engfracmech.2017.03.034
0013-7944/

Aydogmus [12] manufactured an Mg-TiNi IPC by spark plasma sintering method and examined the effects of processing conditions on the ductility of the composite. Liu et al. [13] investigated fatigue behavior of an aluminum foam-polyurethane IPC under cyclic compression. Shadlou and Wegner [14] used the molecular dynamics method to simulate the behavior of a SiC/Cu IPC and investigated the effects of nano-structural phase shapes on the mechanical responses.

Analyses of stress and deformation fields in IPCs usually follow the conventional micromechanics/continuum approach for composites, i.e., an IPC is treated as a homogenized material at the macroscopic level with its effective properties determined using micromechanics models [15]. Poniznik et al. [15] and Peng et al. [16] examined various theoretical and computational models for estimating the effective Young's modulus and Poisson's ratio. Feng et al. [17] developed a micromechanics model to evaluate the elastic and plastic properties of IPCs. Agarwal et al. [18] estimated the elastic properties of IPCs using the unit cell and self-consistent models. Tohgo et al. [19] presented a micromechanical model to determine the stiffness matrix and elastic-plastic responses of composites with interpenetrating microstructure using the concept of matricity. Myers et al. [20] used a numerical homogenization approach to estimate the elastic modulus of ceramic-metal IPCs and compared their results with experimental results. Abueidda et al. [21] estimated the coefficient of thermal expansion of periodic architectured IPCs using a finite element method. Leclerc et al. [22] used both FFT and FE methods to estimate Young's modulus and thermal conductivity of an alumina/aluminum IPC and compared their results with measured data. Dalaq et al. [23] evaluated the effective elastic properties of IPCs with architectured 3D sheet reinforcements.

An advantage of ceramic/metal IPCs is their improved transport properties due to the interconnected metal phase which usually has excellent electrical and thermal conductivities. Hence, the thermal shock resistance of IPCs may be significantly improved. Thermal shock resistance of IPCs has been examined only in a few studies. Hong et al. [24] estimated thermal shock resistance parameters for TiB_2/Cu and TiB_2/Ni IPCs based on their measured thermomechanical properties. Jin [25] considered an edge crack in an IPC strip using a local thermal non-equilibrium model. To better understand thermal cracking and thermal shock resistance behavior of ceramic/metal IPCs, the effective thermal conductivity of the composite needs to be estimated with reasonable accuracy. Leclerc et al. [22] numerically calculated the effective thermal conductivity of an IPC using a penetrable-concentric-shell model. The model assumes that the IPC is a particulate composite with interconnected and penetrable particles. We have not found other published literature in modeling the effective thermal conductivity of IPCs.

In this paper, we first develop an effective thermal conductivity model for IPCs using the concept of matricity of the constituent phases. We then consider an IPC plate with symmetrically located double edge cracks under a thermal shock. The temperature, thermal stress, and thermal stress intensity factor are then obtained using the newly developed thermal conductivity model. Numerical examples for an Al_2O_3/aluminum IPC are presented to examine the differences between the thermal stress/thermal stress intensity factor for the IPC and those for the corresponding aluminum particulate Al_2O_3-matrix composite.

2. A matricity-based effective thermal conductivity model for IPCs

Consider a two-phase IPC with interpenetrating α and β phases. Denote by L_α and L_β the lengths of the skeleton lines in the α and β phases, respectively. Fig. 1 schematically shows a cross section of a two-phase IPC and the skeleton lines in each constituent phase. Perfect phase interpenetration occurs in an IPC if the skeleton lines are continuous in the respective constituent phases. The matricities of the α and β phases are defined using the lengths of the skeleton lines as follows [19,26,27]

$$M_\alpha = \frac{L_\alpha}{L_\alpha + L_\beta}, \quad M_\beta = \frac{L_\beta}{L_\alpha + L_\beta} \tag{1}$$

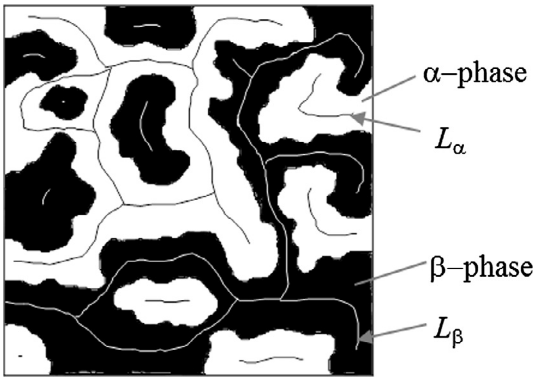


Fig. 1. Schematic interpenetrating microstructure on a cross section of an IPC composed of α and β phases and the lengths of skeleton lines L_α and L_β in the α and β phases, respectively.