THERMAL FRACTURE ANALYSIS OF FUNCTIONALLY GRADED COATINGS ON A HOMOGENEOUS SUBSTRATE

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Abstract
The paper deals with thermal fracture analysis of a functionally graded coating (FGC) on a homogeneous substrate (FGC/H) with the goal to find a direction for optimizing the material combination and gradation of FGCs to improve the thermal fracture resistance of FGCs.

1. Introduction

Functionally graded coatings (FGCs) are used in different engineering structures, but the most important application is in high temperature protection components such as gas turbine engine parts where thermal barrier coatings (TBCs) protect metal parts from overheating. To increase the capacity of the engines, the operating temperature should be increased, and this depends on the further improvements of FGCs. Conventional TBCs often have the problems of spallation and cracking in service owing to high residual stresses between the ceramic coating and the metallic substrate. FGCs with a gradual compositional variation from heat resistant ceramics to fracture-resistant metals have been used in order to reduce residual stresses and improve the long-term performance of TBCs. However, in FGCs, defects and microcracks can occur as a result of the manufacturing process or operation. In this regard, the study of fracture of FGCs is an important problem.

2. Formulation of the problem and results

The general geometry of the problem is shown in Fig.1a. It is supposed that pre-existing arbitrarily located cracks are present in the FGC. The FGC/H is cooled by ΔT (from operating temperature) and additional tensile load is applied to the structure, Fig. 1a. The thermomechanical properties of the FGC are assumed to be continuous functions of the thickness coordinate. The thermal and elastic properties of FGMs are modeled from the point of view of their practical application and suitability for solving the optimization problem in the future. In particular, the formulas based on the rule of mixtures (RoM), applied for composite materials, are useful for these purposes. Early studies, which were focused on estimating the effective properties of FGMs, e.g. [1], have shown good validity of such models in micromechanical modeling of FGMs. To apply a fracture criterion for the FGC, it is necessary to know the fracture toughness K_{Ic} of the FGC, which varies with the coating depth. Therefore, the fracture toughness K_{Ic} of the FGC is evaluated based on the available values of the fracture toughness of the constituent materials of the FGC, and applying appropriate RoM formulas. The mechanical and thermal properties of materials vary significantly with temperature and this is taken into account in the parametric analysis by choosing appropriate material parameters.

As in the previous author's works, e.g., [2], the thermal and thermo-elastic problems are formulated by means of singular integral equations. The solution is obtained numerically, using special quadrature formulae (based on Chebyshev polynomials) for the integrals. The semi-analytical approach allows to correlate the structural material parameters (material gradation, crack parameters) and the thermo-mechanical loading parameters with the main fracture characteristics, such as the thermal stress intensity factors (TSIFs), the critical heat fluxes, as well as the fracture angles, i.e. the angles of initial crack propagation directions. A detailed parametric analysis helps to find a direction for optimizing the gradation of the FGC (material parameters) and the structure (geometrical parameters).

A series of numerical experiments are carried out. Programming is performed in the Matlab environment. Fig. 2 shows the influence of the thermal load Q and the gradation parameter λ on the critical loads for the three edge cracks inclined by 90° to the surface (Fig. 1b). The results for crack 1 only are presented (Fig.2). The behavior of crack 3 is similar to that of crack 1, and for crack 2 the critical loads are less than for cracks 1 and 3. The distance between the cracks is d = 4.0, the half crack length is a = 1.0 and h = 4. An increase of the thermal loading Q causes a decrease of the critical load (Fig. 2), i.e., a reduction of the resistance to crack propagation. This is due to the higher loading (additional residual stress) acting on the cracks.

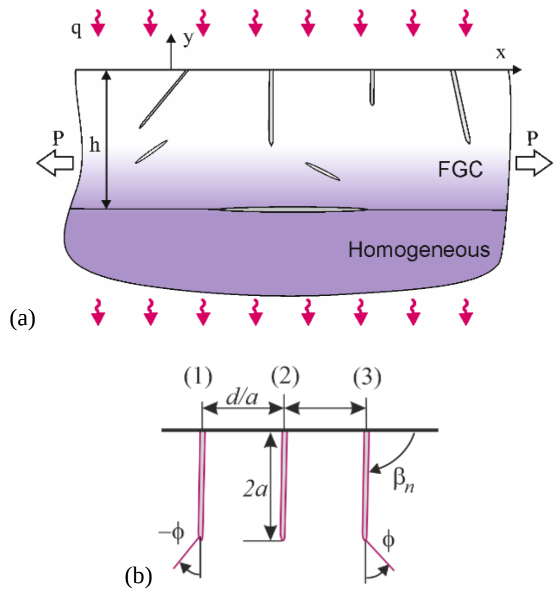

Fig. 1. Geometry of the problem (a), three edge cracks (b)

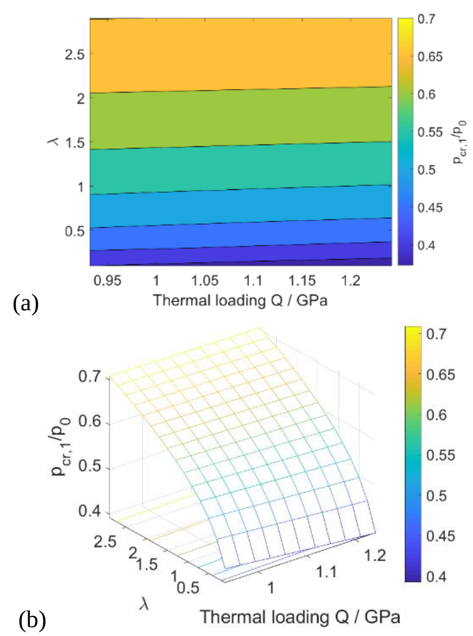

Fig. 2. Critical loads as functions of λ and thermal load Q

As the parameter λ increases, an increase in critical loads is observed, as shown in Fig. 2. A higher gradation parameter means higher metal content and less ceramic content. Therefore, the fracture toughness through the thickness of the FGC as a whole increases when the gradation is shifted towards the metal. But the main purpose of TBC systems is that the ceramic component prevents the overheating of the base metal due to its low thermal conductivity. So, it is important to have a balance of ceramic and metal contents in order to have a functional coating.

3. Conclusions

Based on the developed theoretical model, which makes it possible to correlate material parameters, geometric parameters and main fracture characteristics, it is possible to solve an optimization problem, for example: to find the gradation parameter and the location of cracks that maximize thermal critical stresses, that is, increase the fracture toughness for FGCs.

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