THERMOELASTIC ANALYSIS OF FUNCTIONALLY GRADED MATERIALS SUBMITTED TO SHOCKS

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Summary In this present work, it presents a model to solve the strongly coupled thermomechanical problem submitted to thermodynamic solicitations. Traditional staggered algorithm without upsetting the unconditional stability property characteristic of fully implicit schemes is used. Numerical simulations are presented for a bar with materials FGM submitted to thermal loadings and analysis is accomplished for cases of thermal shocks.

Introduction

Layered composite materials due to their thermal and mechanical merits compared to single-composed materials, have been widely used on a variety of engineering applications. However, the interfaces might represent regions of stress concentration and, due to that, risk of presenting failure mechanisms like lost of cohesion. For instance, linear elastic materials present stress singularities at the interfaces or at the free edges. In recent years, nonhomogeneous materials have been developed to attenuate the interfacial stresses under a new concept: functionally graded materials (FGMs). FGMs are composites whose mechanical properties vary smoothly or continuously along its domain. They have been used in thermal protection systems due to their high temperature resistance in order to decrease thermal stresses distribution and to increase the effect of protection from heat. It is possible by controlling the volume fractions of these materials to obtain very different thermomechanical responses. The utilization of FGMs in the attenuation of stress wave propagation[1] can be very useful in important engineering applications like, for instance, the re-entry motion of space vehicles, in which a rapidly changing temperature can lead to a dramatic failure scenario. In this type of situations the dynamic thermoelastic response should be considered. Dynamic thermoelastic problems have been studied, since several decades, in different structures[2, 3]. Transient response prediction of thermodynamical loaded structures without mechanical coupling[4] considering FGMs have been studied. The present work presents a numerical formulation to solve the strongly coupled thermomechanical problem submitted to thermal shock like solicitations. A staggered algorithm without upsetting the unconditional stability property characteristic of fully implicit schemes is used. The proposed scheme is a fractional step method associated with a two phases operator split of the linearized thermoelasticity system into an adiabatic elastodynamics phase, followed by a heat conduction phase. Numerical simulations are presented for an FGM bar submitted to an abrupt variation of external temperature representing thermal shocks.

Numerical Modeling of the coupled FGM thermomechanical problem

Here, a FGM material is considered as binary composite in which a power-law distribution governs the composition of the basic material volume fraction. Based on microstructures theory, this volume fraction determines the effective mechanical properties of the composite. Particularly, the rule of mixture was employed. The coupled thermomechanical stems from the balance equations of momentum and energy and from constitutive equations that use the effective thermomecanical properties. Among then, the parameter that is responsible for thermomechanical coupling. This parameter has a direct relation with the thermal dilatation coefficient and the Bulk modulus, and it is very important to verify this thermomechanical effect and defines the strategy for the solution of this kind of problem.

The proposed strategy for the solution of this linear coupled first order system of partial differential equations of mixed hyperbolic parabolic type in this thermoelastic problem is a staggered scheme in which partitions this linear differential operator in two distinct phases. It consists in one adiabatic elastodynamic phase, in which the entropy of the system is held constant, followed by a heat conduction phase at fixed configuration[5]. This method of solution for this problem obtains, as a consequence, no dissipation within the mechanical phase, since the total entropy is remained constant, while the dissipation in the subsequent thermal phase is the total dissipation generated by heat conduction. Initially one solves the adiabatic elastodynamic phase with spatial discretization by the Finite Element Method (FEM) combined with the time discretization provide by the Crank Nicholson scheme, well known to be second order accurate and unconditionally stable. Using the values obtained in the mechanical phase, the final temperature field by applying an unconditionally B-stable scheme to heat conduction is computed. A rigorous stability analysis of this specific split of the evolution thermoelastic problem by the staggered algorithm is achieved making use by Von Neumann stability and via the energy method analysis[5].

Numerical Results

To assess the thermoelastodynamical response in FGM structures, a simulation involving a one-dimensional composite bar with two dissimilar materials of uniform thickness with transversal area 3.10^{-4} m^2 and length total 310mm is presented. The bar is divided into two different regions, the first one of 10mm corresponds to the thermal protection while the second region represents the basic structure .The metal and ceramics layers selected are SUS304 steel and PSZ ceramic. In order to understand the role played by different composites obtained by using different distributions of the components, two situations are analyzed. In the first case the composite presents two homogenous regions, therefore not constituting an FGM and presenting an interface. In the second one, a typical smooth transition is provided by an FGM with the same volume fraction of the components. In the first case, the thermal shield is constituted of pure ceramic and in the second situation a FGM composite is adopted. These materials are submitted to external abrupt temperature variation in the left corner and the bar's initial temperature is 300K. In both cases, the bar is clamped at the ends and thermically isolated at 300K in the right border. A pulse de temperature is applied to these materials to estimate the stress wave propagation by thermal shock conditions.

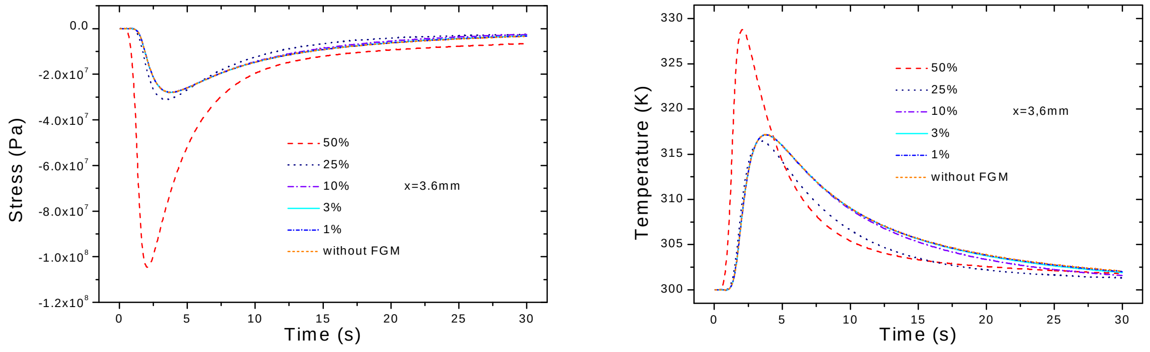

Figure1- Stress and temperature distributions at 3.6mm of PSZ/steel FGM bar submitted to temperature pulse 1000K with variation of material composition.

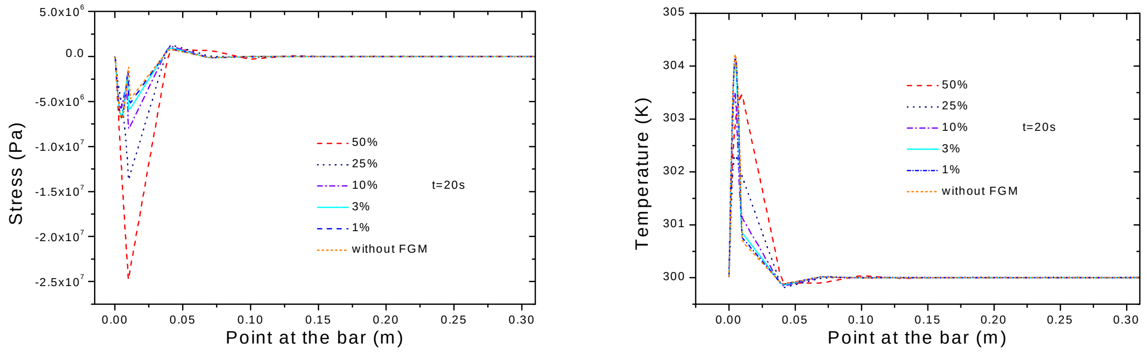

Figure2- Stress and temperature distributions in the domain of PSZ/steel FGM bar at the time 20s after submitted to temperature pulse 1000K with variation of material composition.

The numerical solution involves a spatial discretization consisting of 20 linear finite elements, 10 in each dissimilar material. Initially, two numerical simulations are considered, corresponding to application of temperature submitted to different materials. The figure1 shows the stress in time at 3.6mm of the first corner of the bar. One can observe that the bar experiments tension in the beginning, immediately followed by compression. This fact occurs because the bar is clamped in both ends. The compositional variation in the FGM bar, given by volumetric percentual, breeds new stress and temperature fields as observed. One can verify that when decreasing the volumetric percentual material, which means that a greater quantity of PSZ ceramic is used in the FGM, the amplitude of stress and temperature decrease. Furthermore, in the first case, where the FGM solution is not applied, the initial portion of the bar corresponding to the thermal shield, present the lower peak stress. Nonetheless two important aspects must be considered. The peak stress obtained with FGM's shield are in compression, which seems no to represent an important danger, as ceramics are fragile materials and do not resist to traction. The second, and most important, aspect is related to the fact that the stress distribution obtained when FGM shows a significant better behavior in what concerns the interface between the thermal protection and the structure as it is presented in Figure2.

Conclusions

A numerical formulation based on a staggered approach is used to understand the role of FGM materials for enhancing the quality of thermal protection systems. The variation of the composition is analyzed by comparing the thermomechanical of the different resulting systems.

References

[1] Jin Z.-H., Paulino G.H.: Transient thermal stress analysis of cracked functionally graded materials, *Ceramic Transactions* **114**: 747-754, 2001.

[2] Cho H., Kardomateas G.A.:Thermal shock stresses due to heat convection at a bounding surface in a thick orthotropic cylindrical shell. *Int J. Solids Struct* **38**: 2769-2788, 2001.

[3] Praveen G.N., Reddy J.N.:Nonlinear transient thermoelastic analysis of functionally graded ceramic-metal plates. *Int J. Solids Struct* **35**: 4457-4476, 1998.

[4] Turteltaub S.: Optimal control and optimization of functionally graded materials for thermomechanical processes. *Int J. Solids Struct* **39**:3175-3197, 2002.

[5] Armero F., Simo J.C.: A new unconditionally stable fractional step method for non-linear coupled thermomechanical problems. *Int J. Num Met in Eng* **35**: 737-766, 1992.