AN EXPERIMENTAL INVESTIGATION AND VALIDATION OF THERMO-ELASTIC MODELS ON THERMAL CONDUCTIVITY BEHAVIOUR OF Al 6061-SILICON CARBIDE-GRAPHITE HYBRID METAL MATRIX COMPOSITES

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Abstract
Metal matrix composites are regarded to be one of the most predominant classifications in composite materials. The thermal characterization of metal matrix composites by using laser flash apparatus is a sophisticated technique meant for the determination of thermal diffusivity and thermal conductivity. In this research paper, the determination of thermal conductivity and thermal diffusivity 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 results have indicated that, the thermal conductivity and thermal diffusivity for different compositions of hybrid MMCs decrease by the addition of Graphite with Silicon Carbide to the matrix alloy Al 6061. Empirical or thermo-elastic models viz., rule of mixtures, series model, geometric model and Maxwell's model have been validated for the evaluation of thermal conductivity of composites.

Keywords: *Thermal characterization; laser flash; thermal conductivity; thermal diffusivity; stir casting; reinforcements; empirical models.*

1. INTRODUCTION

Composite materials which are being extensively used in the present scenario for day-to-day applications play a dominating role in manufacturing sector for the fabrication of highly sophisticated equipments and components. The market of composite materials is unpredictable and is cumbersome to obtain the most reliable information for manufacturing volumes. The composite materials generally exhibit superior characteristics than that of the matrix material. Modern composite materials are usually optimized to achieve a proper balance of properties for a given range of applications [1].

Metal Matrix Composites (MMCs) have fascinated the researchers in all perspectives. Metal matrix composites are the innovative 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. MMCs have greater advantage compared to other composites. These materials possess high temperature resistance, high yield strength and yield modulus and can be strengthened by different thermal and mechanical treatments. Metal matrix composites can be designed to process the thermal qualities viz., low Coefficient of Thermal Expansion (CTE), high thermal capacity and high thermal conductivity that are best suited for aerospace engineering, automotive components, thermal management of electronic equipment and electronic packaging applications. Aluminium Silicon alloys have extensive applications in industries due to their properties viz., high fluidity, low melting point, high fatigue strength, corrosion resistance, good castability characteristics, high tensile strength, high wear resistance and lower coefficient of thermal expansion. 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 [2] [3]. Aluminium Matrix Composites (AMCs) possess better property of friction and excellent wear resistance due to the combined effect of the strength of Silicon Carbide influenced on the matrix and lubrication property of Graphite [2].

In the present scenario, thermal characterization and analysis of composite materials have been gaining greater impetus. 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 knowledge of the thermophysical properties has been mandatory 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 properties 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 [4].

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 properties viz., thermal conductivity and thermal diffusivity. 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 [4]. 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 for materials with high thermal diffusivity [5] [6]. The assessment of thermal properties will benefit to evaluate heat capacity, variation in the intensity of heat, heat diffusion and heat release rate [7]. For aerospace and automotive applications, low coefficient of thermal expansion, moderate thermal conductivity, specific heat capacity and high electrical conductivity of the composites will enhance the efficiency in all perspectives. The technique that has been adopted in the experimental investigation of thermal conductivity and thermal diffusivity is laser flash apparatus. Some of the most important papers concerning the thermal properties of Aluminium-Silicon Carbide-Graphite hybrid composites have been presented.

Davis et al. [8] in their research paper have explained the thermal conductivity of metal matrix composites, which are potential electronic packaging materials and have been calculated by 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.

Cem Okumus et al. [9] in their paper have studied on thermal expansion and thermal conductivity behaviour of Al/Si/SiC/Graphite 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 behaviour of hybrid composites with various Graphite contents and different Silicon Carbide particle sizes (45 μm and 53 μm) have 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.

Molina et al. [10] have investigated the behaviour of thermal conductivity of Aluminium-Silicon Carbide (SiC) composites based on high volume fraction of Silicon Carbide particles. It has been investigated by comparing data for composites fabricated by infiltrating liquid aluminium into preforms made either from a single particle size, or by mixing and packing SiC particles of two largely different average sizes 170 μm and 16 μm. For composites based on powders with a monomodal size distribution, the thermal conductivity increases steadily from 151 W/mK for particles of average diameter 8 μm to 216 W/mK for 170 μm particles. For the bimodal particle mixtures the thermal conductivity increases with increasing volume fraction of coarse particles and reaches a roughly constant value of 220 W/mK for mixtures with 40 or more vol.% of coarse particles. It has been shown that all present data can be accounted for by the differential effective medium (DEM) scheme taking into account a finite interfacial thermal resistance.

Parker et al. [11] 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.

Chen et al. [12] 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 have been presented. Key factors controlling the thermophysical properties have been discussed in detail.

Hohenauer et al. [13] have experimented on flash methods to examine thermal diffusivity and thermal conductivity of metal foams. The results of thermal conductivity have been obtained by using a laser flash device. In particular, a Magnesium alloy has been investigated. To meet the requirements of flash technique, coplanar samples have been prepared. A finite element model has been generated to study the influence of the preparation method and measurement techniques.

It has been evident from the literature review that, thermal characterization and analysis of Aluminium Matrix Composites (AMCs) have to be given greater emphasis. However, investigations concerning the thermal characterization and analysis of composite materials of AMCs are scarce. Many experimental investigations have been carried out pertaining to thermal characterization of Aluminium Silicon Carbide composites, but limited work has been accomplished concerning Aluminium-Silicon Carbide-Graphite hybrid MMCs. The literature review has indicated the need for further investigations on thermal characterization and analysis of Aluminium matrix composites. If these materials are to be used for many engineering applications, the thermal aspects of AMCs need to be given more emphasis. Hence it becomes important that the evaluation of thermal aspects and characteristics of hybrid composites cannot be ignored in order to transform the material from design stage to manufacturing stage.

In the present scenario, research has been accomplished on mechanical and tribological properties of hybrid composites substantially, but limited research has been carried out on Aluminium-Silicon Carbide-Graphite hybrid composites relating thermal characterization and analysis. It has been reported in the literature that, the experimental investigation on thermal characterization and analysis of Aluminium and Silicon Carbide has been carried out concerning low and high weight fraction [9]. But, research on thermal characterization and analysis of Al 6061 with Silicon Carbide (SiC) and Graphite (Gr) hybrid metal matrix composites pertaining to low and high weight fraction have been very deficient. The pertinent thermal properties of Aluminium based hybrid MMC reinforced with Silicon Carbide and Graphite have to be investigated in terms of varying weight fraction and smaller particle sizes. Casting techniques viz., stir casting, centrifugal casting and squeeze casting have been extensively used.

One of the major advantages of Aluminium-Silicon Carbide-Graphite hybrid metal matrix composites is that, these composites are self-lubricating materials comprising Graphite, yet their strength can be improved by the presence of Silicon Carbide ceramic phase. These AMCs possess better property of friction and excellent wear resistance due to the combined effect of the strength of Silicon Carbide influenced on the matrix and lubrication property of Graphite [9] [12]. Silicon Carbide exhibits mechanical and thermal properties and has been used extensively as a prominent reinforcement. Graphite represents an optimal combination of strength, ductility and thermal properties for pertinent engineering applications. Graphite has superior characteristics viz., tensile strength, improved castability, damping capacity and machinability. From literature review, Graphite has been used scarcely. Hence in this research work, Graphite has been used as reinforcement concurrently with Silicon Carbide and Aluminium matrix alloy considering low weight fraction of hybrid composites.

2. FABRICATION OF HYBRID COMPOSITES

Aluminium-Silicon Carbide-Graphite hybrid metal matrix composites specimens have been stir 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%). Aluminium alloy (Al 6061) has been used as the matrix material to which the particulates of Silicon Carbide of average particle size of around 15 to 25 microns and particulates of Graphite of average particle size of around 60 to 70 microns have been used as reinforcements. 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. The powders of Silicon Carbide and Graphite have been added by direct mixing and top pouring stir casting system has been adopted. In this research paper, the evaluation of thermal properties viz., thermal conductivity, thermal diffusivity and specific heat capacity have been accomplished. Different specimens have been considered as per American Society for Testing and Materials (ASTM) standard. The specimen size for the determination of thermal conductivity is diameter 12.7 mm and thickness 3 mm and for the determination of CTE, length is 10 mm and diameter is 5 mm. The specimen size for determination of specific heat capacity is powder form or pellets, approximately 20 mg. The hybrid composite specimens have been fabricated commercially. Also, from room temperature to 800^0C, the atmosphere for fabrication process has been maintained.

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 (about 3 to 5 g) 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% mass 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 400 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 are fabricated to the required sizes. Five specimens have been separately considered for the determination of thermal conductivity with different specimen sizes. Metallography is an investigative study of the microstructure of the materials. The analysis of the microstructure of materials benefits in determining the exact procedure about material processing and is 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 or mass fraction 2.5%, 5%, 7.5% and 10% have been prepared for the study of microstructure by using standard metallographic procedure. The samples have been grinded and polished by using an emery paper. Polishing has been accomplished by using powder of Alumina to achieve surface finish. Keller's reagent has been applied to the samples. The microstructural analysis has been carried out for Al 6061 with varying mass fraction of reinforcements Silicon Carbide and Graphite.

3. MICROSTRUCTURAL ANALYSIS OF Al 6061-SiC-Gr HYBRID COMPOSITES

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, moduli of elasticity, thermal conductivity, specific heat capacity and thermal expansivity.

Microstructural characterization with varying mass fraction of hybrid metal matrix composites has been accomplished by using Scanning Electron Microscope (Hitachi S-3400 N). Scanning Electron Microscope (SEM) has been used to examine the cohesive interfacial bonding, porosity, particle size and dispersoid concentration of the reinforcements. The microstructures with magnification 500X have been used to investigate the behavior of hybrid composites. One of the vital challenges in functional and engineering materials is the study of morphology controlled process based on the growth of crystal. During microstructural examination, the structure of the material is studied under high magnification. The properties of a material determine the level of performance for a specific application.

The microstructure of the hybrid composites has been carried out for Al 6061 and reinforcements Silicon Carbide and Graphite by varying the mass fraction. The microstructural analysis of the hybrid composites has been advantageous to study the morphology and presence of porosity. This helps to understand the distribution of reinforcements with the matrix alloy Al 6061. It is accounted in the literature that, the evaluation of the distribution of reinforcements and porosity is favourable to carry out thermal analysis and characterization of composites [9].

4. DETERMINATION OF DENSITY AND POROSITY OF HYBRID COMPOSITES

The density of hybrid MMCs has been determined using the relationship between volume and mass. The relative density has been calculated on the base of apparent density determined by hydrostatic method and theroetical density calculated on the base of mixtures low [1]. The equation (1) has been used to calculate density of the hybrid composites using rule of mixtures. $\rho_{C,}\, \rho_m$ *and* ρ_p are the density of composite, matrix and particles and V is the volume fraction. The difference between the theoretical and experimental density of hybrid composites is very marginal and has been proved to have negligible porosity.

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

5. DETERMINATION OF THERMAL DIFFUSIVITY AND THERMAL CONDUCTIVITY USING LASER FLASH APPARATUS

Laser Flash technique is resourceful for the determination of thermal conductivity and thermal diffusivity. The thermal conductivity of metals, alloys or composites can be measured by comparative method with steady state longitudinal heat flow in a temperature range from room temperature up to about 1000°C [14]. In the past experimental investigations and review, it has indicated clearly the potential prospects of further investigations on thermal characterization and analysis of Aluminium matrix composites. It has been reported in the literature that, the experimental study on Aluminium and Silicon Carbide has been carried out pertaining to low and high mass fraction [9]. But, limited work has been carried out on thermal characterization of Al 6061 with Silicon Carbide (SiC) and Graphite (Gr) based on low mass fraction of hybrid metal matrix composites. Table 1 depicts the technical specifications of 447 Nano Flash Thermal Diffusivity apparatus.

Table 1. Technical Specifications of LFA 447 (Nano Flash) Apparatus

Specifications	Details
Standard sample size	Disc shaped with diameter 12.5-12.7 mm and thickness 2-3 mm
Temperature range	Ambient temperature to 300°C
Thermal Diffusivity	0.01 mm^2/sec to 1000 mm^2/sec
Thermal Conductivity	0.1W/m K to 2000 W/m K
Flash source	Xenon Flash lamp Wavelength ranges from 150 nm to 1000 nm
Sensor type	Infrared Detector
Utilities	115 V to 230 V, 50/60 Hz, 15 A Controller
Range of scanning	50 mm× 50 mm

The thermal diffusivity of hybrid composites has been measured by using a NETZSCH model LFA 447 Nano Flash diffusivity apparatus. For the determination of thermal conductivity and thermal diffusivity, the sample should be disc shaped and size is as per ASTM standard. Five samples have been considered with different percentage compositions. The samples have been measured by using a standard sample holder (diameter of 12.7 mm and thickness 3 mm). The samples have been coated with Graphite on the front and back surfaces in order to increase absorption of the flash light on the sample's front surface and to increase the emissivity on the sample's back surface.

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). 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 illustrates the technical specifications of NETZSCH DSC 200 F3 Maia apparatus.

Table 2. Technical Specifications of NETZSCH DSC 200 F3 Maia

Specifications	Details
Temperature range	-170°C to 600°C
Heating rates	0.001K/min to 100 K/min
Cooling rates	0.001 K/min to 100 K/min
Sensor	Heat Flux system
Measurement range	0 mW to 600 mW
Cooling options	Forced air, vortex tube and liquid Nitrogen (upto -170°C)
Atmospheres	Static and dynamic conditions
Automatic sample charger	Upto 20 samples
Weight of the sample	Approximately 15 mg to 20 mg
Make	NETZSCH

To determine thermal conductivity of composites, it is necessary to determine specific heat capacity and thermal diffusivity. Also, the density of hybrid composites has to be determined mandatorily. From the fundamentals of heat transfer, the thermal conductivity can be determined by taking the product of thermal diffusivity (α), specific heat capacity (Cp) and density (ρ) of hybrid composites. Eq. (2) depicts the formula to calculate thermal conductivity.

$$K = \alpha \times C_P \times \rho \qquad \text{----------- (2)}$$

In this research work, the determination of coefficient of thermal expansion has been carried out by using LINESIS 75 Horizontal Platinum Dilatometer. For the determination of coefficient of thermal expansion, the sample should be cylindrical shaped and the sample size is as per ASTM standard. The size of the cylindrical sample is diameter 5 mm and length 10 mm. Five samples have been considered with different percentage compositions. Al 6061 is the matrix alloy and reinforcements Silicon Carbide and Graphite 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. Standard data analysis or rate sintering software (RCS) has been used to evaluate the coefficient of thermal expansion of hybrid composites tested and have been determined at intervals of 20°C.

6. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 1, 2, 3, 4 and 5 depict the micrographs for different compositions of the hybrid MMCs.

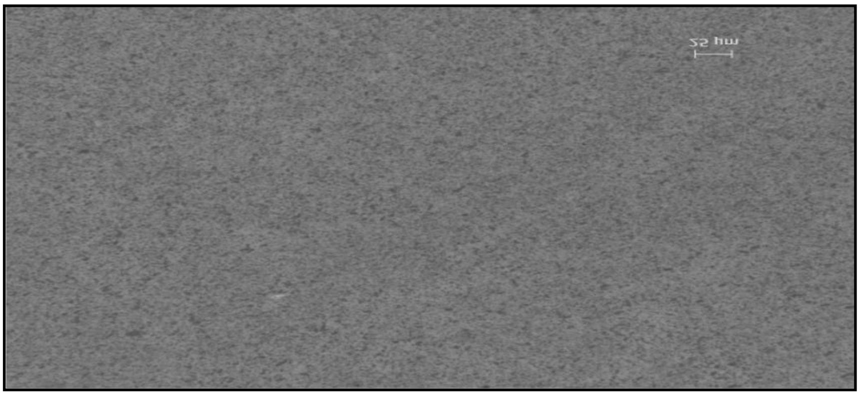

Fig. 1. Microstructure of Al 6061

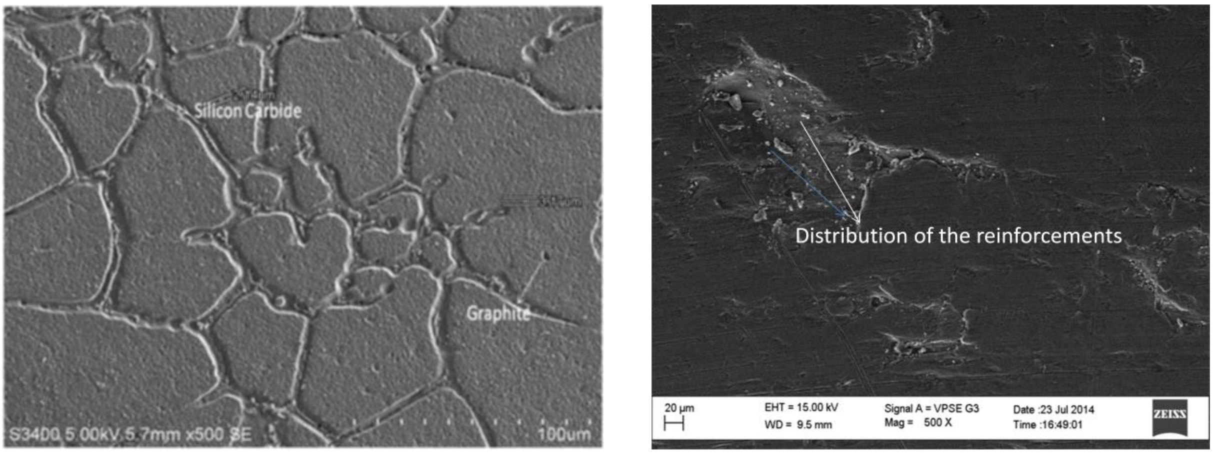

Fig. 2 (a) and (b) Microstructures of Al 6061 with 1.25% Silicon Carbide and 1.25% Graphite

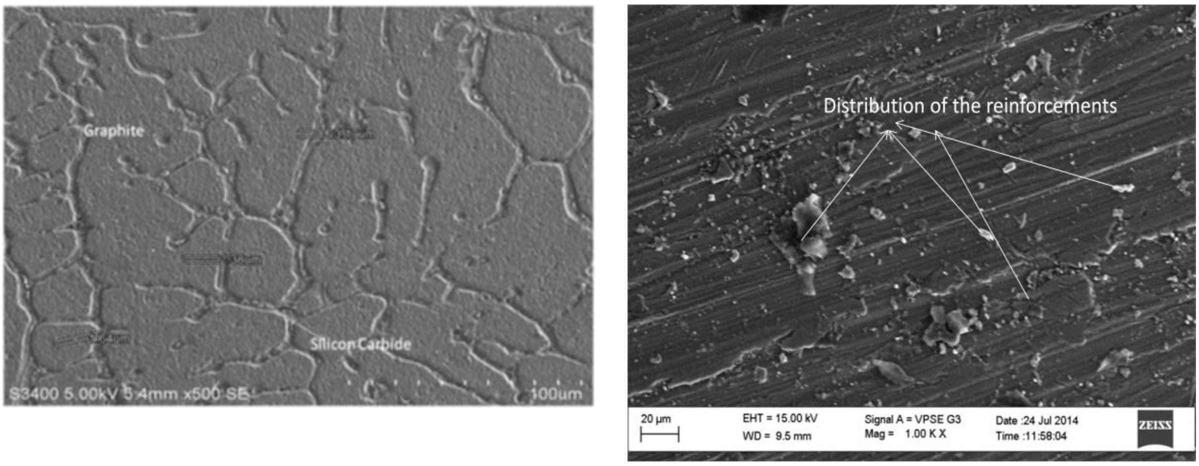

Fig. 3 (a) and (b) Microstructures of Al 6061 with 2.5% Silicon Carbide and 2.5% Graphite

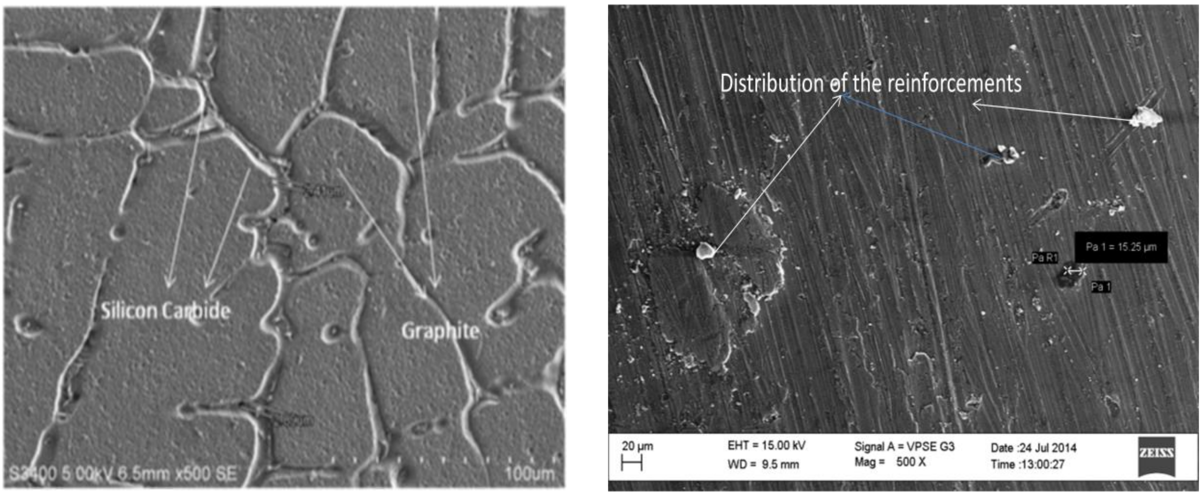

Fig. 4 (a) and (b) Microstructures of Al 6061 with 3.75% Silicon Carbide and 3.75% Graphite

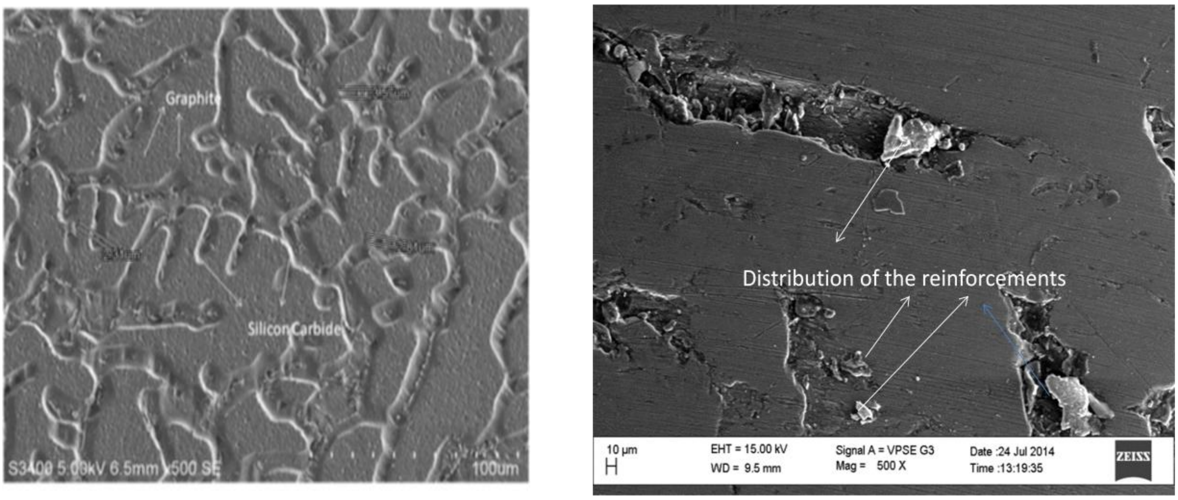

Fig. 5 (a) and (b) Microstructures of Al 6061 with 5% Silicon Carbide and 5% Graphite

Fig. 1 depicts the micrograph of Al 6061 with no reinforcements. It illustrates the morphology of the matrix alloy. This figure depicts the inclusion of the matrix alloy with complete dispersion. Fig. 2, 3, 4 and 5 illustrate the micrographs of Al 6061 with the addition of reinforcements Silicon Carbide and Graphite with varying mass fraction 2.5%, 5%, 7.5% and 10%. Fig. 2, 3, 4 and 5 (a) depicts the micrographs of the samples before testing process, which indicate the interfacial bonding and particle sizes of the reinforcements. Fig. 2, 3, 4 and 5 (b) illustrates the micrographs of the samples after testing process that indicate the distribution of the reinforcements. It can be observed that, with the addition of Silicon Carbide and Graphite with varying weight or mass fraction, the distribution of the reinforcements is uniform with the absence of cracks and detrimental pores. It has been reported in the literature that, by increasing Graphite content in the composite matrix leads to grain refinement for Aluminium and eutectic Silicon and porosity [9]. It has been reported that, due to the increase in volume fraction of the reinforcements, the distribution is more reliable with negligible porosity [15] [16]. From the literature, it has been investigated that, porosity can severely degrade the thermal and mechanical properties of MMCs [17].

Fig. 2, 3, 4 and 5 depicts that, cohesive interfacial bonding between the matrix alloy and reinforcements has been accomplished. It can be noticed that, due to the increase in mass fraction of different percentage compositions of hybrid composites, there has been an improvement in cohesive bonding between matrix and reinforcements. Also, due to the variation in mass fraction of the reinforcements by performing constant stirring, the dispersoid concentration has been uniform with negligible porosity and no massive clustering has been observed. The clustering of particles may occur due to the poor stirring speed, duration of stirring and presence of porosity [18] [19]. The particle sizes and distribution of the reinforcements of hybrid composites with varying mass fraction have been shown in the micrographs. It has been described in the literature that, by increasing the content of Graphite in the composite matrix has been led to the refinement of grain for Aluminium and eutectic Silicon and reduction in porosity [17] [20]. The evaluation of the distribution of reinforcements and porosity has been favourable to accomplish thermal characterization of composites. Also, it has been investigated that, porosity can deteriorate the thermal and mechanical properties of MMCs [9] [16] [18] [20] [21] [22] [23].

Fig. 6 illustrates the element compositions of Al 6061 with equal proportions of Silicon Carbide and Graphite, which has been carried out by using Energy Dispersive X-ray Spectroscope (EDAX). It has been observed that, percentage of Aluminium is maximum and percentage of Silicon and Magnesium are minimum. Carbon and Graphite has been absorbed due to the phenomenon of diffraction.

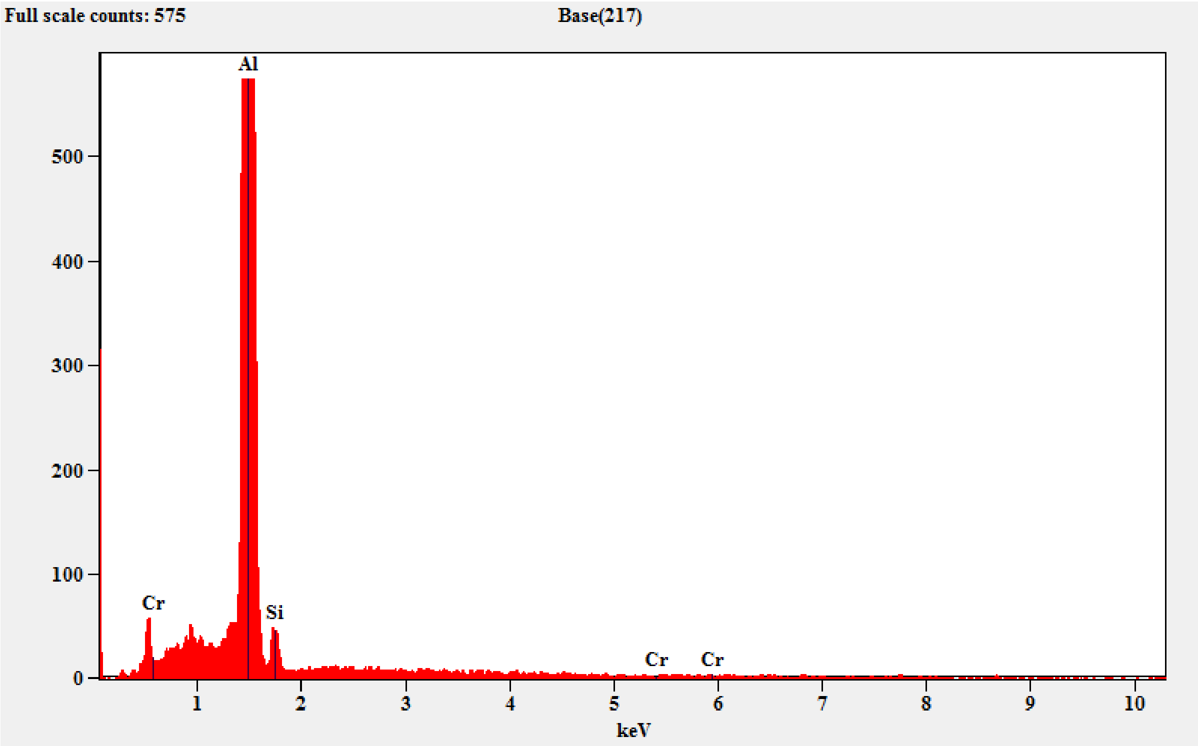

Fig. 6. Elemental Compositions of Al 6061 + 2.5% SiC + 2.5% Gr

Table 3 illustrates the elemental characterization of hybrid metal matrix composites.

Table 3. Elemental Characterization of Hybrid Metal Matrix Composites

Composition of the Elements (Weight %) / Hybrid Composite Specimens	Aluminium	Silicon	Magnesium (Mg) and Chromium (Cr)
Sample 1	99.69	0.25	Mg- 0.06
Sample 2	98.67	1.33	--------
Sample 3	97.62	2.38	-------
Sample 4	96.12	3.7	Cr- 0.18
Sample 5	95.99	4.01	--------

It has been reported in the literature that, the density of Al 6061 is 2.7 g cc^{-1}, Silicon Carbide is 3.21 g cc^{-1} and Graphite is 2 g cc^{-1}. Table 4 refers to the density of hybrid composites for the varying mass fraction (2.5%, 5%, 7.5% and 10%) with precipitation hardening matrix alloy Al 6061.

Table 4. Density of Hybrid Composites with Varying Weight Fraction

Serial Number	Hybrid Composite Specimens	Density /g cc^{-1} (Apparent or Experimental) Water Displacement Method	Density /(g cc^{-1}) (Theoretical) Rule of Mixtures	Percentage Porosity
1.	Al 6061 (Sample 1)	2.7	2.7	0
2.	Al 6061 + 1.25% SiC + 1.25% Gr (Sample 2)	2.694	2.696	0.07%
3.	Al 6061 + 2.5% SiC + 2.5% Gr (Sample 3)	2.685	2.692	0.26%
4.	Al 6061 + 3.75% SiC + 3.75% Gr (Sample 4)	2.676	2.679	0.11%
5.	Al 6061 + 5% SiC + 5% Gr (Sample 5)	2.661	2.668	0.26%

Table 5 depicts the determination of specific heat capacity (C_P) of hybrid composites.

Table 5. Specific Heat Capacity of Hybrid Composites with Varying Weight Fraction at 300°C

Serial Number	Hybrid Composite Specimens	Specific Heat Capacity (J kg^{-1} K^{-1})
1.	Al 6061	980
2.	Al 6061 + 1.25% SiC + 1.25% Gr	968
3.	Al 6061 + 2.5% SiC + 2.5% Gr	947
4.	Al 6061 + 3.75% SiC + 3.75% Gr	924
5.	Al 6061 + 5% SiC + 5% Gr	918

Fig. 7 illustrates the variation of thermal diffusivity (α) with temperature for different percentage compositions of hybrid metal matrix composites. It can be observed that, the thermal diffusivity of hybrid composites decreases for varying weight fraction at all temperatures. It has been depicted that, there has been a gradual 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 reported that, the decrease in thermal diffusivity dominates the temperature dependence of thermal conductivity in the high temperature region [16]. Thermal conductivity was found to decrease as the content of Graphite is enhanced depending on temperature increase. The reinforcements have lower thermal conductivity and hence thermal diffusivity diminishes due to variation in temperature. Also, the specific heat capacity decreases strongly at temperatures below room temperature and dominates the temperature dependence of thermal conductivity.

Fig. 8 depicts the variation of thermal conductivity with temperature for different compositions of hybrid metal matrix composites. The effect of the addition of Graphite to investigate thermal conductivity behaviour in Aluminium-Silicon Carbide-Graphite hybrid metal matrix composites has been discussed. It has been observed that, Al 6061 has higher thermal conductivity of 168 W/m K and Al 6061 + 5% SiC + 5% Gr reveals low thermal conductivity of 163 W/m K at 300°C. It has been noticed that, by the addition of reinforcements Silicon Carbide and Graphite with Al 6061, there has been a gradual reduction in the thermal conductivity of hybrid composites at all temperatures. Generally, the thermal conductivity of materials varies as the temperature changes drastically. It can be observed that, with the increase in temperature, the thermal conductivity of hybrid composites gradually increases. But at higher temperatures, 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 resulted in the considerable diminish in thermal conductivity of hybrid metal matrix composites at low weight fraction.

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 [16]. But from the present experimental investigation, it has been observed that, by the addition of Graphite and Silicon Carbide with Al 6061 there has been no substantial variation in thermal conductivity of hybrid composites. 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 evident 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. The thermal conductivity of Graphite (100 W/m K) is very low compared to Aluminium 6061 (166 W/m K) and Silicon Carbide (150 to 180 W/m K). From the literature, Aluminium-Graphite composites exhibits high thermal conductivity at higher volume fraction and larger particle sizes have been advantageous providing better interfacial thermal resistance and heat transfer [17].

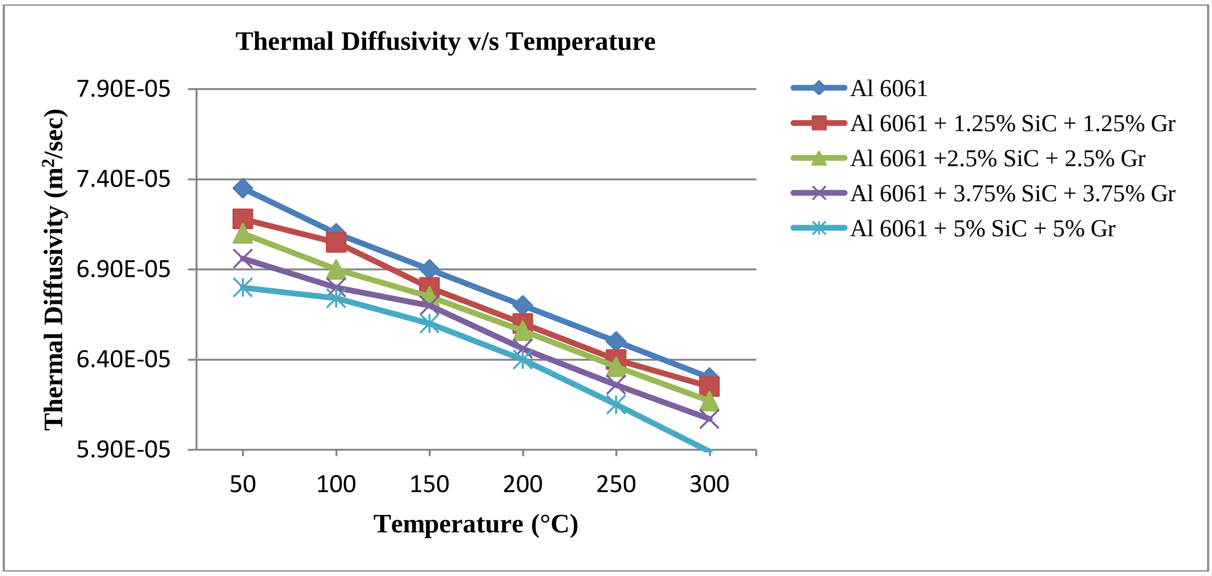

Fig. 7. Variation of Thermal Diffusivity with Temperature for Varying Mass Fraction of MMCs

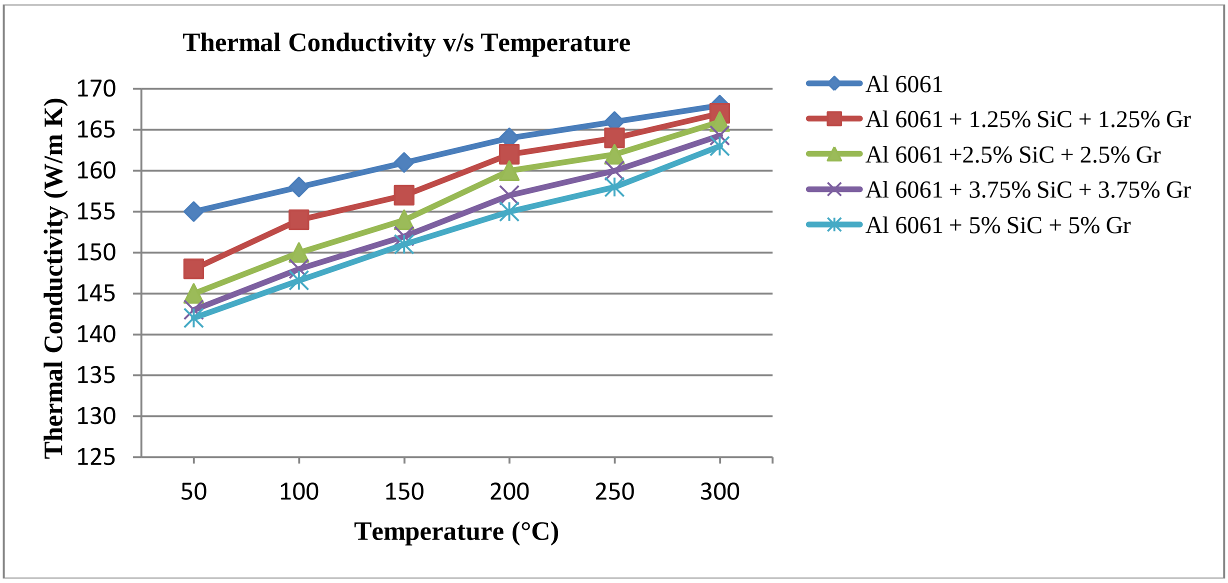

Fig. 8. Variation of Thermal Conductivity with Temperature for different compositions of MMCs

Effective thermal conductivity of composites is generally determined based on the thermal conductivity of constituents, volume fraction, shape, microscale arrangement and interfacial thermal resistance between the constituent phases. The interfacial thermal resistance plays a vital role in understanding the effect of thermal conductivity behavior of composites. The interfacial thermal resistance in a composite refers to the conglomerated effect of the thermal contact resistance and the thermal boundary resistance. The particle sizes of the reinforcements are very important to examine the significant effect of interfacial thermal resistance, which is favorable for the investigation of thermal conductivity behavior of composites. Many experiments have been shown that, the interfacial thermal resistance has a remarkable effect on the effective thermal conductivity of composite materials. If the particle size of the reinforcements is too small, interfacial thermal resistance play a significant role and the magnitude of thermal conductivity of composites will be high [9] [16].

The thermal conductivity of hybrid composites depends on the particle or grain size of Silicon Carbide, as a result, interfacial thermal resistance has a strong influence in comprehending the effect of thermal conductivity behavior. It has been reported that, due to an increasing volume fraction of Silicon Carbide with any Aluminium matrix alloy, the variation in thermal conductivity of composite materials depicts an increasing trend for smaller particle sizes and decreasing trend for larger particle sizes. It has been noticed that, due to the increase in volume fraction of Silicon Carbide the thermal conductivity of Silicon Carbide gradually increases [18]. Based on these investigations, it can be inferred that, the thermal conductivity of hybrid composites significantly diminishes due to the enrichment of Graphite. 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 MMCs. When the MMCs undergo heating process, expansion and deformation processes occurs steadily.

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. This salient attribute has been beneficial to carry out thermal characterization of hybrid composites. From the literature, Aluminium-Silicon Carbide composites are attractive with many outstanding features viz., high thermal conductivity, low thermal expansivity and low density. With any Aluminium matrix alloy, the addition of Silicon Carbide will enhance thermal conductivity and flexural strength [28] [29] [30]. 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 Silicon Carbide can be attributed to the interfacial properties between the Aluminium matrix and the particles of Silicon Carbide. It has been apparent that, decreasing the grain size results in a larger surface area between Aluminium matrix alloy and Silicon Carbide. The interfacial reaction between Aluminium matrix and Silicon Carbide can reduce the thermal conductivity of composites [30].

Fig. 9 depicts the variation of CTE with temperature for different compositions of hybrid MMCs. It has been noticed that, the CTE of hybrid composites with different percentage compositions increases with the increase in temperature. It has been observed that, Al 6061 has high coefficient of thermal expansion or thermal expansivity of 23.6 × 10^{-6}/°C, but Al 6061 + 5% SiC + 5% Gr reveals low coefficient of thermal expansion of 20.86 × 10^{-6}/°C at 300°C. Generally, the thermal expansivity of materials increases as the temperature increases. It has been noticed that, by the addition of reinforcements Silicon Carbide and Graphite with Al 6061, there has been a reduction in the coefficient of thermal expansion at all temperatures. The CTE of Graphite is very low compared to Al 6061 and Silicon Carbide. This is due to the fact that, the coefficients of thermal expansion for Al 6061 are 23 × 10^{-6}/°C, Silicon Carbide is 8 × 10^{-6}/°C and Graphite is 1 × 10^{-6}/°C.

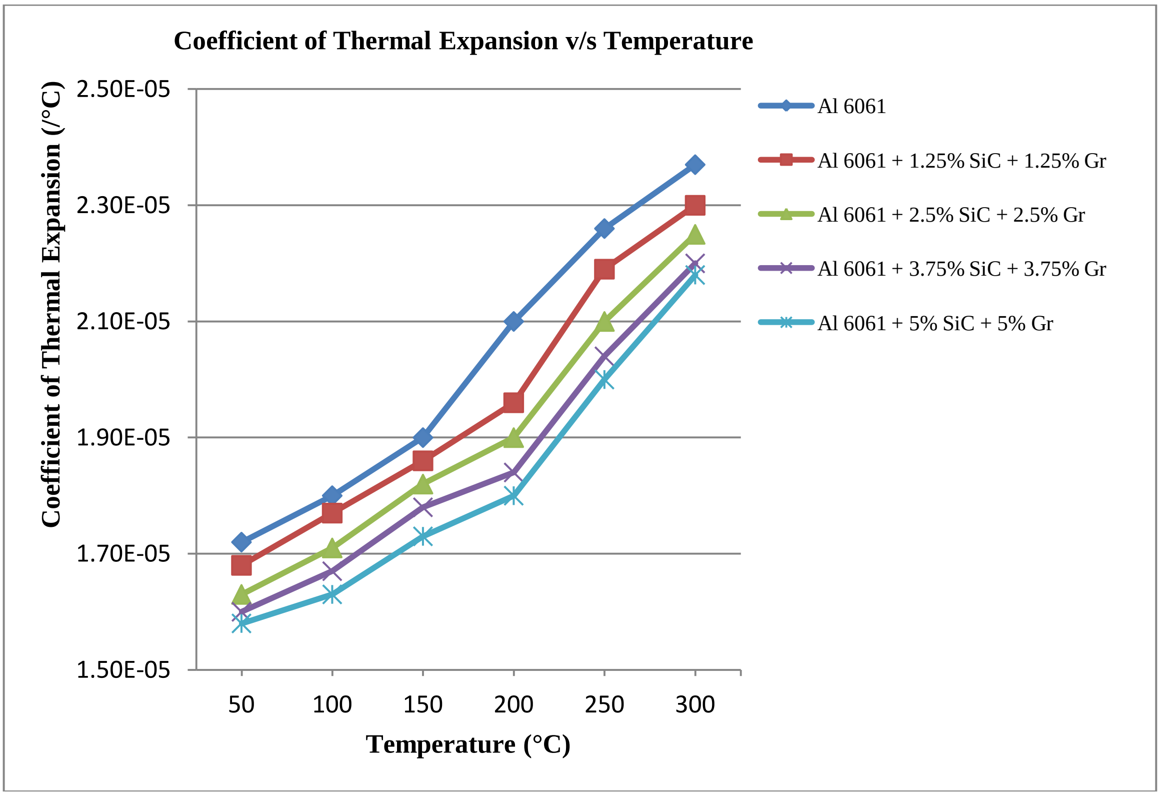

Fig. 9. Variation of CTE with Temperature of Hybrid Composites

7. MATHEMATICAL VALIDATION OF THERMAL CONDUCTIVITY MODELS

Theoretical prediction of effective thermal conductivity (K_e) for multi-phase composite materials is very constructive for analysis and optimization of the material performance and for new material designs. Several attempts have been made to develop expressions for effective thermal conductivity of two-phase materials by various researchers viz., Maxwell, Lewis, Neilsen, Cunningham, Peddicord, Hadley, Rayleigh, Russell, Bruggemann, Meridith, Tobias, Hamilton, Crosser, Cheng, Vechon and Torquato [24] [25] [26] [27] [28]. The different mathematical or thermo-elastic models have been used to validate the theoretical results and can be compared with the experimental results effectively [20] [21] [22] [23] [29] [31]. Also, these empirical models will greatly benefit to understand the variation of thermal conductivity depending on the variation in percentage volume fraction of the composites. Generally, a graphical representation between thermal conductivity versus weight or volume fraction of composites can be depicted to indicate the variation in thermal conductivity. The models that have been used to validate thermal conductivity theoretically depend on the thermal conductivity and weight fraction of matrix and reinforcements.

The important models that have been validated based on the thermal conductivity of composites are:

1. Series model: $K_e = \frac{K_m K_f}{\emptyset K_m + (1-\emptyset) K_f}$ -----------(3)

2. Parallel model: $K_e = \emptyset K_f + (1-\emptyset) K_m$ -----------(4)

3. Geometric model: $K_e = {K_f}^{\emptyset} + {K_m}^{(1-\emptyset)}$ -----------(5)

Historically, more sophisticated heat transfer models can be classified as either flux law models, where the temperature field is solved for an assumed geometry, or Ohm's law models based on an electrical series resistance analogy. The earliest flux law was proposed by Maxwell, who considered cube of a suspension containing a single particle.

4. Maxwell's model: $K_e = K_m \frac{K_f + 2K_m + 2\emptyset (K_f - K_m)}{K_f + 2K_m - \emptyset (K_f - K_m)}$ ---------(6)

Lewis and Neilsen, by using an elastic moduli model, modified the Halpin-Tsai analogy equations to include the shape of the particles and orientation of packing for a two phase system.

5. Lewis-Neilsen equation: $K_e = K_m \left[\frac{1 + A B \emptyset}{1 - B \psi \emptyset}\right]$ ---------(7)

Where, $A = K_E - 1$, $\beta = \frac{K_f/K_m - 1}{K_f/K_m + 1}$ $\psi = 1 + \left(\frac{(1-\emptyset_m)}{{\emptyset_m}^2}\right)\emptyset$

Where, K is the thermal conductivity, K_f is the thermal conductivity of the reinforcements, K_m is the thermal conductivity of the matrix and $\emptyset$ is the volume fraction.

Numerical models have been developed over the last century to predict the thermal conductivity of two-phase composites for which dispersion of a second phase in a continuous medium of the first phase is assumed. The models have been applied to solid-gas or solid-solid composite systems [29] [30]. Many experimental studies have been carried out to investigate the thermal conductivity of MMCs reinforced with isolated particles. The thermo-elastic models can be used to predict the dependence of thermal conductivity of particle reinforced metals depending on the reinforcement content. These models do not consider the case for which the reinforcing particles are interconnected or the presence/effects of voids generated during the processing of the composites. The empirical models that have been considered for the validation of thermal conductivity are ROM, Series, Maxwell and Geometric models. Fig. 10 depicts the comparison of experimental values of thermal conductivity with the thermo-elastic models.

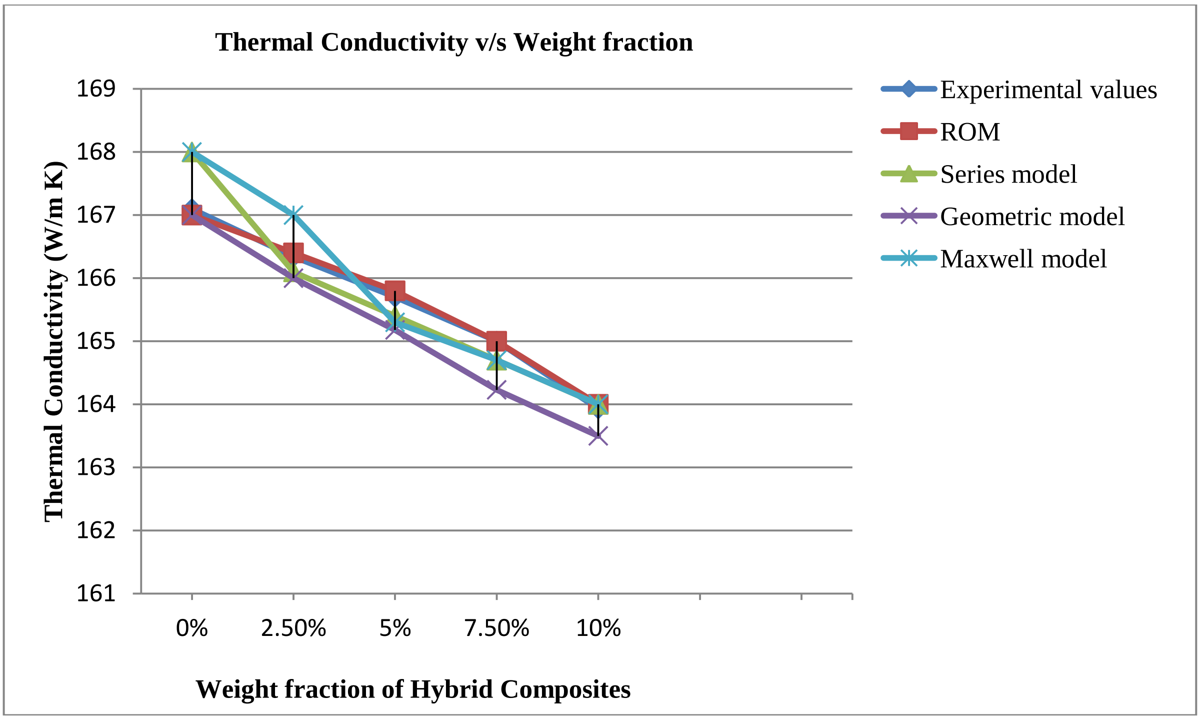

Fig. 10. Validation of the Thermo-elastic Models with Experimental Results

The experimental values of thermal conductivity with varying weight fraction of hybrid composites closely matches with Rule of Mixtures (ROM), Series and Maxwell models, whereas the values of thermal conductivity slightly deviate from Geometric model. It can be inferred that, experimental data are in good agreement with ROM, Series and Maxwell models. It has been observed from the experimental investigation that, the thermal conductivity of hybrid composites with varying weight fraction has been gradually decreasing. Volume fraction of matrix and reinforcements of hybrid composites commensurate ROM, Series and Maxwell models. But in Geometric model, thermal conductivity is marginally deviating from experimental results due to the small variation in volume fraction of matrix and reinforcements. Table 6 illustrates the validation of thermo-elastic models based on the thermal conductivity behaviour of hybrid composites.

Table 6. Validation of Thermo-Elastic Models based on Thermal Conductivity

Hybrid Composite Specimens	Experimental values (W/m K)	Series model (W/m K)	ROM (W/m K)	Maxwell model (W/m K)	Geometric model (W/m K)
Sample 1	167.58	168	167.5	168	167
Sample 2	166	166.1	166.4	167	166
Sample 3	164.35	165.4	165.8	165.3	165.1
Sample 4	163.87	164.7	165	164.7	164.23
Sample 5	163	164	164	164	163.5

7. CONCLUSIONS

The following conclusions have been drawn based on the results obtained:

1. The micrographs by using Scanning Electron Microscope depicted that, cohesive interfacial bonding has been accomplished between the matrix alloy and reinforcements. Also, due to the variation in weight fraction of the reinforcements by performing constant stirring, the dispersoid concentration is uniform with negligible porosity and no massive clustering has been observed. The dispersoid concentration of reinforcements in Aluminium-Silicon Carbide-Graphite hybrid metal matrix composites has been beneficial for thermal characterization of composites.
2. Al 6061 has high thermal conductivity, but Al 6061 + 5% SiC + 5% Gr hybrid composites reveal low thermal conductivity. By the addition of reinforcements Silicon Carbide and Graphite with Al 6061, there has been a decline in thermal conductivity at higher temperatures for different percentage compositions of hybrid metal matrix composites. The thermal conductivity decreases over the range of temperatures with variation in density, volume fraction of

Silicon Carbide, internal structure of the composites, dispersoid concentration in the reinforcements and porosity of hybrid composites. The addition of Silicon Carbide with Al 6061 increases the thermal conductivity, but thermal conductivity of hybrid composites decreases due to the enhancement of Graphite. The thermal diffusivity of hybrid composites decreases with increase in temperature as the reinforcements Silicon Carbide and Graphite have lower thermal conductivity. As the thermal conductivity and density of hybrid composites drops, thermal diffusivity gradually decreases.

3. The experimental values of thermal conductivity with varying weight fraction of hybrid composites closely matches with ROM, Series, and Maxwell models. It can be observed that, experimental data are in good agreement with ROM, Series and Maxwell models, but has slightly deviated from Geometric mean model. The thermal conductivity of hybrid composites with varying weight fraction are gradually decreasing. Volume fraction of matrix and reinforcements of hybrid composites commensurate ROM, Series and Maxwell models. But in Geometric mean model, thermal conductivity is marginally deviating from experimental results due to the variation in volume fraction of matrix and reinforcements. With the addition of reinforcements of low mass fraction, thermal conductivity of hybrid has been observed to be low.

SCOPE FOR FUTURE WORK

In continuation with research work, the following areas have been identified which have potential for further research.

- Experimental investigation on thermal characterization and analysis can be carried out on Aluminium-Silicon Carbide-Graphite hybrid metal matrix composites at high weight fraction or volume fraction. Computational or numerical investigation on Aluminium-Silicon Carbide-Graphite can to be accomplished comprehensively.

- The detailed thermal and mechanical characterization for different combinations of composites viz., Aluminium-Silicon Carbide, Aluminium-Graphite and Aluminium-Silicon Carbide-Graphite hybrid composites at both low and high volume fraction can be carried out independently. A comparative study can be achieved for different combinations of hybrid composites. This can be accomplished by using Statistical Design of Experiments approach. Computational or numerical investigation is also recommended.

- Selecting different Aluminium matrix alloys and by using reinforcements viz., Boron Carbide, Zirconium, Titanium Dioxide and Titanium Boride, thermal properties can be characterized and analyzed.

- Other than Aluminium matrix composites, Magnesium and Copper based composites can also be considered for the thermal characterization particularly at high temperature condition.

- Morphological examination can also be carried out by using Atomic Force Microscope and X-ray Diffractometer. Thermal characterization of hybrid composites can be accomplished by using powder metallurgy by considering smaller mesh or grit sizes to enhance thermal characteristics.

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