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# Effect of changing rate of residual stress on thermal expansion behavior of magnesium borate whisker-reinforced aluminum composite

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**Abstract**

Magnesium borate whisker-reinforced aluminum matrix composite is a new aluminum matrix composite with high properties and low cost. In the study, the residual stress changing behaviors on heating and cooling of the composite were investigated through the coefficient of thermal expansion (CTE) curves. On heating, the tensile stress relaxation and compressive stress generation in the matrix of the composite results in the CTE of composite is smaller than that predicted by mixture rule, but the compressive stress relaxation in the matrix of composite causes the CTE of composite is larger than that predicted by mixture rule. The tensile and compressive stress changing rates with temperature are linear on heating in the matrix of the composite at lower and higher temperature ranges. The CTE of the composite on cooling is smaller than that on heating.


*Keywords:* Coefficient of thermal expansion; Magnesium borate whisker; Aluminum matrix composite; Residual stress

## 1. Introduction

Whisker-reinforced aluminum matrix composites (AMCs) have attracted much attention in the last two decades because of their higher properties [1–3], including SiC whisker-reinforced AMCs, $Al_{18}B_4O_{33}$ whisker-reinforced AMCs, and so on. However, some drawbacks about whisker-reinforced AMCs have not been overcome, and the most important one is the higher cost of whiskers. Magnesium borate ($Mg_2B_2O_5$, MBO) whisker can be synthesized from byproducts of seawater desalting or the compounds containing Mg and B of saline, the cost of the whisker is very low, which is almost equal to that of aluminum alloy. Recently, we found that MBO whisker-reinforced AMC (MBOw/Al) prepared by squeeze casting method exhibits very good mechanical properties [4]. But the thermal expansion properties of the composite have not been revealed.

Because of the importance of the CTE for metal matrix composite applications, many researches have been done for the CTE of particulate and long fiber reinforced aluminum composite, and many theoretical models such as Turner's [5], Kerner's [6], and Schapery's [7] models have been employed to discuss the thermal expansion behaviors of the composites. Although these models can be used to predict the reinforcement content dependence of CTEs of composites, it is difficult to obtain the exact information about the relationship between the composite CTE and temperature.

In general, the coefficient of thermal expansion (CTE) of whisker is much lower than that of aluminum alloy, so residual stress (RS) always exists in whisker-reinforced AMC [8–10]. For the composite cooled from higher temperature, the average compressive stress exists in whiskers; but tensile in matrix. Obviously, the temperature change makes the RS change, which affects the CTE of composite [9,10]. In this case, the relationship between CTE and temperature for composites can be obtained. It is very important to probe the RS changing behaviors using CTE curve with temperature, because not only the effect RS change on the mechanical properties of composite at elevated temperature but also the difficulty of RS change measurement.

In the present study, using a simple model [11], we analyze the RS relaxation and generation behaviors in MBOw/Al composite through the CTE curve.

## 2. Experimental

The aluminum alloy matrix composite with the volume fraction of MBO whisker of 20% was fabricated using squeeze casting method at the temperature of 800 °C, and the temperature of die and whisker preform of 500 °C. Some properties of MBO whisker is listed in Table 1 [12]. The matrix is commercial aluminum alloy 2024 (AA2024). Before CTE measurement, the

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Table 1
Properties of MBO whisker

| | |
|---|---|
| Length (μm) | 10–30 |
| Diameter (μm) | 0.5–2 |
| Density (g/cm$^3$) | 2.91 |
| Tensile strength (GPa) | 3.9 |
| Elastic modulus (GPa) | 264.5 |
| Thermal expansion coefficient (K$^{-1}$) | 11 |
| Melting point (°C) | 1360 |

composite was heated at 490 °C for 1 h, and then quenched into water with room temperature.

The microstructure was analyzed using optical microscope (OM) on an Olympus OM and transmission electron microscope (TEM) on a Philips CM-12 TEM, and the thin foils for TEM observation were thinned using ion milling. The CTE of the composite was measured using a Netzch DIL 402C dilatometer with heating rate and cooling rates of 5 °C/min. The physical CTE curves were obtained using the software of Netzch Company.

## 3. Results and discussion

### 3.1. Microstructures of the composite

Fig. 1 shows the OM and TEM images of the MBOw/Al composite. In Fig. 1(a), one can find that the distribution of whiskers is random, and no crack can be found. Fig. 1(b) presents the typical microstructures of MBO-Al interface, transverse and longitudinal sections of MBO whisker. As shown in Fig. 1(b), the interfacial reaction between the whisker and aluminum matrix is light, and the transverse section of MBO whisker exhibits irregular polygon. Lot of TEM observations demonstrate that no interfacial crack can be observed at the interface, which shows indirectly that the interface bonding in the composite is good.

### 3.2. Physical CTE curves and stress change analysis on heating

Fig. 2 gives the heating curves of relative elongation and CTE versus temperature of MBOw/Al composite. As shown in Fig. 2(a), the relative elongation smoothly increases with the testing temperature increasing. In Fig. 2(b), it can be found clearly that the CTE curves can be divided into three regions: within region A, from 100 to 200 °C, the CTE of the composite increases linearly with temperature increasing; within region B, from 200 to 300 °C, the CTE of the composite increases more quickly than that in region A with temperature increasing; within region C, from 300 to 400 °C, the CTE of the composite is almost a constant.

The nonlinear dependence of CTE on temperature on heating can be hardly interpreted by the models mentioned above. Recently, we put forward a simple model to analyze the effect of residual stress change on the CTE of the composite [11,13], which is summarized as follows. If we assume that no interface sliding at interface in the composite takes place during CTE

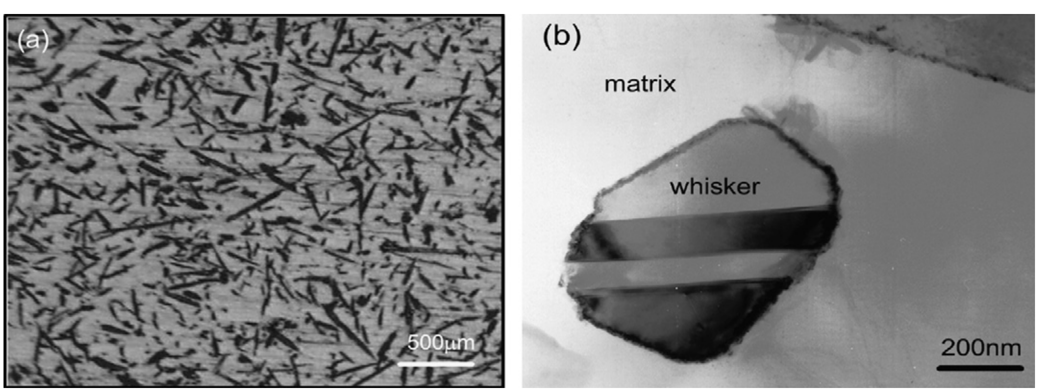


Fig. 1. OM (a) and SEM (b) images of MBO/Al composite.

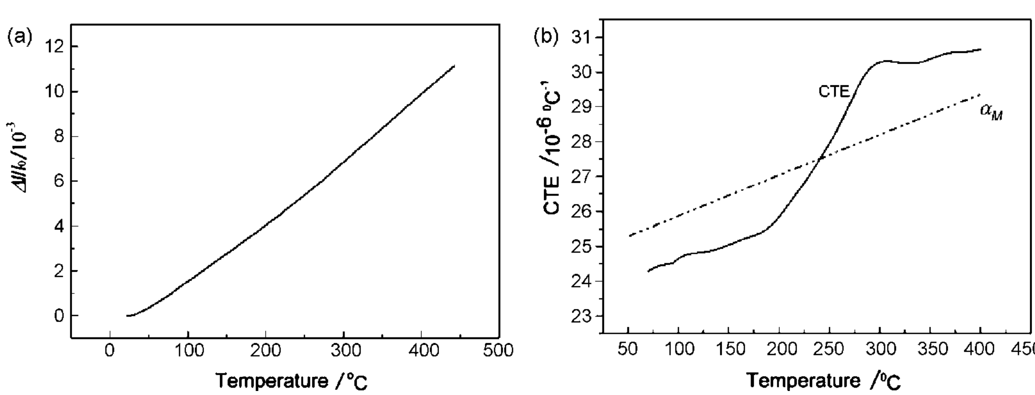


Fig. 2. Curves of relative elongation (a) and CTE (b) vs. temperature of MBOw/Al composite on heating.

measurement and the shear deformation is neglected, we can obtain

$$\left.\begin{aligned} \mathrm{d}U_\mathrm{m} &= U_\mathrm{m}\beta_\mathrm{m}\mathrm{d}T + U_\mathrm{m}^0\frac{\mathrm{d}\sigma_\mathrm{m}}{K_\mathrm{m}} \\ \mathrm{d}U_\mathrm{f} &= U_\mathrm{f}\beta_\mathrm{f}\mathrm{d}T + U_\mathrm{f}^0\frac{\mathrm{d}\sigma_\mathrm{f}}{K_\mathrm{f}} \end{aligned}\right\} \tag{1}$$

where $U_\mathrm{m}$ and $U_\mathrm{f}$ are the volumes of matrix and whisker, $\beta_\mathrm{m}$ and $\beta_\mathrm{f}$ the bulk CTEs of matrix and whisker, $\sigma_\mathrm{m}$ and $\sigma_\mathrm{f}$ are the residual stresses of matrix and whisker, $K_\mathrm{m}$ and $\mathrm{K_f}$ are the bulk moduli of matrix and whisker, $T$ is the temperature, and $U_\mathrm{m}^0$ and $U_\mathrm{f}^0$ are the volumes of stress-free matrix and whisker. Using the condition of stress balance between the whisker and matrix, the following formula ca be obtained [11,13]

$$\alpha_\mathrm{c} = \alpha_\mathrm{M} + \frac{V_\mathrm{m}}{3K}\frac{\mathrm{d}\sigma_\mathrm{m}}{\mathrm{d}T} \tag{2}$$

and

$$\frac{1}{K} = \frac{1}{K_\mathrm{m}} - \frac{1}{K_\mathrm{f}}$$

where $\alpha_\mathrm{M} = V_\mathrm{m}\alpha_\mathrm{m} + V_\mathrm{f}\alpha_\mathrm{f}$, i.e. the mixture rule of CTE of composite, $V_\mathrm{m}$ and $V_\mathrm{f}$ are the volume fractions of matrix and whisker, $\alpha_\mathrm{m}$ and $\alpha_\mathrm{f}$ are the CTEs of matrix and whisker.

Using the above model, the stress change in the matrix of the composite on heating can be analyzed according to the physical CTE curve. Because $K_\mathrm{f}$ is much larger than $K_\mathrm{m}$, $1/K$ is positive. Therefore, the effect of the changing rate of RS in matrix on the CTE of composite can be concluded as shown in Table 2.

On the basis of above analysis, the RS change on heating can be analyzed. On heating, the changing order of RS in the matrix is tensile RS relaxation, compressive RS generation and compressive RS relaxation. The change of RS in matrix results in the temperature dependence of CTE of composite.

In region A shown in Fig. 2(b), the CTE increases with temperature monotonously and is smaller than $\alpha_\mathrm{M}$, which is corresponding to the tensile RS relaxation at low temperature and compressive RS generation at higher temperature in the matrix of the composite. Because the change of average RS in matrix is proportional to the temperature change [14], in the region, the tensile RS in the matrix relaxation is elastic relaxation [9], and the compressive RS generation in the matrix is also elastic, as shown schematically in Fig. 3. This result is quite different from that found in SiCw/Al composite [9], in SiCw/Al composite, both elastic and plastic relaxations of tensile RS in the matrix take place on heating. The difference is caused by the difference of CTE between SiC and MBO whiskers. Because the CTE of SiC whisker (about $4 \times 10^{-6}/^\circ\mathrm{C}$)[11] is much smaller than that of MBO whisker (about $11 \times 10^{-6}/^\circ\mathrm{C}$)[12], the RS in SiCw/Al composite should be larger than that in MBOw/Al composite, in this case, the relaxation of larger RS in SiCw/Al composite may cause the plastic deformation of the matrix.

Table 2
Effect of RS changing on the CTE of composite on heating

| Change of RS in matrix | $\alpha_\mathrm{c}$ and $\alpha_\mathrm{M}$ relation |
|---|---|
| Tensile RS relaxation | $\alpha_\mathrm{c} < \alpha_\mathrm{M}$ |
| Compress RS generation | $\alpha_\mathrm{c} < \alpha_\mathrm{M}$ |
| Compressive RS relaxation | $\alpha_\mathrm{c} > \alpha_\mathrm{M}$ |

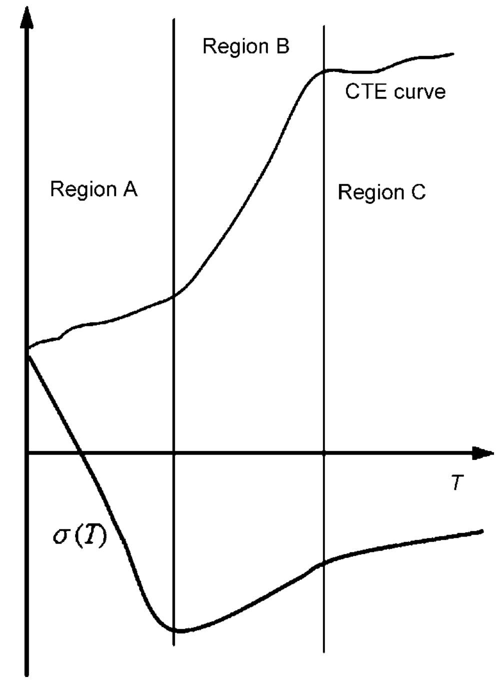


Fig. 3. Schematic diagram of RS changing tendency of MBOw/Al composite on heating.

In region C shown in Fig. 2(b), the CTE curve is also linear and the CTE is larger than $\alpha_\mathrm{M}$, so it is considered that the curve is corresponding to the compressive RS in the matrix elastic relaxation, as shown schematically in Fig. 3.

Region B in the CTE curve of Fig. 2(b) is a transition region. The CTE changing behavior may be caused by two reasons. One is the elastic and plastic RS relaxations happen simultaneously on heating, because the lower yield strength of the matrix at elevated temperature. The other is the transition temperatures from tensile RS to compressive RS are different for the matrix regions around different whiskers with different sizes, because the RS is closely related to the size of the whisker.

The RS changing schematic tendency of RS in the matrix are given schematically in Fig. 3.

### 3.3. *Physical CTE curves and stress change analysis on cooling*

Fig. 4 gives the cooling curves of relative elongation and CTE vs. temperature for MBOw/Al composite. As shown in Fig. 4(a), the relative elongation decreases smoothly with the testing temperature decreasing. In Fig. 4(b), it can be found clearly that the CTE curves can be divided into two regions: within region A, from 400 to 200 °C, the CTE of the composite decreases nonlinearly with temperature decreasing; within region B, from 200 to 75 °C, the CTE of the composite decreases linearly.

Because of the RS in the matrix is compressive at 400 °C the changing order of RS in matrix on cooling is compressive RS relaxation and tensile RS generation, so the $\mathrm{d}\sigma_\mathrm{m}/\mathrm{d}T < 0$. In this

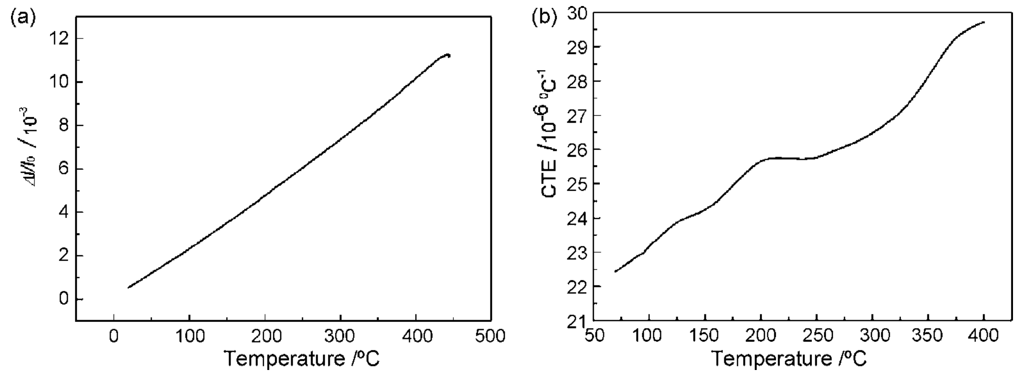


Fig. 4. Curves of relative elongation (a) and CTE (b) vs. temperature of MBOw/Al composite on cooling.

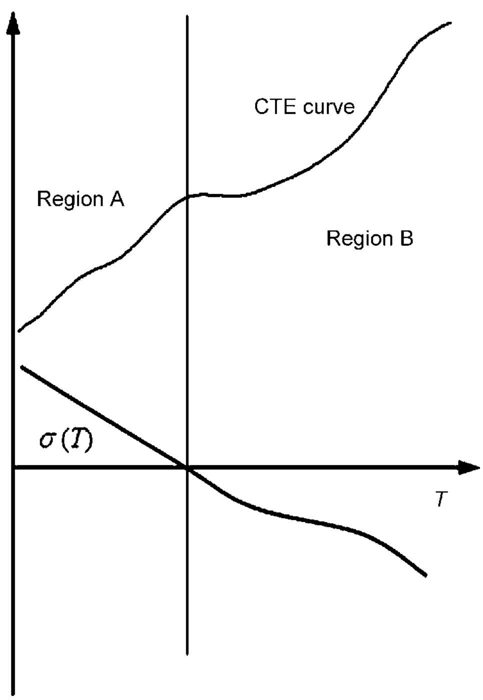


Fig. 5. Schematic diagram of RS changing tendency of MBOw/Al composite on cooling.

case, the CTE of the composite on cooling is lower than that on heating, which can be confirmed simply through the comparison of Fig. 2(b) and Fig. 4(b).

Region A shown in Fig. 4(b) is obviously corresponding to the relaxation of compressive RS in the matrix, in which the nonlinear CTE curve results from the simultaneous plastic and elastic relaxations. Region B shown in Fig. 4(b), the CTE curve is linear and corresponding to the generation of tensile RS in the matrix without plastic relaxation. The changing tendency of RS in the matrix on cooling of the composite is shown schematically in Fig. 5.

On the basis of above analysis, one can find that the RS changes on heating and cooling are asymmetry in MBOw/Al composite, thus the CTE of the composite on heating is quite different from that on cooling.

## 4. Conclusions

The CTE of MBOw/Al composite is closely related to the residual stress changing rate. The tensile stress relaxation and compressive stress generation in the matrix of the composite results in the CTE on heating of composite is smaller than that predicted by mixture rule, but the compressive stress relaxation in the matrix of composite causes the CTE of composite on heating is larger than that predicted by mixture rule. On heating, the residual stress in the matrix of composite is elastically relaxed in lower or higher temperature region.

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