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Thermal residual stress investigation in AS52/ Al18B4O33 magnesium matrix composite by thermal cycling test

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ABSTRACT

Purpose: MMCs have microscopic scale thermal residual stress that is generated after cooling from high temperature Because of the difference of thermal expansion coefficient between the matrix and reinforcement. Because of their high service temperature, automobile parts experience thermal cycling between room and service temperature. Those thermal cycles can vary the properties of the MMCs by changing residual stress field. In this study, the relations between residual stresses and hardness were investigated.

Design/methodology/approach: For the residual stress investigations, thermal cycling test was performed. After thermal cycling testing, the thermal residual stress of the MMC was investigated using high resolution X-ray diffraction test. On the other hand, the residual stress was calculated by the finite elements method and it was compared to the experimental results.

Findings: The residual stress relaxed in the matrix with thermal cycling. With the relaxation of the residual stress, the hardness of the composite was decreased.

Research limitations/implications: In this study, the relaxation of residual stress of MMCs was observed with thermal cycling. Further investigations for the mechanical properties, like tensile behaviour and wear properties, should be needed in next study.

Originality/value: In this study, numerically calculated residual stress in magnesium matrix MMCs was compared with experimental results.

Keywords: Composite materials; Mg; Al18B4O33; MMCs; Residual stress; Thermal cycling

MATERIALS

1. Introduction

Because of its higher relative strength and stiffness than Fe and Al alloys, magnesium alloys are very attractive materials in aerospace, aircraft and automobile industries [1-4]. However, the commercial application of them is severely restricted by poor high temperature strength and creep properties.

On the other hand, metal matrix composites (MMCs) reinforced with discontinuous reinforcement (short fibre, whisker or particle) are attractive for applications requiring higher thermal stiffness and strength than monolithic alloys. Aluminium borate whisker ($9(Al_2O_3)\bullet 2(B_2O_3)$, $Al_{18}B_4O_{33}$) seem to be good candidate for the reinforcement of magnesium matrix MMCs because it is chemically stable in magnesium alloys and exhibits good mechanical properties at relatively low cost [5].

MMCs have microscopic scale thermal residual stress that is generated after cooling from high temperature because of the difference of thermal expansion coefficient between the matrix and reinforcement. So, that residual stress is one of the inherent properties of composites and cannot remove by heat treatment [6]. The development of such stresses and the mechanical behaviour of MMC in the presence of these stresses has been thoroughly studied by several authors using analytical, numerical and/or experimental methods[7-12]. The results of these studies indicate that the mechanical properties such as hardness, tensile stress and wear properties of MMC largely depend on the residual stress.

Because of their high service temperature, automobile parts experience thermal cycling between room and service temperature. Those thermal cycles can vary the properties of the MMCs by changing residual stress field. In this study, residual stress was investigated using thermal cycling test. For better understanding of the experimental result, finite element analysis was carried out.

2. Experimental procedure

2.1. Specimen preparation

Chemical composition of the magnesium matrix used in this investigation were AS52 (4.1~5.3wt% Al, 2.37wt% Si). The reinforcement was $Al_{18}B_4O_{33}$ with diameter of 0.5~1.0 μm and length of 10~30 μm. Three reinforcement volume fractions, 15, 25 and 35 vol.% were introduced by a squeeze infiltration method. A preform was infiltrated by molten magnesium alloy under high pressure. The mold and the preform were preheated to 450°C, and magnesium alloy melt being superheated to 750°C was poured over the preform. The pressure of a plunger was 70 MPa and kept for 60 seconds.

2.2. Measurement of residual stresses

Residual stress analysis was carried out by Rigaku D/MAX 2200 X-ray diffraction machine with multipurpose goniometer, using the $\sin^2\psi$ technique. The measurements were carried out within a ψ range of 0-20, step size 5 in ψ. The X-ray radiation used was Cu Kα, where the diffraction angle for the peak AS52 (112) is 2θ=63.4.

2.3. Thermal cycling test

Each specimen was machined to cubic forms that had 10x10x10 mm in dimensions. After that, the specimens were annealed by holding at 400°C for 4 hours to minimize macroscopic scale residual stresses, which could occur during fabrication and machining process.

Then, thermal cycling tests were performed. Each cycle of the test was carried out by quenching in water at 25°C for 10 sec after the specimens were kept at the 2 different temperatures of 200 and 300°C in an electric furnace for 10 min for the investigations of residual stresses changes. Specimens were heated in the furnace under the argon atmosphere to prevent oxidation. Hardness of each specimen was investigated in every 5 cycles.

3. Finite element analysis

The residual stress fields of the specimens were calculated by the finite element method (FEM). Unit cell models for the finite element analysis were set to have three $Al_{18}B_4O_{33}$ volume fractions of 15, 25 and 35%, as shown in Fig. 1. $Al_{18}B_4O_{33}$ was assumed to have a square packing arrangement for using the advantage of symmetry. The finite element meshes were made finer in the boundary between the reinforcement and the matrix. The boundary conditions specified were such that coordinate planes Ox and Oy were planes of symmetry, which indicated the freedom of the vertical direction at each plane was zero and the plane was restricted along that direction. And the conditions specified the other two planes leaving that define each unit cell as free to moving. The mechanical properties of the matrix and the reinforcement used in the models are shown in Table 1.

In this study, two mechanical models are considered for the comparison of results between without and with plastic deformation of the matrix phase. First model considered both the matrix and the reinforcement components to have thermoelastic behaviours. And second model considered the reinforcement component to have a thermoelastic behaviour and the matrix material to behave in a thermoelastic-viscoplastic way. To calculate the result of the second model, experimental stress-strain curve of AS52 monolithic alloy was used for the calculation of the plastic strain (Fig. 2).

For the calculations of thermal residual stresses, it was assumed that the initial stress at the end of annealing time was zero. The models first calculated thermal strain at each node by following Equation.

$$\varepsilon_{th}^{x} = \varepsilon_{th}^{y} = \varepsilon_{th}^{z} = \alpha(T - T_{ref}) \quad (1)$$

where α, Tref(=400oC), T(=25oC) and εth are thermal conductivity, reference temperature, applied temperature and thermal strain, relatively. Using static state thermal strain results calculated by Eq.1, the system calculated thermal stresses by Eq.2.

$$\vec{K}_n \cdot \Delta\vec{u}_n = \Delta\vec{f}_n \quad (2)$$

where $\mathbf{K}_n$, $\Delta\mathbf{u}_n$ are global stiffness matrix and the displacement increment vector, and $\Delta\mathbf{f}_n$ is the incremental nodal force vector, which evaluated at time instant t_n and corresponding to the time increment Δt. The solution of system Eq. 2 was then used to update the system configuration and all the state variables. In this study, $\mathbf{K}_n$ and $\Delta\mathbf{u}_n$ indicated Young's modulus and thermal strain, and the system calculates Δfn as the corresponding thermal load. The flow chart of the analysis is shown in Fig. 3.

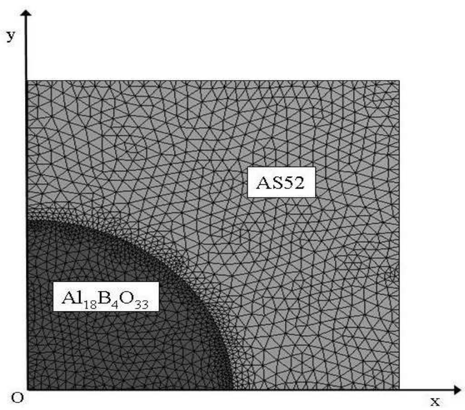

Fig. 1. Representative meshed unit cell of 35% AS52/$Al_{18}B_4O_{33}$ MMCs

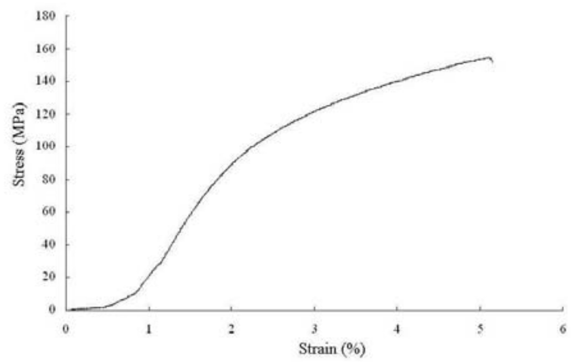

Fig. 2. Stress-Strain curve of AS52 monolithic alloy, at 25°C

Table 1.
Mechanical properties of MMCs

	AS52	$Al_{18}B_4O_{33}$
Poison's Ratio	0.35	0.24
Specific Heat ($JKg^{-1}K^{-1}$)	1040	780
Modulus of Elasticity (GPa)	44	392
Thermal Conductivity ($Wm^{-1}K^{-1}$)	156	20
Coefficient of Thermal Expansion(K^{-1})	0.000026	0.0000042

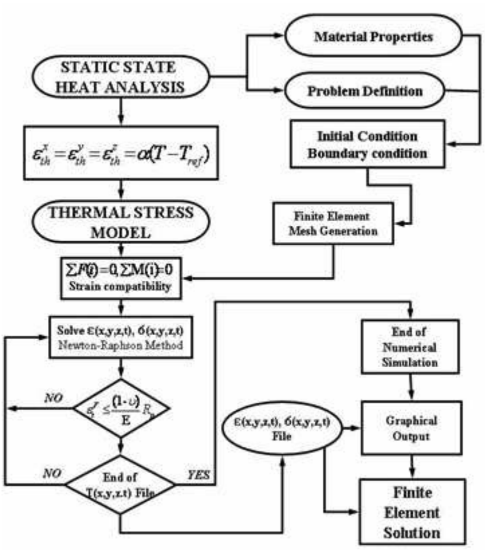

Fig. 3. Flow chart for the numerical modelling of the thermal stresses during thermal cycling test

4. Result and discussion

SEM microstructures of the AS52 MMC with volume fractions of 15, 25 and 35% are shown in Fig. 4. Those micrographs showed that a sound composite was successfully fabricated by the squeeze infiltration method.

The evolution of the hydrostatic stress, σ_h, is shown in Fig. 5. Because of relatively high stress of σ_y, the hydrostatic stresses in the matrix phases are tensile both without and with plastic strain. And when the plastic deformation occurs, mean hydrostatic stress reduced by the plastic flows of the matrix phase. From that result, residual stress in matrix phases expected to change from high tensile stress to lower when the plastic flow was occurred.

Fig. 6 shows measured residual stresses by XRD as function of numbers of cycles, with calculated mean hydrostatic stresses. In previous work, Weiland et al.[13] pointed out that the residual stress in MMCs could be relaxed by plastic flow of the matrix during thermal cycling. They suggested that the matrix yielding was restrict by Orowan strengthening at the first cooling, in that it resulted thermally generated dislocations increasing the local yielding point. For this reason, they stated that the matrix behaved largely elastically at the first cooling, even when the stress level was higher than the yielding point of monolithic matrix material. And they also observed that the thermal cycling induced plastic flow in the matrix, and that occurred stress relaxation. The experimental results shown in Fig. 6 seem to the good agreement with the previous result. The measured residual stress levels were similar to calculated results without plastic deformations before thermal cycles. And the stress generally relaxed with thermal cycling number in all three volume fractions, with approaching the values calculated with plastic deformation. The relaxations of residual stresses became more clearly with the increase of reinforcement volume fraction. Δt, the temperature drop during thermal cycling, also influenced the relaxation of residual stress.

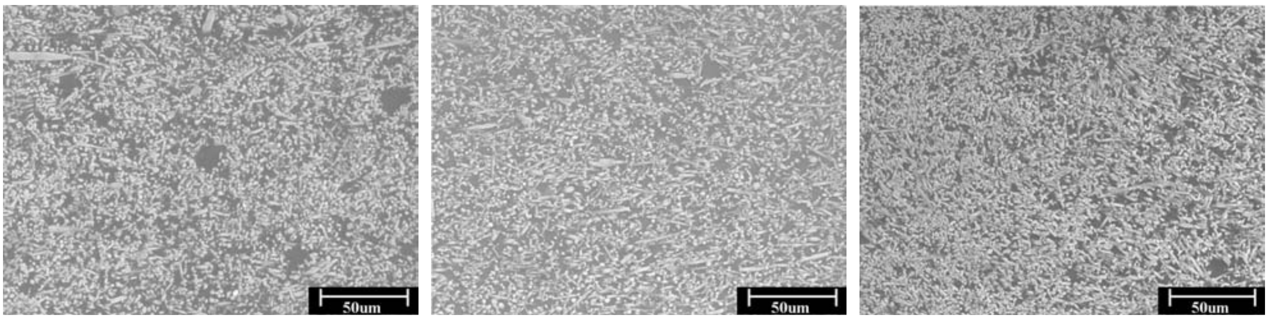

Fig. 4. SEM microscope of AS52/ $Al_{18}B_4O_{33}$ MMCs, (a) 15 vol.%, x500, (b) 25 vol.%, x500 and (c) 35 vol.%, x500

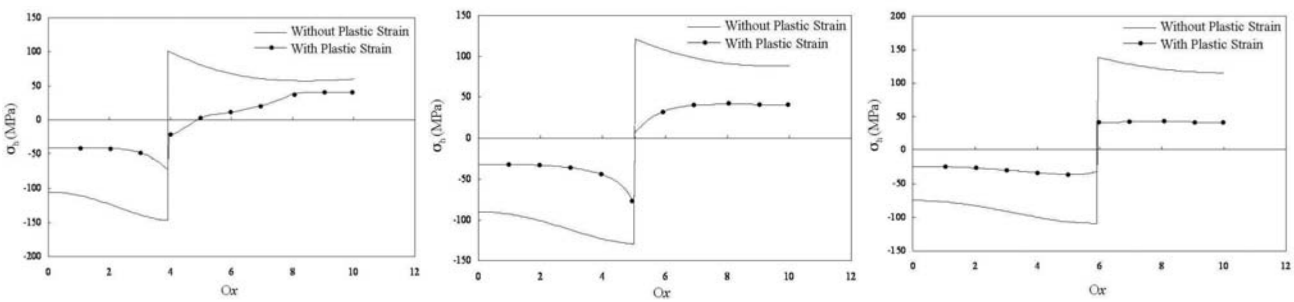

Fig. 5. Profiles of hydrostatic stress component σ_h registered along Ox, for the simulations performed with and without plastic strain in matrix phases, (a) 15 vol.%, (b) 25 vol.% and (c) 35 vol.%

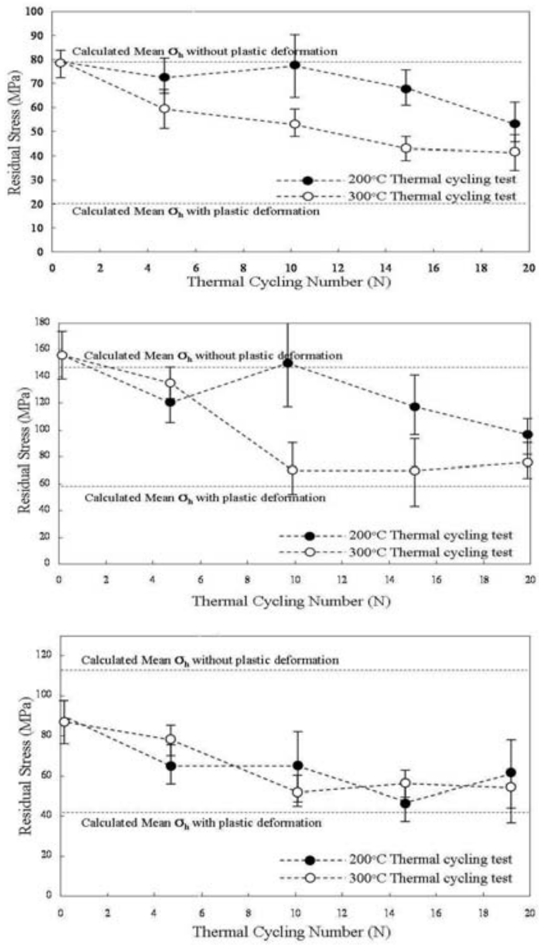

Fig. 6. Residual stress as function of numbers of cycles in AS52/ $Al_{18}B_4O_{33}$ MMCs, measured by XRD, (a) 15 vol.%, (b) 25 vol.% and (c) 35 vol.%

In this study, the final residual stress level after thermal cycling test seems to the independent of Δt, and Δt only affected to the relaxation rate. In general, the residual stress relaxation observed at lower cycles when Δt increased from 200 to 300°C.

5. Conclusions

From experimental results and numerical calculations of the residual stress in AS52/ $Al_{18}B_4O_{33}$ composite using thermal cycling test, the following conclusions can be drawn.

The residual stresses of AS52/Al18B4O33 MMCs relaxed with thermal cycling numbers, and these relaxations of residual stresses became more clearly with the increase of reinforcement volume fraction. When the temperature drop(Δt) during thermal cycling is large, the relaxation rate of residual stress increased.

From the comparison of experimental results and numerical calculations of the residual stress, the relaxation of residual stress seems to be occurred by plastic flow of the matrix. This results were in good agreement with previous work by Weiland et al..

Acknowledgements

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