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Thermal Expansivity Behavior and Determination of Density of Al 6061-Sic-Gr Hybrid Metal Matrix Composites

S A Mohan Krishna[1], Dr. T N Shridhar[2], Dr. L Krishnamurthy[3]

[1]*Associate Professor, Department of Mechanical Engineering, Vidyavardhaka College of Engineering, Mysore, India,*

[2, 3] *Dept. of Mechanical Engineering, The National Institute of Engineering, Mysore-570 008, India*

Abstract: *Metal Matrix Composites (MMCs) covers a very wide range of materials to simple reinforcements of castings with low cost refractory wool, to complex continuous fires lay-ups in foreign alloys. In particular, many of the considerations arising due to fabrication, processing and service performance of composites are related of processes that take place in the interfacial region between matrix and reinforcement. The thermal characterization of hybrid metal matrix composites is increasingly important in a wide range of applications. In the present scenario, research work is accomplished on hybrid composites based on thermal expansion as limited research has been carried out on hybrid composite based on thermal properties. The coefficient of thermal expansion is one of the most important properties of MMCs. Since nearly all Metal Matrix Composites are used in various temperature ranges, measurement of CTE as a function of temperature is necessary in order to know the behaviour of the material. In this research paper, the thermal expansion behaviour of Al-SiC-Gr composites is investigated and its response are studied between 50°C to 350°C using Horizontal Platinum Dilatometer. The assessment of thermal parameters of composites will benefit to analyze heat capacity, variation in the intensity of heat, heat diffusion and heat release rate. The density of the composites is also determined using water displacement method. The theoretical and experimental values are determined to check the porosity of composites. Using Rule of Mixtures, the theoretical density is determined and the same is compared with the experimental value, which help to understand the distribution of reinforcements.*

Key words: *Thermal Characterization, Coefficient of Thermal Expansion, Hybrid Composites, Temperature and Dilatometer.*

I. Introduction

A composite material is a macroscopic combination of two or more distinct materials having a recognizable interface between them. Composites are used not only for their structural properties, but also for electrical, thermal, tribological and environmental applications [1]. The applications of these materials are absolutely appreciative and applicable in almost all areas of mechanical engineering. Aluminium Silicon alloys in particular finds extensive and increased applications in industries due to their properties viz., high fluidity, low melting point, high strength, corrosion resistance, good casting characteristics and lower coefficient of thermal expansion [2]. Thermal Analysis of Metal Matrix Composites is required to clearly examine the thermal properties viz., Thermal Conductivity, Temperature Difference, Thermal Capacity or Heat Difference, Coefficient of Thermal Expansion and Rate of Heat Transfer. Thermal Analysis is also often used as a term for the study of Heat Transfer to measure Heat capacity and Thermal Conductivity.

The behaviour of composite materials is often sensitive to changes in temperature. This is mainly because, the response of the matrix to an applied load is temperature dependent and changes in temperature can cause internal stresses to be set up as a result of differential thermal contraction and expansion of the constituents. Thermal analysis of hybrid composites is a pragmatic approach to clearly study its thermal characteristics. Most of the thermal studies are mainly concerned with Aluminium matrix composites but minimum information is available on hybrid composites [3].

II. Literature Review

Aluminium Matrix Composites (AMC) consists of Aluminium or its alloys as the continuous matrix and a reinforcement that can be particle, short fiber or whisker or continuous fiber. Research and development activities of the last decade have resulted in the evolution of a class of MMCs termed as Discontinuously Reinforced Aluminium (DRA) composites. Particle or discontinuously reinforced Aluminium Matrix

Composites have become very important because they are economical when compared to continuous fiber reinforced composites and they have relatively good isotropic properties compared to fiber-reinforced composites. These materials have caught the attention of producers and researchers all over the world because of their outstanding properties such as high-strength-to-weight ratio, improved wear and elevated temperature resistance and low density. In addition these materials are comparatively easier to manufacture than the continuously reinforced composites and have a great potential to be available at low cost [4]. These AMCs, which are high performance materials, have also attracted considerable attention from automotive industries and component suppliers. Though initially aimed only at aerospace and defence products, AMCs have progressively moved into higher volume applications. These materials employ a metallic matrix such as Aluminium to which is added reinforcement materials such as Alumina (Al_2O_3) or Silicon Carbide. The net result is a composite material with enhanced mechanical properties particularly with regard to density and stiffness and other mechanical properties [5].

S Cem Okumus, Sardar Aslam et al [6] in their paper have studied on Thermal Expansion and Thermal Conductivity behaviour of Al/Si/SiC hybrid composites clearly highlights that Aluminium-Silicon based hybrid composites reinforced with silicon carbide and graphite particles were prepared by liquid phase particle mixing and squeeze casting. The thermal expansion and thermal conductivity behaviour of hybrid composites with various graphite contents (5.0; 7.5; 10 wt.%) and different silicon carbide particle sizes (45 µm and 53 µm) were investigated. Results indicated that increasing the graphite content improved the dimensional stability, and there was no obvious variation between the thermal expansion behaviour of the 45 µm and the 53 µm silicon carbide reinforced composites.

R Arpon, E Louis et al [7] have analyzed that thermal expansion behaviour of Aluminium/SiC composites with bimodal particle distributions where it summarizes that The thermal response and the coefficient of thermal expansion (CTE) of Aluminium matrix composites having high volume fractions of SiC particulate have been investigated. The composites were produced by infiltrating liquid Aluminium into preforms made either from a single particle size, or by mixing and packing SiC particulate of two largely different average diameters (170 and 16 µm, respectively). The experimental results for composites with a single particle size indicate that the hysteresis in the thermal strain response curves is proportional to the square root of the particle surface area per unit volume of metal matrix, in agreement with current theories. Instead, no simple relationship is found between the hysteresis and any of the system parameters for composites with bimodal particle distributions. On the other hand, the overall CTE is shown to be mainly determined by the composite compactness or total particle volume fraction; neither the particle average size nor the particle size distribution seems to affect the overall CTE. This result is in full agreement with published numerical results obtained from finite element analyses of the effective CTE of Aluminium matrix composites. The results also indicate that the CTE varies with particle volume fraction at a pace higher than predicted by theory.

R A Saravanan, J Narciso et al [8] have investigated on thermal expansion behaviour of particulate metal matrix composites explains that Aluminium-matrix composites containing thermally oxidized SiC particles of controlled diameter ranging from 3 to 40 µm have been produced successfully by vacuum assisted high-pressure infiltration. Their thermal-expansion coefficients (CTEs) were measured between 25°C and 500°C with a high-precision thermal mechanical analyzer (TMA), and compared with the predictions of various theoretical models. The thermal-expansion behavior of the three-phase $Al/SiC/SiO_2$ composite shows no significant deviation from the predictions of elastic analysis, since the measured CTEs lie within the elastic bounds derived by Schapery's analysis. The effect of particle size is quite evident in the pressure-infiltrated composites: the larger the particles, the greater the thermal expansion of the composite. The observed behavior of these composites is discussed in terms of particle size, silica layer formed during oxidation, and thermal stresses developed as a result of the CTE mismatch between the reinforcement and the matrix.

Tran Nam, Requena et al. [9] have studied on effect of thermal cycling on the expansion behaviour of Al/SiC composites is carried out where the coefficient of thermal expansion (CTE) and accumulated plastic strain of the pure aluminium matrix composite containing 50% SiC particles during thermal cycling (within temperature range 298–573 K) were investigated. The composite was produced by infiltrating liquid aluminum into a preform made by SiC particles with an average diameter of 14 microns. Experiment results indicated that the relationship between the CTE of Al/SiC and temperature is nonlinear; CTE could reach a maximum value at about 530 K. The theoretical accumulated plastic strain of Al/SiC composites during thermal cycling has also been calculated and compared with the experimental results.

N Chawla, X Deng et al [10] comprehensively describes thermal expansion behaviour of Aluminium matrix composites with densely packed SiC particles where the coefficient of thermal expansion (CTE) of Al-based metal matrix composites containing 70 vol.% SiC particles (Al/SiC) has been measured based on the length change from room temperature to 500°C. In the research work, the instantaneous CTE of Al/SiC was studied by thermo-elastic models and micromechanical simulation using finite element analysis in order to explain abnormalities observed experimentally. The CTE was predicted according to analytical thermo-elastic models of Kerner, Schapery and Turner. The CTE was modeled for heating and cooling cycles from the temperature range 20^0C to 500^0C considering the effects of microscopic voids and phase connectivity. The finite element analysis is based on a two-dimensional unit cell model comparing between generalized plane strain and plane stress formulations. The thermal expansion behaviour is strongly influenced by the presence of voids and confirms qualitatively that they cause the experimentally observed decrease of the CTE above 250^0C.

The literature review presented extensively will refer to the work carried out on composite materials pertaining to mechanical, tribological and thermal properties. In the present scenario, work is accomplished on hybrid composites based on mechanical properties but limited research has been carried out on hybrid composite concerned with thermal properties and characterization. Thermal studies on composite materials are getting greater importance in the present scenario. Thermal analysis will help to understand the properties of materials as they change with temperature. It is often used as a term for the study of heat transfer through structures. Metal Matrix Composites can be customized to provide good CTE matching for thermal management and thermal conductivity applications. It is essential to evaluate new materials for the thermal stability and to measure properties including CTE and thermal conductivity for specialty products [6].

III. Experimental Procedure

In the research work, the coefficient of thermal expansion is determined using Linesis 75 Platinum Horizontal Dilatometer. Fig 3.1 shows a typical Platinum Horizontal Dilatometer. Thermal expansion is the tendency of matter to change in volume in response to change in temperature. The degree of expansion to the change in temperature is called the material's coefficient of thermal expansion and generally varies with temperature. Coefficient of Thermal Expansion is one of the most important properties of MMCs. Since nearly all Metal Matrix Composites are used in various temperature ranges, measurement of CTE as a function of temperature is necessary in order to know the behaviour of the material. Several different systems for measurement of CTE can be used depending on the temperature conditions. One of the most common systems used is a dilatometer. A dilatometer measures the length or the volume changes of the sample, when the sample follows a temperature program and submits a small force. In a push rod dilatometer, the change in length of the sample is detected by an inductive displacement transducer. Calibration and corrections of measurements are done by using various standards and comparison with materials of known expansion. The measurement of the coefficient of thermal expansion (CTE) can be carried out in the temperature range from approximately – 150°C to 1500°C.

Linesis 75 Platinum Horizontal Dilatometer comprises of Thyristor controlled unit, Linear Variable Differential Transformer (LVDT), automatic pressure control unit, variety of sample holders and RCS (Rate Controlled Sintering) software. The coefficient of thermal expansion (CTE) can be controlled by two parameters simultaneously namely wall thickness and volume fraction comprehensively. The CTE values have a stronger dependence on particle volume fraction than the wall thickness in the range of temperatures explored. The thermal expansion results with the variation of temperature for the composites and the matrix are shown for different percentage composition. It is obvious that the CTE of the composites and matrix increases with increase in temperature.

The pushrod dilatometer method for measuring thermal expansion is experimentally simple, reliable and easy to automate. In this method, the relative expansion of the specimen is transmitted referring to cooled or heated zone to a measuring device (an extensometer) by means of tubes and/or rods of a stable reference material. In this technique, the specimen is placed at the end of a tube and a smaller rod is placed in the tube in contact with the specimen. An extensometer has the capability to detect the difference in expansion between the specimen and an equal length of the tube. The most widely used extensometer is the LVDT (Linear Variable Differential Transformer).

Fig 3.1- Linesis 75 Platinum Horizontal Dilatometer

IV. Results & Discussion

For the determination of CTE, the size of the cylindrical sample is diameter 5 mm and length 10 mm. 5 samples are considered with different percentage compositions. Al 6061 is the base alloy and reinforcements SiC and Gr with different percentage compositions 1.25%, 2.5%, 3.75% and 5% are selected. All the specimens were tested from room temperature to 360°C. This temperature range was selected so as to include the entire usable range of the composites, without the formation of liquid phase in the matrix. The data were obtained in the form of per cent linear change versus temperature. Standard data analysis software was used to evaluate the CTE of the composites tested and was determined at intervals of 20 °C. Rate Controlled Sintering (RCS) is an asset for standard dilatometer software. During measurement using dilatometer, the change in length of the sample for the required temperature range is considered. The purpose of RCS is to determine the optimal sinter process, especially the optimal temperature-time profile. Some of the salient parameters considered during the determination of CTE are sample length, relative density of the samples and sintering temperature. The melting point of Aluminium is 560°C. But during the testing process, it was limited to 360 °C, as there is greater possibility of reaching molten condition.

The evaluation of CTE of hybrid metal matrix composites is relatively difficult to predict because several factors namely volume fraction, morphology and distribution of the reinforcements, matrix plasticity, interfacial bondage, and the internal structure of the composites, may influence the results. During the evaluation of CTE, thermal strain can be attributed to thermal stress and higher thermal stress can lead to the generation of strain between the heating and cooling cycles [6]. The thermal expansion behavior of Al alloy reinforced with Silicon Carbide and Graphite were measured at prominent temperatures varying from 20°C to 350°C. The CTE of the hybrid composites are lower than the conventional Al-SiC composites with the same volume fraction of SiC. The thermal expansion behaviour of the hybrid composites depends on the intrinsic thermal expansion properties of SiC and double interpenetrating structure [11].

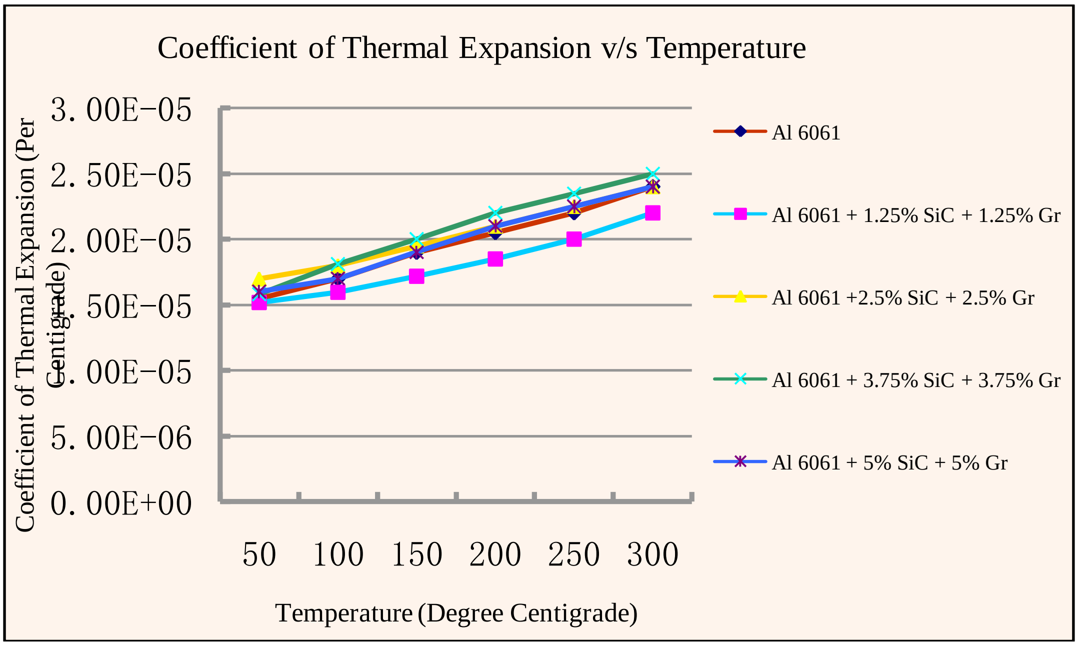

Fig 4.1: Variation of CTE v/s Temperature for different compositions of MMC

Fig 4.1 shows the variation of CTE and temperature for different compositions of hybrid MMC. It is noticed that, the CTE of the hybrid composites with different percentage compositions increases with the increase in temperature. There is consistency in the increase of CTE for different temperatures recorded at regular intervals. During the testing of different samples, the elongation was observed to be low, as such the increase in the values of CTE of the mentioned compositions of hybrid MMCs were in endurable limits ranging from 15 $\times 10^{-6}$/°C to 26 $\times 10^{-6}$/ °C. Al 6061 + 3.75% SiC + 3.75% Gr exhibited the maximum value of CTE, whereas Al 6061 + 1.25%SiC + 1.25% Gr exhibited lower magnitude of CTE and Al 6061 exhibited normal value of CTE.

The percentage volume fraction of SiC estimated was low, facilitating CTE to increase drastically and exhibits the expected trend. The hybrid composites have lower volume fractions of SiC than conventional Al-SiC composites with the same CTEs [11]. The decrease in the maximum temperature for CTE values for graphite reinforced composites is considered as a result of relaxation of the compressive stress in the matrix. The reduction in CTE values can be attributed to the lower CTE value of graphite compared to Al-Si matrix alloy and SiC reinforcement and the ability of the reinforcements to effectively constraint the expansion of the matrix. The thermal strain of all hybrid composites increases as the amount of graphite is increased, indicating that introducing a high amount of graphite to Al-Si based composites may not be beneficial to attain dimensional stability [12]. It was examined that the thermal response and the coefficient of thermal expansion (CTE) of Aluminium matrix composites have high volume fractions of SiC particulate. In Al-SiC composites, the thermal expansion behavior will be influenced by the thermal expansion of Aluminium and the tightened restriction of SiC particles. The CTE of the particle reinforced MMCs is usually affected by a variety of factors namely interfacial reactions, plasticity due to CTE mismatch between particle and matrix during heating or cooling processes and residual stresses [13].

Determination of Density for The Hybrid MMC

Density of MMC material can be determined using the relationship between volume and mass. A special technique for the determination of the density where pores are taken into account is the determination by using water displacement (Archimedian density).

Table 4.1 shows the determination of density for different compositions This method allows the determination of the density in air compared to its displacement in water or other liquid of known density. Depending upon the nature of the specimen (e.g., open or closed cell), the resultant value may deviate from the true mass. A clean specimen is weighed accurately in air using a laboratory balance. The same specimen is weighed while suspended in water or other liquid of such density that the specimen will sink. Deducting the mass of the suspension wire from the weight in liquid, the volume of the specimen is calculated from the effect of displacement by a liquid of known density (Archimedean principle). This allows the determination of density of specimens with irregular shapes, uneven surfaces, or porosity. Caution must be exercised to assure that no air is trapped within the specimen. Placing the specimen in a vacuum while submerged in the displacement liquid will usually avoid error.

Table 4.1: Determination of density for different compositions

Sl.No.	Material Identification	Density (g/cc)
1	Al-6061	2.7
2	Al-6061 with 1.25% SiC + 1.25% Graphite	2.69
3	Al-6061 with 2.5% SiC + 2.5% Graphite	2.689
4	Al-6061 with 3.75% SiC + 3.75% Graphite	2.681
5	Al-6061 with 5% SiC + 5% Graphite	2.678

Using Rule of Mixtures, the density of the composites was calculated and the values were compared with experimental. The variation was very marginal and proved to have negligible porosity.

V. Conclusions

The following conclusions are drawn based on the results obtained:

1. It is noticed that, the CTE of the hybrid composites with different percentage compositions increases with the increase in temperature. There is consistency in the increase of CTE for different temperatures recorded at regular intervals.
2. During the testing of different samples, the elongation was observed to be low, as such the increase in the values of CTE of all compositions were in endurable limits.
3. The percentage volume fraction of SiC estimated was low, facilitating CTE to increase drastically and exhibits the expected trend.
4. The hybrid composites have lower volume fractions of SiC than conventional Al-SiC composites with the same CTEs.
5. In Al-SiC composites, the thermal expansion behavior will be influenced by Aluminium and the tightened restriction of SiC particles.
6. Al 6061 + 3.75% SiC + 3.75% Gr exhibited the maximum value of CTE, whereas Al 6061 + 1.25%SiC+ 1.25% Gr exhibited lower magnitude of CTE and Al 6061 exhibited normal value of CTE.
7. The theoretical and experimental values of density of composites were compared and it proved to have negligible porosity.

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