Thermomechanical Properties of Functionally Graded Al-SiC$_p$ Composites

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Abstract

A theoretical model is applied to the analysis of thermomechanical properties of Al-SiC$_p$ FGMs in this study. Functionally graded Al-SiC$_p$ composites (Al-SiC$_p$ FGMs) consisted with 10 layers gradually changing volume fractions of Al and SiC$_p$ were fabricated using the pressureless infiltration technique. Al-SiC$_p$ FGMs plates of total thickness of 3mm, 5mm and 7mm with fairly uniform distribution and compositional gradient of SiC$_p$ reinforcement in the Al matrix throughout the thickness was successfully fabricated. The curvature of Al-SiC$_p$ FGM plates was measured to check the internal stress distribution predicted via a theoretical model for the analysis of thermo-mechanical deformation. The evolution of curvature and also internal stresses in response to temperature variations could be predicted for the different combinations of geometric thickness of FGM plates. Theoretical prediction of thermally induced stress distribution makes it possible to design FGM structures without any critical failure during the usage of them.

Keywords : Al-SiC$_p$, FGM, Pressureless infiltration, Microstructure, Thermomechanical properties

1. Introduction

In recent years, engineering materials would be subjected to more critical environments and conventional materials could not meet to the environments such as high stressed and high temperature situations. As a result, research has been performed actively to develop advanced materials. Metal matrix composites (MMCs) have received the spot-light as a class of advanced engineering materials because of their potential applications in numerous industrial fields such as the automotive and aerospace industries for engine parts as well as electronic packaging purposes. In these applications, layered materials have been used to shield the critical environment, but the internal residual stresses within the layered materials with sharp interface induced by the difference in the coefficient of thermal expansion between the composed materials often provide the source of failure such as delamination of interfaces [1-2]. Functionally gradient materials (FGMs) which exhibit a variation in chemical composition and/or microstructural parameter over definite geometrical distance [1-2] have been suggested for the solution to prevent these failures. However, a systematic thermomechanical analysis is needed for the customized structural design of gradient or multilayered structure. In this study, the Al-SiC$_p$ FGM (metal matrix composite), was fabricated using the pressureless infiltration technique. The micro-structural characteristics and mechanical properties of the Al-SiC$_p$ FGM were evaluated. The theoretical model for the analysis of thermomechanical properties, especially internal stresses of the Al-SiC$_p$ FGM was developed for the design of multilayered systems.

2. Experimental and Results

Table 1. Characteristics of Al and SiC$_p$ powders used in this study

	Al	SiC$_p$
Elastic Modulus [GPa]	62	319
Poisson's ratio	0.23	0.34
CTE* [K^{-1}]	23.0×10^{-6}	4.7×10^{-6}
Density [Mg/m^3]	+2.70	2.55
Melting Points [°C]	660	2410
Hardness [Hv]	40	1920

*CTE is the coefficient of thermal expansion.

The characteristics of Al (50μm, Al) and SiC$_p$ (44.6μm, SiC$_p$) powders used in this study are listed in Table 1. The Al-SiC$_p$ FGMs containing 10 layers with different volume fraction of Al and SiC$_p$, ranging interval from 90%Al-10%SiC$_p$ to 10%Al-90%SiC$_p$ were fabricated using the pressureless infiltration technique Functionally graded (FG) Al-SiC$_p$ preforms were prepared by the following sequences; (i) Al and SiC$_p$ powders with variation of volume fractions were mixed with dilute water, (ii) inorganic binder (silica colloidal) was added to the slurry of Al and SiC$_p$ mixture, (iii) organic binder (starch) was added for the flocking effect[3] between the inorganic binder and SiC$_p$, (iv) the prepared slurry of Al, SiC$_p$, the inorganic and the organic binders was heated for drying, (v) after drying, the consolidated body of binder coated Al and SiC$_p$ was crushed, (vi) sequentially compositional gradient of Al and

SiC_p mixture were stacked and pressed to prepare preforms. In order to obtain the enough strength of the FG preforms, sintering heat treatment was carried out in the electrical furnace at 400 °C for 4 hours. Preform was placed in the tube furnace and Al-10%Mg alloy was infiltrated at 920°C for 3 hours. Magnesium in Al-10%Mg is the effective element to decrease the viscosity of Al alloys and thus improve the wettability during infiltration [4]. Al-SiC_p FGM plates of total thickness of 3 mm, 5 mm and 7 mm were fabricated, and microstructure analysis was performed throughout the thickness direction of Al-SiC_p FGMs plates. The curvatures of Al-SiC_p FGMs plates were measured using 3D laser digitizer to check the internal stress distribution within the plates.

Fig. 1. Microstructures of gradient layer of Al-SiC_p FGM with thickness of 3mm

Table 2. Curvature of Al-SiC_p FGMs

Thickness (mm)	Radius (m)	Measured curvature (m^{-1})	Calculated curvature (m^{-1})
7.0	54.92	181.06	188.24
5.0	51.69	193.46	201.57
3.0	43.24	231.23	244.33

The microstructure of 3mm Al-SiC_p FGM plates is shown in Fig. 1. It reveals the layers with compositional gradient throughout the thickness direction of plate. In each layer, fairly uniform distribution of the constituent phases, Al and SiC_p was observed and any noticeable defect was not found in the microstructure of Al-SiC_p FGM. It is noted that the volume fraction of FG preform and finally fabricated Al-SiC_p FGM are different in the layers of plates. The volume fractions of composed layers in preforms and infiltrated Al-SiC_p FGM are shown in Table 2.

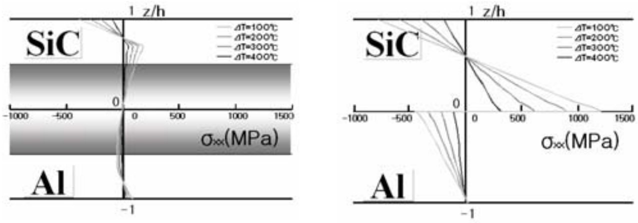
The theoretical model for analysis of stresses and curvature which develop in FGM subjected to temperature fluctuations based on the classical beam and plate theory of continuum mechanics was suggested by K. M. Cho and D. H. Song [5, 6]. The interfaces between layers are assumed to be perfectly mechanically bonded. Theoretical model for unsymmetric FGM structure is represented by the following equations.

$$\varepsilon_0 = [\alpha_0 + \Delta\alpha f(\rho)]\Delta T \quad (1)$$

$$\chi = \Delta\alpha\Delta T g(\rho) \quad (2)$$

$$\sigma(z) = E^*(z)\Delta\alpha\Delta T G \quad (3)$$

Where ε_0 is the strain at z = 0; χ is the curvature; $\sigma(z)$ is the thermal stress; $f(\rho)$ and $g(\rho)$ are the functions depending on the thickness of layers and elastic modulus of materials; ΔT is the temperature change from the initial stress-free state; G is the geometrical function for layers in the plate structure.



(a) (b)

Fig. 2. The calculated distributions of thermal stress in (a) Al-SiC_p FGM (3mm) and (b) Al-SiC_p bimaterial (3mm) with sharp interface as a function of temperature change

Table 2 shows the measured and calculated curvatures of Al-SiC_p FGMs during thermal shock. The curvature of Al-SiC_p FGM can be calculated from equation (2). It is seen that the calculated curvatures are close to the measured ones. The distribution of thermal stress in FGMs can be predicted with using the measured curvature. It is reported that the thermo-mechanical properties of the FGMs with over 10 layers, generally, are approximately equal to those of the FGMs with continuous functionally graded layer [2, 6]. Fig. 2(a) and (b) reveals the calculated distributions of thermal stress in Al-SiC FGMs and Al-SiC layered structure with sharp interface as a function of temperature change. It is clearly seen that the functionally graded structure is more effective to prevent the failure such as delamination.

3. Summary

The Al-SiC_p FGMs plates consisting of 10 layers gradually changing the volume fractions of Al and SiC_p were fabricated successfully using the pressureless infiltration technique. The theoretical model for the thermomechanical analysis could be reasonably applied to predict the internal stress distribution of Al-SiC_p FGMs plates fabricated, and thus can be used effectively to design the multilayered FGM structures. The Al-SiC_p FGM is more effective than Al-SiC_p bimaterial with sharp interface for preventing the failure due to the reduced and smooth transition in thermal internal stress.

4. References

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