EFFECT OF LATERAL PLACEMENT OF CERAMIC AND METAL GRAINS ON THERMAL STRESS DISTRIBUTION THROUGHOUT FGMS

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Abstract

The properties of Functionally Graded Materials (FGM) are characterized by gradual variation of volume fraction of their constituents or phases over the thickness direction. They are normally ceramic in one side and metal in the other side. This kind of material has been employed as thermal barrier and also as coatings in many applications including turbine blades. Thermal stress behavior of FGMs is normally studied by simulating the material as a composite laminate where the properties of each layer are found by averaging the properties and volume fraction of FGM constituents through the thickness of the layer. However, it should be mentioned that the grains of FGM constituents are usually placed irregularly through the layers and the effect of lateral placement of grains is neglected which may affect the distribution of the stresses.

In the present study a finite element micromechanical model is developed to study the effect of lateral placement of grains on thermal stress distribution. Furthermore, the former approach leads into an average thermal stress through the layer width, while, here the thermal stress is presented in micro size (grain size) level. The obtained results show that the effect of lateral placement of the grains is noticeable when the unit cell width of the FGM is large enough to influence the stress distribution.

1 Introduction

The Concept of Functionally Graded Materials (FGMs) was proposed in 1984 in Japan. FGMs are multi-component composites in which the volume fractions of constituents are varied along the dimensions of material. The main application of FGM is in Thermal Barrier Coatings (TBCs). These FGMs are normally ceramic in one side and metal in the other side and can restrict initiation of cracks in ceramic and the interface of bound coating layers which increases adhesion of these layers [1]. High thermal loadings on ceramic surface of TBCs produce high thermal residual stresses in FGM layers. The residual stresses could lead to initiation of cracks and some other defects in TBCs. It is believed that unknown aspects of FGMs behavior under long run thermal loadings account as a primary reason for Columbia space shuttle crash in 2003 [2].

The residual stress in FGMs has been the subject of several researches. Both macro and micromechanical modeling approaches have been used in these studies. Jacoub Aboudi has named these two approaches as uncoupled and coupled, respectively. [3]

In the macro mechanical approach, FGM is modeled as a multi-layer composite in which mechanical properties of each layer is found by averaging the properties and volume fraction of FGM constituents through the thickness of the layer. In this approach, each layer is modeled as a composite. There are several models which relate mechanical properties of two constituent composite to volume fraction and mechanical properties of each one of the constituents. Some models are presented and compared in [4]. Upper and lower boundaries for material properties of composites are presented in [5]. Most researchers have used this approach to calculate the residual stresses in FG materials.

In micromechanical approach FGM is modeled by placement of the grains of constituents in special arrangements. In some studies [6], grains are modeled using real FGM cross section SEM images. In some other studies [7], rectangular or hexagonal-shaped grains have been used. In these studies longitudinal arrangement of grains (number of each constituent's grains in each layer) is found by averaging the volume fraction of the constituents in each layer. In parallel, lateral arrangement of grains (placement of grains in each layer) is considered to be irregular.

The residual stress calculated by means of micromechanical approach is referred to as grain size stress. The high grain size stresses could lead to small scale cracks and these small scale cracks may in turn lead to large scale cracks. So, the grain size stress could be responsible for initiation of large scale defects. According to [8], the average value of the grain size stresses in each layer could equal the micro-mechanically calculated stresses of the layer.

In [8], the residual stress has been calculated for 2D-FGMs. These kinds of FGMs are consisting of three constituents unlike the conventional FGMs which contain two constituents, only. In 2D-FGMs the volume fraction of the constituents is a function of both width and thickness of the structure. It was shown in [9] that the performance of FGMs could be improved using 2D-FGMs instead of conventional FGMs when thermal loading is varied over the coated area.

In the present study a finite element micromechanical model is developed to study the effect of lateral placement of FGM grains on thermal stress distribution. This effect is examined by changing the width of FGM model, as well. Furthermore, the macro mechanical approach leads into an average thermal stress through the layer width, while, here the thermal stress is presented in grain size level. In this study the maximum grain size stress of the constituents in each layer is represented. The average stress of each layer which can represent the macro mechanical stress of the layer is also provided. For further studies the effect of grain shapes could be examined.

2 Modeling

Functionally graded materials could be modeled by a variation of volume fraction of constituents over thickness of the model. In micromechanical approach, the grains of constituents are arranged in a particular way to meet the desired volume fraction variation of the constituents over the structure thickness.

The graded model selected for this study is based on a rectangular grain array of constituents which are placed in a desired arrangement. Figure (1) shows a typical arrangement of rectangular grains in the FGM layer.

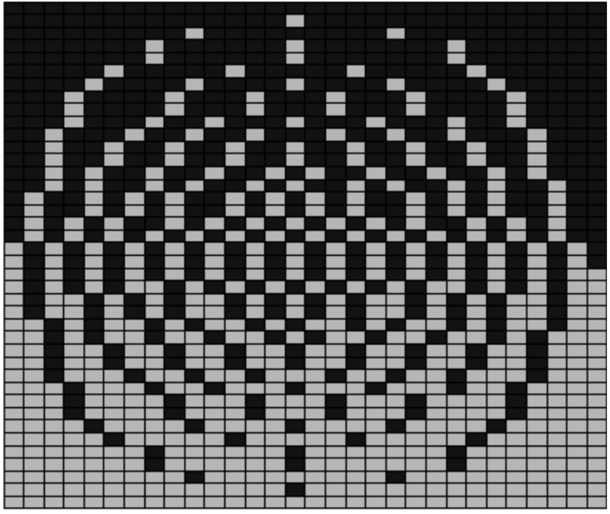

Fig. 1. Modeling of FGM's with rectangular grains for the constituents

Figures (2a and 2b) show some different lateral arrangement of the grains of constituents where volume fraction of constituents is constant through each layer of FGM.

The plane223 element of ANSYS element library is chosen to model the FGM coating. This element is capable of solving thermo physical problems; so no further operations are needed to compute thermal stresses.

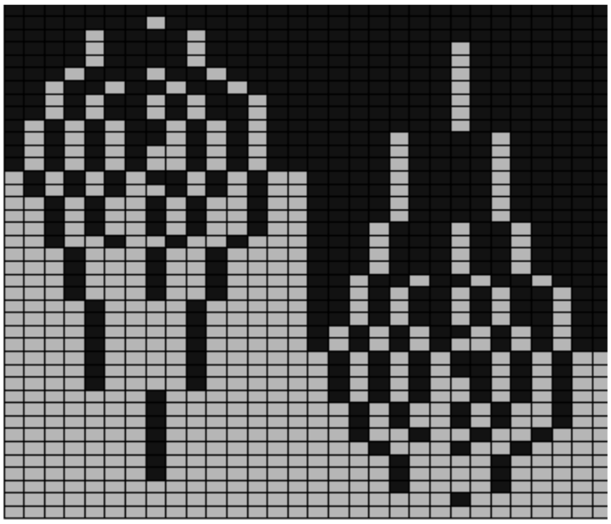

Fig. 2a. Some different lateral arrangement of grains

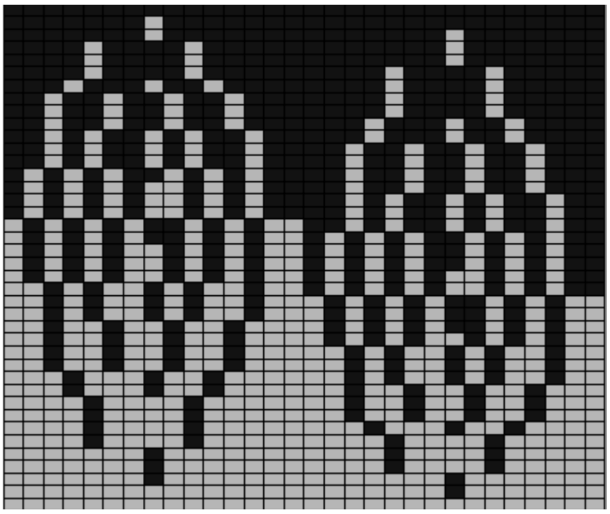

Fig. 2b. Some different lateral arrangement of grains

Figure (3) shows the meshing used to model the substrate FGM and ceramic layers.

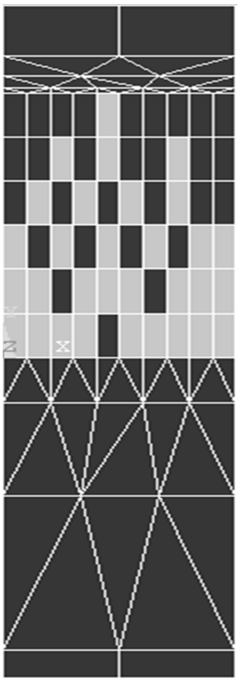

Fig. 3. FEM meshing of the FGM models

The variation of volume fraction of constituents along the thickness is assumed to be linear. Temperature dependent material properties of the substrate, bond coat and ceramic layers are presented in Tables (1a to 1c).

Table 1a Metal properties

Temp. ($^{\circ}$K)	E_m (GPa)	α_m	K_m $(\frac{W}{m\ ^{\circ}C})$	ν_m	C_m $(\frac{J}{^{\circ}C})$
300	64.5	1.03e-5	3.82	0.3	460
1000	53	1.05e-5	7.93	0.3	617
1500	43	1.14e-5	9.86	0.3	617

Table 1b Ceramic properties

Temp. ($^{\circ}$K)	Ec (GPa)	α_c	Kc $(\frac{W}{m\ ^{\circ}C})$	νc	Cc $(\frac{J}{^{\circ}C})$
300	13.6	7.5e-6	0.67	0.25	492
1000	10.4	9.0e-6	0.58	0.25	614
1500	8	9.7e-6	0.56	0.25	652

Table 1c Substrate properties

Temp. ($^{\circ}$K)	Es (GPa)	αs	Ks $(\frac{W}{m\ ^{\circ}C})$	νs	Cs $(\frac{J}{^{\circ}C})$
300	206.7	1.53e-4	15.37	0.3	434
1000	130.9	2.23e-4	15.37	0.3	434

Macro mechanical stress of each layer is computed by averaging the grain size stresses in that layer.

The thermal loading (T = 1473 ◦K) is applied to the coating through convection while the temperature of substrate is set at ambient temperature of 273 ◦K. The convection heat transfer coefficient is assumed to be 2873 watt per square of meter degrees of centigrade. The substrate, FGM and ceramic layer thicknesses are 2, 0.6 and 0.2 mm respectively and the model width is assumed to be 0.15 mm.

3 Results and discussion

In the first part of this section, a discussion about the maximum grain size stress of each constituent and average stress in each FGM layer is presented. In the subsequent section, the effect of lateral distribution of the grains of constituents is examined. In the same section, the effect of lateral distribution of grains with different width for the FGM model is also presented.

3.1 Thermal stress distribution

Figure (4) shows thermal stress distribution over thickness of the coating. For the substrate and ceramic layers the maximum thermal stress is equivalent to the average thermal stress. This is due to the homogenous behavior of substrate and ceramic parts. However, due to non-homogeneous behavior of the FGM region, the value of the maximum thermal stress in this region is not equivalent to average thermal stress. Maximum thermal stress in ceramic-rich layers is greater than the maximum thermal stress in metal-rich layers of the FGM. It is considered to be the result of higher temperature of metal grains in ceramic-rich layers as well as inclusion behavior of metal grains in ceramic matrix (see Figures 4 and 5). However, the average through thickness thermal stress of FGM is decreased from metal-rich to ceramic-rich layers.

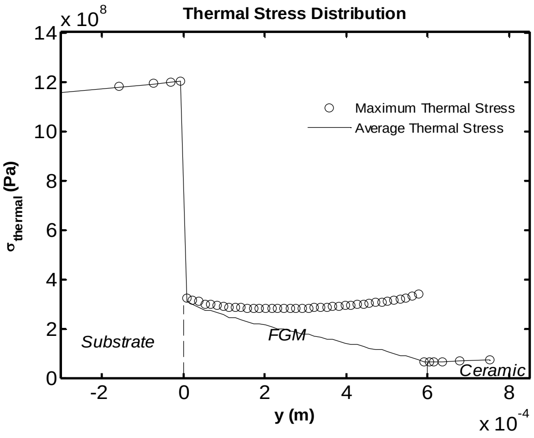

Fig. 4. Thermal stress distribution over thickness of coating

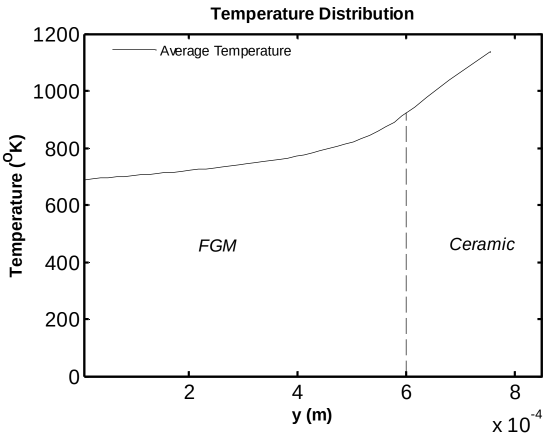

Fig. 5. Temperature distribution over thickness of FGM and ceramic

Figure (6) shows location of the grains with maximum stress. It is seen that maximum stress in every layer occurs in metal grains.

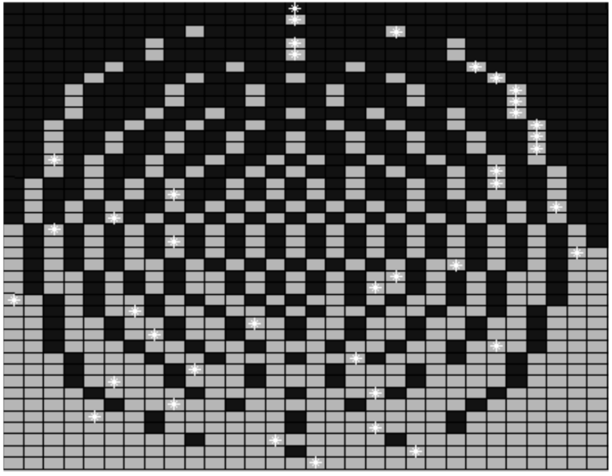

Fig. 6. Maximum stress location shown by * Black and gray elements represent ceramic and metal grains Respectively.

Figure (7) shows the metal and ceramic maximum stresses and average stress distribution through thickness of FGM. It shows that the maximum stress in ceramic grains occur in metal-rich layers of FGM where the grains behave as inclusions in metal matrix. The average stress through each layer is equal to the mean value of metal and ceramic grains stresses through the layer. So the stress in metal rich layers, where volume fraction of metal is more than ceramic volume fraction, is dominated by metal grains stresses. It should also be noted that this stress is higher than average stress in ceramic-rich layers where average stress is dominated by ceramic grains stresses.

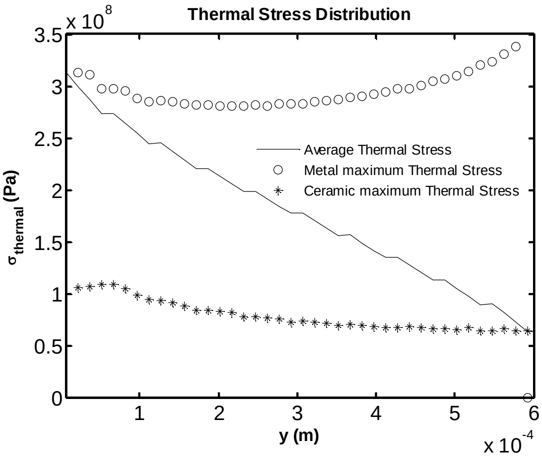

Fig. 7. maximum stress and average stress distribution for metal and ceramic.

3.2 Effect of lateral placement of grains

To examine the effect of lateral placement of the grains, two models are considered. These models are shown in Figures 8 and 9 which are named normal and triangular grain placement models, respectively.

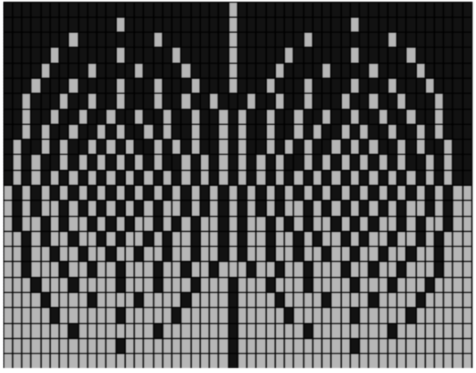

Fig. 8. Normal placement of grains

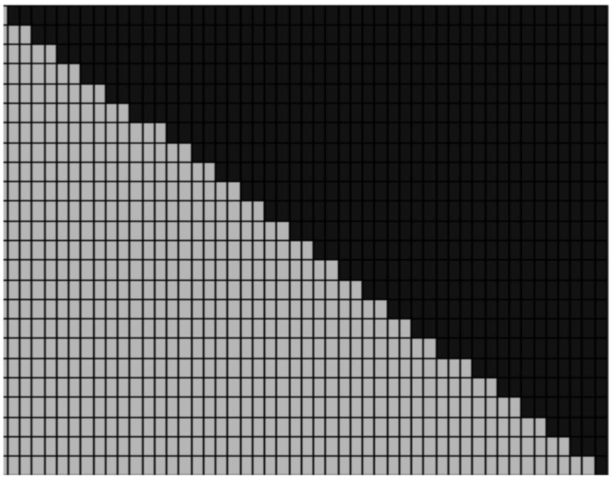

Fig. 9. Triangular placement of grains

Figure 10 shows the effects of lateral placement of grains on maximum and average stress distributions of the FGM. It is understood that lateral distribution of grains results in small changes in average stress distribution; however it is accompanied with larger changes in maximum thermal stress distribution. According to Figure 10, the maximum thermal stress is decreased by using triangular lateral placement of grains, instead of normal lateral placement. It is because of the lower temperature of metal grains in triangular placement of grains (see Figure 11. This phenomenon is justified by opening the heat transfer channel in triangular placement of grains, where the constituent grains are located beside each other. However, in normal placement of grains the heat flux is trapped in metal grains (because the interfaces of metal grains with ceramic grains do not allow heat flux to cross the metal grains easily) and it will result in higher temperature of metal grains. The other reason for lower maximum stress in triangular grain placement arises from the minor interfaces of metal and ceramic grains in this placement (see Figure 8).

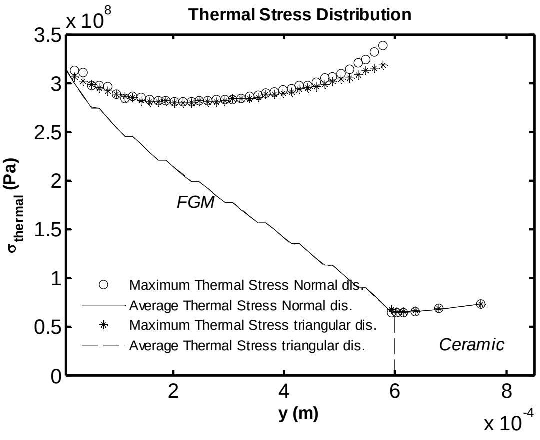

Fig. 10. Effect of lateral placement of grains on maximum and average stress

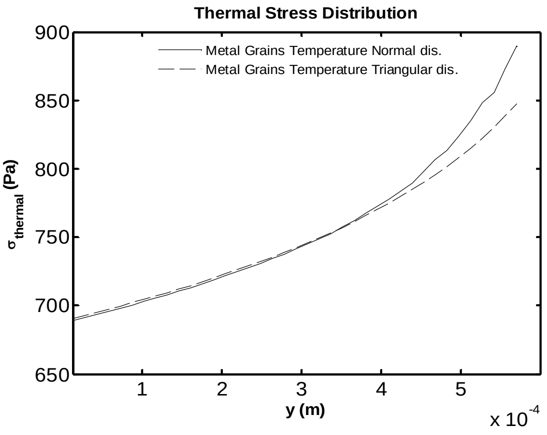

Fig. 11. Effect of lateral placement of grains on metal grains temperature

3.2.1 Effects of lateral placement of grains on models with variable width

Figure 12 shows that the effect of lateral placement of grains is highly pronounced when the width of model is increased. It happens because the width of heat transfer channel, which was introduced in previous section, is increased and therefore the temperature of metal grains is decreased more than the case in which the model width is less due to using triangular placement (see Figure 13).

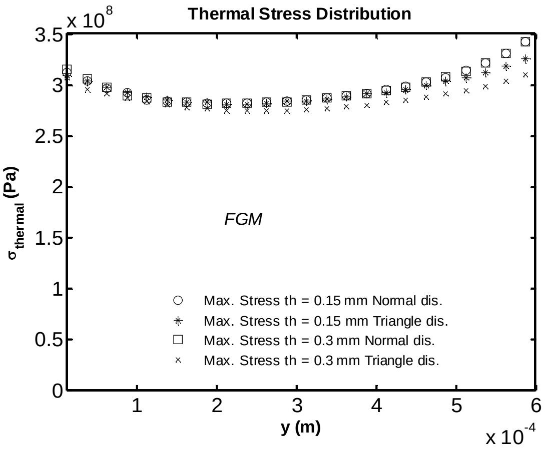

Fig. 12. Effect of lateral placement of grains on maximum stress when model width is changed

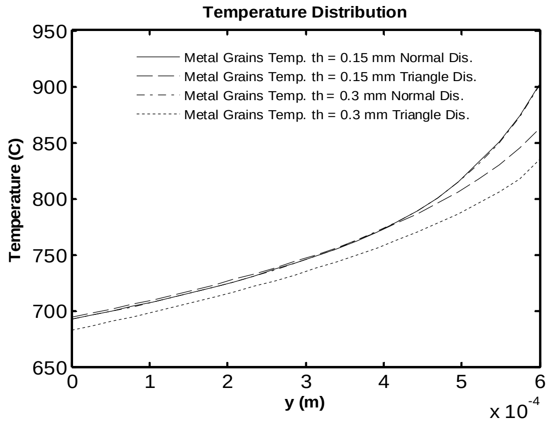

Fig. 13. Effect of lateral placement of grains on the temperature of metal grains when model width is changed

Also, according to Figures 12 and 13, maximum thermal stress distribution and temperature distribution of normal lateral grain placement of FGM is independent of the model width. This conclusion was predictable because the used boundary conditions make the models the same. In fact with the applied boundary conditions all the considered models represent the same macro scale example problem.

4. Conclusions

This study concerns grain size stresses in FGMs which are used as a part of thermal coating. It was shown that maximum grain size stress occurs in metal grains and maximum stress magnitude is impressed by inclusion behavior of ceramic and metal grains. Also, the effects of lateral placement of grains on thermal stress distribution are observed. Finally, it was shown that maximum grain size stress can be decreased by using triangular lateral placement of the grains.

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