Effect of Thermal Stresses on the Thermal Expansion and Damping Behavior of ZA-27/Aluminite Metal Matrix Composites

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When the fabrication of a metal matrix composite (MMC) involves its cooling from a high temperature, plastic-elastic residual deformation fields can be generated within and around the particle due to the differential thermal expansion between the particle and matrix metal. The present investigation is concerned with the effect of thermal residual stresses on the thermal expansion and damping behavior of aluminite particulate-reinforced ZA-27 alloy MMCs. Composites were prepared by the compocasting technique with 1, 2, 3, and 4 wt.% of aluminite reinforcement. Thermal expansion and damping properties have been studied experimentally as a function of temperature over a temperature range 30 to 300 °C both in the heating and cooling cycle. The thermal expansion studies exhibited some residual strain, which increased with the increase in the weight percent of the reinforcement. The damping capacity of both the composites and matrix alloy is found to increase with the increase in temperature during the heating cycle, whereas in the cooling cycle, damping behavior exhibits a maximum, which becomes more pronounced with the increase in the weight percentage of the reinforcement. The appearance of the maximum may be linked with dislocation generation and motion as a result of plastic deformation of the matrix at the metal/reinforcement interface. This phenomenon is attributed to the thermal stresses generated as a result of coefficient of thermal expansion (CTE) mismatch between the composite constituent phases. The thermal stresses have been estimated in both the cases using simple models.

Keywords aluminite, CTE, damping capacity, thermal stresses, ZA-27

1. Introduction

In recent years, a great deal of progress has been achieved in the development and production of particulate-reinforced metal matrix composites (MMCs). When compared with unreinforced metals/alloys, MMCs exhibit significant improvements in strength, elastic modulus,[1,2] wear resistance,[3] fatigue resistance,[4] and damping capacity[5] in addition to high-temperature mechanical properties[6] and low thermal expansion.[7] A low coefficient of thermal expansion (CTE) and high damping capacity are desirable for applications such as electronic heat sinks and space structures. The wide spread use of MMCs in structural applications is dependent on their proper and complete characterization under various conditions of mechanical and thermal loading. One of the important aspects of MMCs that needs to be understood in a better way is the influence of thermal residual stresses on the properties of materials. When MMCs are fabricated at a certain high temperature and cooled down to room temperature, residual stresses are induced into the matrix and reinforcement because of the significant difference between the thermal expansion coefficients of the two constituents. The residual stresses would have some undesirable effects on the mechanical, thermal, and physical properties of the composites. A number of articles on experimental work and numerical computations of thermal stresses have been found in the literature.[8,9] However, due to the complexity of the MMCs, a better understanding of the residual stresses in these materials is still lacking.

Zinc-aluminum (ZA) alloys are a relatively a new family of zinc foundry alloys having superior melting and casting characteristics.[10] Their fabrication requires lower energy requirements compared to aluminum, brass, and cast iron. These alloys have a wide range of freezing temperature resulting in a different behavior of the microstructure of the alloy for each composition.[11] Among the zinc aluminum foundry alloys, ZA-27 exhibits attractive physical and mechanical properties combined with tribological properties, making it a choice alloy for a multitude of end use applications.[12] Though the mechanical and tribological properties of ZA-27 based composites have been widely studied,[13,14] less information is available regarding some of the important physical properties such as thermal expansion, damping behavior, electrical resistivity, *etc.*

The present investigation has been undertaken with the objective of studying both the thermal expansion and damping behavior of aluminite particulate-reinforced ZA-27 alloy MMCs as a function of temperature. The thermal stresses generated in the composite as a result of the differences in the CTEs between the matrix and reinforcement have been evaluated using simple models. In MMCs, the difference between CTEs of the matrix and reinforcement results in the fact that metal/ceramic interface will be in equilibrium only at the temperature at which they are brought into contact. At any other temperature,

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Table 1 Chemical composition of ZA-27 alloy (ASTM B669-82)

Aluminum	Cu	Mg	Zn
25–28%	1–2%	0.01–0.02%	Balance

there will be biaxial or triaxial stress fields due to the difference in the physical and mechanical properties of the constituents of the composite. The thermal stresses may be of considerable magnitude, which can elastically/plastically deform the metal matrix that surrounds the reinforcement. The existence of a plastically deformed matrix due to thermal stresses near the reinforcement containing high dislocation density has been confirmed by transmission electron microscopy.[15,16] The present work is based on the fact that, during the cooling of MMCs, stress concentrations originating from the difference in CTEs of matrix and reinforcement should induce dislocation movements in the matrix surrounding the reinforcement. This results in microplastic strain.[17] Therefore, the thermal expansion studies of MMCs must exhibit these residual strains and at the same time dislocation movements should contribute to MMCs damping behavior.

2. Experimental Procedure

2.1 Material Preparation

In the present study, the ZA-27 alloy having the chemical composition as per the ASTM B669-82 ingot specifications given in Table 1 has been used as the base alloy. The reinforcement is basically a hydrous sulfate having density of 1.66 g/cm^3 and particle size of about 100 μm. Its chemical composition is Al_2O_3, SO_3, $9H_2$ O. A thermogravimetric analysis (TGA) study of the aluminite sample confirms the fact that at higher temperatures it transformed irreversibly into stable Al_2O_3. The percentage of aluminite was varied from 1 to 4 wt.%. The compocasting technique was used to prepare the composite, which is similar to the one used by Sharma *et al*.[18] In this process, the matrix alloy (ZA-27) was first superheated above its melting temperature and stirring was initiated to homogenize the temperature. The temperature was then lowered gradually until the alloy reached a semisolid state. At this temperature (440 °C), the preheated aluminite particles were introduced into molten slurry. Stirring was continued until the interface between the particles and the matrix promoted wetting. The melt was then superheated above its liquidus temperature of 500 °C and finally poured into the lower die-half of the press and the top die was brought down to solidify the composite by applying high pressure. Microstructural analysis was carried out, which showed that a significant part of the particles was retained in the melt.

2.2 CTE Measurement

Specimens for CTE testing were machined from the prepared MMC samples with the dimensions 10 $\times$ 5 $\times$ 5 mm. The specimen surfaces were ground with series of silicon carbide papers of 100, 200, 400, 600, and 1000 grit and then polished with 3 μm diamond paste to obtain a fine-surface finish. The specimens were then washed in distilled water, followed by acetone, and then allowed to dry thoroughly. About four specimens of each sample were tested to achieve the reproducibility of experimental results. Percent linear change (PLC) measurements were performed from 30 to 300 °C at the rate of 5 °C/min with commercial thermal mechanical analyzer equipment (TMA, model 2940, DuPont, Wilmington, DE) both in the heating and cooling cycle. The sample is placed on a quartz stage and a moveable probe is kept on the top of the sample. The thermal expansion of the specimen was detected by a linear variable differential transformer (LVDT) attached to the probe. The furnace surrounding the sample stage and probe provides a heating/cooling environment during the measurements. A thermocouple adjacent to the sample monitors the sample temperature so that dimensional change can be followed as a function of temperature. The data were obtained in the form of PLC versus temperature curves. Standard TMA data analysis software was used to evaluate the CTE of the base alloy as well as that of the composites.

2.3 Damping Measurement

A dynamic mechanical analyzer (DMA, model 983, DuPont) includes sample arms and clamps, flexure pivot, LVDT, electromagnetic driver, and a temperature programmer interfaced with a computer. The specimen is subjected to a flexural sinusoidal strain with constant amplitude, and resultant bending stress is measured simultaneously. The sample is held between two end clamps and enclosed in an environmental chamber that provides heating and cooling capability. The electromagnetic driver applies flexural strain to the specimen and resultant stress on the sample is measured by LVDT. The specimens were displaced by 250 μm peak to peak at the drive clamp corresponding to a maximum strain of 2.6 $\times$ 10^{-4}. The sample length measured between the clamps was approximately 38 mm. The temperature of the specimen was varied from 30 to 300 °C, both in the heating and cooling cycle at the rate of 10 °C/min, and the corresponding plots of loss modulus and storage modulus were obtained.

3. Results

3.1 Microstructure

Microstructures play an important role in the overall performance of the alloys as well as composites. The physical properties depend on microstructure, and in the ZA-27 alloy, the microstructure is a complex function of the casting process and subsequent cooling rates.[19] A study of the Zn-Al phase diagram[20] shows that as ZA-27 alloy is cooled from the melt to room temperature, it goes through several phases, namely, (α + L), β, (α + β), and finally (α + η). The induction of low Cu content in the ZA-27 will lead to formation of an intermetallic compound $CuZn_4$ (ε) at 377 °C through a ternary eutectic reaction given by[21]

$$L \rightarrow \alpha + \eta + \varepsilon \qquad \text{(Eq 1)}$$

At a lower temperature of 268 °C, a ternary phase known as Al_4Cu_3Zn (T') will result from the reaction[20]

$$\varepsilon + \alpha \rightarrow T' + \eta \qquad \text{(Eq 2)}$$

The microstructure of the ZA-27 as-cast alloy consisted of a cored aluminum-rich matrix (α, fcc), and interdendritic zinc-rich phase (η, hcp), $CuZn_4$ (ε), and Al_4Cu_3Zn (T'). The light etching constituent shown in Fig. 1(a) is the aluminum-rich (α) phase, while the grey structure surrounding it is a mixture of zinc-rich (η) and aluminum-rich phases. The dark regions are zinc-rich (η) phase.

The microstructures (Fig. 1b) of the aluminite-reinforced composites show negligible solid solubility of aluminite in either the aluminum- or zinc-rich phases. The grain size of the ZA-27 matrix alloy is somewhat larger than that of the composites. As a result, there were large clusters of aluminite within some areas of the matrix, while other areas were entirely aluminite depleted. The segregation was more pronounced in the 4% aluminite composites. When analyzed at higher magnifications (Fig. 1c), the structures reveal that the relatively colder particle chilled the metal and initiated nucleation. The dendrites grow away from the particle, due to the restriction caused by the particle-to-solute enrichment. Thus, the grains grow outward from the particle and the last remaining eutectic liquid solidifies around the particles. However, no gap is observed between the particle and the matrix, and the particles are well bonded with the matrix.

3.2 Coefficient of Thermal Expansion

The results of CTE expressed as a PLC of different weight percentages of particle-reinforced MMCs as a function of temperature are shown in Fig. 2. These curves exhibit some residual strain on cooling, which increases with the increase in the weight percentage of reinforcement. The residual strain in the case of base alloy has the minimum value. The variation of CTE of the composites as well as the base alloy with temperature is shown in Fig. 3. The curves show that the CTE decreases with the increase in the weight percentage of the reinforcement. But in all the cases there is a moderate increase in CTE values with the increase in temperature.

3.3 Damping Capacity

The damping capacity (tan ϕ) versus temperature curves for the base alloy and composites both in the heating and cooling cycles are shown in Fig. 4. The damping capacity of the composites as well as matrix alloy has been found to increase with the increase in temperature and also with the increase in reinforcement. But the heating and cooling curves exhibit hysteresis behavior in all cases, which becomes more prominent with the increase in the weight percent of the reinforcement. In the heating cycles of all the cases, a maxima (peak) is observed at 300 °C, while in the cooling cycles, the peak appears at about 225 °C.

4. Discussion

Though CTE is a basic physical property, it is relatively difficult to predict the same in the case of MMCs because it is influenced by several factors, which include physical properties of matrix and reinforcement. Comparatively, composites featuring isotropic reinforcements such as aluminite particulate-reinforced ZA-27 alloy MMCs exhibit a simpler thermomechanical behavior. The PLC versus temperature curves in the case of all the composites exhibit some residual strain on cooling. These curves show that the particulate composites began deforming plastically at a slightly lower temperature and exhibited a relatively larger residual contraction than the unreinforced alloy. In order to calculate these thermal stresses, an expression based on a simple theoretical model developed by Tummala and Friedberg[22] has been used, which is given by

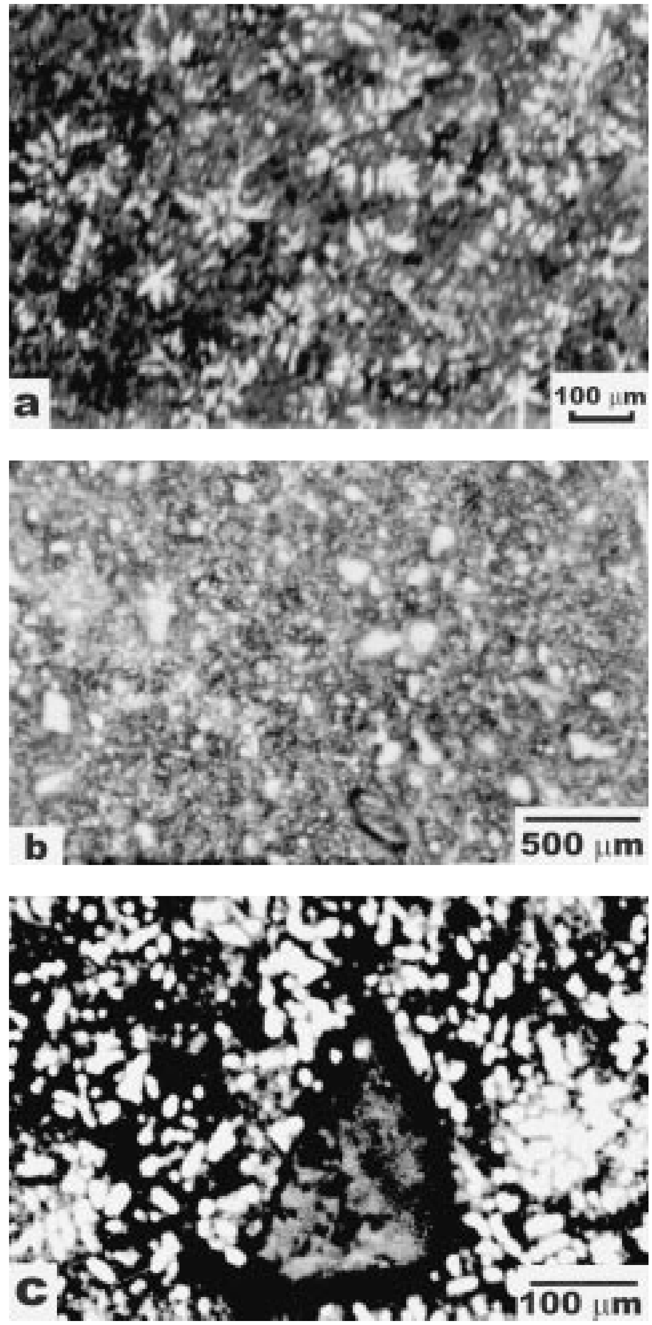

Fig. 1 Microstructure of (**a**) ZA-27 matrix alloy and ZA-27/4% aluminite MMCs at (**b**) lower magnification and (**c**) higher magnification

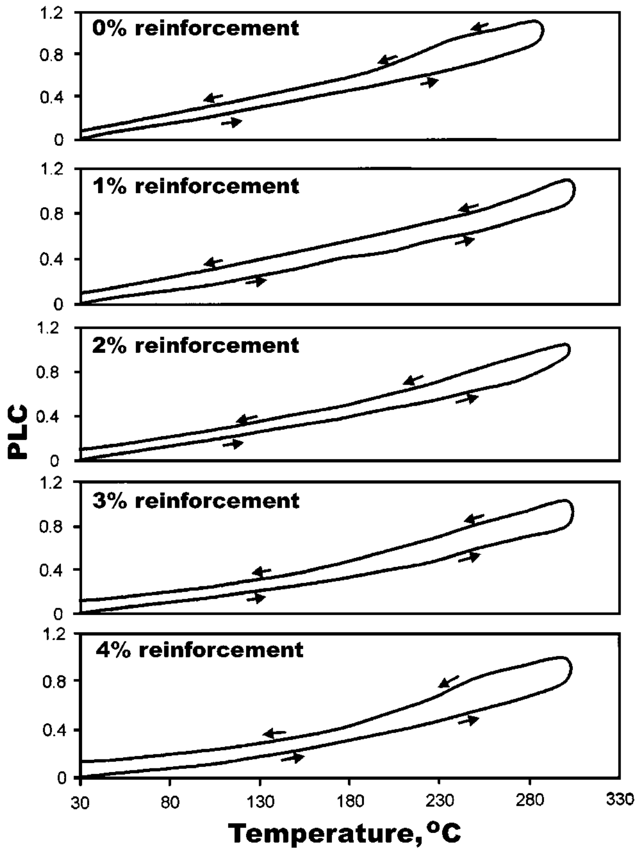

Fig. 2 Graphs showing PLC vs temperature of ZA-27/aluminite MMCs

$$P = \frac{(\alpha_d - \alpha_m)\,\Delta T}{[(1 + \mu_m)/2E_m] + [(1 - 2\mu_d)/E_d]} \quad \text{(Eq 3)}$$

where P is the pressure or stress at the matrix/reinforcement interface; α_m, μ_m, and E_m represent the CTE, Poisson's ratio, and elastic modulus of the matrix, respectively; and α_d, μ_d, and E_d represent the same quantities for the reinforcement. Substituting $\alpha_m = 26 \times 10^{-6}$/°C, $\alpha_d = 7.4 \times 10^{-6}$/°C, $\mu_m = 0.33$, $\mu_d = 0.22$, $E_m = 79$ GPa, and $E_d = 275$ GPa, Eq 3 gives

$$P = 1.778 \text{ MPa} \times \Delta T \quad \text{(Eq 4)}$$

For a change in temperature of 1 °C, the thermal stresses are calculated to be 1.778 MPa at the interface between the matrix and reinforcement, which is of the same order obtained by other studies.[23]

Thermal stresses in MMCs have already been studied by internal friction or damping capacity measurements.[24] The existence of the damping maximum is particularly important since this maximum could be related to the thermal stresses, which are generated in the composites. In the absence of thermal stresses, the dislocation can vibrate around its equilibrium position and contribute to the damping. This partly accounts for the observed damping capacity of the base alloy. When the composite specimen is cooled, tensile thermal stresses arise in the matrix due to the particulate distribution and induce a long-range movement of the dislocations, which is superposed on the oscillatory motion imposed by the damping apparatus. This interaction is supposed to be the origin of the observed maximum.

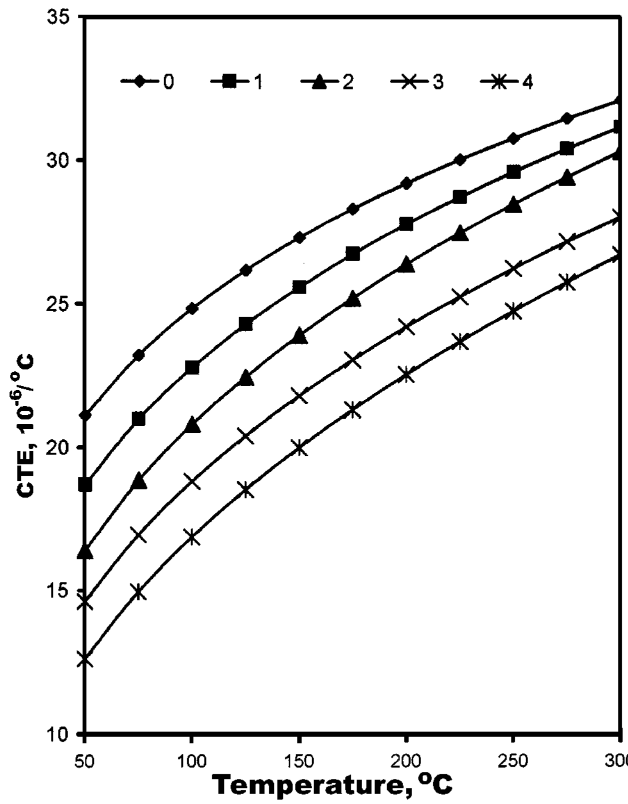

Fig. 3 The graph showing CTE vs temperature of ZA-27/aluminite MMCs

The vibration frequency and strain amplitude dependence of the damping maximum suggests that the relaxation processes are of thermal origin and are stress dependent. The expression for activation energy corresponding to the thermally activated relaxation process is given by[25]

$$f\tau_0 \exp(E/kT_P) = 1/2\pi \quad \text{(Eq 5)}$$

where f is the vibration frequency, τ_0 is the relaxation time, E is the activation energy, k is the Boltzmann constant, and T_p is the peak temperature. The data used in evaluating activation energies E_h and E_c, corresponding to heating and cooling peaks, respectively, of the 4% aluminite-reinforced composite are given in Table 2.

The thermal stresses generated in the composite are given by

$$\sigma_{th} = (E_h - E_c)/2\nu^* \quad \text{(Eq 6)}$$

where ν^* is the activation volume and is given by $\nu^* = 400$ $\mathbf{b}^3$ ($\mathbf{b}$ is the length of the Burgers vector of dislocations in the matrix alloy = 0.25 nm). A value of $\sigma_{th} = 1.359$ MPa was calculated, which is in close agreement with the value obtained by thermal expansion studies.

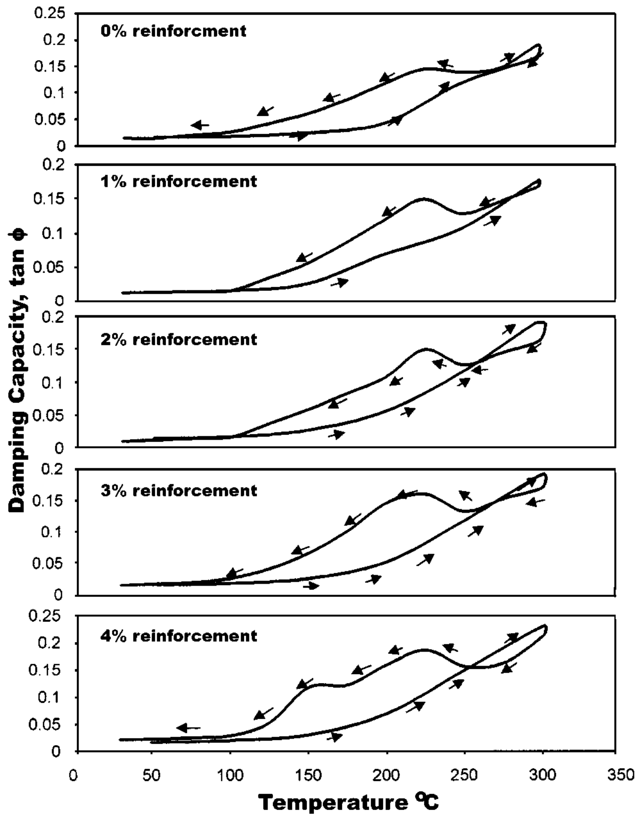

Fig. 4 Graph showing damping capacity vs temperature of ZA-27/aluminite MMCs

Table 2 Data used in the calculation of activation energies

Parameters	Heating peak	Cooling peak
Peak temperature (T_p) in °C (K)	300 (573)	225 (498)
Relaxation time (τ_0) in μs	2.5427	8.0574
Vibration frequency (f) in Hz	10	10
Activation energy (calculated), eV	0.4323	0.3261

In PLC and damping tests, the hysteresis observed between heating and cooling curves is attributed to internal thermal stresses existing in the composites due to CTE mismatch between matrix and reinforcement during fabrication and subsequent thermal cycling. Theses thermal stresses change sign during heating and cooling (compressive stresses during heating and tensile stresses during cooling).[26] The hysteresis is also seen in the matrix alloy because the matrix is a binary alloy, with constituent elements having different properties, which may lead to mismatch stresses between them. This accounts for the small hysteresis in the matrix alloy, which increases with the increase in the reinforcement in the composites.

5. Conclusions

The thermal expansion and damping behavior of ZA-27 alloy matrix and composites with aluminite as reinforcement has been studied over a temperature range 30 to 300 °C both in the heating and cooling cycles. Thermal expansion studies showed residual strains and maxima were obtained in the heating and cooling curves of the damping behavior of the composite. These investigations revealed the presence of residual thermal stresses generated in the composite due to the difference in the CTE between the matrix and reinforcement. The long-range mobility of dislocations in the metal matrix around the reinforcement seems to be the critical parameter for stress relaxation at the matrix/reinforcement interface. This parameter has been characterized by damping measurements. The thermal expansion study of thermal stresses leading to plastic deformation in the matrix and residual strain obtained is particularly useful in any application of the composite at elevated temperatures. The thermal stresses have been evaluated in both cases of thermal and damping studies and found to be in good agreement with each other.

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