Investigation on the Influence of Basalt Short Fiber on Thermo-Physical Properties of Aluminium Metal Matrix Composites

S. Ezhil Vannan, S. Paul Vizhian

Abstract- The objective of this research work was to investigate on the influence of basalt fiber on the microstructure and thermo-physical properties of Al /basalt short fiber metal matrix composites (MMCs). The MMCs were fabricated by liquid metallurgical technique and the basalt short fiber varies from 0 to 10 wt. %. The developed MMCs were characterized for damping, coefficient of thermal expansion, specific heat and electrical resistance using dynamic mechanical analyzer, thermal mechanical analyzer, differential scanning calorimeter and four probe electrometer respectively. The results shows that the specific damping properties and specific heat increase with increasing basalt fibers addition\ but, electrical resistivity and coefficient of thermal expansion decreased.

Key words: Metal Matrix composites (MMCs), Basalt fiber, Dynamic mechanical analyzer (DMA), Thermal mechanical analyzer (TMA), Differential scanning calorimeter (DSC)

I. INTRODUCTION

Industries need for lightweight, dimensionally stable materials for critical aerospace applications opened new frontiers of advanced materials [1-3]. Metal matrix composites (MMCs) can withstand the extreme conditions often encountered in various environments such as automobile engine and space environments [4-6]. By the combination of a matrix material with a reinforcement such as fibers or particles, special thermo-physical properties of the material can be achieved. This allows to tailor the thermo-physical properties of the MMC material by varying with content of the fibers/ particles [7].

The physical properties such as coefficient of thermal expansion (CTE), damping properties, heat capacity and electrical properties of MMCs can be tailored by varying the nature, wt.% and morphology of the reinforcement phase in the composites. A low CTE and high specific heat are desirable for application such as electronic heat sinks and space structure, Further, a low density is desirable for aerospace applications particularly include Al and cu based alloys, however these materials do not meet the requirements in advanced electronic packaging applications for low CTE, high thermal conductivity, low density and low cost. It is essential to evaluate new materials for their thermal stability and to measure their physical properties. The limitations of conventional metallic materials have led to increased focus on particle reinforced Al MMCs as potential candidates for a variety of uses.

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By varying the matrix, reinforcement and volume fractions, the MMCs can be customized to provide a good CTE matching for thermal management and thermal conductivity applications [8]. Al MMCs reinforced with SiC particles have up to 20 % improvement in yield strength, a lower coefficient of thermal expansion and a higher modulus of elasticity, and they are more wear resistant than the corresponding nonreinforced matrix alloy systems [9].

As per authors knowledge although many researchers worked on physical properties of particle reinforced MMCs but very few /no research works are focused on the effect of short fiber reinforced MMCs on their physical properties. The objective of the work, investigate the effect of basalt fiber on physical properties such as CTE, damping, specific heat and electrical resistivity of MMCs.

II. EXPERIMENTAL STUDIES

2.1 Composites preparation

The matrix alloy used in the present investigation was Al alloy, which has basalt short fiber reinforcement. Fibers in roving form were bundled and cut into short fibers of uniform length by constant-length cutter. The short basalt fiber was cleaned in distilled water and dried at 90°C. The composites were prepared by adding 0, 2.5, 5 & 10 wt.%. of basalt short fiber (2mm of length) by liquid metallurgy technique. The basalt short fibers 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 pre-heated (773 K) basalt short fiber were added into the vortex of the liquid melt which was degassed using pure nitrogen gas for about 3 to 4 min. The resulting mixture was tilted and poured into preheated permanent moulds.

2.2 Damping properties

The experimental technique used in the present work employs a dynamic mechanical analyzer (DMA) which has the capability of simultaneous measurement of dynamic modulus and loss modulus. The sample measuring dimension 70mm x 10mm x 2mm is clamped at both ends firmly. The specimen is enclosed in an environmental chamber that provides heating and cooling arrangement, the system is interfaced with a computer. In the present work, the strain amplitude was fixed between 10^{-4} -10^{-5}.

The temperature was varied between 30°C to 300°C both in the heating and cooling cycle at a constant rate of 10°C / min and, the plots of E′ and E″ were obtained. The frequency of vibration was maintained at the natural frequency of vibration for each specimen that ranged between 4-10Hz.

2.3 Electrical properties

The apparatus designed to measure electrical resistivity of the composite specimens in the present work is based on standard four point probe technique. Among these, the two inner terminals are connected to digital micro voltmeter and outer two terminals are connected to a Keithley 228A voltage / current source. The specimen is mounted horizontally on the hot plate, adjacent to the thermocouple junction. The bakelite strip is brought down so that the free ends of the springs make contact with the sample and the strip is held firmly in the same position. A constant current of 2A is passed through the specimen and the corresponding voltage developed is measured using the micro voltmeter. The direction of the current is reversed, and the voltage is recorded again. The average of the two values is taken to avoid any thermo emf effects.

2.4 Thermal expansion studies

The coefficient of thermal expansion of the MMCs as well as the unreinforced matrix alloy is determined using thermal mechanical analyzer (TMA) equipment. The TMA instrument consists of a furnace for heating the specimen and can operate in the range -70°C to 1200°C. The two end faces of the samples were polished with different grits of SiC papers followed by fine polishing using 1μm diamond paste. About four specimens of each composite sample were tested to achieve reproducibility of experimental results. The data were obtained in the form of dimension change as a function of temperature in the range 30°C-300°C both in the heating and cooling cycles. The CTE values were determined on the basis of calculated slope fit between two selected temperatures on the dimension change versus temperature curves.

2.5 Thermal conductivity

The heat capacity of the MMCs has been obtained as a function of temperature using a differential scanning calorimeter, DSC model, DuPont 2910. The sample is powdered and packed thoroughly and introduced into the sample pan. The instrument is calibrated as per ASTM E 968-83 standards over the temperature range 30°C to 350°C. Next, the sample is run through 30°C to 300°C at a heating rate of 10°C/ min, and the data is obtained through a computer interfaced with the system.

III. RESULTS AND DISCUSSION

3.1 Damping behaviour

The plots of loss modulus (E″) and storage modulus (E′) as a function of temperature in the temperature range 30°C-300°C, both in the heating and cooling cycle for the matrix alloy as well as for the alloy. The combined plots for loss modulus, storage modulus and damping capacity as a function of temperature for the alloy are given in Fig.1. The plots indicate that the loss modulus increases while the storage modulus decreases with the increase in temperature in all cases. However, both loss modulus and storage modulus increase marginally with the increase in basalt short fiber contents. The damping capacity, on the other hand shows an increase with the increase in basalt short fiber content as well as temperature also. The variations are more prominent at temperatures above 150°C, particularly in the range 280°C-300°C.

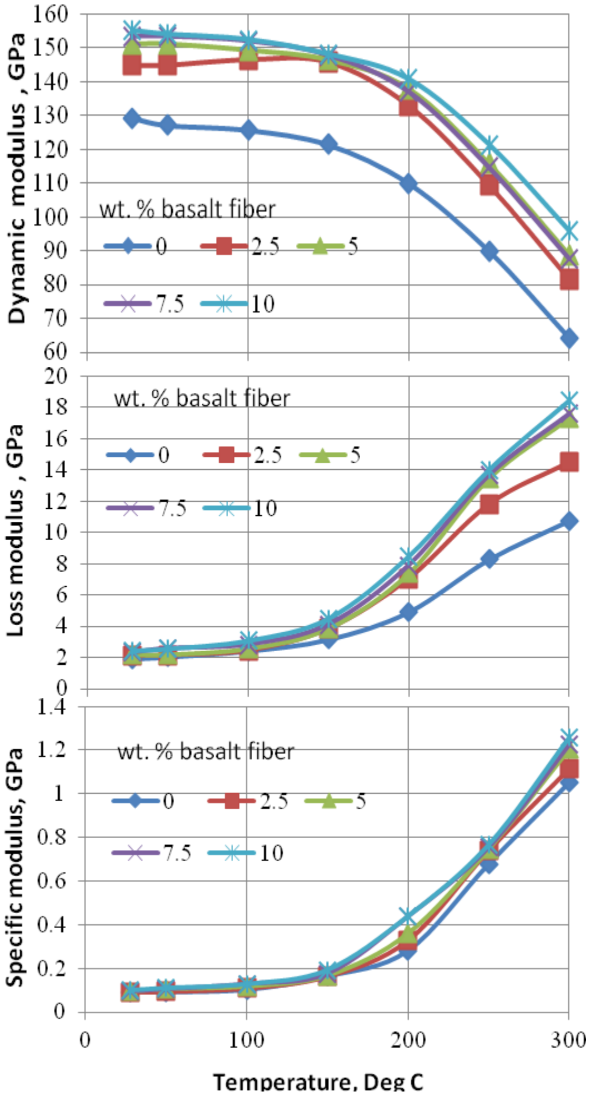

Fig 1 Typical a) dynamic modulus, b) loss modulus and c) specific damping capacity vs. Temperature at 10 Hz.

This rapid increase in damping capacity with temperature is characteristic of the low temperature tail of a grain boundary relaxation. The observed improvement in damping capacity with the addition of basalt short fiber may be attributed to modifications in the microstructure of the matrix due to the presence of the basalt short fiber. Therefore, an attempt has been made to explain the damping behavior of the Al/basalt short fiber in terms of various damping mechanisms.

3.2 Electrical behavior

The electrical resistivity of Al /basalt short fiber MMCs as a function of ageing is given in Fig, 2. The plot indicates that with the increase in the weight percentage of the basalt short fiber, the electrical resistivity increases marginally.

The Al matrix alloy possesses high electrical and thermal conductivity hence exhibiting low electrical and thermal resistivity due to large concentration, of charge carriers or electrons. The resistivity in the matrix alloy arises due to scattering of electrons by lattice vibrations (phonon scattering), impurities and by structural imperfections such as dislocations. When the alloy is reinforced with ceramic inclusions such as basal short fiber which possess very high resistivity ($10^{14}\Omega$cm), it is quite evident that the overall resistivity of the alloy becomes more. Deve et al [10] have suggested that electron scattering at the interface will raise the resistivity, which may be significant with smaller basal short fiber particles such as basalt short fiber in the present work.

Further, due to the large difference in the thermal expansion coefficients of the matrix and the basalt short fiber, the dislocation density is more in the alloy when compared to unreinforced alloy, which can raise the insitu resistivity of the matrix. In addition, the grain size of the matrix is reduced due to the presence of the reinforcement [11]. Therefore, all these microstructural features such as high dislocation density, reduced grain size, and high vacancy concentrations contribute to a higher electrical resistivity in the alloy.

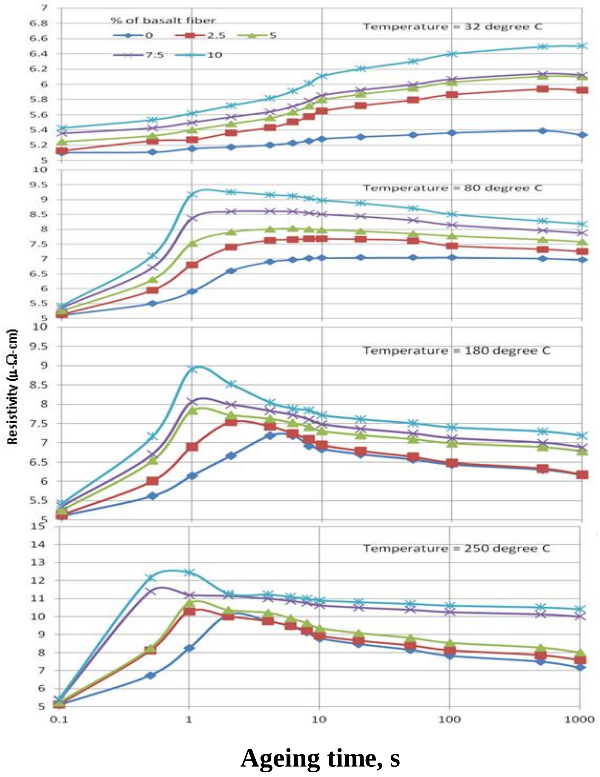

Fig. 2 Typical Graph showing electrical resistivity vs. temperature of Al/basalt MMCs

The electrical resistivity of the alloy as a function of temperature in the range 50°C –300°C both in case of as cast and heat treated conditions for different percentages of basalt short fiber is given in Fig.2. The electrical resistivity in all the cases is observed to increase monotonically with the increase in temperature.

The electrical resistivity is a function of temperature since the amplitude of vibration of a lattice atom varies with temperature and the mean free time of an electron decreases with the rise in temperature. With the increase in temperature, the electron mobility becomes more resulting in greater electron scattering at the interface. This along with phonon scattering due to lattice vibrations of the matrix at higher temperatures is responsible for the increased resistivity as the temperature rises.

These results show that Al /basalt short fiber MMCs offer scope for high electrical and thermal conductivity in combination with good mechanical strength. A problem commonly arises in these situations is that conventional strengthening by alloying leads to sharp reduction in the conductivity of materials. But in the present work, it is observed that by adding basalt short fiber, good improvement in mechanical properties is achieved without sacrificing much of the matrix conductivity.

The graphs indicated that the heat-treated samples of alloy exhibited reduced resistivity when compared to ascast samples of the same material. However, with the increase in the weight percentage of basalt short fiber, the resistivity values in case of as cast and heat-treated samples differ very slightly from each other particularly in the higher temperature range. This behavior of the electrical resistivity of the alloy in response to heat treatment can be explained as follows.

The effect of heat treatment on the matrix alloy results in a decrease in the lattice imperfections and vacancy concentrations, which mainly contribute to its electrical resistivity. But, with the addition of basalt short fiber to the matrix alloy, the main contribution to electrical resistivity comes from electron scattering at the interface and grain boundaries due to reduced grain size which remain unaffected by heat treatment. This explains the negligible difference between the electrical resistivity values of the as cast and heat treated samples of the alloy in the higher temperature range becoming more noticeable for higher weight percentage of the basalt short fiber.

3.3 Thermal Behaviour

The plot (Fig.3) gives one sample curve of dimension change (μm/m) and CTE as functions of temperature for the Al/Basalt short fiber MMCs. The dimension change increases almost linearly with the increase in temperature. The CTE values which are obtained on the basis of calculated slope fit of this curve varies very slightly in the lower temperature range up to 250°C. In a temperature range of about 280°C-300° C, the dimension change increases rapidly with the increase in temperature where as the CTE curve exhibits a sharp peak in the same temperature region.

The increase in dimension change with the increase in temperature may be explained as follows. In case of MMCs, the mean atomic spacing increases with the increase in

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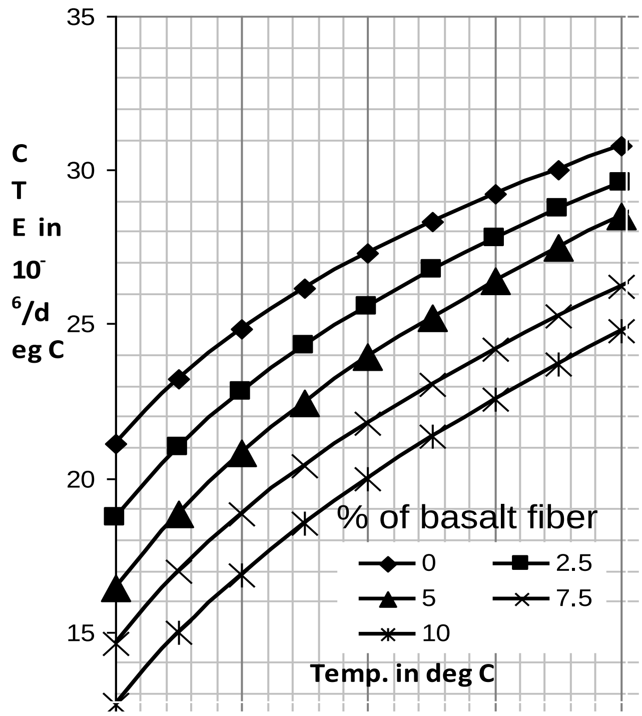

Fig. 3 CTE vs. temperature of basalt fiber reinforced Al MMCs

temperature. These results in the increase in dimension change as temperature rises. The sharp increase in dimension change in the range 280°C-300°C is due to an eutectoid phase transformation from β → α + η + ε phases involving an increase in lattice parameter and change in crystal structure. The behaviour of CTE, which is the slope of dimension change curve, is therefore justified.

3.4 Thermal Conductivity

The DSC thermograms of the alloy give the plots of total heat and heat capacity as functions of temperature before and after heat treatment. The Fig. 4 plots indicate the total heat to be increasing linearly with the increase in temperature exhibiting some non- linearity around 150°C and in the region 280°C –300°C. The slope of the curve which gives heat capacity, accordingly remains almost a constant and does not vary much with the increase in temperature except giving a sharp peak in the range 280°C-300°C. The specific heat of heat-treated sample is observed to be slightly lesser than that of the as cast samples.

When the alloy material is subjected to a homogenizing heat treatment, voids are reduced and the structure becomes more orderly. This results in higher force constant which gives higher vibrational frequency (it is as if the springs joining the atoms are made stiffer) and this in turn gives rise to a lower specific heat. The peaks in the DSC thermograms in the range 280°C –300°C appear due to a phase transformation and associated precipitation processes.

The DSC thermograms of the AL matrix alloy and that of the MMCs is shown in Fig.4. All the thermograms show a distinct exothermic peak corresponding to a precipitation formation process and an endothermic peak corresponding to precipitation dissolution process.

It is observed that the peak temperature for precipitate formation decreases with increasing basalt short fiber content suggesting that the presence of basalt short fiber accelerates the kinetics of formation of these phases. Further, the sizes of the precipitation formation peaks, which are proportional to the volume fractions of the different phases, formed vary with increasing basalt short fiber content.

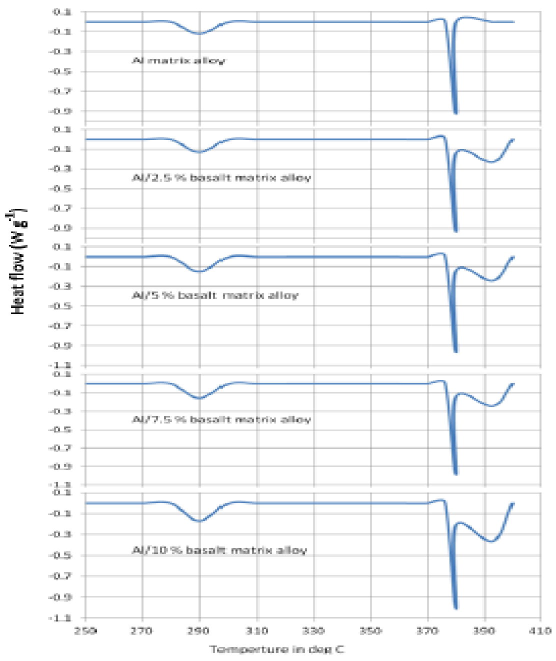

Fig 4 DSC diagram of

IV. CONCLUSIONS

- The damping capacity of Al/basalt short fiber alloy is found to increase with the increase in temperature. The mechanisms mainly responsible for the damping behavior of the MMCs under study are: thermoelastic damping, grain boundary damping, thermal mismatch induced dislocation damping and interface damping.
- The dynamic modulus of Al/basalt short fiber alloy is observed to increase with the increase in the weight percentage of the basalt short fiber content while it decreased with the increase in temperature.
- The coefficient of CTE of the MMCs has decreased with the increase in the weight % of the basalt short fiber content.
- The residual thermal strain is found to increase with the increase in the weight percentage of basalt short fiber content. The evaluation of thermal stresses indicates the existence of considerable magnitude of thermal stresses within the MMCs.
- The electrical resistivity of ascast as well as heat-treated MMCs increases with the increase in temperature which has been attributed to greater electron mobility, lower mean free time and hence greater electron scattering.
- The addition of basalt short fiber content results in an increase in the electrical resistivity of the alloy, which may be attributed to reduced grain size and greater electron scattering at the interface.
- The thermal conductivity of as cast as well as heat-treated Al/basalt short fiber alloy decreases with the increase in the weight % of the basalt short fiber content. The study also indicates that, even if the basalt short fiber content is in effect semi conducting, it tends to depress the conductivity somewhat less than an alloying operation designed to bring about the same degree of strengthening.

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- The thermal conductivity of heat-treated samples is more than that of the ascast samples. This improvement in thermal conductivity as a result of heat treatment is significant from the application point of view of the MMCs under study. This is because; a high thermal conductivity will reduce thermal gradients so that thermal distortions are minimized.

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