Thoretical Study of the Improvement of Brittle Fracture Characteristics in Functionally Graded Material Bodies(傾斜機能材料のぜい性破壊特性の改善に関する理論的研究)

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論文内容要旨

Introduction

Functionally graded materials (FGMs) are special composites consisting of two or more distinct material phases and are mixture of them such that the composition of each changes continuously with space variables and thus have both thermal and mechanical nonhomogeneities. The main advantages of composition grading in FGMs appear to be improved bonding strength, toughness, wear and corrosion resistance, and reduced residual and thermal stresses. Some typical examples include thermal barrier coatings of high temperature components in gas turbines, surface hardening for tribological protection and graded interlayers used in multilayered microelectronic and optoelectronic components. However, although the absence of sharp interfaces in FGMs does largely reduce material property mismatch, cracks may occur when they are subjected to external loadings, which may ultimately cause failure. To protect this failure and take full advantages of FGMs, fracture study of these materials is therefore necessary to understand, quantify, and improve their toughness. The objective of this study is to improve the brittle fracture characteristics in FGM bodies under mechanical loading. First, an approximation method is developed to calculate the stress intensity factor for a crack in FGM bodies with incompatible eigenstrain and an arbitrary distribution of material properties. This method is applied in inverse calculations of material composition profiles from prescribed apparent fracture toughness that corresponds to improved brittle fracture characteristics in FGM bodies. For this purpose, three different geometries are considered: i) semi-infinite FGM bodies, ii) infinite FGM plates with a circular hole, and iii) thick-walled FGM pipes.

Approximation Method for Stress Intensity Factors

Functionally graded materials are nonhomogeneous solids and, therefore, their nonhomogeneities have to be considered in studying the fracture behavior of these materials. The consideration of these nonhomogeneities complicates the analytical studies due to mathematical difficulties. Thus it is often conventional to regard the material properties to be some certain assumed functions of space variable, for instance, exponential and power functions, in order to simplify the problems. However, in designing with FGMs *i.e.* in the inverse problems, in which material composition profiles have to be determined to achieve desired fracture characteristics, special functional forms of the properties cannot be assumed. Since these assumed functional forms of the properties may not be physically realizable for some material composition profiles obtained by inverse calculation. Therefore, as an alternate approach, an approximation method is developed in this study to calculate the stress intensity factors for a crack in FGMs, which is not restricted to any specific property distributions, but can treat any arbitrary distributions

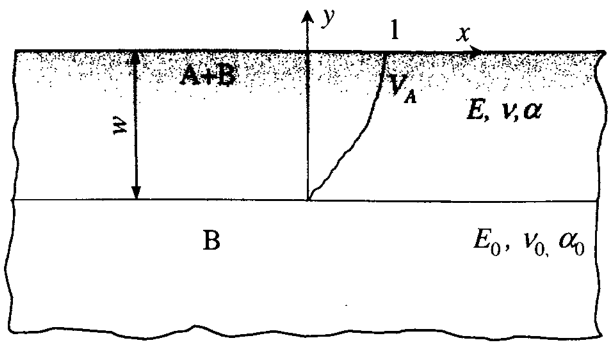

Fig. 1 Analytical model of a semi-infinite FGM body.

of the properties. This approximation method of stress intensity factors is employed in inverse problems to calculate material composition profiles of FGM bodies for prescribed fracture characteristics. The concept of the approximation method is explained below.

First, the FGM bodies are homogenized by simulating their nonhomogeneous properties by a distribution of equivalent eigenstrain. The distribution of the equivalent eigenstrain to be determined is such that the elastic fields are identical in both the FGM and the homogeneous bodies under the same loading conditions. After determining the distribution of the equivalent eigenstrain, a method is formulated to calculate the stress intensity factor for a crack in the homogeneous bodies subjected to external loadings. Since the equivalent eigenstrain is determined from the condition of identical elastic fields in the uncracked FGM and homogeneous bodies, the elastic filed in the cracked homogeneous bodies cannot exactly represent the elastic field in the cracked FGM bodies. Therefore, the stress intensity factors calculated for a crack in the homogeneous bodies with the equivalent eigenstrain represent the approximate values of the stress intensity factors for the same crack in the corresponding FGM bodies and hence the term approximation method has been used. The method is validated by comparing the results of stress intensity factors obtained for a crack in a nonhomogeneous infinite medium with those obtained by exact methods.

Improving the Brittle Fracture Characteristics in Semi-Infinite FGM Bodies

A model of semi-infinite FGM body is shown in Fig. 1. It consists of two constituents A and B and their volume fractions V_A and V_B continuously vary only in the region of finite width w in the direction perpendicular to the bounding surface. The constituent beyond w is purely B. The Young's modulus, Poisson's ratio and coefficient of thermal expansion of the graded and homogeneous regions are denoted by E, ν, α and E_0, ν_0, α_0, respectively. Using the approximation method for this model, the inverse calculations of material composition profiles of the graded region are carried out for improving the brittle fracture characteristics by providing higher apparent fracture toughness against an edge crack perpendicular to the bounding surface and loaded by a far field uniform applied load in the x-direction. In numerical calculations, a semi-infinite TiC/Al_2O_3 FGM body is considered in which the materials A and B, respectively, correspond to TiC and Al_2O_3. Figure 2 shows the prescribed apparent fracture toughness and the corresponding composition profiles obtained by inverse calculations are shown in Fig. 3. The line corresponding to $V_A = 0$ in Fig. 2 represents the intrinsic fracture toughness of Al_2O_3. It is seen that the prescribed

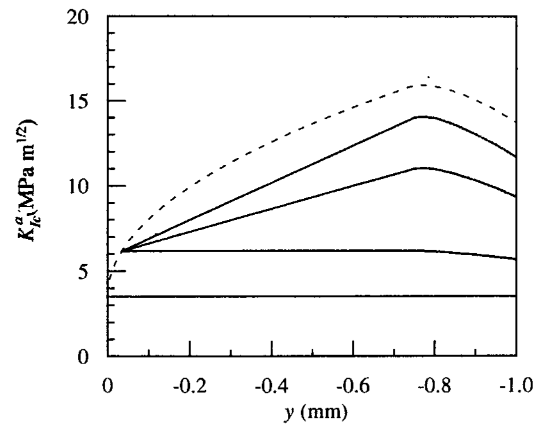

Fig. 2 Prescribed apparent fracture toughness of a semi-infinite TiC/Al_2O_3 FGM body.

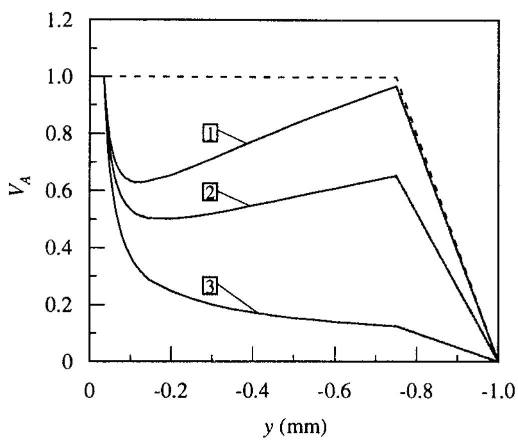

Fig. 3 Composition profiles of TiC in a semi-infinite TiC/Al_2O_3 FGM body.

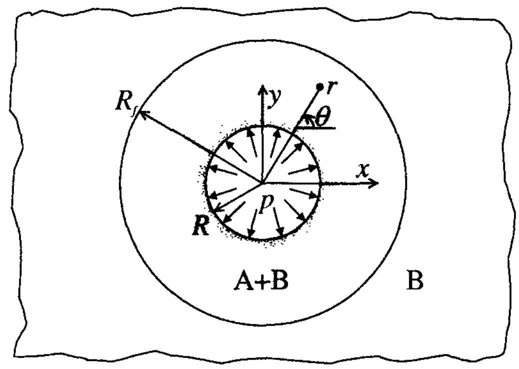

Fig. 4 Analytical model of an infinite FGM plate with a circular hole.

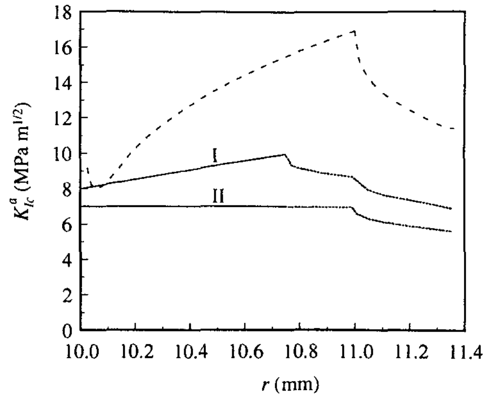

Fig. 5 Prescribed apparent fracture toughness around a circular hole in an infinite TiC/Al_2O_3 FGM plate.

apparent fracture toughness considered in examples 1, 2, and 3 is higher than the intrinsic fracture toughness of the constituents. Thus it can be said that the composition profiles shown in Fig. 3 give improved brittle fracture characteristics in the semi-infinite FGM body.

Improving the Brittle Fracture Characteristics in Infinite FGM Plates with a Circular Hole

Shown in Fig. 4 is a model of infinite FGM plate with a circular hole of radius R. The volume fractions of the constituent materials A and B continuously and radially vary in the region $R \leq r \leq R_f$ only. The region $r \geq R_f$ is homogeneous, which consists of material B only. For this model, the inverse calculations of material composition profiles are carried out for improving the brittle fracture characteristics around the circular hole by providing higher apparent fracture toughness against a radial edge crack emanating from the hole subjected to a uniform applied pressure. Materials A and B are, respectively, chosen as TiC and Al_2O_3 for numerical calculations. Figure 5 exhibits prescribed apparent fracture toughness along the radial direction that represents improved brittle fracture characteristics around the hole and Fig. 6 displays the corresponding composition profiles obtained by inverse calculations.

Improving the Brittle Fracture Characteristics in Thick-Walled FGM Pipes

A model of thick-walled FGM pipe is portrayed in Fig. 7. It consists of two constituent materials A and B whose volume fractions vary radially from the inner surface to the outer surface of the pipe. The inner and the outer radii of the pipe are denoted by R_i and R_0, respectively. The inverse calculations of material composition profiles are

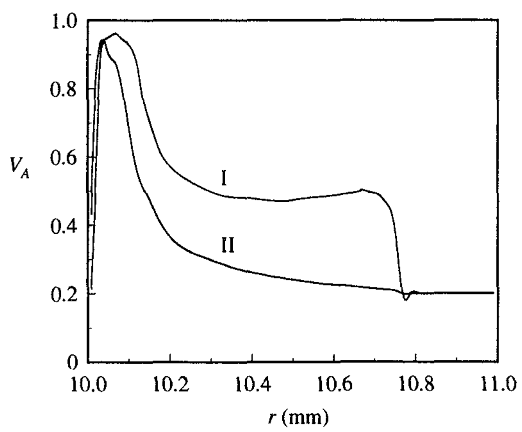

Fig. 6 Composition profiles around a circular hole in an infinite TiC/Al_2O_3 FGM plate.

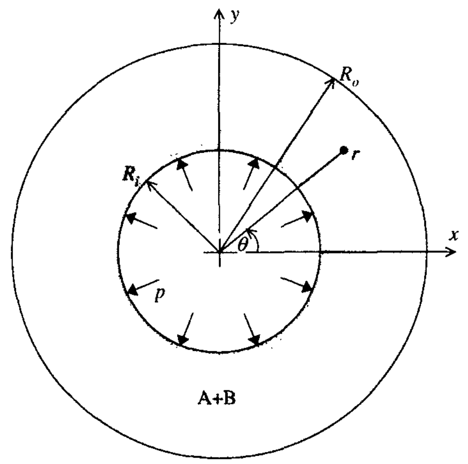

Fig. 7 Analytical model of a thick-walled FGM pipe.

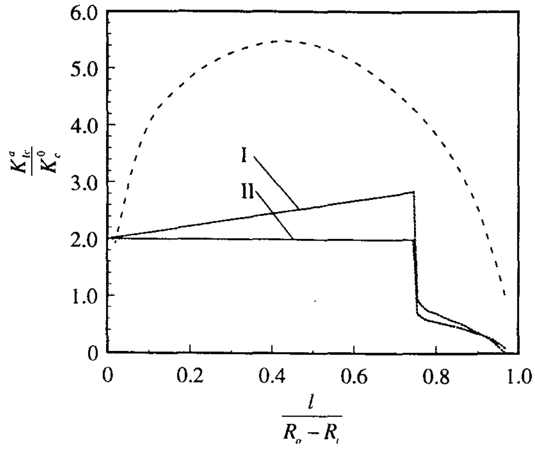

Fig. 8 Prescribed apparent fracture toughness in a thick-walled TiC/Al_2O_3 FGM pipe.

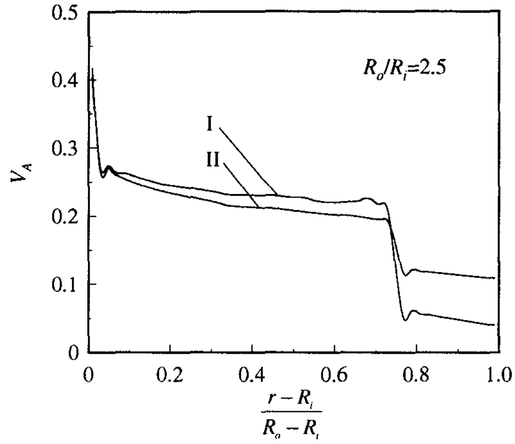

Fig. 9 Composition profiles of TiC in a thick-walled TiC/Al_2O_3 FGM pipe.

carried out for improving the brittle fracture characteristics that offer higher apparent fracture toughness against a radial edge crack emanating from the inner surface of the pipe subjected to an internal uniform pressure. For numerical calculations, TiC and Al_2O_3 are taken as constituents A and B, respectively. Figure 8 depicts the normalized prescribed apparent fracture toughness K_{Ic}^a/K_c^0, where K_c^0 is the intrinsic fracture toughness of Al_2O_3, and the corresponding composition profiles obtained by inverse calculations are shown in Fig. 9.

Conclusions

Inverse problems of calculating material composition profiles are solved for improving the brittle fracture characteristics in FGM bodies. Three different geometries of FGM bodies are considered: i) semi-infinite FGM bodies, ii) infinite FGM plates with a circular hole, and iii) thick-walled FGM pipes. In these bodies, apparent fracture toughness corresponding to improved brittle fracture characteristics is prescribed and inverse calculations of material composition profiles are carried out by using an approximation method of calculating stress intensity factors for FGM bodies with distributed incompatible eigenstrain and arbitrary variation of material properties.

The numerical results obtained for a semi-infinite TiC/Al_2O_3 FGM body reveal that i) material composition profiles in semi-infinite FGM bodies have significant effects on their brittle fracture characteristics, ii) semi-infinite FGM bodies can be designed with desired apparent fracture toughness within possible limits by properly choosing their material composition profiles, iii) for the same composition profile, apparent fracture toughness is higher in plane strain condition, iv) the apparent fracture toughness is influenced significantly by introducing periodic cracks. For the same composition profile, the semi-infinite FGM bodies with periodic edge cracks have higher apparent fracture toughness. Further, the apparent fracture toughness increases as the crack spacing decreases.

From the numerical results obtained for an infinite TiC/Al_2O_3 FGM plate with a circular hole, it can be concluded that i) choosing composition profiles appropriately can improve the brittle fracture characteristics around the hole in infinite FGM plates, ii) the improved brittle fracture characteristics can be maintained up to the distance much greater than the thickness of the FGM region around the hole.

The numerical results obtained for a thick-walled TiC/Al_2O_3 FGM pipe show that i) the apparent fracture toughness can be improved up to a certain thickness of the pipe wall. After that it decreases and becomes worse than the intrinsic fracture toughness of the constituents, ii) with maximum possible volume fraction V_A at the inner surface, the composition profile that is steeper near the inner surface provides the higher apparent fracture toughness over a certain region at the inner side. This criterion is different in the cases of semi-infinite FGM bodies and infinite FGM plates.

審査結果の要旨

航空、宇宙分野をはじめとし広範囲な産業分野において、材料内部で組成や微視組織を傾斜分布化させることによって、より高い材料機能を発現できる可能性を秘めた傾斜機能材料に大きな期待が寄せられている。この材料開発のためには、傾斜機能材料設計、製造及び評価の観点からの研究がきわめて重要となっている。本論文は、ぜい性破壊特性を対象とした傾斜機能材料設計において有効かつ簡便な理論的手法を確立し、傾斜分布化によるぜい性破壊特性の改善において有用な研究成果をまとめたもので全文6章よりなる。

第 1 章は序論であり、本研究の背景及び目的を述べている。

第 2 章では、傾斜機能材料の不均一性に対して、弾性場を同値とする等価固有ひずみを導入して、傾斜機能材料内のき裂先端での応力拡大係数を簡便に求めることができる近似解法を考案し、傾斜機能材料内部の見かけの破壊じん性値を算定する手法を提示している。これは優れた成果である。

第 3 章では、薄いコーティング材のぜい性破壊特性の改善を想定して表面近傍の組成が傾斜分布化された半無限体を取り上げ、逆問題解法により指定されたとおりの見かけの破壊じん性値を実現する組成分布を得ることができることを示している。これは薄いコーティング材の傾斜機能材料設計において有益な成果である。

第 4 章では、円孔を有する平板の円孔周りのぜい性破壊特性の改善のために、非線形計画法に基づく逆問題解法を提示している。さらに、傾斜機能材料の不均一性に対する等価固有ひずみの算出法を工夫し、数値解析を行って、円孔周りの指定されたとおりの見かけの破壊じん性値を実現する組成分布を得ている。これらは重要な成果である。

第 5 章では、第 4 章で用いた手法と同様の手法を用いて、厚肉の円筒形パイプについて、指定されたとおりの見かけの破壊じん性値を実現する組成分布を得ている。この成果は、厚肉パイプの傾斜機能材料設計において有用である。

第 6 章は結論である。

以上要するに本論文は、ぜい性破壊特性を対象とした傾斜機能材料設計において有効かつ簡便な理論的手法を確立し、数値解析を行うことによってぜい性破壊特性の改善において有用な成果を得たものであり、航空宇宙工学及び機械工学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。