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論文内容要旨

Chapter 1 Introduction

Advanced materials can provide specialized properties or combinations of properties. Metal matrix composites are one of the strongest candidates as a structural composite for many high temperature and aerospace applications. The main objective of using a metal matrix composite is to increase service temperature or specific physical properties of structural composites by replacing existing superalloys [1]. In metal matrix composites, microstructural inhomogeneities are commonly found [2]. It would be advantageous to be able to predict the physical properties of a metal matrix composite if the details of these inhomogeneities are known. The physical properties of metal matrix composites are strongly influenced by many factors of microstructure including the moduli and strengths of the constituents ; the shape, size, orientation, volume concentration and distribution of the reinforcements ; the nature of the reinforcement-matrix interface [3]. Thus, a good knowledge of microstructure is a prerequisite to the design and development of the performance of metal matrix composites.

Silicon carbide whisker reinforced aluminum composites (SiC-Al composites) are known as metal matrix composites for stiff, high-strength and light-weight applications. The cross sectional shape of the whisker is circular, elliptical, triangular or hexagonal [4-6]. One of the used environments for most of the metal matrix composites is the thermal environment, particularly in high temperatures. The common problem has been the large difference in thermal expansion characteristics of ceramics and metals [7]. The partial debonding is inevitably induced in composite materials and can be precursor to serious degradation of physical properties. Functionally graded materials (FGM) offer solution to the thermal stress problem and may create wide interest. Typically, FGMs are made from a mixture of constituents. Specially designed graded interface layers are used in metal matrix composites to improve matching of the coefficients of thermal expansion (CTE) between constituents. These property gradients have to be appropriately tailored to gain advantage of the properties of constituents. Such a design would allow a gradual change in thermal expansion mismatch, minimizing the thermal stresses arising from cooling and heeting. Thus, the development of functionally graded metal matrix composites is necessary to improve material stability in severe environments.

Applications of quantitative nondestructive evaluation (QNDE) to intelligent processing and in-service inspection of metal matrix composites are closely related to techniques for microstructure characterization. The quality control of microstructure through QNDE is highly desirable. QNDE is also important for the in-service inspection of high-cost structures whose failure could have tragic consequence. The evaluation of elastic waves propagating in metal matrix composites is, therefore, indispensable to the investigation of microstructure, the estimation of physical properties, and the interpretation of QNDE. The results give rise to frequency dependent phase velocities and attenuations of the coherent waves in metal matrix composites.

In this paper, studies of the scattering of plane elastic waves in a composite material with functionally graded microstructures are performed from a theoretical and numerical point of view.

Chapter 2 Scattering of compressional and shear waves by a polygonal inclusion

In this chapter, the scattering of in-plane compressional and shear waves by a polygonal inclusion is studied by using the boundary element method (BEM) [8]. The results of the single scattering problem are applied to the propagation of elastic waves in a composite material containing a dilute concentration of polygonal inclusions. The effective complex wave numbers follow from the coherent wave equations which are related to the structural parameters accounting for processing induced variations in the microstructure, and the effective elastic moduli can be obtained from the phase velocities of the coherent plane waves. The solutions obtained are based on the plane strain assumption. Numerical calculations for a SiC-Al composite are carried out for a moderately wide range of frequencies, and the effects of inclusion shape and orientation on the scattering cross sections, and the phase velocities and attenuations of coherent plane waves and the effective elastic moduli for a dilute composite are shown graphically. Furthermore, using the results of the scattering problem, the inverse problem is attempted to identify characteristics of a inclusion with known shape and orientation.

Chapter 3 Influence of microstructure on scattering of plane elastic waves by a partially debonded elliptical inclusion

In this Chapter, the scattering of elastic waves by a partially debonded elliptical inclusion is studied by using the boundary element method [9]. The region of debonding is modeled as an interface crack with non-contacting faces that cannot transmit surface tractions. This is an acceptable approximation for a real interface crack if the faces do not touch when the composite material is disturbed. The separation of the faces, the crack opening displacement, produces a scattered field. Computations are made for a SiC-Al composite. Graphical results showing the effects of inclusion orientation, aspect ratio and debonding on the scattering cross sections, the phase velocities and attenuations of coherent plane waves and the effective elastic moduli for a dilute composite are presented.

Chapter 4 Multiple scattering of plane elastic waves in a fiber-reinforced composite medium with graded interfacial layers

The primary objective of this Chapter is to study the multiple scattering of time-harmonic elastic waves in a metal matrix composite containing randomly distributed parallel fibers with graded interfacial layers [10]. Two modes of incident waves are in-plane compressional and shear waves. The same-size circular fibers of identical properties and same-thickness interface layers with nonhomogeneous elastic properties are assumed. The method of solution consists of first solving the scattering problem by a large number N of arbitrarily distributed fibers in an infinite matrix, the resulting equations are then averaged by considering the positions of the fibers to be random with a statistically uniform distribution, and these averaged equations are solved by using Lax's quasicrystalline approximation. Two types of interface layers, graded interface layer which consists of varing proportions of constituents and imperfect interface layer, are considered. In the graded interface layer, many continuous transitions from one structure to another with the change of volume concentration of one of the constituents across the thickness, can be controlled by the structural parameter. For calculating the properties of the graded interface layer, micromechanical model of skeletal structure is used. In addition, the static effective elastic constants of composite materials are considered. Numerical calculations for a SiC-fiber-reinforced Al composite are carried out for a moderately wide range of frequencies and the effects of interface properties on the phase velocities and attenuations of coherent plane waves, and the effective elastic moduli are shown graphically.

Chapter 5 Multiple scattering of plane elastic waves in a particle-reinforced composite medium with graded interfacial layers

Following Chapter 4, we analyze the effects of graded interface layers and multiple scattering by a distribution of particles on the time-harmonic plane elastic wave propagation in a metal matrix composite [11]. The same-size spherical particles of identical properties with same-thickness nonhomogeneous interface layers are assumed to be randomly distributed. In analysis, the equations of the scattering problem by a large number N of particles are averaged and solved by using Lax's quasicrystalline approximation. The complex wave numbers giving the phase velocities and attenuations of coherent plane waves, and the effective elastic moduli for a SiC-particle-reinforced Al composite are obtained numerically and shown in graphs for various interface properties at desinated frequency.

Chapter 6 Conclusions

The main results and conclusions of the present research work are summarized.

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論文審査結果の要旨

本論文は，航空・宇宙機器等に用いられる先端複合材料の最適設計・開発および信頼性・安全性評価システムを確立するため，複雑なミクロ構造を有する金属マトリックス複合材料の弾性波散乱挙動に関する理論的研究成果をまとめたもので，全編6章からなる。

第1章の序論では，先端複合材料の設計・開発・評価がリンクされた研究開発体制の必要性および本研究で対象とした金属マトリックス複合材料の弾性波散乱挙動に関する研究の位置付けを述べると共に，本研究の目的と意義を明らかにしている。

第2，3章は，様々なミクロ構造を有する繊維強化金属マトリックス複合材料を対象に，平面弾性波散乱問題を境界要素解析したものである。先ず，第2章では，SiC ウイスカ繊維の断面形状は3角形，6角形であり，繊維強化金属マトリックス複合材料の物理的特性に影響を及ぼすため，多角形介在物を対象に平面弾性波散乱解析を行っている。数値例では SiC-Al 複合材料を考え，散乱断面積，有効平面弾性波の位相速度・振幅減衰および有効弾性定数の円振動数依存性に及ぼす介在物断面形状・配向の影響を明らかにしている。また，第3章では，高温環境下において，繊維とマトリックスの線膨張係数の相違により生じた界面はく離を有する楕円介在物を対象に平面弾性波散乱解析を行い，介在物アスペクト比・配向および界面はく離の影響を，それらの寸法，状態のバラツキを考慮して系統的に検討している。

第4章では，傾斜機能材料を合目的に最適設計し，高温環境下での熱応力緩和効果の向上を図るため，傾斜組成制御層を有する繊維強化金属マトリックス複合材料を対象に，平面弾性波多重散乱問題を理論解析している。解析に際し，高介在物群体積含有率の場合に有効な解を得るため，介在物間の相互干渉を考慮した対相関関数を導入して変位場の配置平均をとり，Laxの準結晶近似，消滅定理を用いている。また，傾斜組成制御層の物性値と組成の関係を，骨格構造を考慮したマイクロメカニカルモデルにより表している。数値例では同様に SiC-Al 複合材料を考え，有効平面弾性波の位相速度・振幅減衰および有効弾性定数の円振動数依存性に及ぼす傾斜組成制御層の影響を明らかにしている。さらに，傾斜組成制御層を考慮しない場合の円振動数を0とした有効弾性定数を求め，Eshelby 法や複合則等によって得られる静的解との比較も行っている。

第5章では，第4章に引き続き，傾斜組成制御層を有する粒子分散強化金属マトリックス複合材料の平面弾性波多重散乱解析を行い，傾斜組成制御層の影響を解明している。

最後に，第6章の結論では，各章で述べた内容を概括すると共に，得られた知見を整理して本論文の総括としている。

以上要するに，本研究は，ミクロ構造を有する金属マトリックス複合材料の弾性波散乱挙動の理論的解明に成功し，先端複合材料の設計・開発・評価に資する結果を提供したもので，材料加工プロセス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。