FAILURE MODEL OF PROTECTIVE COATINGS

Asher A. Rubinstein and Yaliang Tang
Department of Mechanical Engineering, Tulane University
New Orleans, LA 70118, USA

Summary. The integrity and reliability of protective coatings under thermal and mechanical loadings are addressed. A rigorous analytical – computational model is presented. It relates the loading and the developing system of cracks through the coating and along the interface with associated crack driving parameters. The developed model serves as a guiding tool for service life predictions.

INTRODUCTION

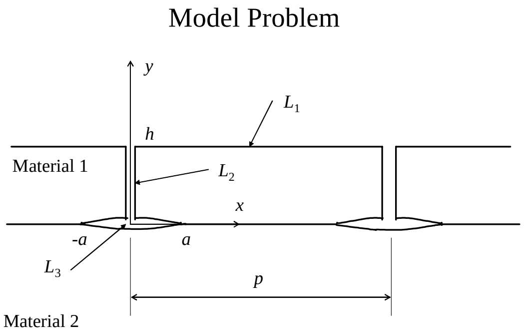
The efficiency of aircraft engines can be improved significantly by increasing the temperature in the combustion chambers and the gas path temperatures in the high-pressure turbine sections. The temperatures in these areas of today's high thrust engines exceed the temperature capability of typical turbine metallic alloys. To combat this situation, ceramic thermal barrier coatings (TBCs) have been developed for application to turbine and diesel engine components. The ceramic layer is deposited on a metallic alloy substrate. In the course of fabrication, the formation of the surface of the coatings has a mud pie appearance with a system of small surface cracks serving as the boundaries. In a reasonably short service period, these initial cracks propagate through the thickness of the coating layer and reach the coating - substrate interface. These initial cracks through the coating layer form a network that in two-dimensional illustration may be presented as a periodical crack system. The formation and propagation of the interfacial cracks connecting the initial periodical system are essential steps of the developing failure in TBCs. The development of an analytical - computational model characterizing the failure process in TBCs in detail is the primary purpose of this project. The developed model is planned to be used as a tool for service life prediction of components with TBCs. In practical terms, one needs to determine the actual fracture mechanics parameters that initiate internal microcracks and promote their growth during specific thermo-mechanical service cycles.

THE MODELING CONCEPT

The initial surface cracks may be relatively short initially but, as was observed, they may reach the interface between the ceramic coating and the base metal in a relatively low number of service cycles. Typically, these cracks do not propagate through the interface into a substrate but rather deflect and continue to grow along or near the interface. Thus, the main safe service period of TBCs is primarily dependent on the time, or number of service cycles, required for these cracks to cross the link holding the individual "grains" attached to the substrate. The two dimensional schematic illustration of this process is given in Figure 1, which illustrates the model problem. The initial interface cracks are depicted as a periodically distributed net of cracks.

The modeling approach is based on the described observations. The practical goal is to determine the safe service time of the components with TBCs. Taking a conservative approach, the modeling effort concentrates on the time required for the cracks to bridge the interfacial link holding the coating layer. To make this determination, it is necessary to evaluate all crack growth driving parameters as they develop along the crack path. Determination of the stress intensity factors and the energy release rate as the crack progresses along the interface is a necessary step toward service life prediction. Establishing an analytical - computational relationship between these parameters and the thermomechanical loading parameters during the service cycle is the basis of the life prediction scheme for TBCs.

Although the process is three dimensional, a two dimensional problem could provide sufficient information regarding the nature of the process. The average "grain" size, that is, the parameter describing the initial spacing of the net of surface cracks, determines the size of periodic crack cells in a two-dimensional cross section. That is a period *p*, as illustrated in Figure 1. The initial spacing of the surface cracks depends on the fabrication process parameters and, possibly, can be controlled by the manufacturing process.



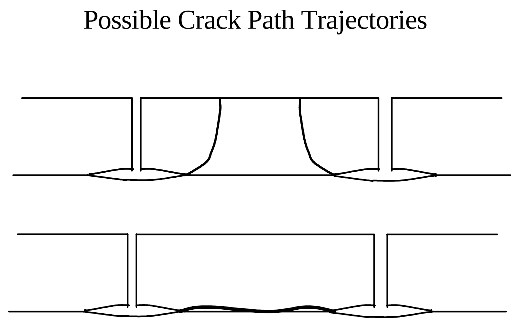


Figure 1. Initiation and growth of Interface cracks.

Figure 2. Illustration of possible crack path trajectories

Two alternative crack path directions are illustrated in Figure 2. Identification of a specific crack path option for a given TBS system is an important component of failure model development in this framework.

The numerical examples were computed using the data from experiments described by Zhu and Miller [1]. The definitions of the stress intensity factors and the energy release rate along the interface used in the computations are consistent with the definitions introduced by Rice and Sih [2].

The numerical examples represent the stress states developed under the thermal loads applied as a constant temperature at the surface and as a result of a cyclic temperature. Similarly, the heat flux boundary conditions were used.

CONCLUSIONS

Essential data leading toward an understanding of the interface crack driving force developed due to thermal loadings were established using a rigorous analysis of the corresponding thermoelastic problem. The present work is a basic development toward a service life prediction model for TBCs. This is an important technological step for potential commercial applications of the TBCs.

Acknowledgement. The work presented here was supported by NASA under Grant NAG3-2689.

References

[1] Zhu, D. and Miller, R. A. Influence of high cycle thermal loads on thermal fatigue behavior of thick thermal barrier coatings. NASA technical report, 3 – 10, NASA TP – 3676, 1998.

[2] Rice, J. R. and Sih, G. C.(1965) Plane problems of cracks in dissimilar media. *Journal of Applied Mechanics*. Vol.32, pp.418-423.