Damping and Thermal Properties of Al/Al_2O_3 MMCs – A Comparative Study

Dr. Madhu. B. V, Senior Grade Lecturer, Mechanical Engg. Dept., Smt. L. V. (Govt.) Polytechnic, Hassan, Karnataka, India, bvmadhu2000@gamil.com

Dr. M. Krishna, Professor & Head, Mechanical Engg. Dept., R V College of Engineering, Bangalore, Karnataka, India, krishna_phd@yahoo.co.in

Abstract - Nowadays it is commonly considered that high damping and low thermal expansion material which have good mechanical properties used as structural materials for different applications. The present investigation is based on the effect of thermal residual stresses on the both thermal expansion and damping behavior of Al/Al_2O_3 metal matrix composites (MMCs). MMCs processed by compocasting technique with 5, 10 and 15% by weight of Al_2O_3 particle reinforcement. Thermal expansion and damping properties have been studied experimentally as a function of temperature over a temperature range room temperature to 400°C both in the heating and cooling cycle. During cooling the thermal stresses are relaxed by microplsticity of the matrix near the interface. Reproducible hysteresis loops in the damping vs. temperature; lot was measured. Result shows the thermal expansion studies exhibited some residual strain, which increased with the increase in the weight % 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 exhibited maxima which became more pronounced with the increase in the weight percentage of the reinforcement. The damping maximum height decreases if the matrix strength is increased by increasing reinforcement. The appearance of the maxima 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 mismatch between the composite constituent phases. The thermal stresses have been estimated in both the cases using simple models.

Keywords — Compocasting, Damping, CTE, TMA, PLC.

I. INTRODUCTION

Aluminum metal matrix composites (MMCs) offer designers many added benefits as they are particularly suited for applications requiring high specific strength at elevated temperatures, good structural rigidity, dimensional stability [1]-[5] and low coefficient thermal expansion (CTE) [6]. Low CTE and high damping capacity are desirable for applications such as electronic heat sinks and space structures.

The MMCs in structural applications are dependent on their proper and complete characterization under various conditions of mechanical and thermal loading. One of the important aspects of MMCs is the influence of thermal residual stresses on the properties of the materials. When MMCs are fabricated at a certain high temperature and cooled to the room temperature, residual thermal stresses are induced into the matrix and reinforcement because of the significant difference between the CTE of the two constituents. The residual stresses would introduce some undesirable effects on the physical and thermal properties of the composites. Several publications on experimental works and numerical computations of thermal stresses have been found in the literature [7], [8]. However, due to the complexity of the MMCs, a better understanding of the residual stresses in these materials is essential.

Earlier research works show that Al_2O_3 particle reinforced Al MMCs offer lightweight, low CTE [6], excellent mechanical properties [9],[10], good structural stability at high temperature [11],[12], good wear [13], and corrosion resistance [14].

Following are the objectives of the present investigation:

1) Study of CTE and damping behavior of Al_2O_3 particulate reinforced Al MMCs as a function of temperature.

 DOI : 10.35291/2454-9150.2022.0206

2) Study of thermal stresses generated in the composite as a result of the differences in the CTE between the matrix and reinforcement using simple models.

3) Study of the effect of thermal residual strain on the thermal and damping behavior of MMCs.

II. Experimental Procedure

A. Material Preparation

The matrix material used in this study, Al6061, has excellent casting properties and reasonable strength. This alloy is best suited for mass production of lightweight metal castings. The Al_2O_3 particulates of 30-50 μm were used as the reinforcement and the Al_2O_3 content in the composites was varied from 5 to 15% in steps of 5% by weight. Table I shows the chemical composition of Al6061 and Al_2O_3. Liquid metallurgy technique was used to fabricate the composite materials in which the Al_2O_3 particles were introduced into the molten metal pool through a vortex created in the melt by the use of an alumina-coated stainless steel stirrer. The coating of alumina on the stirrer is essential to prevent the migration of ferrous ions from the stirrer material into the molten metal. The stirrer was rotated at 550 rpm and the depth of immersion of the stirrer was about two-thirds the depth of the molten metal. The Al_2O_3 particles pre-heated to 500 °C were added into the vortex of the liquid melt which was degassed using pure nitrogen for about 3 to 4 min. The resulting mixture was tilt poured into preheated permanent moulds.

TABLE I CHEMICAL COMPOSITION OF AL6061 ALLOY

Constituents	Composition in %
Mg	0.92
Si	0.76
Fe	0.28
Cu	0.22
Ti	0.10
Cr	0.07
Zn	0.06
Mn	0.04
Be	0.003
V	0.01
Al	Bal.

B. CTE Measurement

The specimens for CTE testing were machined to 10mm x 5mm x 5mm dimensions. The specimen surfaces were ground using series of Silicon Carbide papers of 100, 200, 400, 600, & 1000 grit and then polished with 3μm diamond paste to obtain a fine finish. The specimens were washed using distilled water and acetone separately and dried. Percent linear change (PLC) measurements were made in the temperature range 25 to 500ºC at the rate of 5ºC/min using a Commercial Thermal Mechanical Analyzer Equipment (model TMA 2940, Dupont, USA) both in heating and cooling cycles. The sample was placed on a quartz stage and a moveable probe was kept on top of the sample. The thermal expansion of the specimen was detected using a linear variable differential transformer (LVDT) attached to the probe. The furnace surrounding the sample stage and the probe provides high temperature environment during measurements. The thermocouple adjacent to the sample picks up the temperature so that the dimensional changes can be obtained 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 compute the CTE of the base alloy and the composites.

C. Damping Measurement

Specimens were machined and polished to 70mm x 10mm x 2mm dimensions following according the procedure presented under CTE measurement. A Dynamic Mechanical Analyzer (DMA model 983, Dupont) used for measuring damping capacity includes sample arms and clamps, flexure pivot, LVDT, electro-magnetic driver and a temperature programmer interfaced with a computer. The specimen was subjected to a flexural sinusoidal strain with constant amplitude and the resultant-bending stress was measured simultaneously. The sample was held between the two end clamps and enclosed in a chamber that provides heating and cooling capability. The electro-magnetic driver applies flexural strain to the specimen and the resultant stress on the sample was measured by LVDT. The specimens were displaced by 250-μm peak to peak at the drive clamp corresponding to a maximum strain of $2.6x10^{-4}$. The sample length measured between the clamps was approximately 38 mm. The temperature of the specimen was varied from 25°C to 500°C both in the heating and cooling cycles at the rate of 10°C/min.

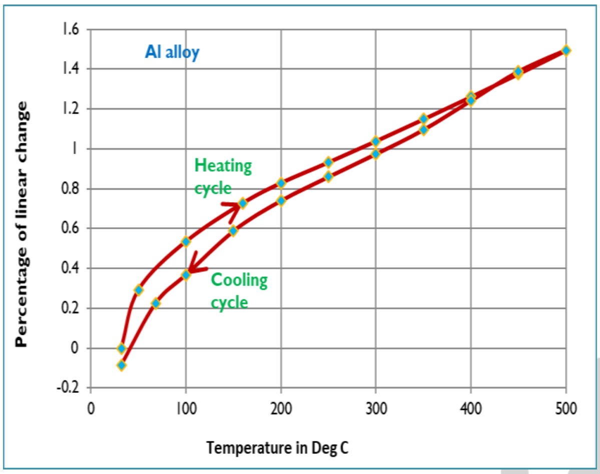
III. Results

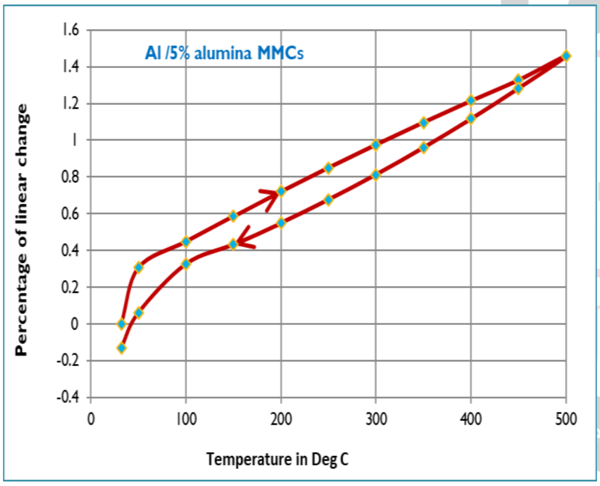
A. Thermal Expansion Properties

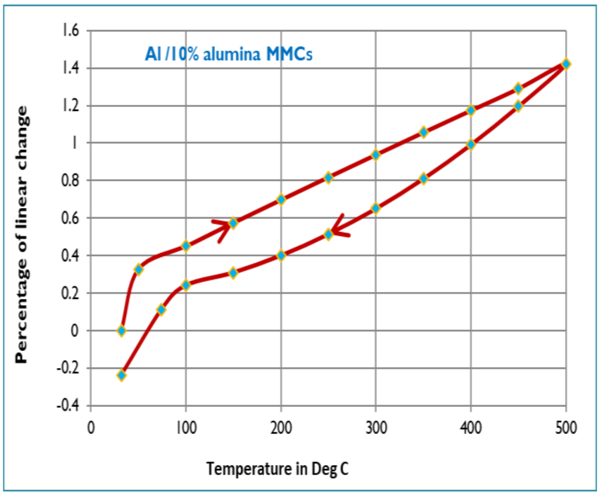
The results of CTE expressed as PLC as a function of temperature for different weight % of reinforcement in the Al6061 MMCs is shown in Fig.1. The PLC data showed reasonably good agreement with a maximum variation of 0.05 at 500 °C for the majority of the specimens tested. The PLC curve for the heating cycle shows linear increase with increase in temperature, while for the cooling cycle it shows a parabolic decrease with the decrease in temperature. These heating and cooling curves exhibit some hysteresis residual strain, which increases with increase in the weight % of the Al_2O_3 reinforcement. The residual strain in the case of unreinforced matrix alloy is found to have a minimum value. The area of the hysteresis

 DOI : 10.35291/2454-9150.2022.0206

between the curves increases with increase in the Al_2O_3 reinforcement. The variation of CTE with temperature of the composites as well as the unreinforced matrix alloy is shown in Fig. 2. While CTE of the composite decreases with increase in weight % of Al_2O_3, it moderately increases with increase in temperature. One observes a drastic reduction in the CTE of the composite in comparison with that of the matrix alloy, which indicates that in these composites, there is good interfacial bonding, due to the existence of macroscopic strain.







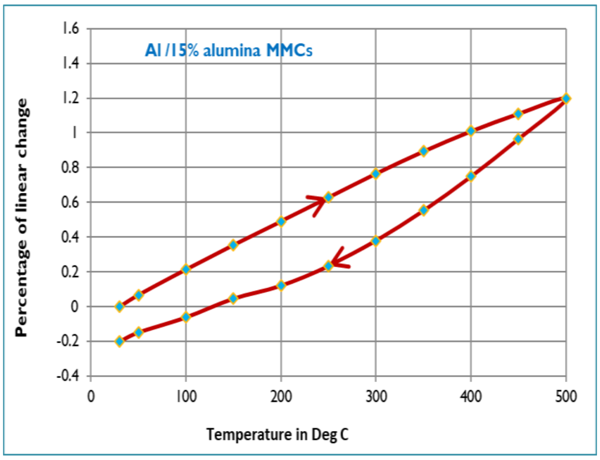


Fig. 1. Percent linear change (PLC) as a function of temperature at rate of heating and cooling cycle 5 °C/min for the Al_2O_3 reinforced Al composites. H-heating cycle and C-cooling cycle.

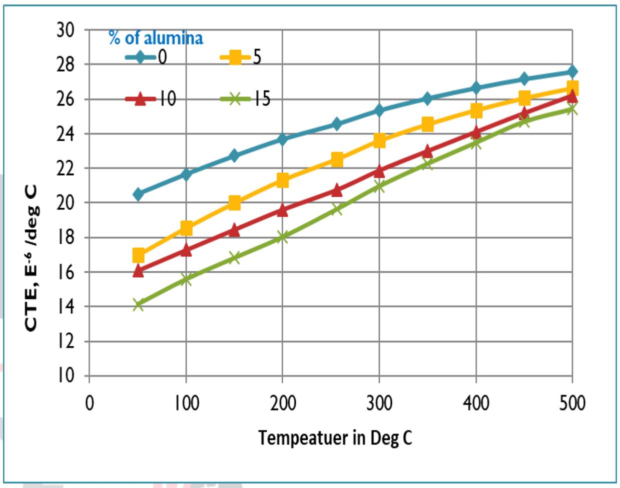


Fig. 2. Average coefficient of thermal expansion as a function of temperature varied at 5°C/min in heating and cooling cycles for the Al_2O_3 reinforced Al composites.

B. *Damping Capacity*

Damping capacity (tanϕ) verses temperature curves for the base alloy and the composites for heating and cooling cycles are shown in Fig. 3. Several interesting trends are observed from the curves that are found to be the characteristic feature of the Al_2O_3 reinforced Al composites. In the heating cycle, from 25-150°C, damping capacity seems to increase marginally with increase in temperature, from 150-300 °C it is found to increase rapidly with increase in temperature, and from 300-500 °C it increases mildly but linearly with increase in temperature. Also, in the heating cycle, for both the unreinforced matrix alloy and reinforced composites, a maxima (peak) is observed at 500 °C. In the cooling cycle, a closer observation of Fig. 3 reveals some interesting details on the hysteresis behavior and the maxima (peak) phenomena of the composites exhibited between the heating and cooling curves. In the cooling cycle, different nature of curves is observed. Initially, from 500-400°C the damping capacity marginally decreases, from 400-250°C it increases, from 250-25°C it steeply decreases with decrease

 DOI : 10.35291/2454-9150.2022.0206

in temperature. Overall, the damping capacity and the area of the hysteresis curve increase with increase in reinforcement. Careful observation of the damping capacity data in the 225-250 °C range shows a peak. The damping capacity of the composites as well as the matrix alloy has been found to increase with the increase in temperature and increase in reinforcement.

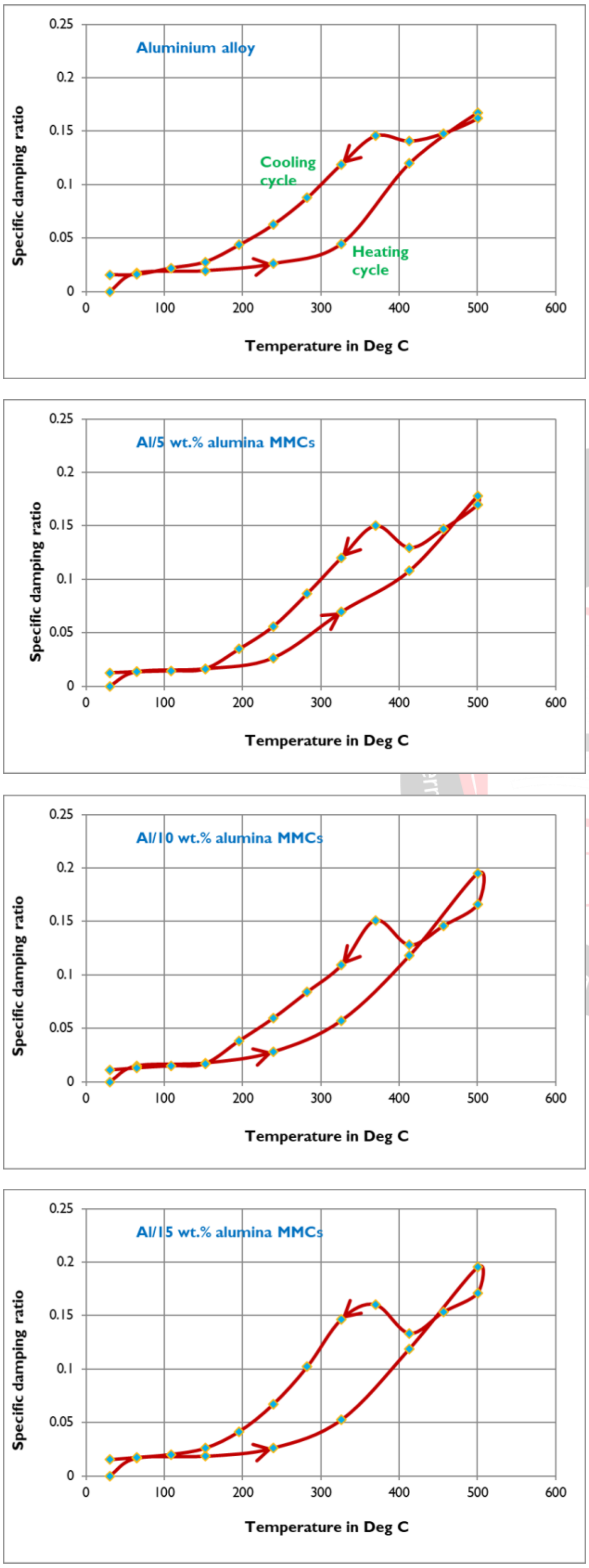


Fig. 3. Damping capacity (tan φ) at 0.1 Hz of as-cast Al-6061 alloy and Al_2O_3 reinforced Al composites in heating and cooling at 10 °C/min. H-heating cycle and C-cooling cycle.

IV. Discussion

A. Thermal Behavior

During cooling, the metal matrix contracts more than that of the ceramic particles, hence high-density dislocation is developed around the particles as a micro-plastic zone. The increase in the dislocation activity results in an increase of the thermal as well as the mechanical property loss [15], [16]. The dislocation near the interface has been observed from transmission electron microscopy [17]. The PLC verses temperature curves for the composites exhibit some hysteresis strain in the cooling cycle. The computed values of the percentage area covered by the heating and cooling curves are 5.89, 8.26, 16.7 and 22.7 in case of base alloy, 5%, 10%, and 15% Al_2O_3 reinforced composites respectively. When the ceramic weight % is small, it may be assumed that each ceramic particulate is surrounded by the matrix phase, and the average inter-particle spacing is not influenced by the presence of the ceramic phase with lower CTE [18]. The ceramic particles are in hydrostatic state and their surrounding matrix phase suffers a compressive radial stress. On the other hand, in case of higher weight % of reinforcement, the average inter-particle spacing is significantly influenced. However, the Al matrix alloy phase with a higher CTE should undergo shrinking on cooling, resulting in a tensile residual stress development. During contorted secondary heating and cooling cycles, the matrix alloy covers the particulate and shrinks. The result of this is the hysteresis as observed between the heating and cooling curves. The thermal strain depends on the difference in the CTE between the particle (αp) and the matrix (αm) and the temperature difference ΔT. The thermal strain [19] is given by:

$$\varepsilon T = \Delta\alpha\ \Delta T = (\alpha m-\alpha p)\ (T-T0) \qquad (1)$$

where T and T0 are the melting and room temperatures respectively. According to Hooke's law, elastic stress strain relation is given by:

$$\sigma th = E\ \varepsilon T\ /(1-\nu) \qquad (2)$$

where E is the stiffness and ν is the Poisson's ratio of the matrix. It is assumed that the thermal strain is purely elastic and the stress changes linearly with temperature which is given by combining Equations (1) and (2):

$$\sigma th = E\ (\alpha m - \alpha p)\ (T-T0)/(1-\nu) \qquad (3)$$

$$\sigma\ th = E\ (\alpha m - \alpha p)\ \Delta T/(1-\nu) \qquad (4)$$

For $\alpha m = 26 \times 10^{-6}$/°C, $\alpha p = 2.6 \times 10^{-6}$/°C, E = 70 GPa and ν = 0.3

 DOI : 10.35291/2454-9150.2022.0206

Equation (3) gives $\sigma th = 2.34$ MPa x ΔT (5)

For 1°C change in temperature, the computed value of thermal stresses is 2.34 MPa at the interface between the matrix and the reinforcement, and this value is in good agreement with those obtained in other studies [20].

B. Damping Behavior

Al/Al_2O_3 composites have been developed with higher stiffness (E) and lower density (ρ). (E/ρ) 1/2 also represents the velocity of the elastic waves in the material. Thus, higher specific stiffness results in a higher natural frequency for the components [21], which is one of the reasons for increase in the damping capacity of the composites. Perez et al. [22] have reported that the dislocation concentration found in Al matrices of ceramic particulate-reinforced MMCs is in the order of 1013 to 1014 cm^{-2}. Kim [18] has reported that if the heat dissipation were taken into account as part of the plastic work, the predicted dislocation densities of the elastoplaticity model would have been in reasonable agreement with the measured dislocation densities of 109 to 1010 cm^{-2}. These dislocations are generated to accommodate the residual strain around the particulate; but the dislocation concentration near the reinforcement-matrix interface is larger and it decreases with increase in distance from the interface. The thermal stresses in MMCs have been already studied by internal friction or damping capacity measurement [23]. The existence of the damping maxima is particularly important since this maximum may 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 maxima. The dislocation density in the unreinforced matrix is quite low [24]. Hence, the damping capacity is suggested simply to come from the dynamic hysteresis of the lattice defects [25] such as the vacancy or interstitial due to the reinforcement. The stress-induced ordering process of these leads to an inelastic strain, and the damping mechanism is referred to as the linear reversible inelastic relaxation and it opens up the dynamic hysteresis loop.

The dynamic hysteresis loop generally dissipates a smaller quantity of energy while the residual stresses are relaxed from the composite during the heating and cooling cycles.

The vibration frequency and strain amplitude dependence of damping maxima suggest 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 Parrine & Schaller [21]:

$$f\,\tau 0\, e(\xi/k\,TP) = 1/2\pi \quad (6)$$

Where f is the vibration frequency, τ0 is the relaxation time, ξ is the activation energy, k is the Boltzmann constant and TP is the peak temperature. The data used in evaluating the activation energies ξh and ξc corresponding to the heating and cooling peaks respectively of the 6% Al2O3 reinforced composite is given in Table II.

The thermal stress generated in the composite is given by:

$$\sigma th = (\xi h-\xi c)/2v^* \quad (7)$$

Where v* is the activation volume and is given by v* =400 b^3 (b is the length of Burgers vector of dislocations in the matrix alloy = 0.25 nm). Calculated value of σth = 3.081 Mpa.

TABLE II DATA USED IN THE COMPUTATION OF ACTIVATION ENERGIES (eV)

Parameter	Heating Peak	Cooling Peak
Peak Temp. (Tp) in °C (K)	500 (773)	250 (573)
Relaxation time (τ0) in μ sec.	2.5427	8.0574
Vibration frequency (f) in Hz	10	10
Activation energy (Calculated), eV.	0.5832	0.3424

V. CONCLUSION

The thermal expansion and damping behavior of Al6061 alloy matrix and composites with Al_2O_3 as reinforcement has been investigated over a temperature range of 25°C to 500°C both in the heating and the cooling cycles. It was found that the CTE has decreased with alumina by 11% to 72% for 20 wt.% of alumina compared to its base alloy, and the CTE has increased by 1.34 to 2.07 times for 500ºC compared to 50ºC. The thermal expansion studies and damping behavior showed hysteresis residual strains and in addition to this, the damping behavior showed maxima in the heating and cooling curves. A clear hysteresis is observed in the CTE, and the strain between heating and cooling is found in both matrix alloy and composites upon thermal cycling. This hysteresis is larger in the composites containing Al_2O_3 as reinforcements than that of the unreinforced Al6061 alloy. Thermal expansion mismatch leads to residual stress at the interface between reinforcement and matrix alloy, which is invariably much greater than their respect matrix alloy and depends strongly on the properties of the matrix and reinforcement. This study revealed the presence of residual thermal stresses generated in the composite due to the difference in

 DOI : 10.35291/2454-9150.2022.0206

the CTE between the matrix and the reinforcement, which are highest at the reinforcement particle–matrix interface, and they decrease with an increase in distance from the interface. The long-range mobility of dislocations in the metal matrix around the reinforcement seems to be the critical parameter for the stress relaxation at matrix/reinforcement interface. This parameter has been carefully characterized by damping measurement. It was found that the damping capacity was maximum at temperature 500ºC with an increase in a damping ratio of 23% for 20 wt.% of alumina compared to the as-cast Al alloy, and also, the damping ratio has improved by 13 times for 20 wt.% of alumina from 65ºC to 500ºC. The study of thermal stresses leading to plastic deformation in the matrix and the residual strains obtained is particularly useful in any high temperature applications of composites. The thermal stresses have been evaluated separately under thermal expansion studies and damping studies and the results in both the cases are found to be in good agreement with each other.

REFERENCES

[1] Madhu. B. V, K. Prahlada Rao, D. P Girish and M. Krishna, Thermal Mismatch Stresses in a Metal Matrix Composite - A Finite Element Analysis, International Journal of Engineering and Advanced Technology (IJEAT), ISSN: 2249 – 8958, Vol.1, No.1, October 2011, pp. 45-51.

[2] Madhu. B. V, K. Prahlada Rao, D. P Girish, Investigation of effect of thermal stresses on damping and thermal expansion behavior of Al/Al_2O_3 metal matrix composites, Bonfring International Journal of Industrial Engineering and Management Science, Vol.2, No.4, December 2012, pp.131-135.

[3] P.Reynaud, Cyclic fatigue ceramic-matrix composites at ambient and elevated temperatures, Composite Science and Technology, vol.56, (1996), pp.809-814.

[4] S.C.Tjong & Z.Y.Ma, The high-temperature creep behaviour of aluminium-matrix composite reinforced with SiC, Al2O3 and TiB2 particles, Composite Science & Technology, vol.57, 1997, pp.697-702..

[5] H.Akbulut, M.Durman, & F.Yilmaz, Higher temperature young's modulus of aluminium short fibre reinforced Al-Si MMCs produced by liquid infiltration, Materials Science and technology, (1998) vol.14, pp.299-305.

[6] S.C.Sharma, Effect of Al_2O_3 particle on the coefficient of thermal expansion behavior of the Al6061 alloy composites, Metall. & Mat. Trans.A, (2000), vol. 31A, pp. 773-780.

[7] Rajendra U.,Vaidya & K.K Chawla, Thermal expansion of metal-matrix composites, Comp. Sci. & Tech., (1994), vol. 50, pp.13-22.

[8] Eun U. Lee, Thermal stress and strain n a metal matrix composite with a spherical reinforcement particle, Metall. Trans. A, (1992), vol. 23A, pp.2205-2210.

[9] S.C.Sharma & A.Ramesh, Effect of heat treatment of mechanical properties of particulate reinforced Al6061 composites, Jour. of Mat. Engg. & Perf., (2000), vol.9(5), pp.557-561.

[10] K.H.W.Seah, S.C.Sharma, & A.Ramesh, Mechanical properties of cast aluminium alloy 6061-Al_2O_3 particulate composites, Proc. Instn. Mech. Engrs., (2000), vol. 214(L), pp.1-6.

[11] S.C.Sharma, K.H.W.Seah, M.Krishna, & A.Ramesh, Oxidation behaviour of 6061 Al/Al_2O_3 composites at high temperature, Alloys and Compounds, 2000, vol. 306, pp. 270-276.

[12] S.C.Sharma, Oxidation behaviour of 6061 Al/Al_2O_3 composites at high temperature, Jour. of Mat. Engg. & Perf., (2000) vol. 9(3), pp. 344-359.

[13] S.C.Sharma, A study of wear mechanism in particle reinforced aluminium metal matrix composites, Accepted for publication in Jour. of Mat. Engg. & Perf.

[14] S.C.Sharma, A study on stress corrosion behavior of Al6061/Al_2O_3 composite in higher temperature acidic medium using autoclave, Corrosion Science, vol.43, (2001), pp.1877-1889.

[15] H.M.Ledbetter & M.W.Austin, Internal strain (stress) in a SiC-Al particle reinforced composite: an X-ray diffraction study, Mater. Sci. &Eng., (1987), vol.89, pp. 53-61.

[16] E.Carreno-Morelli, S.E.Urreta & R.Schaller, Mechanical spectroscopy of thermal stress relaxation at metal-ceramic interfaces in aluminium-based composites, Acta Mater., (2000), vol. 48, pp.4725-4733.

[17] S.C.Sharma, The effect of ageing duration on mechanical properties of Al6061-garnet composites, Proc. Instn. Mech. Engr, (2001) vol.215, (L), pp.113-119.

[18] C.T.Kim, J.K.Lee, & M.R.Plichta, Plastic relaxation of thermoelastic stress in aluminium/ceramic composites, Metall. Trans. A, (1990), vol. 21A, pp.673-682.

[19] S.Berger, Elastic and plastic strains in Al/TiW/Si contacts during thermal cycles, Mat. Sci. & Engg., (2000), vol. A288, pp.164-167.

[20] Z.M.Sun, J.B.Li, Z.G.Wang & W.J.Li, Residual stresses in silicon carbide particulate reinforced aluminum composites, Acta Metall. Mater., (1992), vol.40 (11), pp. 2961-2966.

[21] N.Srikanth, D.Saravanaranganathan, M.Gupta, L.Lu, & M.O.Lai, Modeling and determination of dynamic elastic modulus of magnesium based metal matrix composites, Mat. Sci & Tech. (2000), vol.16, pp. 309-314

[22] R.J.Perez, J.Zhang, M..N.Gungor, & E.J.Lavernia, Damping behavior of 6061Al/Gr metal matrix composites, Metall. Transa., (1993), vol.24A. pp. 701-712.

[23] L.Parrine & R.Schaller, Thermal Stresses in metal matrix composites studied by internal friction, Acta Mater., (1996), vol.44(12), pp.4881-4888.

[24] Shanthashatry, M.Krishna & Jayagopal Uchil, A study on damping behaviour of aluminite particulate reinforced ZA-27 alloy metal matrix composites, Jour. of Alloys and Compounds, (2001), vol.314, pp.268-274.

[25] Santhashastry, M.Krishna, & Jayagopal Uchil, Effect of thermal stress on the thermal expansion and damping behaviour of ZA-27/aluminite metal matrix composites, Jour. of Mat. Engg. & Perf ., (2001), vol. 10(2), 220-224.

 DOI : 10.35291/2454-9150.2022.0206