

Modeling of Thermomechanical Fracture of Functionally Graded Materials with Respect to Multiple Crack Interaction

V. E. Petrova^{1,2*} and S. Schmauder¹

¹ DMTF, University of Stuttgart, Stuttgart, D-70569 Germany

² Voronezh State University, Voronezh, 394006 Russia

* e-mail: vorava@gmail.com, vera.petrova@dmf.uni-stuttgart.de

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Abstract—Different aspects of thermomechanical fracture of functionally graded materials (FGMs) are considered. Among them are the crack interaction problems in a functionally graded coating on a homogeneous substrate (FGM/H). The interaction between systems of edge cracks is investigated, as well as, how this mutual interaction influences the fracture process and the formation of crack patterns. The problem is formulated with respect to singular integral equations which are referred to the boundary equation methods. The FGM properties are modeled by exponential functions. The main fracture characteristics are calculated, namely, the stress intensity factors, the angles of deviation of the cracks from their initial propagation direction and the critical stresses when the crack starts to propagate. The last two characteristics are calculated using an appropriate fracture criterion. The problem contains different parameters, such as the geometry (location and orientation of cracks, their lengths, and the width of the FGM layer) and material parameters, i.e. the inhomogeneity parameters of elastic and thermal coefficients of the functionally graded material. The influence of these parameters on the thermo-mechanical fracture of FGM/H is investigated. As examples the following real material combinations are discussed: TiC/SiC, $\text{Al}_2\text{O}_3/\text{MoSi}_2$, MoSi_2/SiC , $\text{ZrO}_2/\text{nickel}$ and $\text{ZrO}_2/\text{steel}$.

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Keywords: edge and internal cracking, thermal fracture, functionally graded coating, stress intensity factors, fracture criteria, fracture angle

1. INTRODUCTION

Functionally graded coatings (FGCs) are applied in thermal, wear and corrosion barriers which are used in different fields, such as, nuclear energy (e.g., nuclear reactor components), aerospace (e.g., rocket engine components, space plane body), engineering (e.g., turbine blade, engine components), energy conversion (e.g., thermoelectric generator, fuel cell) as well as many other applications [1–3]. They are subjected to different thermal and mechanical loading and have to resist high temperature, wear and aggressive environments. However, cracks can initiate from initial defects or microcracks may appear during manufacturing or service. Therefore, the study of fracture of FGC structures is important for a better understanding of the fracture resistance of graded coatings.

Thermal fracture of FGCs is significantly affected by a complex crack interaction mechanism, e.g., inter-

acting cracks can enhance or suppress the propagation of each other. The crack patterns strongly depend on the microstructure of the materials and type of loading. Numerous experimental results (e.g., [4–6]) showed that when FGCs are subjected to thermal shock, multiple cracks often occur at the ceramic surface. The studies from laser thermal shock tests [7, 8] indicated that multiple surface precracks with a large density and short lengths reduce the crack driving force at the interface. At the same time very short precracks were most vulnerable to further surface cracking which in turn induced the interface crack. In [8] a functionally graded plate with an array of periodically spaced surface cracks of alternating lengths subjected to thermal shocks was considered. The crack morphology was described by the ratio of the length of the short cracks to that of the long cracks (initial crack length ratio) as well as by the crack spacing. The thermal properties

Fracture Of Functionally Graded Materials

Ian Milne, R. O. Ritchie, B.L. Karihaloo

A red circular graphic with a gradient, appearing as a semi-circle or a partial circle, located to the right of the authors' names.

Fracture Of Functionally Graded Materials:

Fracture of Functionally Graded Materials G.H. Paulino, 2002-10-23 Scientific research on functionally graded materials FGM s looks at functions of gradients in materials comprising thermodynamic mechanical chemical optical electromagnetic and or biological aspects This collection of technical papers represents current research interests with regard to the fracture behaviour of FGM s The papers provide a balance between theoretical computational and experimental techniques It also indicates areas for increased development such as constraint effects full experimental characterization of engineering FGM s under static and dynamic loading development of fracture criteria with predictive capability multiphysics and multiscale failure considerations and connection of research with industrial applications Fracture of Functionally Graded Materials G. H. Paulino, 2002 Special Issue on Fracture of Functionally Graded Materials Glaucio H. Paulino, 2002

Cohesive Modeling of Fracture in Functionally Graded Materials Soma Sekhar Venkata Kandula, 2004 Fracture Mechanics of Functionally Graded Materials, 1996 Functionally graded materials are generally two phase composites with continuously varying volume fractions Used as coatings and interfacial zones they help to reduce mechanically and thermally induced stresses caused by the material property mismatch and to improve the bonding strength In this project some basic problems concerning fracture mechanics of graded materials are identified general analytical methods for solving the related crack problems are developed the singular behavior of the solutions for typical material nonhomogeneities is examined and solutions of some benchmark problems are obtained The results are intended to provide technical support for material scientists and engineers who are trying to develop methods for processing these materials and for design engineers who are interested in using them in technological applications Typical applications of functionally graded materials include thermal barrier coatings of high temperature components in gas turbines surface hardening for tribological protection and as interlayers in microelectronic and optoelectronic components The results found show that by eliminating the discontinuities in material property distributions the mathematical anomalies regarding the crack tip stress oscillations for the interface cracks and the nonsquare root singularities for cracks intersecting the interfaces are also eliminated From the viewpoint of fracture mechanics the importance of this result lies in the fact that in analyzing the components involving functionally graded materials one can use the existing crack tip finite element modeling developed for ordinary square root singularities and apply the energy balance based theories of conventional fracture mechanics *The Mixed Mode Fracture of Functionally Graded Materials* Xiang Long, 2003 *Fracture Behaviour of Functionally Graded Materials* Prabhakar Marur, 2012-05-30 Functionally graded materials FGMs are special composites consisting of two constituent phases whose composition change continuously along one direction The gradual transition in material properties alleviates thermal mismatch problems experienced by clad and coated components The microstructure of FGM is usually heterogeneous and the dominant failure mode of FGM is the crack initiation and propagation from the inclusions The interface crack problem is

studied by examining the asymptotic behavior of stress and displacement fields around the crack in FGM and by comparing the results with known solutions for bimaterial systems The focus is on characterizing the influence of material nonhomogeneity on the fracture parameters and determining the fracture strength of FGM under quasi static and dynamic loading

Fatigue Fracture of Functionally Graded Materials Under Elastic-Plastic Loading Conditions Using Extended Finite Element Method Somanātha Bhaṭṭācārya, 2018 In this chapter extended finite element method XFEM has been used to simulate the fatigue crack growth problems in functionally graded material FGM in the presence of hole inclusion and minor crack under elastic and plastic conditions The fatigue crack growth analysis of alloy ceramic FGMs alloy and equivalent composite is done by XFEM in the presence of multiple discontinuities under mode I mechanical load The validity of linear elastic fracture mechanics LEFM theory is limited to the brittle materials Therefore the elastic plastic fracture mechanics EPFM theory needs to be utilized to characterize the plastic behavior of the material A generalized Ramberg Osgood material model has been used to model the stress strain behavior of the material Plasticity has been checked by Von Mises Yield criteria J integral has been used to calculate the SIF Crack growth direction is determined by maximum principal stress criteria

Functionally Graded Materials Y. Miyamoto, W.A. Kaysser, B.H. Rabin, A. Kawasaki, R.G. Ford, 2013-11-27 Seven years have elapsed since Dr Renee Ford editor in chief of Materials Technology first suggested to me to publish a book on Functionally Graded Materials FGMs She said that the FGM concept then largely unknown outside of Japan and a relatively few laboratories elsewhere would be of great interest to everyone working in the materials field because of its potentially universal applicability There was no book about FGMs in English at that time although the number of research papers review articles and FGM conference proceedings had been increasing yearly We discussed what the book should cover and decided it should present a comprehensive description from basic theory to the most recent applications of FGMs This would make it useful both as an introduction to FGMs for those simply curious about what this new materials field was all about and also as a textbook for researchers engineers and graduate students in various material fields The FGM Forum in Japan generously offered to support this publication program is very difficult for an individual author to write a book that Because it covers such a wide range of various aspects of many different materials I invited more than 30 eminent materials scientists throughout the world who were associated with FGM research to contribute selected topics I also asked several leading researchers in this field to edit selected chapters Dr Barry H Rabin then at the U S

The Role of Interfaces in the Fracture of Functionally Graded Materials, 2005 The research focuses on establishing conditions when interfaces between interlayers are important in governing fracture processes in composites with graded compositions A theoretical framework is sought that could ultimately quantify the role of interfaces when their presence dominates behavior Initial work is driven towards establishing general trends Experimentally multilayer composites have been fabricated by several techniques that aim at modifying interface characteristics The competition between fracture at notches of particular depth

parallel to the interface and interface fracture is examined A numerical model is being constructed to obtain crack tip and interface free edge stress fields to better understand experimental trends Also models are being devised to examine how the presence of the interface modifies the stress field of an edge crack parallel to the interface Experiments in which cracks are extended from notches placed near interfaces have been conducted utilizing optical moir interferometry conducted at INEEL The crack driving force and mode mixity as a function of type of interface and proximity to interface are being determined

Experimental Fracture Measurements of Functionally Graded Materials Ray Douglas Carpenter, 2013 The primary objective of this research was to extend established fracture toughness testing methods to a new class of engineering materials known as functionally graded materials (FGMs) Secondary goals were to compare experimental results to those predicted by finite element models and to provide fracture test results as feedback toward optimizing processing parameters for the in house synthesis of a MoSi₂/SiC FGM Preliminary experiments were performed on commercially pure CP Ti and uniform axial tensile tests resulted in mechanical property data including yield strength 268 MPa ultimate tensile strength 470 MPa and Young's modulus 110 GPa Results from 3 point bending fracture experiments on CP Ti demonstrated rising R curve behavior and experimentally determined J-Q fracture toughness values ranged between 153 N mm and 254 N mm Similar experimental protocols were used for fracture experiments on a 7 layered Ti/TiB FGM material obtained from Cercom in Vista California A novel technique for pre cracking in reverse 4 point bending was developed for this ductile brittle FGM material Fracture test results exhibited rising R curve behavior and estimated J-Q fracture toughness values ranged from 0.49 N mm to 2.63 N mm A 5 layered MoSi₂/SiC FGM was synthesized using spark plasma sintering (SPS) Samples of this material were fracture tested and the results again exhibited a rising R curve with K_{IC} fracture toughness values ranging from 2.7 MPa m^{1/2} to 6.0 MPa m^{1/2} Finite Element Models predicted rising R curve behavior for both of the FGM materials tested Model results were in close agreement for the brittle MoSi₂/SiC FGM For the relatively more ductile Ti/TiB material results were in close agreement at short crack lengths but diverged at longer crack lengths because the models accounted for fracture toughening mechanisms at the crack tip but not those acting in the crack wake

Functionally Graded Materials 2000 Kevin Trumble, Keith Bowman, Ivar E. Reimanis, Sanjay Sampath, 2001-02-28 Functionally Graded Materials (FGM) has served as a unifying theme for interdisciplinary research for more than a decade The biannual International Symposium on Functionally Graded Materials has provided a forum for research on materials with spatial variation in microstructures or chemistries and have brought together a small but richly interactive community of FGM researchers from university industry and government labs all around the world This new volume brings to readers current advancements and information on the topic of Functionally Graded Materials More than 150 researchers from 20 different countries came together in Estes Park Colorado for FGM 2000 to bring this information to the rest of the research world FGM continues to be a vigorous topic stimulating new materials research and this proceedings will keep you informed of all the latest developments in this area

Proceedings of the 6th International Symposium on Functionally Graded Materials Estes Park Colorado USA September 10-14 2000 *Ceramics Transactions Volume 114* Recent Advances in Smart Manufacturing and Materials Rajeev Agrawal, Jinesh Kumar Jain, Vinod Singh Yadav, Vijaya Kumar Manupati, Leonilde Varela, 2021-07-22 This book presents select proceedings of the International Conference on Evolution in Manufacturing ICEM 2020 and examines a range of areas including internet of things for cyber manufacturing data analytics for manufacturing systems and processes and materials The topics covered include modeling simulation and decision making in cyber physical systems for supporting engineering and production management innovative approach in materials development biomaterial applications and advancement in manufacturing and material technologies The book also discusses sustainability in manufacturing and supply chain management including circular economy The book will be a valuable reference for beginners researchers and professionals interested in smart manufacturing in engineering production management and materials technology **Comprehensive Structural Integrity** Ian Milne, R. O. Ritchie, B.L. Karihaloo, 2003-07-25 The aim of this major reference work is to provide a first point of entry to the literature for the researchers in any field relating to structural integrity in the form of a definitive research reference tool which links the various sub disciplines that comprise the whole of structural integrity Special emphasis will be given to the interaction between mechanics and materials and structural integrity applications Because of the interdisciplinary and applied nature of the work it will be of interest to mechanical engineers and materials scientists from both academic and industrial backgrounds including bioengineering interface engineering and nanotechnology The scope of this work encompasses but is not restricted to fracture mechanics fatigue creep materials dynamics environmental degradation numerical methods failure mechanisms and damage mechanics interfacial fracture and nano technology structural analysis surface behaviour and heart valves The structures under consideration include pressure vessels and piping off shore structures gas installations and pipelines chemical plants aircraft railways bridges plates and shells electronic circuits interfaces nanotechnology artificial organs biomaterial prostheses cast structures mining and more Case studies will form an integral part of the work **Functionally Graded Materials** Nathan J. Reynolds, 2012 Functionally graded materials FGMs are composites with gradually varying material content This book presents current research in the study of FGMs including the fracture and contact problems of functionally graded materials FGMs obtained by combustion synthesis techniques thermoplastic simulation of FGMs the thermal buckling analysis of functionally graded arbitrary straight sided quadrilateral plates the mechanical response of metal ceramic FGMs and simulation of quasi static crack propagation in FGMs Fracture Behaviour of Functionally Graded Materials Prabhakar R. Marur, 1999 *IUTAM Symposium on Mechanics and Reliability of Actuating Materials* W. Yang, 2006-06-28 Actuating materials hold a promise for fast spreading applications in smart structures and active control systems and have attracted extensive attention from scientists of both mechanics and materials sciences communities High performance and stability of actuating materials and

structures play a decisive role in their successive applications as sensors and actuators in structural control and robotics The advances of actuating materials however recently encountered a severe reliability issue For a better understanding toward this issue scientific efforts are of paramount significance to gain a deep insight into the intricate deformation and failure behaviors of actuating materials To examine the state of the art in this subject the general assembly of IUTAM approved in August 2002 at Cambridge University UK a proposal to hold an IUTAM symposium to summarize the relevant research findings The main themes of the symposium are i the constitutive relations of actuating materials that couple mechanical electrical thermal and magnetic properties as well as incorporate phase transformation and domain switch ii the physical mechanisms of deformation damage and fatigue crack growth of actuating materials iii the development of failure resilient approaches that base on the macro meso and micro mechanics analyses iv the investigation of microstructural evolution stability of phase transformation and size effects of ferroelectric ceramics shape memory alloys actuating polymers and bio actuating materials The above problems represent an exciting challenge and form a research thrust of both materials science and solid mechanics The IUTAM Symposium GA Advances in Heterogeneous Material Mechanics 2008 Jinghong Fan, Haibo Chen, 2008 The International Conference on Heterogeneous Material Mechanics ICHMM in Huangshan China June 3-8 2008 follows the successful inaugural ICHMM held in ChongQing China in June 2004 The ICHMM series is the first international forum that focuses exclusively on various issues related to the behavior of heterogeneous materials in a broad sense The object of the ICHMM is to present and publicize integrated scientific and engineering approaches to the measurement and modeling of phenomena at the interface of materials science physics chemistry biology and solid mechanics Preface p xxxix Functionally Graded Materials 1996 I. Shiota, Y. Miyamoto, 1997-09-02 Since a formulated concept of functionally graded materials FGMs was proposed in 1984 as a means of preparing thermal barrier materials a coordinated research has been developed since 1986 The 125 papers presented here present state of the art research results and developments on FGM from the past decade A wide spectra of topics are covered including design and modeling fracture analysis powder metallurgical processes deposition and spray processes reaction forming processes novel processes material evaluation for structural applications organic and intelligent materials Three reviews associated with national research programs on FGMs promoted in Japan and Germany and the historical perspective of FGM research in Europe are presented as well The resulting work is recommended to researchers engineers and graduate school students in the fields of materials science and engineering mechanical and medical engineering *Advances in Mechanical and Industrial Engineering* Muhamad Mat Noor, Hoang Anh Tuan, Purna Chandra Mishra, 2022-07-01 The International Conference on ADVANCES IN MECHANICAL AND INDUSTRIAL ENGINEERING ICAMIE 2020 aims to solidify knowledge of sister branches of research on Mechanical Engineering applied to Industry Health Sectors Energy Sector Agricultural Sector etc Mechanical Engineering is a core branch of Engineering with its own peculiarities and very diverse areas of action ICAMIE 2020 will widen the scope of

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and leann are in the process of robbing a house when the two residents of the house show up

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