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13. ABSTRACT (Maximum 200 words)

The main objective of this contract was to study macroscopic and microscopic methods for the nondestructive characterization of interfacial bonding properties in two-phase metal-matrix composites such as alumna-reinforced aluminum alloys. The research obtained is documented in five theses and eight papers whose abstracts are included in the appendix. The major accomplishments are summarized in studies performed to characterize the interfacial bonding by measurements of acoustoelastic constants, acoustic nonlinearity parameter, temperature dependence of ultrasonic velocity and the coefficient of thermal expansion. Also under this contract a facility to fabricate Aluminum-Silicon Carbide composites was developed and is planned to be used in future studies related to this ARO program.

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Nondestructive Characterization of Interfacial Bonding in Two-Phase Metal-Matrix Composites

Final Report

Kamel Salama

University of Houston

November 1995

U.S. Army Research Office

DAAL03-92-G-0039

A. Statement of the Problem Studied

The major objective of this contract is to study the macroscopic and the microscopic methods for the nondestructive characterization of interfacial bonding properties in two-phase metal-matrix composites such as alumina-reinforced aluminum alloys. Knowledge of these properties are important to the understanding of bonding mechanisms between the two phases for the transfer of loads in these composites. This knowledge is also necessary for the development of models used to describe bonding stresses in two-phase metal-matrix composites. The macroscopic methods are based on the physical nonlinear elastic behavior of solids and utilize measurements of the linear dependences of ultrasonic velocities on stress and temperature as well as the acoustic nonlinearity parameter. The microscopic method utilizes the capabilities of the high-frequency (in the GHz range) scanning acoustic microscopy (SAM) to characterize experimentally the local individual interface bonding of the alumina particles and fibers while they are embedded in the aluminum matrix. Based on these results, a model is to be developed to give a theoretical characterization of the bonding between the two phases.

B. Summary of Important Results

The research accomplished during contract No. DAAL03-92-G-0039 of the Army Research Office program is documented in five theses[1-5] and 8 papers[6-13]. Abstracts of these theses and papers are attached in the appendix. The major accomplishments obtained under this program are summarized in studies performed to characterize the interfacial bonding in two-phase metal-matrix composites by measurements of acoustoelastic constants, acoustic nonlinearity parameter, temperature dependence of ultrasonic velocity and the coefficient of thermal expansion. Also under this contract a facility to fabricate A1/SiC composites is being developed, and is planned to be used in future studies related to this program. The following summarizes the studies performed under this contract. Details of these studies are described in the theses and papers documenting this work.

A. Acoustoelastic Constants/Third-Order Elastic Constants

In these studies the acoustoelastic constants were determined in two sets of SiC particle reinforced metal-matrix composites with the Al alloys 7064 and 8091 as matrices[2,8,10]. Also the temperature dependence of these constants were determined from measurements at the

1

temperatures 0, 25 and 55°C. The values of the acoustoelastic constants were then used to compute the third-order elastic constants.

From these studies, it was found that the relative changes in the acoustoelastic constants are considerably larger than those for the absolute values of velocity, which indicates higher sensitivity of the nonlinear acoustic quantities to the amount of reinforcement in the composite. For instance, the acoustoelastic constant of C_{21} changes by 30% due to the addition of 15% SiC particulate while the longitudinal velocity changes only by 5% with the same addition. Also from these studies it was observed that the strongest influence of temperature is for the third-order elastic constant l, and the behavior of this constant as a function of reinforcement at 0° C is opposite to that at 55° C with the room temperature behavior more similar to that at 55° C. In the alloy 8091, the relative change in l over the temperature increase of 55° C is 34% and for the alloy 7064 is 150%. At 0° C the constant l increases with reinforcement while it decreases at 55°C. This behavior is markedly different from that of the matrix alloy, and is attributed to the presence of the second phase reinforcement as well as the bonding stresses at the interface between the two phases[8]. Since the contribution of a second phase is not likely to be large[14], it is concluded that the difference in the temperature behavior of third-order elastic constants is mainly due to interfacial bonding developed by thermal stresses at the interface. This lead to the conclusion that measurements of the temperature dependence of third-order elastic constants can be used for the characterization of interfacial bonding in metal-matrix composites.

On the theoretical side, a method of computing the effective elastic moduli of nonlinear composites with imperfect interface is developed in detail by using a perturbation scheme[10]. The imperfect interface effects are analyzed by using the linear imperfect interface model[15]. Also the particulate composites of nonlinear elastic materials are analyzed by using representative of the spherical cell (RC) model and the generalized self-consistent scheme (GCS) model. The second-and third-order effective elastic constants of SiC spherical particles reinforced aluminum matrix composite are then calculated. The numerical results show that the second-and third-order effective elastic moduli calculated by the RC model and the GSCS model are close to each other and the second-order effective elastic moduli for the composite with perfect bonding match the experimental results. The results also show that the second-order effective elastic moduli are monotonic functions of volume fraction regardless of whether the interface is perfect or not and the rule of mixture is a reasonable way to predict the composite's second-order effective elastic moduli for perfect bonding case. In addition it was found that the introduction of the imperfect interface gives a softer composite

whose second-order effective elastic moduli are smaller that those with perfect bonding. From a physical point of view, this is quite understandable and is what one would expect, and lead to a possibility of the evaluation of bonding using second-order effective elastic moduli.

B. Acoustic Nonlinearity Parameter

In these studies the acoustic nonlinearity parameter, which is a measure of the materials deviation from ideal Hookean behavior, was determined in Al-SiC composites containing various amounts of reinforcement[7,16]. The measurements were performed along the extrusion direction of the composites using harmonic generation. The results indicate a linear decrease in the acoustic nonlinearity parameter as a function of reinforcement, which is contradictory to the increase observed in aluminum alloys containing various amounts of precipitates[14]. This contradiction is attributed to the coherency of the precipitates in the aluminum alloys while the SiC particles in the metal-matrix composite have no coherency with the matrix. From these studies, it was also observed that the presence of reinforcement particulate increased the temperature dependence of the nonlinearity parameter in the composite which is opposite to that of the monolithic alloys where the acoustic nonlinearity parameter in the composite decreases with increasing temperature[7]. This behavior was attributed to the distortion in the matrix generated by interfacial stresses which is reduced as the temperature is increased and thermal stresses at the particle interface are relaxed. These results indicate that measurements of the acoustic nonlinearity parameters at different temperatures provide characterization of bonding stresses in metal-matrix composites.

C. Temperature Dependence of Ultrasonic Velocity

In earlier studies, the temperature dependence of ultrasonic velocity has been shown to be sensitive to residual as well as applied stresses in monolithic alloys[17]. In metal-matrix composites, interfacial stresses change with temperature resulting in an overall change in the stress state of the material. In a study using Al-SiC composite, it was found that the presence of small amounts of SiC (10-15%) lead to an increase in the velocity dependence on temperature (10-30%), which is followed by the expected decrease, as more SiC reinforcement is added[11]. This behavior is attributed to the presence of thermal residual stresses which have been shown to be tensile in the matrix[18], and the increase in the temperature relaxes these stresses by placing the matrix under compression. Since compressive stresses decrease ultrasonic longitudinal velocity in

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metals[19], the observed increase in the temperature dependence of ultrasonic velocity is attributed to the relief of the tensile stresses. However, at large values of reinforcements (in excess of 25), the change in the stress state of the composite can no longer be detected due to the large amounts of second-phase which has very small temperature dependence. These results demonstrate the possibility of using the measurement of the temperature dependence of ultrasonic velocity to evaluate interfacial stresses in metal-matrix containing dilute amount of reinforcement.

D. Coefficient of Thermal expansion

Thermal expansion is basically due to the nonlinear nature of the material and is related to other nonlinear properties of the solid, namely, the stress and the temperature dependencies of ultrasonic velocities. In order to explore the possibility of using the coefficient of thermal expansion in the nondestructive characterization of interfacial bonding in metal-matrix composites, we studied the thermal expansively in three aluminum alloys reinforced with SiC particulates[3,12],. In all composites studied, the coefficient of thermal expansion is found to decrease linearly with particle content, which is shown to be closely related to the increase of the elastic constants with reinforcement of the composites. Unlike elastic constants, however, the value of the thermal expansion coefficients show greater propensity to lower theoretical bounds because the measurements of thermal coefficients examine a larger volume of the sample than that of ultrasonics where the wavelength is shorter. The ultrasonic measurements determine the local stress state in the composite while the coefficient of thermal expansion is influenced by the stress state of the system. Both properties (elastic constants and thermal expansion), however, are found to be related through a model[14] linking strain to the elastic and thermal stresses in the composite. The relationships developed in these studies show that both measurements can be used for the nondestructive characterization of metal-matrix composites.

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C. Publications

1] P. Foltyn, " Nondestructive Investigation of Thermal Stresses in Metal-Matrix Composites Using Ultrasonic Velocity Measurements", M.S. Thesis, University of Houston, 1992

[2] X. Jiang, " Nonlinear Elastic Properties of Particulate Composites with Imperfect Interface", M. S., May 1993.

[3] M. Orrhede, " Elastic Constants and Thermal Expansion of Aluminum/Silicon Carbide Composites", M. S., December 1993.

[4] J. Wahnschaffe, "The Evaluation of Fatigue Behavior in Metal-Matrix Composites using Ultrasonic Technique", M. S., August 1994.

[5] R. Tolani, "Study of Interfacial Bonding in Al/SiC Composites using the Temperature Dependence of Ultrasonic Velocities", May 1995.

[6] B. Grelsson and K. Salama, " Elastic Strength of Particle and Fiber Reinforced Metal-Matrix Composites", Mechanical Behavior of Materials, Vol. 3, p. 145, 1993.

[7] M. Mohrbacher and K. Salama, "The Temperature Dependence of Elastic Nonlinearity in Metal-Matrix Composites", Research in Nondestructive Evaluation, Vol. 4, p. 139, 1992.

[8] M. Mohrbacher and K. Salama, "The Temperature Dependence of Third-Order Elastic Constants in Metal-Matrix Composites", QNDE, Vol. 12, p. 2091, 1993.

[9] P. A. Foltyn, K. Ravi-Chandar and K. Salama, "Study of Interfacial Stress in Metal-Matrix composites Using Ultrasonic Measurements", QNDE, Vol. 12, p. 2099, 1993.

[10] Y. C. Chen and X. Jiang, "Nonlinear Elastic Properties of Particulate Composites", J. Mech. Phys. Solid, Vol. 41, p. 1177, 1993.

[11] P. A. Foltyn, K. Ravi-Chandar and K. Salama, "Effects of Second-Phase on the Nonlinear Behavior of Metal-Matrix Composites", Proc. 6th International Symposium on Nondestructive Characterization of Materials IV, R. E. Green Jr., K. J. Kozaczek, C. D. Ruud, eds., p. 733, 1994.

[12] M. Orrhede, R. Tolani and K. Salama, "Elastic Constants and Thermal Expansion of Aluminum/SiC Metal-Matrix Composites", Research in Nondestructive Evaluation, Submitted, November 1994.

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[14] J. H. Cantrell, W. T. Yost, S. Razvi, P. Li and K. Salama, "Effective Nonlinearity Parameters of Aluminum Alloys as a Function of Volume Fraction of Second-Phase Precipitates", IEEE Ultrasonic Symposium, p. 1075, 1986.

[15] J. Aboudi, "Damage in Composites-Modeling of Imperfect Bonding', Comp. Sci. Technol., Vol. 28, p. 102, 1987.

[16] M. Mohrbacher, "Temperature Dependence of Nonlinear Ultrasonic Effects", M. S., University of Houston, 1991.

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[18] R. J. Arsenault and M. Taya, Acta. Met., Vol. 35, p. 651, 1987.

[19] K. Salama, A. L. W. Collins and J. J. Wang, "The Determination of Tensile Stresses Using the Temperature Dependence of Ultrasonic Velocity", Proc. DARPA/AF Review of Progress in QNDE, p. 265, 1980.

D.   Participating Scientific Personnel

1.   Kamel Salama, Professor
2.   Paul Foltyn, Graduate Student, M. S., Jan 93
3.   Xiaohu Jiang, Graduate Student, M.S., May 93
4.   Mats Orrhede, Graduate Student, M. S., December 93
5.   Jens Wahnschaffe, Graduate Student, M. S., August 94
6.   Rajesh Tolani, Graduate Student, M. S., May 95

Appendix

Theses and Papers Published

NONDESTRUCTIVE INVESTIGATION OF THERMAL STRESSES IN METAL MATRIX COMPOSITES USING ULTRASONIC VELOCITY MEASUREMENTS

A Thesis
Presented to the Faculty of the
Department of Mechanical Engineering
University of Houston

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Mechanical Engineering

by

Paul A. Foltyn
December, 1992

L-1

Abstract

Residual thermal stresses exist in metal matrix composites (MMCs) at room temperature as a direct result of cooling the MMC from its fabrication temperature. Ultrasonic techniques have proven to be useful methods in determining changes in the stress state of engineering materials. In this investigation, the second- and third-order elastic constants were ultrasonically measured in two aluminum-silicon carbide metal matrix composites and in monolithic silicon carbide. Also, the temperature dependence of these constants was determined in the temperature range of -30 to 60°C. From these results, it was shown that the temperature dependence deviates from the law of mixtures for aluminum and silicon carbide. This deviation was interpreted as a result of interfacial stresses developed during solidification. This gives promise for using measurements of the temperature dependence of ultrasonic velocities to evaluate thermal stresses in metal matrix composites.

Nonlinear Elastic Properties of Particulate Composites with Imperfect Interface

A Thesis Presented to

The Faculty of the Department of Mechanical Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in Mechanical Engineering

by

Xiaohu Jiang

May, 1993

L-3

Abstract

A method of computing effective elastic moduli of nonlinear composites with imperfect interface is developed in detail by using a perturbation scheme. The imperfect interface effects are analyzed by using the linear imperfect interface model. It is demonstrated that the third-order effective elastic moduli can be calculated by using only the linear ealstic solutions. The particulate composites of nonlinear elastic materials are analyzed by using representative spherical cell model and the generalized self-consistent scheme model. The second- and third-order effective elastic constants of SiC spherical particles reinforced aluminum matrix composite are calculated. The numerical results show that the third-order effective elastic moduli of the SiC composite are not monotone functions of volume fraction, and that the resulting effective homogeneous material may be nonlinear even for the. composites of linear constituents.

ELASTIC CONSTANTS AND THERMAL EXPANSION OF ALUMINUM / SILICON CARBIDE COMPOSITES

A Thesis

Presented to

the Faculty of the Materials Engineering Interdisciplinary Program

Cullen College of Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Materials Engineering

by

Mats Orrhede

December 1993

L-5

NONDESTRUCTIVE CHARACTERIZATION OF
INTERFACIAL RESIDUAL STRESSES IN
METAL MATRIX COMPOSITES

An Abstract

of a

Thesis

Presented to

the Faculty of the Materials Engineering Interdisciplinary Program

Cullen College of Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Materials Engineering

by

Rajesh Tolani

May, 1995

ABSTRACT

Interfacial residual stresses in metal matrix composites arise from the differential thermal contraction of the matrix and the reinforcement during processing. They also result from the plastic deformation generated while the composite is subjected to extrusion. In this study, the change in the interfacial residual stresses in two set of aluminum matrix Al_2O_3 reinforced composites were investigated between room temperature and 250 C, using ultrasonic velocity and thermal strain measurements. The engineering moduli and thermal expansivity of the composites were compared to the values predicted by Datta-Ledbetter model, Hashin-Shtrikman bounds and Levin model; which showed good agreement. From the experimental results, it is seen that the normalized temperature dependence of the engineering moduli and the coefficient of thermal expansion of metal matrix composites are a function of the matrix, reinforcement and direction of measurement. This gives promise for using ultrasonic velocity and thermal strain measurements for characterizing residual interfacial stresses in metal matrix composites.

Mechanical Behaviour of Materials—VI

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L-9

ELASTIC STRENGTH OF PARTICLE AND FIBER REINFORCED
METAL-MATRIX COMPOSITES

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ABSTRACT

Conventionally, metal matrix composites (MMC) are reinforced with either particles or fibers. Recently, a new class of composites where a mixture of particles and fibers is used as reinforcement has emerged. The particles improve the isotropic mechanical and thermal properties, whereas the fibers introduce directionally favorable properties for specific applications of the material. The elastic properties of three different matrix alloys containing 6% alumina fibers and varying alumina particle volume fractions of 9, 13, and 17% have been determined using ultrasonic velocity measurements. The results show that the elastic moduli increase with the particle content and the composites have the highest elastic stiffness in the directions of the fiber plane. A model is developed to explain the observed elastic moduli of this type of composites. The model uses results of the theories by Ledbetter and Datta for spherical inclusions and Hashin and Rosen for aligned fibers. Furthermore, it includes an averaging procedure suggested by Christensen and Waals. The agreement between measured and calculated elastic moduli is found to be good. In a second series of measurements, the elastic moduli in two sets of extruded MMCs and one set of pressed MMCs are determined. These composites are reinforced with silicon carbide particles. Their elastic moduli as well as their elastic anisotropies are explained using the theories discussed earlier.

INTRODUCTION

In order to increase structural efficiencies in modern design, materials possessing high stiffness and high strength are required. One class of engineering materials fulfilling these requirements are metal-matrix composites (MMCs). In these composites, properties of the material can be tailored by the appropriate selection of matrix and reinforcement materials and by their mutual arrangement in order to meet specific needs of the designed component. The matrix and the reinforcement are to be selected so that they combine their different mechanical and elastic properties in a synergistic way. Also, microstructures resulting from different fabrication processes are found to influence properties of these composites and provide valuable information for their further development.

Many models have been developed to determine the effective elastic moduli of composite materials. Most of these models deal with reinforcement in the form of spherical particles (Ledbetter and Datta, 1986, Budiansky, 1965), ellipsoidal inclusions (Eshelby, 1957, Chow, 1977) or infinitely long fibers (Hashin and Rosen, 1964, Hill, 1964). Ledbetter and Datta used

The Temperature Dependence of Elastic Nonlinearity in Metal-Matrix Composites

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Abstract. Thermal stresses are very important in determining the strength of composites. In metal-matrix composites, these stresses are generated at the matrix-reinforcement interface as a result of the difference in thermal expansion coefficients of matrix and reinforcement during solidification. In order to evaluate these stresses, we studied the effect of temperature on the second- and third-order elastic constants in two metal-matrix composites consisting of the aluminum alloys 8091 and 7064 and silicon carbide particles up to 20% volume fraction. The elastic constants were determined at the temperatures 0, 25 and 55°C using measurements of absolute as well as changes of ultrasonic velocities as a function of applied stress. The values of these constants are used to calculate the acoustic nonlinearity parameters. In both composites, the acoustic nonlinearity parameters increase with the amount of reinforcement, which is opposite to that previously observed in aluminum alloys containing second-phase precipitates. Also, the temperature behavior of the nonlinearity parameters in the composites are opposite to those in the aluminum matrices. These differences in behavior are interpreted as due to the presence of thermal stresses at the matrix-reinforcement interface, and give promise to the possibility of using these parameters in the nondestructive evaluation of these stresses in metal-matrix composites.

Introduction

Metal-matrix composites (MMC) are a class of multi-phase materials consisting of a metallic matrix and a ceramic or metallic material as a reinforcement. They combine the often vastly different properties of matrix and reinforcement materials in a synergistic way. The reinforcement is usually available as short fibers, particles, or whiskers with volume percentages up to 40%. The properties of the composites are influenced by those of the matrix and the reinforcement materials as well as by the properties of the interfacial bonding between the two phases. Due to the different thermal expansion coefficients of matrix and reinforcement, internal stresses are developed at the interface between the metal-matrix and the ceramic phase during processing of the material or during thermal cycling. These stresses may relax by plastic deformation when they reach

THE TEMPERATURE DEPENDENCE OF THIRD-ORDER ELASTIC

CONSTANTS IN METAL-MATRIX COMPOSITES

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INTRODUCTION

Elastic nonlinearity is responsible for the deviation of a material's stress-strain response from the linear relationship represented by Hooke's law. This law can be written in its most general form as

$$\sigma_{ij} = C_{ijkl}\, \varepsilon_{kl} \tag{1}$$

where σ_{ij} and ε_{kl} are the stress and strain tensors respectively, and C_{ijkl} is the tensor of the second order elastic constants. The nonlinear elastic behavior can be determined from measurements of the stress dependence of ultrasonic velocities as well as the distortion of ultrasonic waves by the generation of higher harmonics. Consequently, these effects can be used to nondestructively characterize a material's elastic nonlinearity.

Metal-matrix composites (MMC) are a class of multi-phase materials consisting of a metallic matrix and a ceramic or a metallic material as a reinforcement. The reinforcement is usually available as short fibers, particles or whiskers with volume percentages up to 40%. The properties of the composites are influenced by those of the matrix and the reinforcement materials as well as by the quality of the interfacial bonding between the two phases. Due to the different thermal expansion coefficients of matrix and reinforcement, internal stresses are developed at the interface between the metal-matrix and the ceramic phase during processing of the composite or during thermal cycling.

Recently we reported measurements on the acoustic nonlinearity parameter in two metal-matrix composites of aluminum and SiC particles, where it was observed that the parameter decreased with increasing volume fraction of reinforcement [1]. In this paper, we present results on the effect of temperature on the second- and third-order elastic constants at the three temperatures 0, 25 and 55°C in an aluminum metal-matrix composite. The results indicate that the strongest influence of temperature is on the

STUDY OF INTERFACIAL STRESS IN METAL MATRIX COMPOSITES USING

ULTRASONIC VELOCITY MEASUREMENTS

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INTRODUCTION

The numerous potential applications of metal matrix composites (MMCs) in the military and aerospace industries have resulted in the widespread study of their mechanical properties to determine optimum fabrication techniques for improved composite strength. Due to the difference in the thermal expansion coefficients of the matrix material and its reinforcement, thermally-induced residual stresses exist in the composite as a direct result of cooling from the MMC fabrication temperature. Several nondestructive techniques have been used to determine the residual stress present in various engineering materials. Radiographic techniques have been used extensively, but are somewhat limited in penetration depth and spatial resolution. However, ultrasonic techniques have proven to be a useful nondestructive means of determining bulk mechanical properties of a material. To determine the influence of internal stresses in MMCs on ultrasonic velocities, specimens of various second-phase silicon carbide content were subjected to a change in temperature. As the specimen temperature was raised, interfacial stresses between the aluminum matrix and silicon carbide reinforcement were relaxed, resulting in an overall change in the stress state of the material. Longitudinal ultrasonic waves were used to measure the acoustoelastic effect due to this change in the internal stress of the MMC. Longitudinal waves have been successfully used to determine internal stresses due to the influence of temperature on railroad rails [1] and prestrained aluminum and copper specimens [2]. The ultrasonic velocities in this investigation were measured with a computer automated time-of-flight acquisition system accurate to better than 1 part in 10,000.

EXPERIMENTAL

Two aluminum alloys, Al-7064 and Al-8091 have been studied in this investigation. For each alloy three specimens with various silicon carbide (SiC) content were tested ultrasonically. The three Al-7064 alloy specimens contain 0, 15, and 20% SiC, the Al-8091 specimens contain 0, 10, and 15% SiC. Furthermore, a pure silicon carbide specimen was tested to study wave propagation behavior in monolithic silicon carbide. The aluminum specimens were fabricated as 1 inch diameter extruded rods, then machined flat for ultrasonic testing to dimensions 0.6 x 0.6 x 0.9 inch, the long dimension corresponding to the extrusion direction. The matrix composition of each alloy is presented in Table 1.

NONLINEAR ELASTIC PROPERTIES OF PARTICULATE COMPOSITES

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Abstract

A method of computing effective elastic moduli of isotropic nonlinear composites is developed by using a perturbation scheme. It is demonstrated that only solutions from linear elasticity are needed in computing higher order moduli. As an application of the method, particulate composites of nonlinear elastic materials are analysed.

1. Introduction

The problem of predicting the macroscopic behavior of composite materials is of practical and theoretical importance. Considerable research efforts have been directed to this area with much progress made in the last four decades. A comprehensive account of basic analytic methods developed before 1979 can be found in the monograph of Christensen (1979). Some later progress has been reported in a recent monograph of Aboudi (1991).

Most works reported in the literature have been devoted to composites of linear materials, given the enormous mathematical difficulties involved in nonlinear analysis. Among few research efforts dealing with nonlinear composites, Duva and Hutchinson (1984) studied the effective properties of a power-law viscous material with voids, and Duva (1984) examined the properties of the viscous material reinforced by rigid inclusions. Hashin (1985) studied the nonlinear properties of composite materials with spherical inclusions and porous media with spherical voids, subject to spherical dilatations or compressions. As pointed out by him, a similar analysis for other types of deformations is prohibitively difficult. In a sequence of papers by Willis (1983, 1989, 1991), Talbot and Willis (1985), Ponte Castañeda and Willis (1988), and Ponte Castañeda (1989, 1991), a variational approach has been employed to find bounds and estimates for the effective properties of a class of nonlinear composites. To the knowledge of the authors, no work has been done toward the explicit calculation of the complete set of effective mechanical properties of general nonlinear composites.

The difficulty involved is a real one: the exact solutions to the equations of equilibrium for nonlinear composites are scarce, if any at all. A complete analysis of the effective constitutive functions for nonlinear composites would require a full range of

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EFFECTS OF SECOND-PHASE ON THE NONLINEAR BEHAVIOR
OF METAL MATRIX COMPOSITES

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INTRODUCTION

The mechanical properties of metal matrix composites (MMCs) have made them ideal materials for use in applications where increased material performance is required. Their potential use in the military and aerospace industries has resulted in a widespread investigation into their mechanical properties to determine optimum fabrication techniques for enhanced composite strength. Of the many destructive and nondestructive techniques available for the measurement of composite properties, ultrasonic nondestructive evaluation (NDE) has emerged as a useful tool to the researcher for the study of the mechanical behavior of MMCs. Therefore, an ultrasonic determination of the composite properties can provide insight as to how the material can be enhanced by changes either in composition or fabrication techniques. To this end, the second- and third-order elastic constants were measured in silicon carbide-(SiC) reinforced aluminum alloys and in monolithic silicon carbide as a function of temperature and second-phase. The results give not only the widely used engineering data such as the Young's and shear moduli, but also an indication as to the degree of nonlinearity present in these materials, and how the second- and third-order properties change with the introduction of a second-phase.

EXPERIMENTAL

Specimens

In this investigation, the second-order linear elastic constants were determined for two silicon carbide-reinforced aluminum alloys, namely, Al-7064 and Al-8091. Also, the third-

ELASTIC CONSTANTS AND THERMAL EXPANSION OF ALUMINUM - SiC METAL MATRIX COMPOSITES

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ABSTRACT

The elastic behavior and the thermal expansivity of metal-matrix composites have been investigated using ultrasonic velocity and strain gage measurements. The composites used in this study consisted of three aluminum alloys reinforced with different concentrations of SiC particles. The results show that the elastic constants increase and the coefficient of thermal expansion decrease with particle content. The results also show that the behavior of elastic constants with reinforcement can be best represented by the calculations of the upper and lower bounds of Hashin et al. The behavior of thermal expansion, however, agrees with bounds developed by Schapery. In addition, both properties are found to be related through a model linking the strain to the elastic and thermal stresses in the composite. This relationship gives promise for the non-destructive characterization of the composites using these measurements.

The Evaluation of Fatigue Damage in Metal-Matrix Composites Using Ultrasonic Measurements*

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Discontinous SiC-reinforced aluminum alloys are advanced materials for applications requiring high performance, isotropic mechanical properties. Although most of the composite properties are significantly improved by reinforcement, the fatigue performance is lowered. The objective of this research is to determine the possibility of using ultrasonic measurements in evaluating fatigue damage in metal-matrix composites. Two composites of 6092 aluminum reinforced with 17.5% SiC and 2080 aluminum containing 15% SiC are used in this study. Fatigue tests in tension-tension are performed on samples of these composites, and their S–N behavior are compared to those of the monolithic aluminum alloys. Also, the absolute as well as the stress and temperature dependences of longitudinal and shear ultrasonic velocities are measured on these samples after different levels of fatigue damage. The results show that the absolute velocities are sensitive to fatigue damage and give promise to using ultrasonic measurements in characterizing fatigue life in metal-matrix composites.

Abstract

The elastic behavior and the thermal expansivity of metal matrix composites (MMCs) have been investigated using ultrasonic velocity and strain gage measurements, respectively. The composites used in this study consist of three aluminum alloys reinforced with SiC particles. It was observed that the elastic constants increase and the coefficient of thermal expansion decreases with particle content. The thermal expansivity and the elastic constants in the MMCs are found to have related behavior. This behavior is evaluated in terms of current models, and the models are found to be unsatisfying. An agreement, however, is obtained between measured data and calculations based on rule of mixture of the upper and lower bounds of the elastic moduli developed by Hashin *et al.* The behavior of the experimental results as a function of reinforcement can be represented by an expression obtained from a second-order expansion of the property measured. A fit parameter in this expansion is proposed to be a measure of the strain energy distribution in the composite.

Evaluation of Fatigue Behavior in Metal-Matrix Composites Using Ultrasonic Techniques

A THESIS

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Abstract

Discontinuous SiC-reinforced aluminum alloys are used in applications requiring high performance and isotropic mechanical properties. Most of the composite properties are significantly improved by reinforcement. The objective of this study was to determine the possibility of using ultrasonic measurements in evaluating fatigue behavior in metal-matrix composites. Two composites, Al 6092 17.5% SiC and Al 2080 15% SiC, were used in this study. Fatigue tests in tension-tension were performed on 5, respectively 11 samples, and their S–N behavior were compared. The absolute ultrasonic velocities as well as the stress and temperature dependences of the ultrasonic longitudinal and shear wave velocities were also measured on these samples at different levels of fatigue damage. The absolute velocities increase by up to 6.5% due to fatigue . The acoustoelastic effect for all three wavemodes decreases significantly only in Al 2080 + 15% SiC . Temperature dependence measurements do not exhibit information about the fatigue state in the material.