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Investigation on the Influence of Basalt Fiber on Thermal properties of Al7075/ Basalt Fiber Metal Matrix Composites

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Abstract

This paper reports a study of the Coefficient of Thermal Expansion (CTE) of Al7075/basalt short fiber Metal Matrix Composites (MMCs) as a function of temperature and reinforcement. The percentage of reinforcement was varied from 2.5 to 10 wt. % in steps of 2.5% and the composites were prepared by the liquid metallurgy technique. Using Thermal Mechanical Analyzer (TMA) model DuPont 943 equipment, the changes in the linear dimension as a function of temperature is recorded as Percent Linear Change (PLC). The temperature of the tests ranged from 50°C to 300°C in the steps of 5°C both in the heating and cooling cycles. The results show that the CTE significantly increased with increasing temperature but decreased with increasing basalt fiber. These phenomena are explained.

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Keywords: Al Composites, Basalt fiber, CTE, TMA, PLC.

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1. Introduction

The thermal expansion behaviour of metal matrix composites has been extensively studied, because it affects the mechanical behaviour of the composites in rigorous thermal environments under tight fit situations. Increasing interest in enhancement of properties including lighter weight, higher strength, low thermal expansion, more wear resistance and high operating temperature has driven the automotive and aircraft industry to focus on application of composites as engine components and space structures as means to increase the performance, efficiency and durability of engine components, the stability of the components and structures made of MMCs over a long period of time in severe thermal environments becomes the crucial design concern(S.C Sharma et al.). [1] This stability can be described in two aspects: geometrical changes and mechanical property changes. In the former case, the co-efficient of thermal expansion (CTE) of the composite plays a key role, while in the latter case, the mismatch of CTE between the matrix and reinforcement has a dominant effect [2]. The CTE 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 fiber reinforced MMCs as potential candidates for a variety of uses [3]. Fiber reinforcement composites not only have high specific strengths and modulus at room and elevated temperature but also have excellent wear resistance, high thermal conductivity, low thermal expansion, and good dimensional stability (S.C Sharma et al) [1]. For these reasons metal-ceramic fiber composite are used extensively as electrical contacts, cutting tool, rocket nozzles, spark-plug electrodes, bearing, pistons etc. (Deonath et al.). [4] But many applications of metal matrix composites (MMCs) require controlled thermal expansion characteristics in order to match those of other components (Xu et al.). [5] The higher elastic modulus and reduced coefficient of thermal expansion (CTE) is due to the incorporation of ceramic fiber in to the matrix (Elomari et al.). [6]

Initially Al 7075 was widely used in aerospace sector for production of aircraft structure & defence product. The high material performance and its outstanding property of working at elevated high temperatures in several thermal environments, has fascinated many researchers, producers & suppliers worldwide to find budding application in automotive industries especially in engine parts, such as constrain shafts, cylinders, pistons, and brake rotors (John & Gerald).[7] Bowles et al.[8] have investigated that in a diesel engine, the temperature profiles of the piston area can reach temperature as high as 400°C in certain regions of the piston. The material should have enough stability to withstand high temperature as the piston and cylinder areas are exposed. Minoru & Richard [9] have explained the stability criterion in two ways, one change in geometrical form and other change in mechanical properties. In the first case the coefficient thermal expansion (CTE) of composite material plays a key role, while in the second case the mismatch of CTEs between the metal matrix and reinforcement has a dominant effect.

The objective of the present work is to design superior composite material components for engine applications with lower CTE. Basalt fiber has a lower CTE than Al 7075, and therefore the incorporation of the basalt fiber in the Al 7075 can reduce the CTEs of the resulting composite. An attempt has been made to study the CTE behaviour of Al 7075 matrix reinforced with basalt fiber in the temperature range of 50°C to 300°C for better understanding of thermal design.

1.1. Theoretical considerations

There exists two different CTE's, linear and volumetric one. The coefficient of linear thermal expansion α is defined as:

$$\alpha = 1 / L_{o\,(}\Delta L / \Delta T) \qquad (1)$$

Where L_o = Original length of the sample

ΔL = Change in length over a temperature interval ΔT

The volumetric coefficient of thermal expansion β_v is related to the linear coefficient of expansion α by

$$\alpha = (1/3)\,\beta_v \quad (2)$$

The coefficient of thermal expansion is a constant only over a specific temperature interval and must be defined accordingly. [10]

2. Experimental

2.1. Material selection and composite preparation

In the present study, Al 7075 alloy having the chemical composition as per the ASTM ingot specification given in Table 1 was used as the base matrix alloy. Basalt short fibers were used as reinforcement. The weight percentage of basalt short fiber was varied from 2.5–10 % steps of 2.5 wt. %. The liquid metallurgy technique was used to prepare the composite specimens.

Table. 1. Chemical composition of Al 7075 alloy and basalt fiber

Chemical composition of Al7075 alloy	(Wt.. %)
Si	0.4
Fe	0.5
Cu	1.6
Mn	0.3
Mg	2.5
Cr	0.15
Zn	5.5
Ti	0.2
Al Balance	Bal
Chemical composition basalt fiber	(Wt. .%)
SiO_2	69.51
Al_2O_3	14.18
Fe_2O_3	3.92
MgO	2.41
CaO	5.62
Na_2O	2.74
K_2O	1.01
TiO_2	0.55
MnO	0.44

In this process, the cu coated basalt short fiber was first pre-heated to temperature of 500°C and maintained at that temperature till it was introduced into the Al alloying elements melt. The preheating of the reinforcement is necessary in order to reduce the temperature gradient and to improve wetting between the molten metal and the basalt short fiber. An known quantities of these metals ingots were pickled in 10% NaOH solution at room temperature for ten minutes. Pickling was done to remove the surface impurities. The smut formed was removed by immersing the ingots for one minute in a mixture of 1 part nitric acid and 1 part water followed by washing in methanol. These cleaned ingots after drying in air were loaded into different alumina crucibles. These crucibles kept in different furnace, which were setting metals respected melting temperature. The melts were super heated

and maintained at that temperature. The temperatures were recorded using a chromel - alumel thermocouple. The molten metals were then degassed using purified nitrogen gas. Purification process with commercially pure nitrogen was carried out by passing the gas through an assembly of chemicals arranged in a row (concentrated sulphuric acid and anhydrous calcium chloride, etc.) at the rate of 1000 cc/ minute for about 8 minutes. A stainless steel impeller or stirrer coated with basalt short fiber was used to stir the molten metal and create a vortex. The impeller used for stirring was of centrifugal type with three blades welded at 45° inclination and 120° apart. The stirrer was rotated at a speed of 500 rpm and a vortex was created in the melt. The depth of immersion of the impeller was approximately one third the height of the molten metal above the bottom of the crucible. The reinforcing basalt short fiber, which were preheated in the muffle furnace, were introduced into the vortex at the rate of 120 gm/min. Stirring was continued until interface interactions between the basalt short fiber and the matrix promoted wetting. Then the melt was degassed using pure nitrogen for about 3-4 minutes and after reheating to super heat temperature (540°C), it was poured into the pre heated lower half die of the hydraulic press. The top die was brought down to solidify the composite by applying a pressure of 100 kg/sq.cm. Both the lower die and the upper dies were preheated to 280°C, before the melt was poured into it. The pressure applied enables uniform distribution of the basalt short fiber in the developed composite. [11]

2.2. Experimental Procedure

The coefficient of thermal expansion of the metal matrix composite 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 to 1200°C). The sample is mounted at the bottom a sample holder tube, which is inserted into the furnace. A thermocouple junction is placed in close contact with the sample to record its temperature. A temperature insensitive quartz probe is held on the sample at one end and its other end is connected to a Linear Variable Differential Transformer (LVDT) core. This probe senses and transmits any small change in the movement of the sample. A movable core LVDT senses positive and negative deviations of the probe's position on the specimen. As the specimen expands, contracts or otherwise deforms, the core on the probe moves in the annular space of the LVDT. This relative movement produces a voltage change that is proportional to the linear displacement of the core. The signal is amplified and processed by a computer data recording system. The two end faces of the samples were polished with different grits of SiC carbide papers followed by fine polishing using 1μm diamond paste. The TMA instrument consists of a furnace for heating specimens of each composite sample were tested to achieve reproducibility of experimental results. Tests were conducted for both unreinforced matrix alloy and the composite. The data were obtained in the form of dimension change as a function of temperature in the range (30-300°C) both in the heating and cooling cycles. The coefficient of thermal expansion (CTE) values were determined on the basis of calculated slope fit between two selected temperatures on the dimension change versus temperature curves.

2.3. Specimen Preparation

Specimens for CTE testing 10mm x 5mm x 2mm in size are machined from the prepared MMCs. The surfaces of the sample specimens were polished with 1 micrometer diamond paste. Four samples of each composite were tested under same condition to verify the reproducibility of the data.

2.4. CTE Testing Procedure

CTE measurements were performed from 50°C to 300°C at 5°C per minute using commercially available Thermal Mechanical Analyzer (TMA). The sensitivity of this instrument is 0.1 micrometer, which uses the standard expansion probe (Elomari et al.) [12]. No liquid phase transformation was observed for the above selected temperature range in the present study. The data were obtained in the form of present linear change (PLC) versus temperature. Standard TMA data analysis software was used to evaluate the CTE.

3. Results and Discussion

3.1. Effect of temperature on CTE

The plot of CTE as functions of temperature of as cast Al7075 alloy and Al7075/basalt short fiber-reinforced composites has been presented in Fig. 1. The measured mean values of CTE were plotted as a function of temperature for different weight percentages of basalt short fiber. It can be seen, that the trends of CTE versus temperature curve for different weight percentage reinforcement composite had similar characteristics. The CTE of both pure alloy and composite was found to increase with increasing temperature. One observes a drastic reduction in the CTE of the composite in comparison with that of the as cast Al7075 alloy, which indicates that in these composites, there is good interfacial bonding, due to the existence of macroscopic strain. Xu et al. [14] are of the opinion that the lattice distortion at the interface will affect the CTE value of the composite. Since the interfacial area depends on the size of the fibers, the CTE of composite varies with fiber size as well as shape. Denath et al. [15] believe that the increase in the reinforcement of ceramics fiber slightly decreases CTE. The same results were found by Dellis et al. [16]

3.2. Effect of basalt short fiber on the CTE

The Fig. 2 indicates that, the as cast Al7075 alloy exhibit maximum CTE value and it decreases with the increase in the weight percentage of basalt short fiber. The lower thermal expansion coefficient of basalt short fiber (7.4μm/m°C) leads to a decrease in the CTE values of the as cast Al7075 alloy with the increase in basalt short fiber content as might be expected from a simple rule of mixture approach.

3.3. Effect of thermal stresses on the thermal expansion behavior

The plot of Percentage of Linear Change (PLC) as functions of temperature in the temperature range (50-300°C) both in the heating and cooling cycle of as cast Al7075 alloy and Al7075/ basalt short fiber reinforced composite has been presented in Fig 2. It can be observed from the graph that the trends of PLC versus temperature curve of different weight percentages of reinforcement composite had similar characteristics. All the curves exhibit some residual strain on cooling which increases with the increase in the weight percentage of the basalt short fiber. The residual strain in case of as cast Al7075 alloy has the minimum value. M.A.Dellis et al [16] have observed in case of thermal expansion studies of Al that no hysteresis exists between the heating and cooling parts of the curves in the temperature range from room temperature to 150°C. This behavior may be explained by considering the fact that the thermal stresses remain below the yield stress of the matrix in this temperature range. However, in the present study, due to a large difference in the thermal expansion coefficients of the matrix and the basalt short fiber, high thermal stresses are developed during its cooling from high fabrication temperatures. From a phenomenal point of view, the matrix stress history can be qualitatively described as follows: Starting from a stress free state of material at the fabrication temperature (492°C), the subsequent cooling to room temperature produces a differential contraction between the matrix and the basalt short fiber, if perfect interfacial bonding is assumed. The stress state at a lower temperature can be envisaged as arising from the fitting of an oversized inclusion into an undersized hole in the matrix. The misfit strain is then simply $\Delta\alpha \times \Delta T$. This misfit thermal strain is first accommodated by dislocation generation but at temperatures low enough where the stress relaxation processes become difficult, a set of elastic internal stresses builds up within the matrix and the basalt fiber. At room temperature, the volume averaged internal stresses are expected to be tensile in the matrix ($< \sigma m >$) and compressive in the particulate ($< \sigma r >$) and in the absence of external loads, they are self balanced in the volume of the alloys.

Upon heating in the TMA apparatus, the residual stresses are relaxed elastically with increasing temperature and at some intermediate testing temperature, the volume averaged internal stresses are expected to become zero. On a further increase of temperature, the continued faster expansion of the matrix compared with the fiber causes a

reversal of stress fields, becoming compressive in the matrix and tensile in the fiber. This is because, the strength of the aluminum alloys is strongly reduced at higher temperatures so that the volume averaged internal stresses in the matrix can eventually exceed the yield strength of the material resulting in plastic deformation. The occurrence of this phenomenon is evident from the thermal expansion curves of the alloy, which deviate from linearity due to the contribution from matrix plastic deformation to the overall thermal strain of the alloy. As the plastic deformation is compressive, the net dimension change measured on the alloy sample is expected to be lower than that corresponding to a purely elastic matrix and the resulting CTE is reduced.

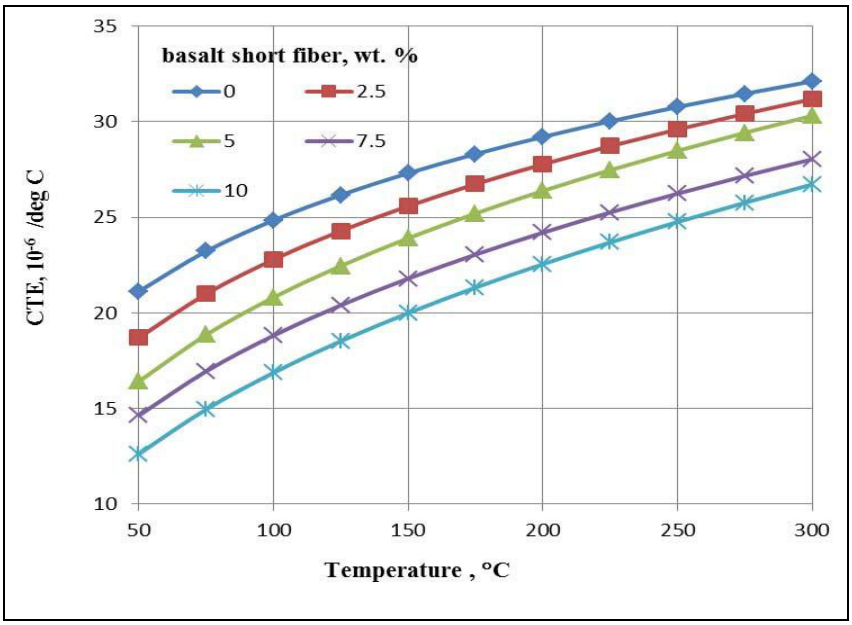

Fig. 1 Effect of temperature on coefficient of thermal expansion of as cast Al7075 alloy/basalt short fiber reinforced metal matrix composites

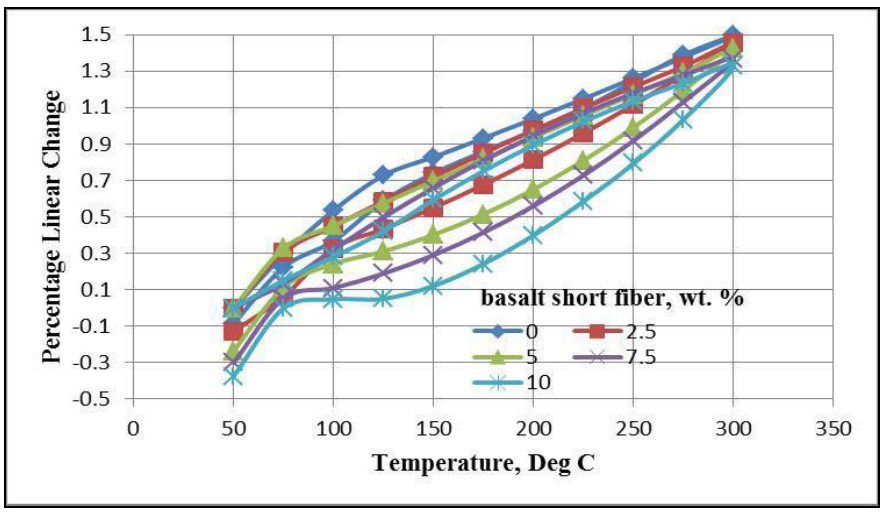

Fig. 2 Effect of temperature on percentage of linear change of Al7075 alloy/basalt dispersed metal matrix composites

4. Conclusion

The coefficient of thermal expansion of Al7075/basalt short fiber composites have been systematically studied using thermal mechanical analyzer technique. The CTE of both unreinforced matrix alloy and the composite is found to increase with increasing temperature but decreased with increasing basalt fiber reinforcement, which is due to high reinforcement stiffness, matrix alloy grain modification, and the dislocation density of the composites due to the difference in CTE between matrix and reinforcement. The dimension change of composite has varied almost linearly with the increase in temperature with a rapid increase in the range (280-300°C). This is due to increase distance of lattice. 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 basalt short fiber reinforced composite. A marginal increase in the CTE value is observed for the basalt short fiber reinforced composite samples when compared to as cast material. Further, the CTE values remain almost uniform over a greater temperature range for the basalt short fiber reinforced composite materials, which is considered as an advantage.

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