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CHARACTERIZATION AND ANALYSIS OF THERMOMECHANICAL AND THERMOELASTIC PROPERTIES FOR ALUMINIUM-SILICON CARBIDE-GRAPHITE HYBRID METAL MATRIX COMPOSITES

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ABSTRACT
Metal matrix composites have been regarded as one of the most major classifications in composite materials. The thermal characterization of hybrid metal matrix composites has been increasingly important for a wide range of applications. In this research paper, the evaluation of thermophysical and thermoelastic properties have been accomplished for Al 6061, Silicon Carbide and Graphite hybrid metal matrix composites from room temperature to 300°C. Aluminium based composites reinforced with Silicon Carbide and Graphite particles have been prepared by stir casting technique. The thermophysical properties viz., thermal conductivity, thermal expansivity, latent heat of fusion, thermal resistivity and thermal shock resistance have been determined. Also, thermoelastic properties viz., modulus of elasticity and Poisson’s ratio have been evaluated. The results have indicated that, the thermal conductivity and thermal expansivity of the different compositions of hybrid MMCs decreases by the addition of Graphite with Silicon Carbide and Al 6061.

INTRODUCTION
A composite material is a macroscopic combination of two or more dissimilar materials having an identifiable interface between them. A composite material exhibits a significant proportion of the properties of both constituent phases such that a superior combination of properties is realized. Composite materials comprises of two phases: one is the matrix, which is continuous and surrounds the other phase, often called the dispersed phase or reinforcement. The main purpose of the reinforcement is to offer strength and stiffness to the composite. A matrix is used to bind the reinforcement together by virtue of adhesive and cohesive characteristics, and provides a solid form to the composite material. The matrix strongly holds the reinforcements in proper orientation and position and distributes the loads consistently among the reinforcements. The matrix material surrounds and supports the reinforcement materials by maintaining their comparative proportions. The reinforcements impart their exceptional mechanical and physical properties to augment the matrix properties. A synergism produces material properties unavailable from the individual constituent materials, while the wide assortment of matrix and intensifying materials allows the designer of the product or structure to choose a most favourable condition [1].

Metal matrix composites are the ground-breaking materials that possess unlimited opportunities for modern material science and development. These materials satisfy the desired conceptions, objectives and requisites of the designer. The reinforcement of metals can have many different objectives. The reinforcement of light metals will have abundant possibility of application in areas where weight reduction has first priority [1]. Metal matrix composites have greater advantage compared to other composites. These materials possess higher temperature, higher yield strength and yield modulus and can be strengthened by different thermal and mechanical treatments. Hybrid metal matrix composites are regarded as one of the advanced materials that comprises of light weight, high specific strength, good wear resistance and low thermal expansivity. Hybrid MMCs are exceptional materials that are fabricated by reinforcements of at least two types of materials into a tough metal matrix. These hybrid composite materials are extensively used in structural, aerospace and automotive industries. Hybrid MMCs have greater relevance to automotive engineering concerning with piston rods, piston pins, braking systems, frames, valve spring caps, disk brake caliper, brake disks and disk pads [2, 3].

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Aluminium alloy is generally used in automotive sector as it encompasses with excellent mechanical properties, better corrosion resistance and wear, low melting point compared to other materials. The most prominent property of this material is of light weight and low production cost, which will attract the researchers from all perspectives [2, 3]. Among modern composite materials, particle reinforced Aluminium matrix composites (AMCs) are finding increased application due to their resourceful mechanical properties and good wear resistance. Aluminium matrix composites consist of Aluminium or its alloys as the continuous matrix and a reinforcement that can be particle, short fibre or whisker or continuous fibre. 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 AMCs have become very important because they are economical when compared to continuous fibre reinforced composites and they have relatively good isotropic properties compared to fibre-reinforced composites [3, 4]. These materials have captivated the attention of researchers and manufacturers 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. These materials are comparatively easier to manufacture than the continuously reinforced composites and have a great potential to be available at low cost.

Aluminium based metal matrix composites are advanced materials having the properties namely high specific strength and modulus, greater resistance, high elevated temperature and low coefficient of thermal expansion. Aluminium based metal matrix composites reinforced with ceramic particles have been the area of interest for numerous researchers. Owing to the properties namely low density, low melting point, high specific strength and thermal conductivity of Aluminium alloys, a wide variety of reinforcements such as Silicon Carbide and Graphite have been reinforced. Aluminium alloy based composites are available with a range of values for the coefficient of thermal expansion, depending on Silicon Carbide content. Aluminium-Silicon Carbide composite is available to match the expansion characteristics of many of the common metals and alloys.

Aluminium-Silicon Carbide composites are attractive with many exceptional features, including higher thermal conductivity, lower thermal expansivity and low density. With any Aluminium matrix alloy, the addition of Silicon Carbide will augment thermal conductivity and flexural strength [3, 4]. The addition of Graphite particles to Aluminium alloys and composites improves sliding wear and seizure resistance compared to non-reinforced Aluminium alloys and composites that do not contain graphite. Aluminium-Graphite composites have been expansively used in a large number of automobile components like cylinder liners, pistons and various types of brakes, air diffusers and bushings. In the present work, anticipation has been made to investigate and characterize the thermal properties of hybrid MMCs involving Al 6061 and Silicon Carbide with the addition of Graphite [3, 4, 5, 6]. Thermal analysis of composite materials is gaining greater impetus in the present scenario. This 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. The thermal analysis and characterization of hybrid MMCs will depend on the factors that influence on the prominent thermophysical properties presents a major challenge since they are sensitive to the type of reinforcement and method of manufacture. The knowledge of the thermo-physical properties has been compulsory for designing the effective heat transfer elements, heat sinks, heat shields and opto-electronic devices. The need for the thermal analysis of hybrid metal matrix composites should be comprehensively discussed. Most of the thermal studies are mainly concerned with Aluminium matrix composites but minimum information is available on hybrid composites. The behaviour of hybrid 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.

Though the research work pertaining to mechanical, tribological and fatigue behaviour of composites is effectively accomplished, due emphasis needs to be given to the work related to the measurement of prominent thermal parameters viz., thermal conductivity, thermal diffusivity, thermal capacity and thermal expansivity. The main property considered in thermal analysis of metal matrix composites is thermal conductivity. The increase in thermal conductivity of composites will depend on strength and porosity, which finds this property in aerospace and automobile applications extensively. Thermal diffusivity is an important property for materials being used to determine the optimal work temperature in design applications referred under transient heat flow. It is the thermophysical property that determines the speed of heat propagation by conduction during changes in temperature with time. The heat propagation is faster is faster for materials with high thermal diffusivity [3]. The assessment of thermal parameters will benefit to evaluate heat capacity, variation in the intensity of heat, heat diffusion and heat release rate. For aerospace and automotive applications, low coefficient of thermal

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expansion, moderate thermal conductivity, specific heat capacity and high electrical conductivity of the composites will enhance the efficiency in all perspectives. The techniques recommended for the experimental investigations of thermal conductivity and thermal diffusivity is laser flash apparatus and determination of thermal expansivity requires dilatometer.

L C Davis and B E Artz [7] in their research paper have explained the thermal conductivity of metal matrix composites, which are potential electronic packaging materials, has been calculated using effective medium theory and finite element techniques. The thermal boundary resistance, which occurs at the interface between the metal and the included phase (typically ceramic particles), has a large effect for small particle sizes. It has been found that Silicon Carbide particles in Aluminium must have radii in excess of 10 µm to obtain the full benefit of the ceramic phase on the thermal conductivity.

S Cem Okumus et al. [8] in their paper have studied on thermal Expansion and thermal conductivity behaviour of Al-Si-SiC hybrid composites. Aluminium-Silicon based hybrid composites reinforced with silicon carbide and graphite particles has been prepared by liquid phase particle mixing and squeeze casting. The thermal expansion and thermal conductivity behaviours of hybrid composites with various graphite contents and different silicon carbide particle sizes (45 µm and 53 µm) has been investigated. Results have indicated that increasing the graphite content improved the dimensional stability, and there has been obvious variation between the thermal expansion behaviour of the 45 µm and the 53 µm silicon carbide reinforced composites.

Parker W J et al. [9] have explained the flash method of determining thermal diffusivity, heat capacity and thermal conductivity. A high-intensity short-duration light pulse is absorbed in the front surface of a thermally insulated specimen a few millimeters thick coated with camphor black, and the resulting temperature history of the rear surface has been measured by a thermocouple and recorded with an oscilloscope and camera. The thermal diffusivity has been determined by the shape of the temperature versus time curve at the rear surface, the heat capacity by the maximum temperature indicated by the thermocouple, and the thermal conductivity by the product of the heat capacity, thermal diffusivity and the density.

Na Chen et al. [10] have reviewed on metal matrix composites with high thermal conductivity for thermal management applications. The latest advances in manufacturing process, thermal properties and brazing technology of SiC/metal, carbon/metal and diamond/metal composites has been presented. Key factors controlling the thermo-physical properties have been discussed in detail.

S X Xu [11] has investigated the temperature profile and specific heat capacity in temperature modulated Differential Scanning Calorimeter (TMDSC) with a low sample heat diffusivity. The paper explains about a specific numerical model that is used to analyze the effects of thermal diffusivity on temperature distribution inside the test sample and specific heat measurement by TMDSC. The sample test results are presented to demonstrate the effects of material thermal diffusivity.

N R Pradhan and H Duan [12] have examined the specific heat and effective thermal conductivity of composites containing single and multi wall carbon nanotubes. The specific heat and effective thermal conductivity in anisotropic and randomly oriented multi-wall carbon nanotube (MWCNT) and randomly oriented single-wall carbon nanotube (SWCNT) composites from 300 K to 400 K has been studied. The specific heat of randomly oriented MWCNTs and SWCNTs exhibited similar behaviour to the specific heat of bulk graphite powder.

E Morintale and A Harabou [13] have described the use of heat flows from DSC curve for calculation of specific heat of the solid materials. On the basis of the second law of thermodynamics, they have established a procedure for calculating the specific heat of solid materials using heat flow in the sample studied, and the rate of heating of the sample.

B Karthikeyan et al. [14] have elucidated specific heat capacity measurement of Al/SiCP composites by using Differential Scanning Calorimeter. Good thermal control systems have been considered for various materials applicable for spacecraft applications. Differential Scanning Calorimeter has been employed to determine the specific heat capacity of 7075 Al /SiC_P composites.

R Arpon and E Louis [15] 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 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.

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R A Saravanan and J Narciso [16] 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.
Tran Nam et al. [17] 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) has been investigated.

It is evident from the literature review that, Aluminium matrix composites should be given major emphasis. However, investigations concerning the thermal characterization and analysis of composite materials of AMCs are scarce. Many experimental investigations have been carried out in the field of thermal analysis and characterization of Aluminium-Silicon Carbide composites, but limited work has been accomplished pertaining to Aluminium-Silicon Carbide-Graphite hybrid MMCs.

In the present scenario, research work on mechanical and tribological properties of hybrid composites have been accomplished substantially, but very limited research has been carried out on Aluminium-Silicon Carbide-Graphite hybrid composites relating to thermal characterization and analysis. It has been reported in the literature that, the experimental study on thermal analysis and characterization of Aluminium and Silicon Carbide has been carried out exhaustively concerning low and high weight fraction [8]. But, research on thermal characterization and analysis of Al 6061 with Silicon Carbide (SiC) and Graphite (Gr) hybrid metal matrix composites concerning with low and high weight fraction has been very inadequate. Hence in the present research, Graphite (Gr) has been reinforced concurrently with Silicon Carbide and Aluminium matrix alloy considering lower weight fraction of the hybrid composites.

FABRICATION OF COMPOSITES

The manufacturing of Aluminium based casting composite by the method of stir casting has been one of the most economical methods of processing metal matrix composites. Stir casting method has been widely used among the different processing techniques available. The simplest and most commercially used technique is the vortex or stir casting technique. Stir Casting is the most popular and commercial method of producing aluminium based composites. The major advantages are simplicity, flexibility and applicability to large quantity production. The essential aspect in stir casting technique is to create good wetting property between the particulate reinforcements and allow the liquid aluminium alloy to melt. It has been reported in the literature that, the homogeneous mixing and wetting property can be obtained by selecting appropriate processing parameters viz., speed of the stirring process, time and temperature of molten metal, preheating temperature of the mould and uniform feed rate of particles [1, 2].

Aluminium matrix composites viz., Aluminium-Silicon Carbide-Graphite hybrid metal matrix composites specimens have been cast by using Aluminium alloy Al 6061 as the matrix material and reinforcements Silicon Carbide and Graphite particulates containing different percentage compositions (2.5%, 5%, 7.5% and 10%) have been fabricated by Stir Casting. Aluminium alloy (Al 6061) has been used as the matrix material to which to which the particulates of Silicon Carbide of average particle size around 25 microns and particulates of Graphite of average particle size 60 to 70 microns have been added as reinforcements. To study the influence of thermal parameters comprehensively, specimens of Aluminium 6061-Silicon Carbide-Graphite hybrid metal matrix composites having various percentage reinforcements (2.5%, 5%, 7.5% and 10%) have been fabricated. Hybrid metal matrix composites specimens have been cast by mixing equal proportions of Silicon Carbide and Graphite reinforcements maintaining the total percentage of reinforcements same (2.5%, 5%, 7.5% and 10%). A specimen of matrix alloy Al 6061 has been cast without the inclusion of any reinforcements. In this research work, the evaluation of thermal properties viz., thermal conductivity, thermal diffusivity, specific heat capacity and thermal expansivity different sample sizes have been considered as per ASTM standards. The sample sizes for the evaluation of thermal conductivity and thermal expansivity are diameter 12.7 mm and thickness 3 mm and diameter 5 mm and length 10 mm respectively. The sample size for estimation of specific heat capacity is powder form or pellets, approximately 20 mg.

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The composite specimen having Aluminium matrix reinforced with Silicon Carbide and Graphite reinforcements have been stir cast. A known amount of Al 6061 alloy pieces in the sintering furnace has been heated and allowed the same to melt at 780^0C. Complete melting of Aluminium has been ensured while preparing the specimen. The alloy pieces have been kept in the crucible and preheated the mould at the required temperature range 750^0C-800^0C. The reinforcements Silicon Carbide and Graphite have been preheated at the above mentioned temperature range. Magnesium has been added to the molten alloy of Aluminium to increase the wettability. Slag has been removed by using scum powder to avoid poor quality casting. In order to remove moisture content in the casting the melt has been maintained at the above mentioned temperature for about 20 minutes. Approximately 5% weight of solid dry hexachloro-ethane tablets or degassing tablets have been used to degas the molten metal at 780^0C. Stirring of the molten metal maintained at around 750^0C, has been accomplished using a mechanical stirrer, to create vortex. The molten metal has been stirred at a speed range of 400-750 rpm for about 10 minutes. The stirring of the mixture has been carried out to ensure uniform dispersoid concentration of reinforcements in the matrix material. After the process of solidification, mould is cooled to avoid shrinkage of casting metal for about 3 hours to complete the process [1, 2, 3]. Then the casting has been separated from the mould which is subsequently cleaned.

The required test specimens were 22 mm diameter and 220 mm length. They have been machined thoroughly. The dimensions chosen agree well with the available literature. The samples have fabricated to the required sizes. In all, five specimens of Aluminium-Silicon Carbide-Graphite hybrid composites with varying weight fraction has been stir cast. Five specimens have been separately considered for the determination of thermal conductivity and thermal expansivity behaviour with different sample sizes.

METALLOGRAPHIC SPECIMEN PREPARATION

The analysis of the microstructure of materials benefits in determining the exact procedure about material processing and being regarded as a critical step for the evaluation of product reliability. Generally, the fundamental steps involved in the metallographic specimen preparation are documentation, sectioning and cutting, mounting, grinding, rough and final polishing, buffing and etching. To investigate the prominent microstructural features in hybrid metal matrix composites, it is extremely essential to accomplish polishing and etching [4].

The samples with varying weight fraction 2.5%, 5%, 7.5% and 10% have been prepared for the study of microstructure using standard metallographic procedure. The samples have been grinded and polished by using an emery paper. The process of polishing has been accomplished by using powder of Alumina to achieve surface finish. Keller's reagent has been applied to the samples and has been observed under optical microscope to characterize the formation of grain boundary and interdendritic segregation. The microstructural analysis has been carried out for Al 6061 with varying weight fraction of reinforcements namely Silicon Carbide and Graphite.

Microstructural analysis of composites is advantageous for mechanical and thermal characterization of composite materials. The examination of dispersoid concentration of the reinforcements, cohesive interfacial bonding, formation of grain boundaries and interdendritic segregation in hybrid composites will influence the determination of mechanical and thermal properties of composites viz., tensile strength, modulus of elasticity, thermal conductivity, specific heat capacity and thermal expansivity . Hence, microstructural characterization has been carried out to accomplish thermal characterization and analysis with varying weight fraction of hybrid composites.

In this paper, microstructural characterization with varying weight fraction of hybrid metal matrix composites have been accomplished by using Optical Microscope. Optical Microscope has been used to investigate the formation of grain boundaries and interdendritic segregation. The microstructures with magnification 200X and 500X have been used to characterize the behavior of hybrid composites.

ANAYSIS USING OPTICAL MICROSCOPE

Nikon Microscope LV 150 with Clemex Image Analyzer has been used. It is basically an upright Optical Metallurgical Microscope and high performance stereo zoom microscope. This is ideally suited to the basic needs of manufacturing and research and development in the field of metallurgy for the analysis of

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microstructure, grain size, inclusion rating, nodular count, particle size, coating layer thickness, depth of carburization etc. This high-resolution microscope has magnification ranging 50X to 1000X with computer interface and is equipped with sophisticated and high resolution Clemax Charged Coupled Device (CCD) camera by using user friendly Clemax software. This software can analyze the customized programmes and data storage Stereo Zoom Microscope for the study of macro, weld and failure analysis.

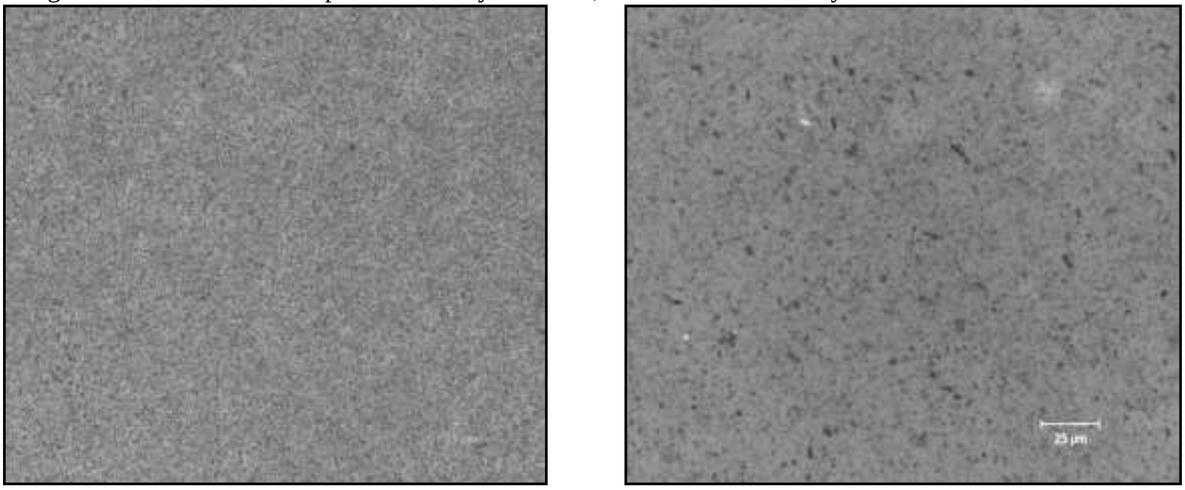

Fig. 1. Microtructures of Al 6061

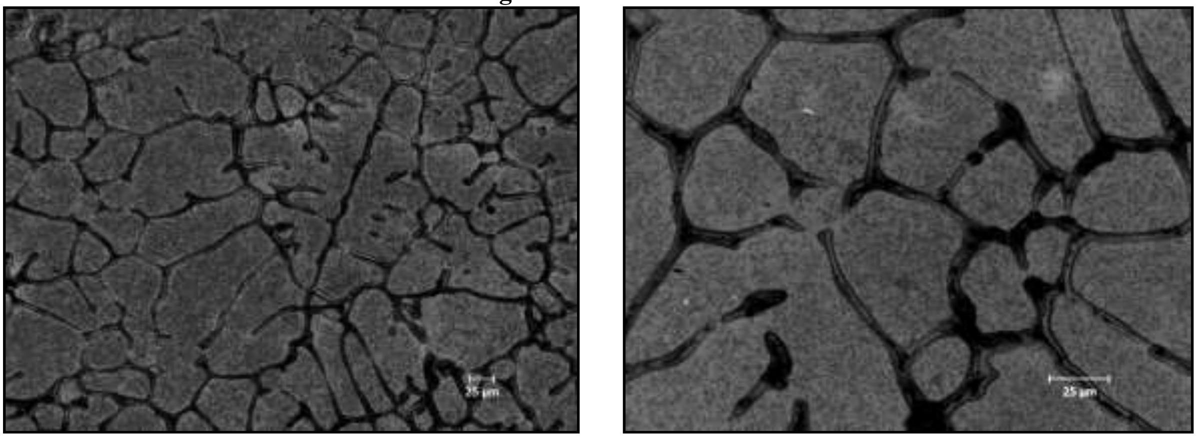

Fig. 2. Microstructures of Al 6061 with 1.25% SiC and 1.25% Gr

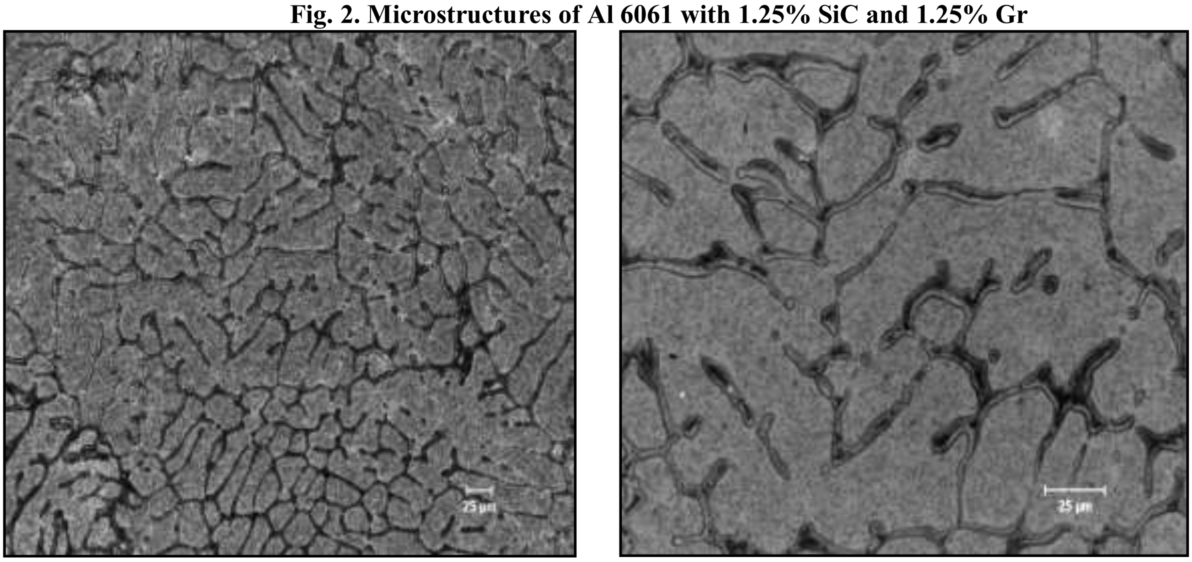

Fig. 3. Microstructures of Al 6061 with 2.5% SiC and 2.5% Gr

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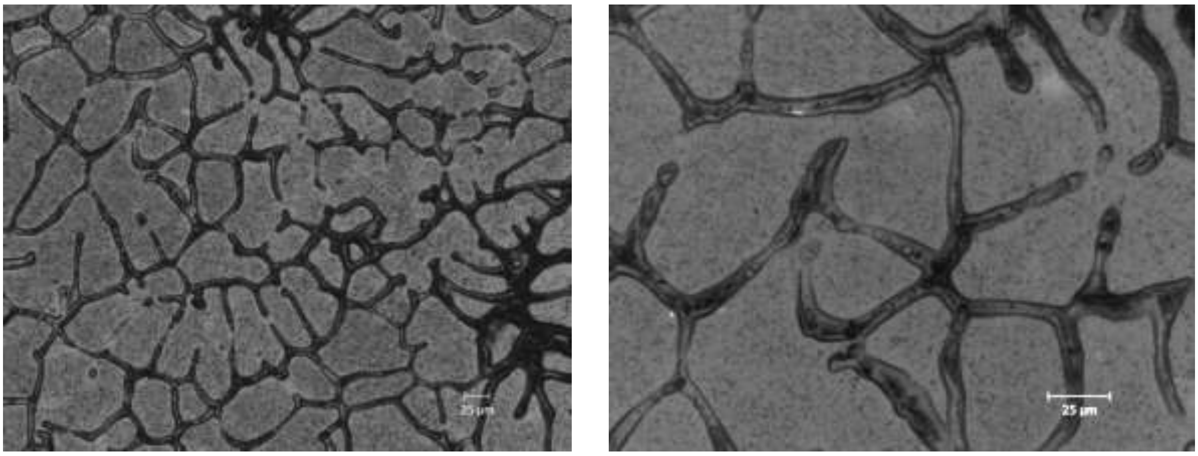

Fig. 4. Microstructures of Al 6061 with 3.75% SiC and 3.75% Gr

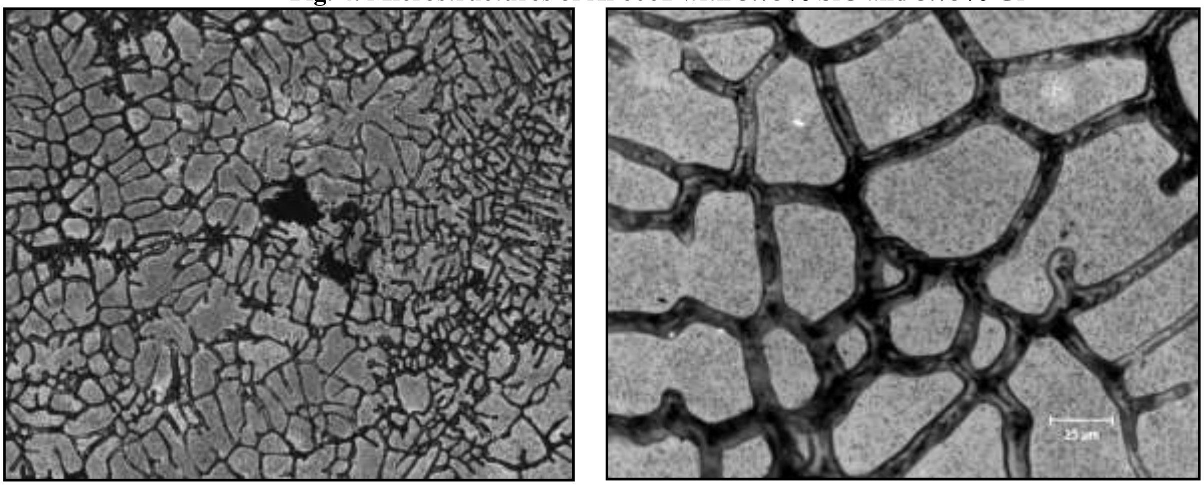

Fig. 5. Microstructures of Al 6061 with 5% SiC and 5% Gr

Fig. 1, 2, 3, 4, and 5 depicts the microstructures of hybrid metal matrix composites reinforced with the particles of Silicon Carbide and Graphite which has been carried out by using Nikon Optical Metallurgical Microscope with Clemex Image Analyzer. The samples with varying weight fraction have been prepared for the study of microstructure using standard metallographic procedure.

Fig. 1 illustrates the microstructure of Al 6061 without any reinforcements. It has been clearly revealed that the fine precipitates of alloying elements have been dispersed in the matrix of Aluminium. The microstructures of hybrid composites for a consistent reinforcement of particles of Graphite with Silicon Carbide have been presented by using optical microscope. The uniform distribution of the reinforcements is an indispensable condition for a composite material to accomplish its performance at extreme superiority [5, 6]. Fig. 2, 3, 4 and 5 depicts the microstructures of Aluminium matrix alloy with varying weight fraction of the reinforcements signifying that the fine precipitates of alloying elements have been dispersed along the grain boundary in the matrix of Aluminium. It has been observed that, the particles of Silicon Carbide and Graphite have been dispersed in the matrix alloy Al 6061. The distribution of the particles of Silicon Carbide and Graphite has been homogeneous with no parallel striations and detrimental pores. The segregation in the internally formed dendrites has been observed because the particles of Silicon Carbide and Graphite has been driven depending of the process of solidification. The presence of these particles in the matrix substantially improves the microstructure, encumbering the coarsening of the initial phase of dendrites during the process of solidification.

The particles of Silicon Carbide have been shifted towards the primary phase of the dendrite boundaries of Aluminium matrix alloy, although some particles have been observed within the grains of the matrix alloy. It has been observed that, the grain boundary appears between the matrix alloy and the grains of Silicon Carbide disperse uniformly near the region of the boundary. It has been reviewed in the literature that, comparatively homogeneous microstructure of Aluminium matrix composites leads to high hardness [7, 8, 10]. The matrix

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alloy Al 6061 has been agglomerated with the grains of Silicon Carbide segregating near the grain boundary, thus forming intra-granular grains. The experimental investigations have demonstrated that, by the addition of the particles of Graphite divulged similar effect with the addition of Silicon Carbide. It has been noticed that, by enhancing the proportion of the particles of Graphite led to the refinement of grains. It has been reported in the literature that, the particles of Silicon have been nucleated consistently depending on the distribution of the particles of Silicon Carbide [8]. It has been reported in the literature that, larger particles of Silicon Carbide has been necessary in large volume fraction of the composite materials. The particles of Silicon Carbide have been distributed homogeneously and Silicon Carbide particles occupy the interstitial positions around coarse particles. It has been corroborated that, a dense and uniform microstructure has been advantageous for electronic packaging equipments due to appreciative mechanical strength and high thermal conductivity [9, 11].

EXPERIMENTAL TECHNIQUES

Thermal analysis of composites can be carried out by using various thermal analyzers viz., Differential Scanning Calorimeter (DSC), Laser Flash Apparatus (LFA), Dilatometer (DIL), Differential Thermal Analysis (DTA), Dynamic Mechanical Analyzer, Mechanical Thermal Analyzer and Thermogravimetric Analyzer (TGA). In this research work, the thermal properties of hybrid composites have been determined by using various thermal analyzers viz., Dilatometer, Laser Flash Apparatus and Differential Scanning Calorimeter. The determination of coefficient of thermal expansion of hybrid metal matrix composites has been accomplished by using a Horizontal Platinum Dilatometer. The determination of thermal diffusivity and thermal conductivity has been achieved by using Laser Flash Apparatus. The determination of specific heat capacity and heat flow has been carried out by using a Differential Scanning Calorimeter.

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THERMOPHYSICAL PROPERTIES OF HYBRID COMPOSITES

The density of hybrid MMCs have been determined by using the relationship between volume and mass. Experimentally, it has been determined by water displacement method (Archimedes principle) and theoretically by using rule of mixtures [1]. In materials science, rule of mixtures is a weighted mean used to predict different properties made of a composite material made up of continuous and unidirectional fibres. It provides a theoretical upper bound and lower bound on properties viz., modulus of elasticity, density, ultimate tensile strength, thermal conductivity and electrical conductivity. Also, rule of mixtures has been beneficial for the theoretical evaluation of different mechanical and thermal parameters [1, 2, 3]. The equation (1) has been used to calculate density of the hybrid composites by using rule of mixtures. ρ is the density, V is the volume fraction and suffixes C, m and p indicates composite, matrix and particles.

$$\rho_C = \rho_m V_m + \rho_p V_p \qquad \text{----------- (1)}$$

Table 1. Density of Hybrid Composites with Varying Weight Fraction

Serial Number	Hybrid composites	Density (g/cc) (Apparent or Experimental)	Density (g/cc) (Relative or Theoretical)	Percentage Porosity
1.	Al 6061	2.7	2.7	0
2.	Al 6061 + 1.25% SiC + 1.25% Gr	2.694	2.696	0.07%
3.	Al 6061 + 2.5% SiC + 2.5% Gr	2.685	2.692	0.26%
4.	Al 6061 + 3.75% SiC + 3.75% Gr	2.676	2.679	0.11%
5.	Al 6061 + 5% SiC + 5% Gr	2.661	2.668	0.26%

It has been reported in the literature that, the density of Al 6061 is 2.7 g/cc, Silicon Carbide is 3.21 g/cc and Graphite is 2 g/cc. Table 1 refers to the density of hybrid composites for the various percentage compositions (1.25%, 2.5%, 3.75% and 5%, equal proportions of SiC and Graphite particles) with precipitation hardening matrix alloy Al 6061. Eq. (1) has been beneficial to evaluate the density of composite materials and they have been validated with experimental results. The difference between the theoretical and experimental density of hybrid composites is very marginal and has been proved to have negligible porosity.

Thermophysical properties of the composite materials can be accomplished by understanding the behaviour of matrix material and reinforcements. The characterization of thermophysical properties viz., density, tensile strength, modulus of elasticity, thermal conductivity, thermal diffusivity, specific heat capacity and thermal expansivity play a very important role to comprehend material behaviour. These properties are usually subjected under varying temperature conditions. So, observations and investigations are not only performed at room temperature but also achieved at high temperatures or under cycling conditions. This is essential to get

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familiarity about the performance of the materials during its use [8]. Metal matrix composites have generated substantial interest in many fields due to customized mechanical properties viz., stiffness, wear resistance and fatigue resistance and tailorable thermal properties namely thermal conductivity and thermal expansivity. The mechanical and thermophysical properties of AMCs can be controlled for specific applications by selecting appropriate types and volume fraction of matrices and reinforcements [8, 9, 11]. These composites are mainly governed by the conductivity of the individual phases, volume fraction, shape and the size of the inclusion phase due to interface thermal resistance [19, 20].

The determination of thermal conductivity and thermal diffusivity has been carried out by using 447 Nano Flash Laser Flash Thermal Diffusivity apparatus. For the determination of thermal conductivity and thermal diffusivity, the sample should be disc shaped and the sample size is as per American Society for Testing of Materials (ASTM) standard. Five samples have been considered with varying percentage compositions of low weight fraction. Al 6061 is the base alloy and reinforcements Silicon Carbide and Graphite with different percentage compositions or weight fraction 2.5%, 5%, 7.5% and 10% have been considered. The diameter of the sample is 12.7 mm and thickness is 3 mm. All the specimens have been tested from room temperature to 300°C. This temperature range has been selected so as to include the entire usable range of the composites, without the formation of liquid phase in the matrix.

It is mandatory to determine the specific heat capacity of hybrid composites for the determination of thermal conductivity. The specific heat capacity of hybrid composites has been determined by using Differential Scanning Calorimeter (NETZSCH DSC 200 Maia F3). Table 2 depicts the determination of specific heat capacity of hybrid composites. Thermal conductivity by using Laser Flash apparatus has been determined by taking the product of thermal diffusivity, density and specific heat capacity of hybrid composites.

Table 2. Specific Heat Capacity of Hybrid Composites with Varying Weight Fraction at 300°C

Serial Number	Hybrid Composites	Heat Capacity (J/kg K)
1.	Al 6061 (Sample 1)	980
2.	Al 6061 + 1.25% SiC + 1.25% Gr (Sample 2)	968
3.	Al 6061 + 2.5% SiC + 2.5% Gr (Sample 3)	947
4.	Al 6061 + 3.75% SiC + 3.75% Gr (Sample 4)	924
5.	Al 6061 + 5% SiC + 5% Gr (Sample 5)	918

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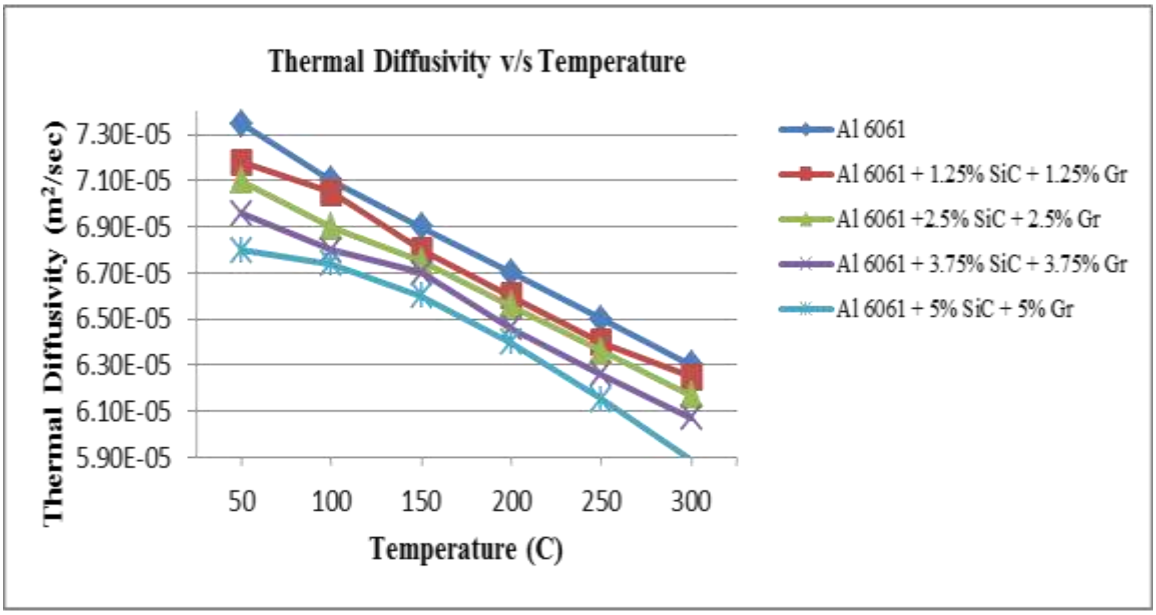

Fig. 6. Variation of Thermal Diffusivity and Temperature for Percentage Compositions of MMCs

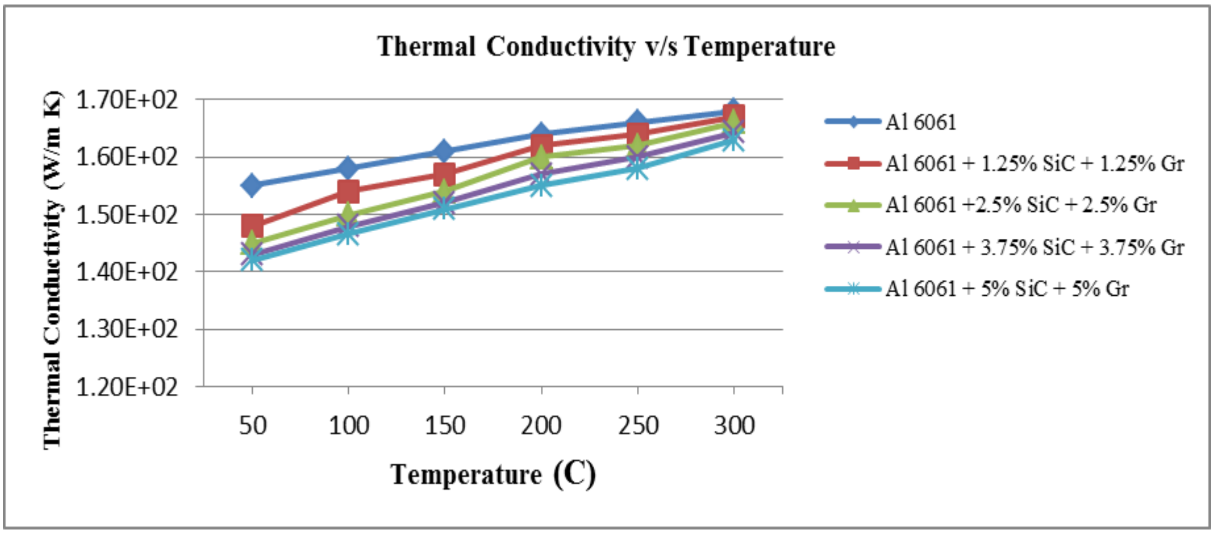

Fig. 7. Variation of Thermal Conductivity and Temperature for Percentage Compositions of MMCs

The thermal conductivity behaviour of hybrid metal matrix composites has been determined with varying weight fraction. The effect of Graphite on thermal behaviour in Aluminium-Silicon Carbide-Graphite hybrid metal matrix composites has been investigated. Fig. 6 depicts the variation of thermal diffusivity with temperature for different compositions of hybrid metal matrix composites. Fig. 7 illustrates the variation of thermal conductivity with temperature for different percentage compositions of hybrid metal matrix composites.

From fig. 7, it has been observed that, Al 6061 has high thermal conductivity of 168 W/m K and Al 6061 + 5% SiC + 5% Gr reveals low thermal conductivity of 163 W/ m K at all temperatures. It has been noticed that, with the addition of reinforcements Silicon Carbide and Graphite with Al 6061, there has been a gradual reduction in the thermal conductivity at higher temperature for different percentage compositions of hybrid metal matrix composites. Generally, the thermal conductivity of materials varies as the temperature changes. It can be observed that, with the increase in temperature, thermal conductivity of hybrid composites drastically increases, but at higher temperature, there has been a decline in thermal conductivity of hybrid composites. Experimentally, it has been inferred that, by the addition of Graphite with Silicon Carbide and Aluminium matrix alloy Al 6061 with varying weight fraction at lower proportions resulted in the considerable reduction in thermal conductivity of the hybrid metal matrix composites.

It has been reported in the literature that, the thermal conductivity considerably increases by reinforcing Silicon Carbide with any Aluminium alloy over the different range of temperatures [8]. But from the present experimental investigation, it can be inferred that, by the addition of Graphite with Silicon Carbide and Al 6061, there has been no substantial variation in thermal conductivity. This confirms that, the addition of reinforcements Silicon Carbide and Graphite concurrently with the matrix alloy has insignificant influence in the increase of thermal conductivity. It has been obvious that, Aluminium and Silicon Carbide composite exhibits higher thermal conductivity, but by the addition of Graphite with Aluminium matrix alloy and Silicon Carbide gradually decreases the thermal conductivity of hybrid composites. It has been reported that, the thermal conductivity of Graphite (100 W/ m K) is very low compared to Aluminium 6061 (167 W/ m K) and Silicon Carbide (180 W/m K). It has been reported that, Graphite content improves the dimensional stability, but by the addition of Graphite with Aluminium matrix composites, there will be no significant variation in thermal conductivity behaviour of hybrid composites. The term 'dimensional stability' refers that, the thermal strain and particles sizes of the hybrid composites viz., Aluminium/Silicon Carbide/Graphite has been increased depending on the amount of Graphite added and has benefitted in achieving better dimensional stability [8]. Based on these investigations, it can be concluded that, the thermal conductivity of hybrid composites significantly diminishes due to the enrichment of Graphite content. The hybrid composites with 5% Silicon Carbide and 5% Graphite reinforced with Al 6061 exhibited low thermal conductivity compared with those of other hybrid composites with almost negligible porosity. The volume fraction of Silicon Carbide is indeed the main factor contributing to the thermal conductivity of MMC.

Thermal conductivity was found to decrease as the content of Graphite is enhanced depending on temperature increase. The reinforcements have lower thermal conductivities and hence thermal diffusivity diminishes due to variation in temperature. Fig. 7 has indicated that, there has been a continuous decrease in thermal diffusivity over the range of temperatures. As the thermal conductivity and density of hybrid composites drops, thermal diffusivity decreases. It has been referred that, the decrease in thermal diffusivity dominates the temperature dependence of thermal conductivity in the high temperature region. Also, the specific heat decreases strongly at temperatures below room temperature and dominates the temperature dependence of thermal conductivity [8]. When the MMC undergoes heating process, expansion and deformation processes occurs steadily. In the present study, the particles of Silicon Carbide and Graphite particles are uniformly distributed in Aluminium matrix and no considerable level of pores have been observed when Graphite is used as reinforcement. From literature, Aluminium-Silicon Carbide composites are attractive with many outstanding features namely higher thermal conductivity, lower thermal expansivity and low density. With any Aluminium matrix alloy, the addition of Silicon Carbide will enhance thermal conductivity and flexural strength [8, 9, 10].

It has been reported in the literature that, the dependency on the overall thermal conductivity pertaining to the particle diameter of spherical particles with equal size has been investigated with many predictions. The reason for the decrease in the thermal conductivity with decreasing grain size of the different compositions of Silicon Carbide can be attributed to the interfacial properties between the Al matrix and the particles of Silicon Carbide [20, 21, 22]. It has been obvious that, decreasing the grain size results in a larger surface area between Aluminium matrix and Silicon Carbide. The interfacial reaction between Aluminium matrix and Silicon Carbide can reduce the thermal conductivity of the composites [23]. It has been demonstrated that, porosity can severely degrade the thermal and mechanical properties of MMCs [8, 9].

Coefficient of thermal expansion (CTE) or thermal expansivity is an important thermal property of Aluminium matrix composites [8, 9]. An attractive characteristic of AMCs is the ability to customize CTE, which can be accomplished by controlling low expansion reinforcement percentage volume fraction, size of the particle, dispersoid concentration of the reinforcements, morphology and particle packing characteristics [24, 25, 26]. Since nearly all Aluminium 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 methods for measurement of CTE can be used depending on the temperature conditions. One of the most common methods used is a dilatometer.

The determination of coefficient of thermal expansion has been carried out by using LINESIS 75 Horizontal Platinum Dilatometer. For the determination of thermal expansivity, the sample should be cylindrical shaped and the sample size is as per ASTM standard. 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 Silicon Carbide (SiC) and Graphite (Gr) with different percentage compositions 2.5%, 5%, 7.5% and 10% have been selected. All the specimens have been tested from room temperature to 300°C. This temperature range has been selected so as to include the entire usable range of the composites, without the formation of liquid phase in the matrix. The data has been obtained in the form of per cent linear change versus temperature. Standard data analysis software was used to evaluate the Coefficient of

Thermal Expansion (CTE) of the composites tested and was determined at intervals of 20°C. Fig. 8 depicts the variation of CTE and temperature for different compositions of hybrid MMC. It has been noticed that, the CTE of the hybrid composites with different percentage compositions increases with the increase in temperature.

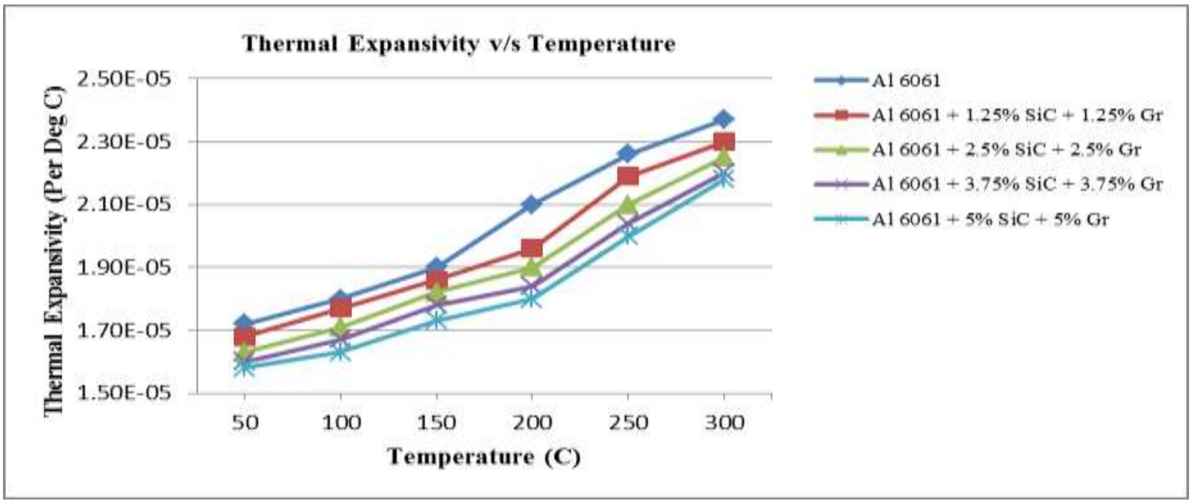

Fig. 8. Variation of CTE v/s Temperature for Hybrid Composites

Fig. 8 depicts the variation of CTE and temperature for different compositions of hybrid MMC. It has been noticed that, the magnitude of CTE of the hybrid composites with different percentage compositions increases with the increase in temperature. From fig. 8, it has been observed that, Al 6061 reveals high thermal expansivity. Generally, the thermal expansivity of materials varies as the temperature changes. It has been be noticed that, with the addition of reinforcements Silicon Carbide and Graphite to Al 6061, there has been reduction in the thermal expansivity at all temperatures for different percentage compositions of hybrid metal matrix composites. Addition of Graphite with Aluminium matrix alloy and Silicon Carbide with varying volume fraction resulted in the reduction in thermal expansivity of the hybrid metal matrix composites. The CTE of Graphite is very low compared to Al 6061 and Silicon Carbide. It has been reported in the literature that, the thermal expansivity for hybrid MMCs considerably increases by reinforcing Silicon Carbide over the different range of temperatures [8]. It has been inferred in the experimentation that, the reinforcement of Graphite with Aluminium-Silicon and Silicon Carbide does not enhance thermal expansivity, thermal conductivity and thermal diffusivity significantly [8]. It has been examined that, addition of Silicon Carbide and Graphite reinforcements with high volume fraction resulted in higher values of thermal capacity, thermal expansivity and thermal conductivity [8, 10, 22, 24, 25, 26]. It has been reported in the literature that, the CTEs of Al 6061 is 23×10^{-6}/°C, Silicon Carbide is 8×10^{-6}/°C and Graphite is 1×10^{-6}/°C.

It has been described in the literature that, 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. 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 [10, 21, 23]. In Al-SiC composite, the behaviour of thermal expansion is generally influenced by the thermal exapnsivity of Aluminium matrix and the tightened restraint of the particles of Silicon Carbide [9].

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From the literature, it has been detailed that, the hybrid composites have lower volume fractions of SiC than conventional Al-SiC composites with the same CTEs. 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 Silicon reinforcement and the ability of the reinforcements to effectively constraint the expansion of the matrix [8, 9]. The thermal strain of all hybrid composites increases as the amount of Graphite has been increased; indicating that introducing a high amount of Graphite to Al-Si based composites may not be beneficial to attain dimensional stability. It has been examined that, the thermal response and the coefficient of thermal expansion (CTE) of aluminium matrix composites have high volume fraction of Silicon Carbide particulate. In Aluminium-Silicon Carbide composites, the thermal expansion behaviour will be influenced by the thermal expansion of aluminium and the tightened restriction of the particles of Silicon Carbide. The CTE of the particle reinforced MMCs is usually affected by a variety of factors viz., interfacial reactions, plasticity due to CTE mismatch between particle and matrix during heating or cooling, and residual stresses [23, 24, 25].

THERMOELASTIC PROPERTIES OF HYBRID COMPOSITES

Tension test is the fundamental mechanical test that can be performed on engineering materials. Tensile test is simple, relatively inexpensive and fully standardized. This test is generally carried out to determine tensile strength and modulus of elasticity of the given material. The important part of the specimen is the gauge section. Experiments have been conducted on Al 6061-Silicon Carbide-Graphite hybrid metal matrix composites to determine the tensile strength and modulus of elasticity. Tensile tests have been carried out at room temperature by using a Universal Testing Machine (UTM) in accordance with the guidelines framed by Bureau of Indian Standards.

In this research work, moduli of elasticity have been determined for hybrid metal matrix composites for varying weight fraction 1.25%, 2.5%, 3.75% and 5% (equal proportions of SiC and Graphite). Five specimens have been tested and the values of tensile strength and modulus of elasticity have been presented in table 5.2. It has been reported in the literature that, modulus of elasticity of Al 6061 is 70 GPa, Silicon Carbide is 150 GPa and Graphite is 10 Gpa. Poisson ratio has been calculated for the hybrid composites using equation (5.2). It has been reported in the literature that, Poisson ratio for Al 6061 is 0.3, Silicon Carbide is 0.2 and Graphite is 0.27. The values of moduli of elasticity and Poisson ratio are beneficial for the determination of mechanical and thermal properties of composite materials [1, 2, 9]. Table 3 confirms the fact that, the tensile strength depicts an increasing trend in case of hybrid metal matrix composites as the percentage reinforcement of Silicon Carbide particulates is increased. The increase in tensile strength is because of the existence of Silicon Carbide reinforcement particles. It has been found that, the tensile strength of hybrid composites increases gradually as the percentage reinforcement increases. Eq. (2) and (3) are beneficial for estimating modulus of elasticity and Poisson ratio by using rule of mixtures. E is the modulus of elasticity, ϵ is Poisson ratio, V is the volume fraction and suffixes C, m and p indicates composite, matrix and particles.

ROM for calculating Modulus of Elasticity, $E = V_p E_P + (1-V_p) E_m$ ---------- (2)

ROM for calculating Poisson ratio: $\epsilon_C = \epsilon_m V_m + \epsilon_p V_p$ ----------- (3)

Table 3. Moduli of Elasticity and Poisson ratio for the Percentage Compositions of Hybrid Composites

Serial Number	Hybrid composites	Tensile Strength (MPa)	Moduli of Elasticity (GPa)	Poisson ratio
1.	Al 6061	125	70	0.3
2.	Al 6061 + 1.25% SiC + 1.25% Gr	130	71.5	0.2984
3.	Al 6061 + 2.5% SiC + 2.5% Gr	134	73	0.2945
4.	Al 6061 + 3.75% SiC + 3.75% Gr	139	74.5	0.2935
5.	Al 6061 + 5% SiC + 5% Gr	144	76	0.2912

It has been observed that, the presence of Graphite particulates in hybrid metal matrix composites has a tendency to vary tensile strength, modulus of elasticity and Poisson ratio. Thus, it is essential to understand to

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what extent the combined effect of particles Graphite and Silicon Carbide influences the tensile strength, moduli of elasticity and Poisson ratio. Hence, an attempt has been made to relate the estimated mechanical properties with thermal characteristics of hybrid metal matrix composites. It has been reported in the literature that, the decrease in tensile strength as the amount of Graphite addition can be attributed to weaker Graphite particulates. Also, the main drawback in using Graphite as reinforcement has been the resulting loss in strength of the entire composite [23, 24, 25].

Generally, latent heat is equal to the amount of energy necessary for the melting of unit mass of crystal material at the freezing point. Materials with high latent heat are more stable. But, latent heat of fusion is defined as the amount of heat required to convert solid phase into liquid phase without change in temperature. In this research, latent heat of fusion of hybrid composites have been determined for the different weight fractions of hybrid composites. It has been observed in table 4 that, the latent heat of hybrid composites decreases as the specific heat capacity decreases gradually. From table 2, it has been observed that, Al 6061 has maximum specific heat or thermal capacity, but Al 6061 + 5% SiC + 5% Gr has low specific heat capacity. From eq. (4), it has been calculated by taking the product of specific heat capacity of hybrid composites and the corresponding raise in temperature. C_P is specific heat capacity and ΔT is the raise in temperature. Mathematically,

$$\text{LH of Fusion} = C_P \times \Delta T \quad \text{-------- (4)}$$

Table 4. Latent Heat of Fusion of Hybrid Composites with Weight Fraction

Serial Number	Hybrid composites	Latent Heat of Fusion (J/kg)
1.	Al 6061	294000
2.	Al 6061 + 1.25% SiC + 1.25% Gr	288000
3.	Al 6061 + 2.5% SiC + 2.5% Gr	282000
4.	Al 6061 + 3.75% SiC + 3.75% Gr	276000
5.	Al 6061 + 5% SiC + 5% Gr	270000

Thermal resistance is the capacity of materials to maintain their internal structure and strength subjected under sharp transformations pertaining to temperature. Thermal resistance of materials is generally characterized by a number of cycles of temperature where a material maintains their internal structure and strength under successive freezing and melting processes [26, 27]. Mathematically, thermal resistance (T_R) is the ratio of the length of the specimen to the product of thermal conductivity and area of the specimen. But, thermal resistivity is the reciprocal of thermal conductivity. Equation (5) is useful for the determination of thermal resistance. Table 5 depicts the values of thermal resistances of hybrid composites with varying weight fraction. It has been noticed that, the thermal resistances gradually increases over the range of temperatures. As the value of thermal conductivity decreases, there will be increase in thermal resistances of hybrid composites.

Thermal shock occurs when a thermal gradient causes different parts of a material to expand by different amounts. This differential expansion can be comprehended in terms of stress and strain. At some point, this stress can exceed the length of the material, causing a crack to form [28, 29]. Mathematically, thermal shock resistance (TSR) is the ratio of product of thermal stress and thermal conductivity to modulus of elasticity and thermal expansivity of the materials. Eq. (5) indicates the relation for thermal shock resistance.

$$TSR = \frac{\sigma \times K\,(1-\nu)}{\alpha \times E} \quad \text{---------- (5)}$$

where, K is the thermal conductivity, σ is the thermal stress, ν is the Poisson ratio, E is the modulus of elasticity and α is the thermal expansivity.

Thermal shock resistance of hybrid metal matrix composites has been calculated at maximum temperature with varying weight fraction using equation (6). Based on thermal expansion and thermal conductivity behavior of hybrid metal matrix composites, thermal shock resistance can be evaluated. It has been observed that, there has been increase in thermal shock resistances of hybrid composites. As thermal conductivity, thermal stresses, thermal expansivity and Poisson ratio varies; there will be variation in TSR. Thermal stresses have been determined by computational investigation by using ANSYS 12. Table 5 represents the estimation of TSR depending on the values thermal stress, thermal conductivity, modulus of elasticity and thermal expansivity that are determined at 300°C.

Table 5. Determination of TSR of Hybrid MMCs with Varying Weight Fraction

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Hybrid composites	Thermal Stress (N/m^2)	Thermal Conductivity (W/m K)	Thermal Expansivity (/°C)	Moduli of Elasticity (Gpa)	TSR (W/m)
Sample 1	0.318×10^9	168	23.6×10^{-6}	70	22,637.3
Sample 2	0.306×10^9	167.4	22.8×10^{-6}	71.5	22,040.8
Sample 3	0.282×10^9	166.78	22×10^{-6}	73	20,658.1
Sample 4	0.281×10^9	165.3	21.6×10^{-6}	74.5	20,393.1
Sample 5	0.279×10^9	164.2	20.8×10^{-6}	76	20,388.7

CONCLUSIONS

- Al 6061 exhibits high value of thermal conductivity, but there is a decline in thermal conductivity at higher temperatures for different percentage compositions of hybrid metal matrix composites with the addition of reinforcements Silicon Carbide and Graphite to Al 6061.

- The thermal conductivity of hybrid composites reduces due to the enhancement of Graphite content. The values of thermal conductivity decreases over the range of temperatures, with variation in density, variation in volume fraction of Silicon Carbide and porosity of hybrid composites.

- With the addition of reinforcements of low volume fraction, thermal conductivity of hybrid has been observed to be low. The variation in thermal conductivity depends on porosity, temperature variation, volume fraction, internal structure of the composites, dispersoid concentration of reinforcements and density of composites.

- The reinforcements have lower thermal conductivities and hence thermal diffusivity diminishes due to variation in temperature. As the thermal conductivity and density of hybrid composites drops, thermal diffusivity decreases. It has been inferred that, the decrease in thermal diffusivity dominates the temperature dependence of thermal conductivity in the high temperature region.

- Al 6061 exhibits high value of thermal expansivity, whereas there is a decline in Thermal Expansivity at higher temperatures for different percentage compositions of hybrid metal matrix composites with the addition of reinforcements Silicon Carbide and Graphite to Al 6061.

- Llatent heat of fusion of hybrid composites have been determined for the different weight fractions of hybrid composites. It has been observed that, the latent heat of hybrid composites decreases as the specific heat capacity decreases gradually.

- It has been observed that, thermal shock resistance vary due to the decreasing trend in all thermal parameters at maximum temperature.

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NOMENCLATURE

X	Magnification
ρ_c	Density of the composite, kg/m^3
ρ_c	Density of the matrix, kg/m^3
ρ_p	Density of the reinforcements, kg/m^3
V_m	Volume fraction of the matrix
V_p	Volume fraction of the reinforcements
E	Modulus of Elasticity
ν_C	Poisson ratio of the composite
ν_m	Poisson ratio of the matrix
ν_p	Poisson ratio of the reinforcements
V_f	Volume fraction of the composite
K	Thermal Conductivity, W/m K
A	Coefficient of Thermal Expansion, /°C
C_P	Specific Heat Capacity, J/kg K
ΔT	Raise in temperature