EXPERIMENTAL AND COMPUTATIONAL APPROACHES TO INVESTIGATE THE EFFECT OF GRAPHITE ON THERMAL AND MECHANICAL BEHAVIOUR IN ALUMINIUM-SILICON CARBIDE-GRAPHITE COMPOSITES

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Metal matrix composites (MMCs) have been regarded as one of the most principal classifications in composite materials. The thermal and mechanical characterizations of hybrid metal matrix composites have been increasingly important in a wide range of applications. The thermal conductivity and coefficient of thermal expansion or thermal expansivity are regarded as the most important properties of metal matrix composites. Since nearly all metal matrix composites are used in various temperature ranges, measurement of coefficient of thermal expansion (CTE) and thermal conductivity as a function of temperature is necessary in order to know the behaviour of the material. In this research paper, the evaluation of thermal conductivity and thermal expansivity have been accomplished for Aluminium 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. Experimentally, thermal conductivity of hybrid composites has been determined by using laser flash apparatus and thermal expansivity of hybrid composites by using dilatometer. The thermal conductivity and thermal expansivity behaviour of hybrid composites with different percentage compositions of reinforcements have been investigated. 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. The thermo-elastic models based on thermal expansivity and thermal conductivity have been validated. Using the experimental values viz., modulus of elasticity, Poisson ratio and thermal expansivity, computational investigation has been carried out to evaluate the thermal properties viz., thermal displacement, thermal strain and thermal stress based on thermal expansion behaviour of hybrid composites. Similarly, by using the experimental values viz., density, thermal conductivity, specific heat capacity and enthalpy at varying temperature ranges, computational investigation has been carried out to evaluate thermal gradient and thermal flux based on thermal conductivity behaviour of composites.

Keywords: *Thermal characterization; thermal expansivity; thermal conductivity; reinforcements; computational; thermal strain; thermal stress; specific heat capacity and enthalpy.*

1. INTRODUCTION

The importance of composite materials as engineering materials has been reflected by the fact that out of over 1600 engineering materials accessible in the market today more than 200 are composites. Composite materials which are being extensively used in day-to-day applications play a staggering role in the manufacturing sector for the fabrication of highly sophisticated equipment and components. Particularly in automotive industry, Metal matrix composites have been used commercially in fibre reinforced pistons and Aluminium crank cases with strengthened cylinder surfaces as well as particle-strengthened brake disk. The composite materials usually divulge superior characteristics when compared to the characteristics of matrix material alone [Introduction to composites, 2002; Cory A. Smith, 2004]. Metal matrix composites are the pioneering materials that possess unrestrained 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 [Parashuram Sonawane and Rajeshkumar Bhandage, 2013]. 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.

Aluminium alloy is generally used in automotive sector as it encompasses with excellent mechanical properties, better wear and corrosion resistance, low melting point compared to other materials. The most prominent property of this material is light weight and low production cost, which will attract the researchers from all perspectives [Introduction to composites, 2002; Cory A. Smith, 2004]. Among modern composite materials, particle reinforced Aluminium matrix composites (PRAMCs) are finding increased application due to their resourceful mechanical properties and good wear resistance. Aluminium matrix composites (AMCs) 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 [Introduction to composites, 2002; Ashish Srivastava et al., 2014]. 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-Silicon Carbide composites are attractive with many exceptional features, including higher thermal conductivity, low thermal expansivity and low density. With any Aluminium matrix alloy, the addition of Silicon Carbide will augment thermal conductivity and flexural strength [Ashish Srivastava et al., 2014]. 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 viz., cylinder liners, pistons and various types of brakes, air diffusers and bushings [Ashish Srivastava et al., 2014; Achutha Kini et al., 2013; Ted Guo et al**.**, 2000**]**. 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

The thermal characterization and analysis of composite materials have been a demanding and challenging task for the researchers. Aluminium matrix composites are comparatively new materials and data pertaining to thermal properties have to be established. This aspect has generated enormous interest in research pertaining to the area of composite materials. The characterization and analysis of thermal properties viz., thermal conductivity, thermal diffusivity, thermal shock resistance, thermal expansivity and specific heat capacity are advantageous for aerospace and automotive applications, electronic packaging and thermal management equipment. Hence, emphasis needs to be given to carry out research on thermal characterization and analysis. This research work intends to enhance the comprehension of the thermal aspects of Aluminium matrix composites.

Though the research work pertaining to mechanical, tribological and fatigue behaviour of composites is successfully accomplished, due emphasis needs to be given to the work related to thermal analysis of composite materials. The assessment of thermal properties of composites viz., thermal conductivity and thermal expansivity 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 expansion, moderate thermal conductivity, specific heat capacity and high electrical conductivity of the composites will enhance the efficiency in all perspectives. The technique recommended for the experimental investigation of thermal diffusivity and thermal conductivity of hybrid metal matrix composites is Laser Flash Apparatus and that of thermal expansivity by using Dilatometer. Computational investigation of MMCs has been accomplished using Finite Element Modelling by using ANSYS.

Metal matrix composites are functional for industrial applications, such as aerospace and automotive streams, due to its enhanced thermal and physical properties. Finite Element Method (FEM) supplies an institutional analysis taking advantages of graphical and computational post-processes. It helps for the systematic analysis of material behaviours and properties, including the investigation of local stress and strain distribution. Nevertheless, there are reports of FEM study on the thermal properties of Al/SiC system compared to that of the experimental research. Finite Element Analysis (FEA) has been used extensively to simulate the thermal and mechanical behaviour of metal matrix composites. The results of various finite element solutions for different types of composites can be compared with the results of various analytical models and with the available experimental investigation. Computational simulations on the thermal analysis of metal matrix composites composed of Aluminium and Silicon Carbide (SiC) has been performed in extended areas of SiC volume fraction. The development of numerical tools for the computational mechanical testing of materials and carrying out numerical experiments will lead to the development of recommendations for the improvement of mechanical structures. The design of materials on the basis of numerical testing of microstructures can be realised if big series of numerical experiments for different materials and microstructures can be carried out quickly, systematically and automatically [Grujicic et al., 2011; Leon Mishnaevsky, 2006; Kush Kumar Dewangan et al., 2010; Eusun Yu et al., 2008; Saraev and Schmauder, 2003]. Few papers concerning thermal conductivity and thermal expansivity behaviour of composite materials have been discussed.

Davis and Artz [2009] in their paper have elucidated that the thermal conductivity of metal matrix composites has been regarded to be the most prospective materials applicable for electronic packaging. It has been computed using an effective medium theory and techniques based on finite element analysis. It has been inspected that the particles of Silicon Carbide in Aluminium should have radii in excess of 10 μm to attain the complete benefit of the ceramic phase based on the thermal conductivity behaviour. The assessment of the effective medium theory has been resulted in the computations of finite element for axisymmetric unit cell models and computational simulation has carried out to confirm the authenticity of the theory.

Cem Okumus et al. [2012] have explored the behaviour of thermal expansion and thermal conductivity of Aluminium-Silicon-Silicon Carbide-Graphite hybrid metal matrix composites. It has been emphasized that Aluminium-Silicon based hybrid composites reinforced with the particles of Silicon Carbide and Graphite has been prepared by the techniques namely liquid phase particle mixing and squeeze casting. The behaviour of thermal expansion and thermal conductivity of hybrid composites with the content of Graphite and the different sizes of particles of Silicon Carbide has been investigated. Results have clearly indicated that by increasing the content of Graphite, improves the dimensional stability, and it has been observed that there has been no substantial variation in the behaviour of thermal expansion of the particle sizes 45 µm and 53 µm Silicon Carbide reinforced composites.

Molina and Rheme [2008] have investigated the behaviour of thermal conductivity of Aluminium-Silicon Carbide composites possessing high volume fraction of the particles of Silicon Carbide. For composites based on powders with the distribution of monomodal size, the thermal conductivity increases progressively depending on the size of the particle. It has been shown that the exiting data has accounted for the differential effective medium (DEM) scheme considering a finite interfacial thermal resistance.

Parker et al. [2000] have enlightened the method of laser flash for the evaluation of specific thermal capacity, diffusivity and thermal conductivity. A highly concentrated short-duration light pulse has been absorbed in the front surface of a thermally insulated specimen coated using camphor black, and the ensuing history of temperature of the rear surface has been quantified by a high resolution temperature sensing instrument and has been recorded using an oscilloscope and camera. The thermal diffusivity has been determined using temperature versus time curve at the rear surface, the thermal capacity by the maximum temperature designated by a temperature sensing instrument, and the thermal conductivity has been computed by considering the product of the thermal capacity, thermal diffusivity and the magnitude of density.

Na Chen and Zhang [2009] have carried out a detailed investigation on the behaviour of thermal conductivity of metal matrix composites for the application of thermal management. The recent advances in the process of manufacturing, thermal properties and technology of brazing of Silicon Carbide, Carbon and Diamond metal composites has been presented. Major factors controlling the thermo-physical properties have been discussed in detail.

Weidenfeller and Hofer [2004] have summarized the prominent thermal parameters namely thermal conductivity, diffusivity and thermal capacity of particle filled polypropylene. It has been investigated that, the samples of composites of polypropylene (PP) with different fillers of varying volume fractions has been prepared by the technique of injection moulding. This will help to comprehend thoroughly the evolution of the properties which is a function of filler content. Some of the standard filler materials have been used for the evaluation of thermal properties. Thermal diffusivities, specific heat capacities and densities of the composite samples have been measured, and thermal conductivities have been determined.

Grujicic et al. [2011] have accomplished the computational investigation of structural shocks in Al/SiC particulate metal matrix composites. In this paper, the propagation of planar, longitudinal, steady structured shock waves within MMCs has been studied computationally. The purpose of this paper has been helpful to advance the use of computational engineering analyses and simulations in the areas of design and application of the MMCs protective structures. This approach has been applicable to a prototypical MMCs consisting of Aluminium matrix and SiC particulates. The computational results have been compared with the experimental counterparts available in the literature in order to validate the computational procedure employed.

Leon Mishnaevsky [2006] has carried out the microstructural effects on damage in composites based on computational analysis. In this paper, microstructural effects on the damage resistance of composite materials have been studied numerically using methods of computational mesomechanics of materials and virtual experiments.

Kush Kumar Dewangan et al. [2010] have described about the numerical computation of effective thermal conductivity of polymer composite filled with rice husk particle. This paper emphasizes a simple 3-dimensional finite element model which has been used to predict the thermal conductivity of polyester composite filled with micro-sized rice husk particle. The simulation has been compared with measured thermal conductivity value obtained from prominent correlations namely Maxwell and Russel models. It has been proved that the effective thermal conductivity of polyester composite decreases as filler concentration increases.

Hai M Duong et al. [2010] have summarized about the computational modelling of thermal conductivity of single walled nanotube polymer composites. In their research, a computational model has been developed to study the thermal conductivity of single walled carbon nanotube. A random walk simulation has been used to model the effect of interfacial resistance on heat flow in different orientations.

Eusun Yu et al. [2008] have carried out investigation on thermal properties of Al/SiC metal matrix composite based on FEM analysis. It has been anticipated to explore the dependencies of thermal and mechanical properties by changing the values of volume fraction. In this paper, the stress analysis about thermally expanded MMC has been emphasized. It has been proved that, as the volume fraction of SiC increases, the stress turned to be compressive.

Saraev and Schmauder [2003] have emphasized the finite element modelling of Al/SiC metal matrix composites with particles aligned in stripes based on two and three dimensional comparison. Three-dimensional finite element calculations comparing to axisymmetric calculations have been performed to predict quantitatively the tensile behaviour of composites reinforced with ceramic particles in stripes. The analyses are based on a unit cell model, which assumes the periodic arrangement of reinforcements. The results have been presented in such a manner that varying the distance between the stripes when particle volume fraction is kept constant significantly influences the overall mechanical behaviour of composites.

Nam et al. [2007] have explored the modelling and numerical computation of thermal expansion of Aluminium Matrix Composite with densely packed SiC particles. In this paper, the physical CTE of Aluminium matrix composite reinforced with 70% volume fraction of SiC particles has been analytically computed to explain the abnormalities in the thermal expansion behaviour obtained experimentally. The numerical modelling has been carried out from 20°C to 500°C using finite element analysis based on two-dimensional unit cell models. A comparison of physical CTE with the experimental results showed better and satisfactory results.

It is evident from the literature review that, Aluminium matrix composites have been better emphasis. However, investigations concerning the thermal characterization and analysis of composite materials of AMCs are inadequate. The summary of literature review can be structured as follows. Many experimental investigations have been carried out pertaining to thermal characterization and analysis of Aluminium-Silicon Carbide composites, but limited work has been accomplished concerning Aluminium-Silicon Carbide-Graphite hybrid MMCs.

The literature review has indicated clearly the potential prospects of further investigations on thermal characterization and analysis of Aluminium matrix composites. If these materials are to be used for many prominent engineering applications, the thermal aspects of AMCs need to be given more importance. Hence it becomes important that the evaluation of thermal 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 hybrid composites based on mechanical and tribological properties has been accomplished substantially, but deficient research has been carried out on Aluminium-Silicon Carbide-Graphite hybrid composites concerning thermal characterization and analysis. It has been reported in the literature that, the experimental study on Aluminium and Silicon Carbide has been carried out exhaustively based on low and high weight fraction [Cem Okumus et al., 2012]. But, limited work has been carried out on thermal characterization and analysis of Al 6061 with Silicon Carbide (SiC) and Graphite (Gr) based on low and high weight fraction of hybrid metal matrix composites. Hence, Graphite (Gr) has been reinforced concurrently with Silicon Carbide considering low weight fraction of hybrid composites. Computational thermal analysis of hybrid composites has been given greater emphasis, as work related to computational investigation of composites has been extremely meagre.

2. FABRICATION OF COMPOSITES

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 particle size around 25 microns and particulates of Graphite of particle size 70 to 80 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. The evaluation of thermal properties viz., thermal conductivity, thermal diffusivity, specific heat capacity and thermal expansivity has been accomplished. Different sample sizes have been considered as per American Society for Testing of Materials (ASTM) standard. 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.

The composite specimens 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^{0}C. 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^{0}C-800^{0}C. 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% mass of solid dry hexachloro-ethane tablets or degassing tablets have been used to degas the molten metal at 780^{0}C. Stirring of the molten metal maintained at around 750^{0}C, has been accomplished by 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 [Ashish Srivastava et al., 2014; Achutha Kini et al., 2013; Ted Guo et al**.,** 2000**]**. Then the casting has been separated from the mould which is subsequently cleaned.

The required test specimens have been 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. 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, specific heat capacity and thermal expansivity with different sample sizes.

3. METALLOGRAPHIC SPECIMEN PREPARATION

Metallography is an investigative study of the microstructure of the materials. Metallographic analysis is considered to be a very important technique. 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, polishing, buffing and etching. To investigate the prominent microstructural features in hybrid metal matrix composites, it is essential to accomplish polishing and etching [Ashish Srivastava et al., 2014; Achutha Kini et al., 2013; Ted Guo et al**.,** 2000**]**.

The samples with varying weight 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 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 Silicon Carbide and Graphite.

4. MICROSTRUCTURAL ANALYSIS OF 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. Hence, microstructural characterization has been carried out to accomplish thermal characterization and analysis with varying weight fraction of hybrid composites.

Miicrostructural characterization with varying weight fraction of hybrid metal matrix composites has been accomplished by using Scanning Electron Microscope (SEM) and Optical Microscope. Optical Microscope has been used to investigate the formation of grain boundaries and interdendritic segregation. The microstructures with magnification 200X, 500X and 1000X have been used to characterize the behavior of hybrid composites. 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 hybrid0020composites.

One of the vital challenges in functional and engineering materials is the study of morphology controlled process based on the growth of crystal. Microstructural analysis of composite materials have been advantageous for the examination of cohesive interfacial bonding, porosity, particle size, grain size and boundaries, interdendritic segregation and dispersoid concentration of the reinforcements. 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. Microstructural analysis of hybrid metal matrix composites has been carried out by using a Scanning Electron Microscope (S-3400N Hitachi). The microstructure of hybrid composites has been carried out for Al 6061 and reinforcements Silicon Carbide and Graphite by varying the weight 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 characterization and analysis of composites [Cem Okumus et al., 2012]. Fig. 1, 2, 3, 4 and 5 depict the micrographs of the different compositions of hybrid MMCs.

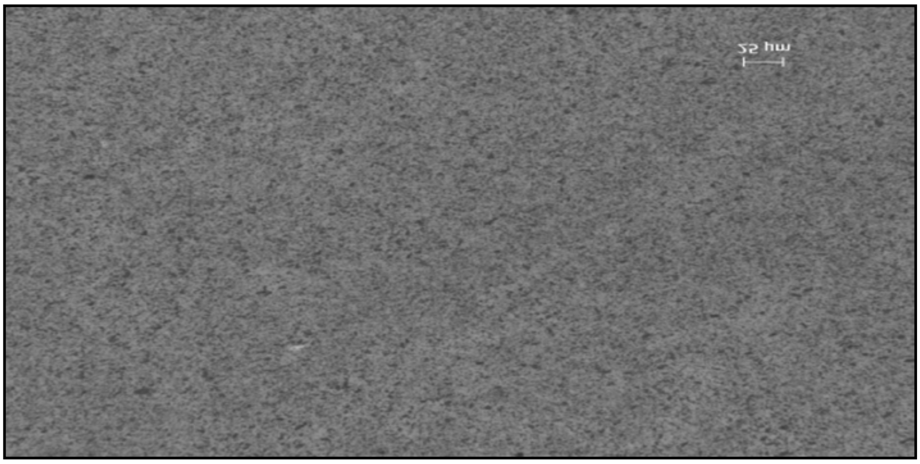


Fig. 1. Microstructure of Al 6061

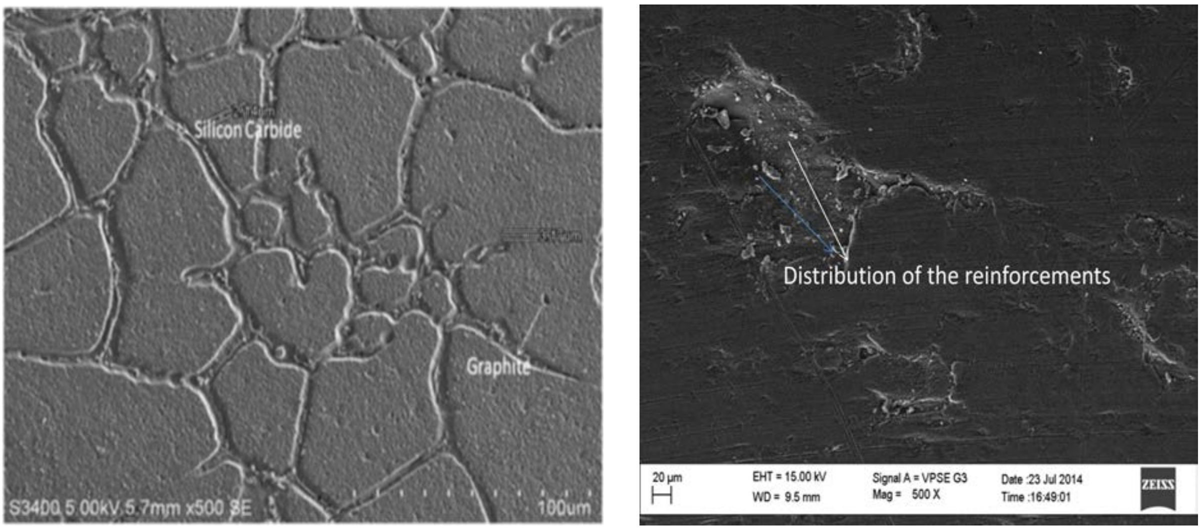


Fig. 2 (a) and (b) Microstructures of Al 6061 with 1.25% Silicon Carbide and 1.25% Graphite

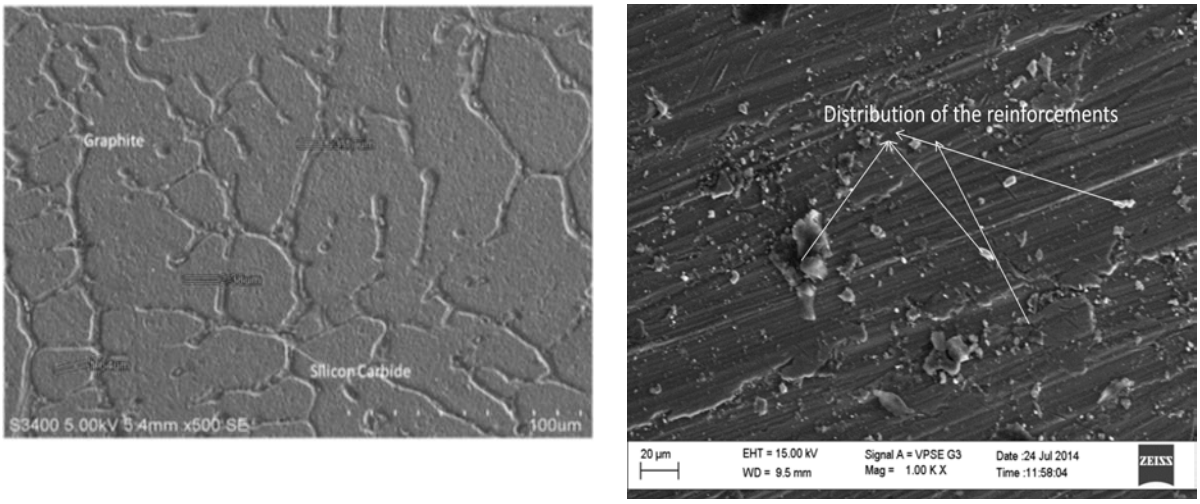


Fig. 3 (a) and (b) Microstructures of Al 6061 with 2.5% Silicon Carbide and 2.5% Graphite

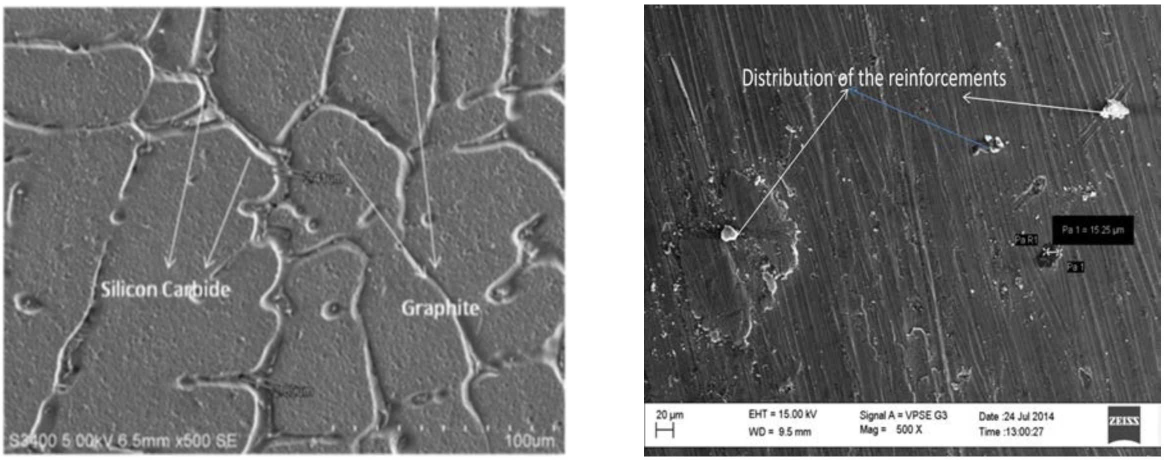
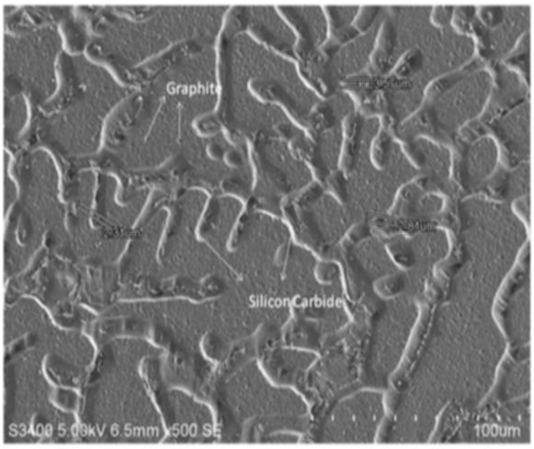


Fig. 4 (a) and (b) Microstructures of Al 6061 with 3.75% Silicon Carbide and 3.75% Graphite



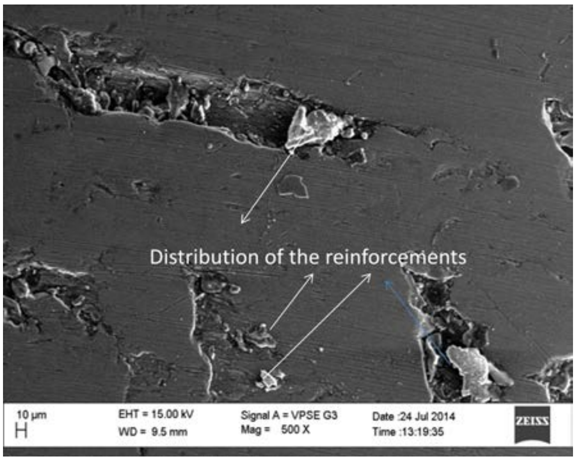


Fig. 5 (a) and (b) Microstructures of Al 6061 with 5% Silicon Carbide and 5% Graphite

Fig. 1 depicts Al 6061 with no reinforcements. Fig. 2, 3, 4 and 5 (a) and (b) depict the micrographs of Al 6061 with the addition of reinforcements Silicon Carbide and Graphite with varying weight fraction 2.5%, 5%, 7.5% and 10%. It can be observed that, with the addition of Silicon Carbide and Graphite with varying 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 [Cem Okumus et al., 2012]. It has been stated that, due to the increase in volume fraction of the reinforcements, the distribution is more reliable with negligible porosity [Naveen and Ramesh, 2014]. From the literature, it has been investigated that, porosity can degrade the thermal and mechanical properties of MMCs [Naveen and Ramesh, 2014].

The porosity has been investigated both experimentally and theoretically. Using water displacement method based on Archimedes principle, experimental values of the density of hybrid composites have been evaluated and the theoretical values of the density have been computed by using rule of mixtures. Water displacement method allows the determination of the density in air compared to its displacement in water or other liquid of known density. Rule of mixtures has been treated as the most fundamental concept used in the principles of composite materials, which is beneficial for the theoretical evaluation of many mechanical and thermal parameters. Rule of mixtures can be applied to evaluate the magnitude of densities of hybrid MMCs depending on the theoretical values of densities and volume fraction of matrix and reinforcements [Anil Kumar et al., 2011; Ashish Srivastava et al., 2014]. Porosity in composite materials can be evaluated by noticing the difference between the theoretical and experimental values of the densities.

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 weight 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 weight fraction of the reinforcements by performing constant stirring, the dispersoid concentration has been uniform with negligible porosity and no massive clustering has been observed. It has been reported that, the clustering of particles may occur due to the poor stirring speed, duration of stirring and presence of porosity [Anil Kumar et al., 2011; Ashish Srivastava et al., 2014]. The particle sizes of hybrid composites with varying weight 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 [Naveen and Ramesh, 2014]. It has been accounted that, the evaluation of the distribution of reinforcements and porosity has been favourable to carry out thermal analysis and characterization of composites. Also, it has been investigated that, porosity can deteriorate the thermal and mechanical properties of MMCs [Zhu Xiao-min et al., 2012; Belete Sirahbizu Yigezu et al., 2013; Lee and Hong, 2003; Antonyraj Arockiaswamy et al., 2013].

It has been reported in the literature that, the agglomeration of the particles of Silicon carbide and Graphite with Aluminium results in neutrally buoyant suspension based on conventional casting and ablation. If the melt is insufficiently mixed, the reinforcements can migrate resulting in large volume percentage of reinforcements in the solidified microstructure. From the literature, it has been emphasized that, when Graphite mixes with Aluminium matrix alloy distribution will be more uniform with the particles of Silicon Carbide. Distributive mixing employs conventional mechanical stirring to pre-mix the Aluminium alloy with the particles of Graphite. During the distributive mixing, the stirrer rotation generates a vortex through which the particles of Graphite have been drawn from melt. The magnitude of force provided stirring the melt by using a mechanical stirrer helps to surpass the barriers of surface energy due to poor wettability of Graphite by Aluminium alloy. When the particles of Graphite have been transferred into the liquid, the distribution is strongly affected by flow transitions. Graphite is a non-load bearing constituent. The particles of Graphite with matrix interface helps in improving fracture resistance and thus establishes cohesive interfacial bonding. The uniform distributions and the nature of the interfacial bonding between the particles of Graphite and matrix alloy have an essential behaviour on the mechanical properties of a composite material,

To investigate grain boundaries and interdendritic segregation, 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 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 with 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.

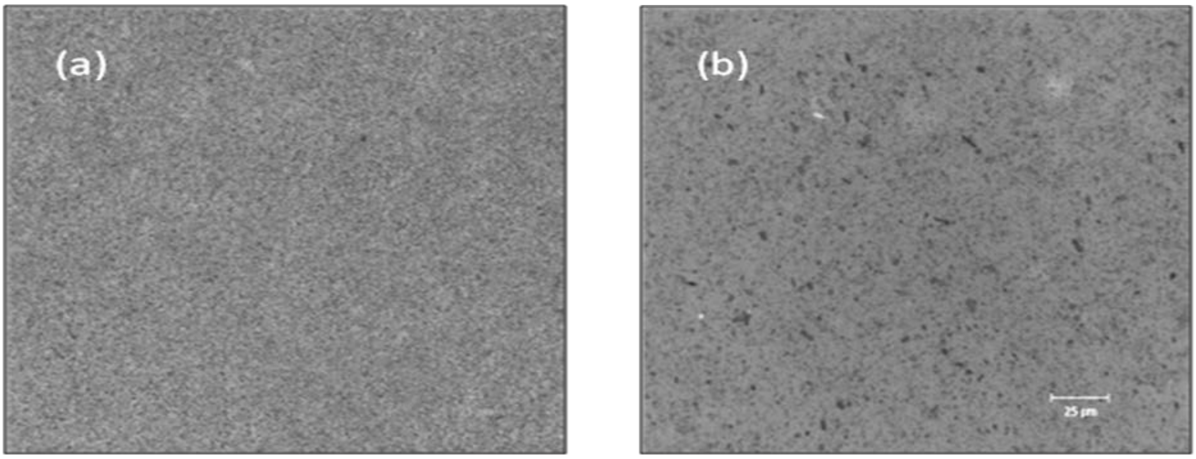


Fig. 6 (a) and (b) Microstructures of Matrix Alloy Al 6061 (Magnification 200X and 500X)

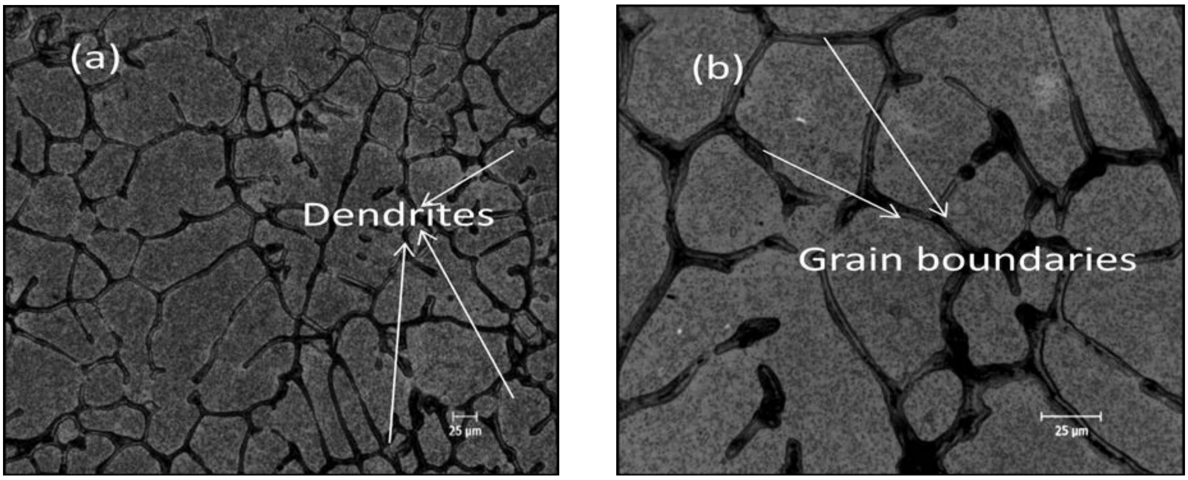


Fig. 7 (a) and (b) Microstructures of Al 6061 Reinforced by Silicon Carbide and Graphite of 2.5% Weight Fraction (Magnification 200X and 500X)

International Journal of Scientific Engineering and Applied Science (IJSEAS) – Volume-2, Issue-1, January 2016
ISSN: 2395-3470
www.ijseas.com

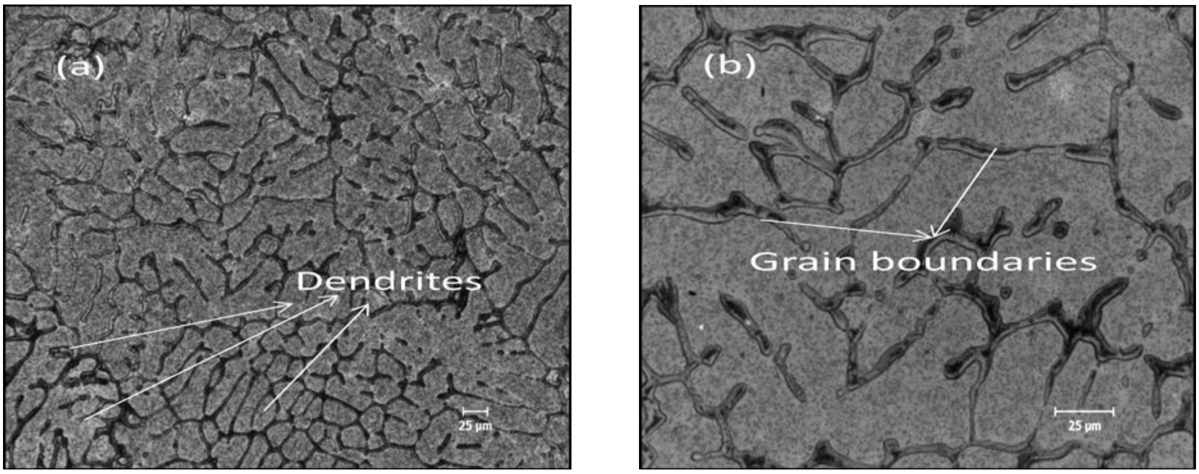


Fig. 8 (a) and (b) Microstructures of Al 6061 Reinforced by Silicon Carbide and Graphite of 5% Weight Fraction (Magnification 200X and 500X)

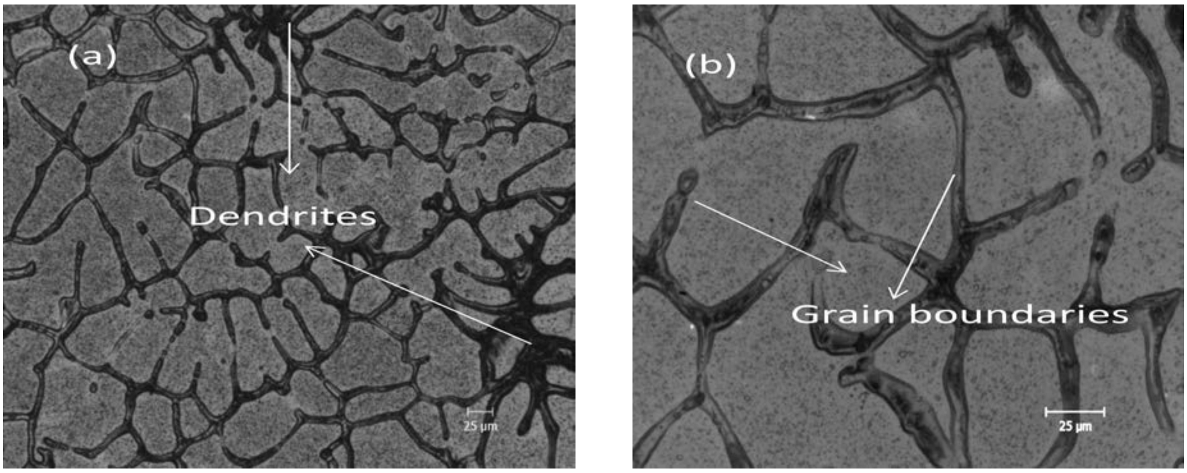


Fig. 4.7 (a) and (b) Microstructures of Al 6061 Reinforced by Silicon carbide and Graphite of 7.5% Weight Fraction (Magnification 200X and 500X)

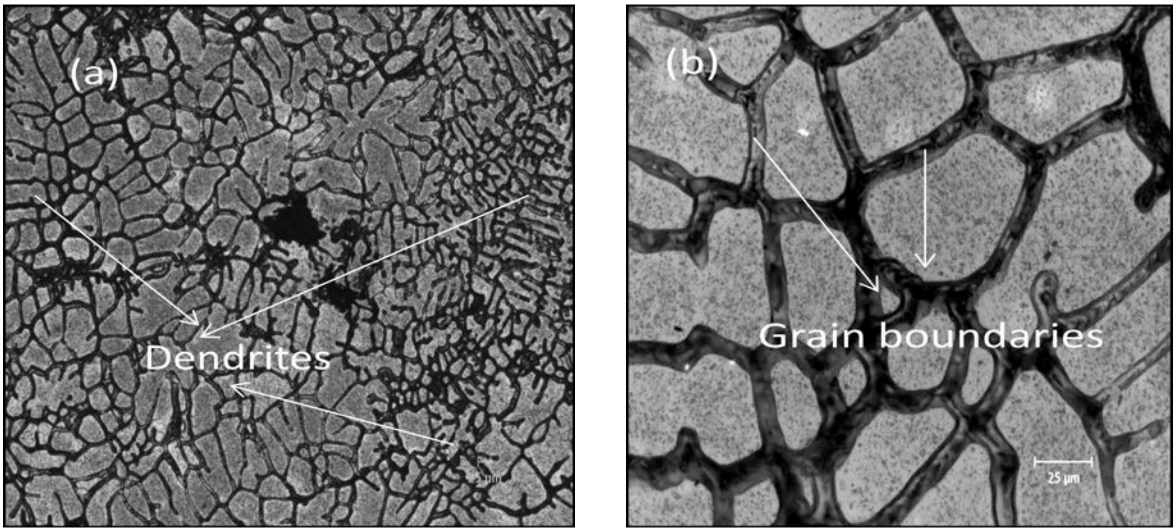


Fig. 10 (a) and (b) Microstructures of Al 6061 Reinforced by Silicon carbide and Graphite of 10% Weight Fraction (Magnification 200X and 500X)

Fig. 6, 7, 8, 9 and 10 (a) and (b) depicts the microstructures of hybrid metal matrix composites reinforced with the particles of Silicon Carbide and Graphite. The samples with varying weight fraction have been prepared for the study of microstructure by using standard metallographic procedure. Fig. 6 depicts the microstructure of Al 6061 without any reinforcements. It has been 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 [Zhu Xiao-min et al., 2012; Belete Sirahbizu Yigezu et al., 2013; Lee and Hong, 2003; Antonyraj Arockiaswamy et al., 2013]. Fig. 7, 8, 9 and 10 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 dispersed 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 [Cem Okumus et al., 2012; Anil Kumar et al., 2011; Ashish Srivastava et al., 2014; Zhu Xiao-min et al., 2012]. The matrix 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 revealed 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. The particles of Silicon have been nucleated consistently depending on the distribution of the particles of Silicon Carbide [Cem Okumus et al., 2012; Anil Kumar et al., 2011; Ashish Srivastava et al., 2014; Zhu Xiao-min et al., 2012]. The larger particles of Silicon Carbide have been necessary in high weight or volume fraction of 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 reviewed that, a dense and uniform microstructure has been advantageous for electronic packaging equipment due to better mechanical strength and high thermal conductivity [Cem Okumus et al., 2012; Anil Kumar et al., 2011; Ashish Srivastava et al., 2014; Zhu Xiao-min et al., 2012].

5. DETERMINATION OF DENSITY AND POROSITY OF HYBRID COMPOSITES

The density of hybrid MMCs have been determined 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 [Introduction to composites, 2002; Ashish Srivastava et al., 2014]. In material 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, mass 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. Eq. (1) has been used to calculate density of the hybrid composites by using rule of mixtures. ρ_c, ρ_m *and* ρ_p are the density of composite, matrix and particles and V is the volume fraction.

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

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 1 refers to the density of hybrid composites for the varying weight fraction (2.5%, 5%, 7.5% and 10%) 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.

Table 1. Density of Hybrid Composites with Varying Weight Fraction

Serial Number	Hybrid composites	Density /g cc^{-1} (Experimental)	Density /(g cc^{-1}) (Theoretical)	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%

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

Laser flash technique is highly resourceful for the evaluation of thermal conductivity and thermal diffusivity. The sample will be positioned on an electronically controlled and programmable robot located in a furnace. The furnace is then held at a predetermined temperature. At this temperature, the sample surface is then irradiated with a programmed energy pulse (laser or xenon flash). This energy pulse results in a homogeneous temperature rise at the sample surface. The resulting temperature rise of the rear surface of the sample is measured by a high speed infrared detector and thermal diffusivity values are computed from the temperature rise versus time data. The resulting measuring signal computes the thermal diffusivity, and in most cases the specific heat (*Cp*) data. Both power and the pulse length can be easily adjusted by the software [Hohenauer, 2009; Maglic et al., 1992].

The thermal conductivity of metals, alloys or composites can be measured by comparative method with steady state longitudinal heat flow in a temperature range room temperature upto 1000°C. The comparative instrument measures heat flow based upon the known thermal properties of standard reference materials. The test specimen is sandwiched between two identical reference samples. This stack is placed between two heating elements controlled at different temperatures. A guard heater will be placed around the test stack to ensure a constant heat flux through the stack and no lateral heat flow losses. As heat flows from the hot element to the cold element the temperature gradient across the stack is measured with thermocouples. In a laser flash method, laser fires a pulse at the sample's front surface and the infrared detector measures the temperature rise of the sample's back surface. The software uses literature-based analysis routines to match a theoretical curve to the experimental temperature rise curve. To determine specific heat capacity, the infrared detector measures the actual temperature rise of the sample [Hohenauer, 2009; Maglic et al., 1992].

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. From the literature review, it is absolutely clear that the investigation pertaining to Aluminium matrix composites have been given greater prominence. If these materials are to be used for many prominent engineering applications, the thermal aspects of AMCs need to be given more importance. Hence it becomes important that the evaluation of thermal characteristics of hybrid composites cannot be ignored in order to transform the material from design stage to manufacturing stage. It has been reported in the literature that, the experimental study on Aluminium and Silicon Carbide has been carried out exhaustively based on low and high weight fraction [Hohenauer, 2009; Maglic et al., 1992]. But, limited work has been carried out on thermal analysis and characterization of Al 6061 with Silicon Carbide (SiC) and Graphite (Gr) based on low weight fraction of hybrid metal matrix composites. Hence, Graphite (Gr) has been reinforced concurrently with Silicon Carbide considering low weight fraction of hybrid composites.

The thermal diffusivity of the hybrid composites has been measured by using a NETZSCH model LFA 447 Nano Flash diffusivity. 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. Al 6061 is the base alloy and reinforcements Silicon Carbide and Graphite with weight fraction 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 sample has been measured by using a standard sample holder (diameter of 12.7 mm and thickness 3 mm). The sample has 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 estimate 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 Composite Specimens	Specific Heat Capacity (J kg^{-1} K^{-1})
1.	Sample 1	980
2.	Sample 2	968
3.	Sample 3	947
4.	Sample 4	924
5.	Sample 5	918

Fig. 11 depicts the variation of thermal diffusivity with temperature for different compositions of hybrid metal matrix composites. Fig. 12 illustratess the variation of thermal conductivity with temperature for different compositions of hybrid metal matrix composites. The different samples have been tested from room temperature to 300°C by using laser flash apparatus. From fig. 12, it has been observed that, Al 6061 exhibits high thermal conductivity with 168 W/mK. Generally, the thermal conductivity varies as the temperature changes significantly. It has been noticed that, with the addition of reinforcements Silicon Carbide and Graphite to Al 6061, there has been reduction in the thermal conductivity at maximum temperature 300°C. It has been observed that, the addition of Graphite to Aluminium matrix alloy and Silicon Carbide resulted in the reduction in thermal conductivity of hybrid metal matrix composites. It has been reported in the literature that, the thermal conductivity for hybrid MMCs considerably increases by reinforcing Silicon Carbide over the different range of temperatures [Cem Okumus et al., 2012]. Based on the experimentation, it has been inferred that, the reinforcement of Graphite with Aluminium and Silicon Carbide does not enhance thermal conductivity and thermal diffusivity significantly. It has been examined that, addition of Silicon Carbide and Graphite reinforcements with high weight or volume fraction resulted in marginal increase in thermal conductivity. This has inferred that, the addition of reinforcements Silicon Carbide and Graphite has insignificant influence in the increase of thermal conductivity. The results have indicated that, Graphite content improves the dimensional stability, and there will be no variation in thermal behaviour of hybrid composites [Cem Okumus et al., 2012; Anil Kumar et al., 2011; Ashish Srivastava et al., 2014; Zhu Xiao-min et al., 2012]. Based on these investigations, it can be concluded that, the thermal conductivity of hybrid composites reduces due to the enrichment of Graphite. It has been inferred that, the composites with 5% Silicon Carbide and 5% Graphite reinforced with Al 6061 exhibited low thermal conductivity compared with those of other hybrid composites for a consistent level of porosity. From literature, Aluminium-Silicon Carbide composites are attractive with many outstanding features, including 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 [Molina and Rheme, 2008; Na Chen and Zhang, 2009; Hohenauer, 2004; Weidenfeller, 2004].

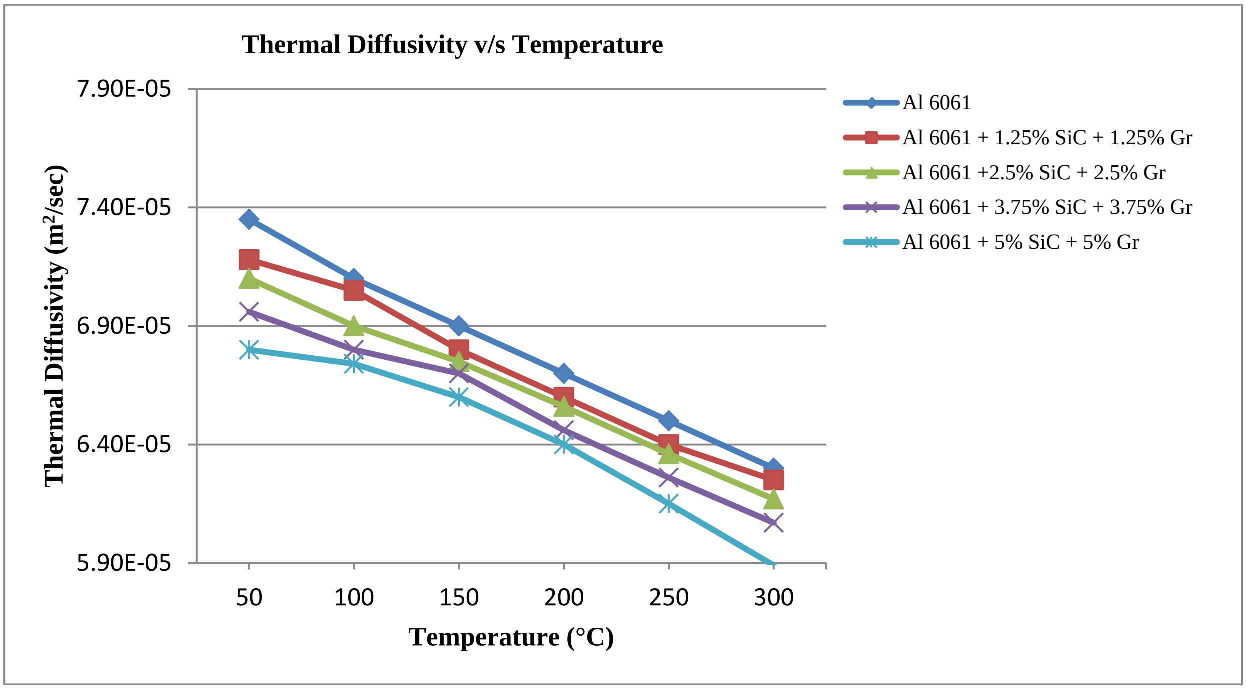


Fig. 11. Variation of Thermal Diffusivity with Temperature for Varying Mass Fraction of MMCs

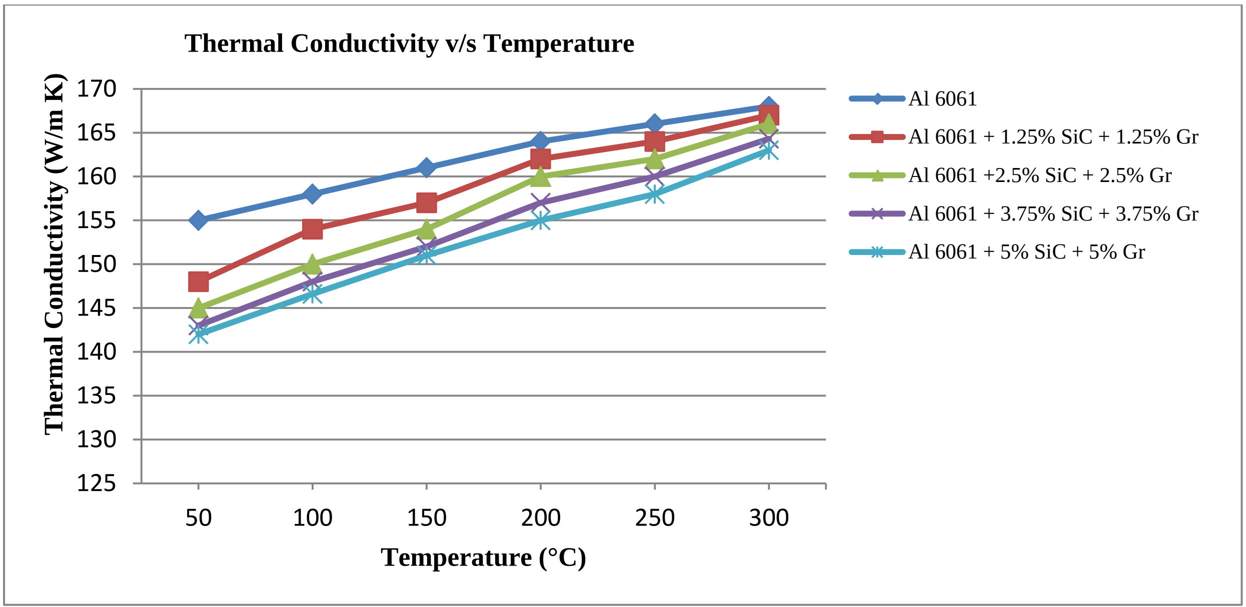


Fig. 12. Variation of Thermal Conductivity and Temperature for different compositions of MMCs

The thermal conductivity of composites has intrigued enormous interest for about a century. 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. The thermal conductivity of hybrid composites is gradually varying as the particle or grain size of Silicon Carbide is relatively smaller and 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. As a matter of fact, the interfacial thermal resistance radically decreases and matches with the experimental results. It has been noticed that, due to the increase in volume fraction of Silicon Carbide the thermal conductivity of Silicon Carbide gradually increases.

It has been reported that, the dependence of the overall thermal conductivity on the particle diameter for spherical particles of equal size was investigated with several predictions. The reason for the decrease of the thermal conductivity values with decreasing grain size of the different compositions of Silicon Carbide can be attributed to the interfacial properties between the Aluminium (Al) matrix and Silicon Carbide. It is obvious that decreasing the grain size results in a larger surface area between Aluminium matrix and Silicon Carbide (SiC). The interfacial reaction between Aluminium matrix and SiC can reduce the thermal conductivity of the composites. The porosity can severely degrade the thermal and mechanical properties of metal matrix composites, SiC and Graphite particles are uniformly distributed in aluminium matrix and no considerable level of pores were observed in the present study when Graphite is used as reinforcement. Thermal conductivity was found to decrease as the content of graphite and the temperature increases, since reinforcements have lower thermal conductivities and because, increased temperature diminish thermal diffusivity. The decrease in thermal diffusivity dominates the temperature dependence of thermal conductivity in the high temperature region. The specific heat capacity decreases strongly at temperatures below room temperature and dominates the temperature dependence of thermal conductivity [Cem Okumus et al., 2012].

7. THEORETICAL VALIDATION OF THERMAL CONDUCTIVITY MODELS

The challenges in modelling complex materials come mainly from the inherent variety and randomness of their microstructures, and the coupling between the components of different phases. Several attempts have been made to develop expressions for effective thermal conductivity of two-phase materials by various researchers namely Maxwell, Lewis and Neilsen, Cunningham and Peddicord, Hadley, Rayleigh, Russell, Bruggemann,Meridith and Tobias, Hamilton and Crosser, Cheng and Vechon and Torquato [Grujicic et al., 2011; Leon Mishnaevsky, 2006; Kush Kumar Dewangan et al., 2010; Eusun Yu et., 2008; Saraev and Schmauder, 2000; Sehrat Durmaz, 2004]. The different mathematical or thermo-elastic models have been used to validate the theoretical results and can be compared with the experimental results effectively. 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 percentage volume fraction of the 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 volume fraction of matrix and reinforcements.

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. 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. 13 depicts the comparison of experimental values of thermal conductivity with the thermo-elastic models. 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.

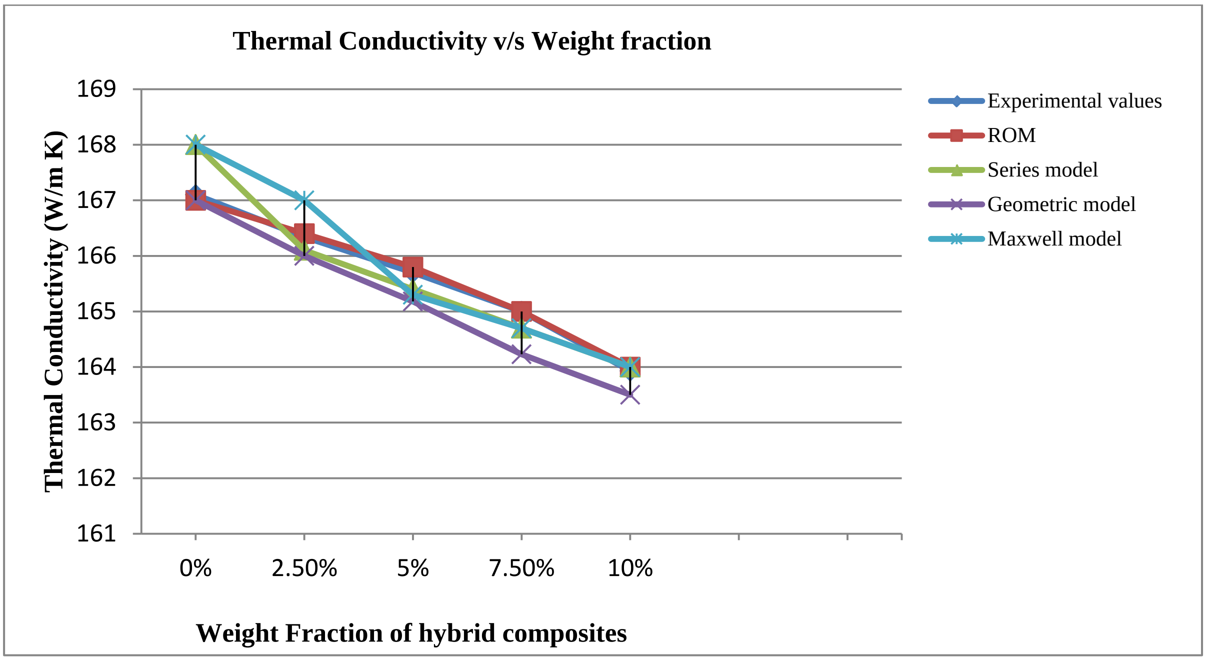


Fig. 13. Comparison of Experimental Values of Thermal Conductivity with Empirical Models

8 EXPERIMENTAL INVESTIGATION ON THERMAL EXPANSIVITY OF HYBRID METAL MATRIX COMPOSITES

Coefficient of thermal expansion or thermal expansivity is an important property of Aluminium matrix composites. 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 [Molina and Rheme, 2008; Na Chen and Zhang, 2009; Hohenauer, 2004; Weidenfeller, 2004]. 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 the measurement of CTE can be used depending on the temperature conditions. One of the most widespread 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. Five samples have 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. Standard data analysis software has been used to evaluate the coefficient of thermal expansion of hybrid composites tested and have been determined at intervals of 20°C.

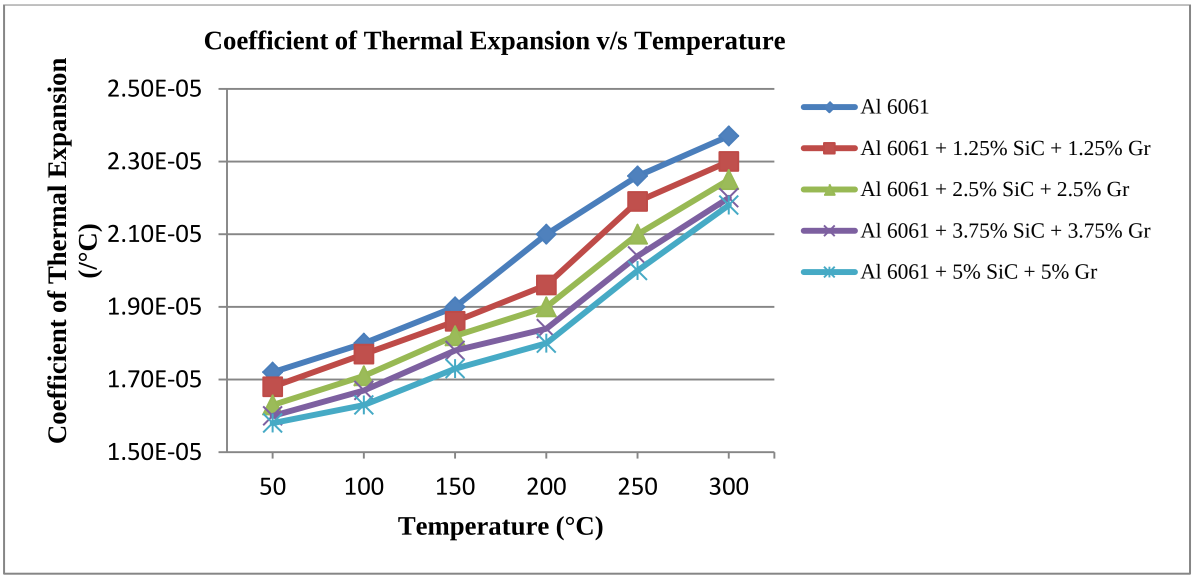


Fig. 14. Variation of CTE v/s Temperature of Hybrid Composites

Fig. 14 depicts the variation of CTE and 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. From fig. 13, it has been observed that, Al 6061 has maximum coefficient of thermal expansion. Generally, the thermal expansivity of materials varies as the temperature changes. 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 higher temperature 300°C. The addition of Graphite with Aluminium matrix alloy and Silicon Carbide of varying weight fraction resulted in the reduction in thermal expansivity of hybrid metal matrix composites. The CTE of Graphite is very low compared to Al 6061 and Silicon Carbide. It has been reviewed in the literature that, the CTEs of Al 6061 is 23.6×10^{-6}/°C, Silicon Carbide is 8×10^{-6}/°C and Graphite is 1×10^{-6}/°C. It has been reported in the literature that, the thermal expansivity of hybrid MMCs considerably increases by reinforcing Silicon Carbide over the different range of temperatures [Cem Okumus et al., 2012]. It has been inferred from the experimental investigation that, the reinforcement of Graphite with Aluminium-Silicon and Silicon Carbide does not enhance thermal expansivity significantly [Cem Okumus et al., 2012]. It has been examined that, addition of Silicon Carbide and Graphite reinforcements with high weight or volume fraction resulted in the drastic increase in thermal expansivity of composites Grujicic et al., 2011; Leon Mishnaevsky, 2006; Kush Kumar Dewangan et al., 2010; Eusun Yu et., 2008; Saraev and Schmauder, 2000; Sehrat Durmaz, 2004].

It has been reported in the literature that, the evaluation of CTE of hybrid metal matrix composites is relatively difficult to predict because several factors viz., 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 [Zhang and Wu, 2004; Elomari and San Marchi, 1997].

From the literature, it has been reported that, the hybrid composites have low volume fraction 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 [Zhang and Wu, 2004; Elomari and San Marchi, 1997]. 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 of aluminium matrix composites have high volume fractions of SiC particulate. In Al-SiC composites, the thermal expansion behaviour will be influenced by the thermal expansion of aluminium and the tightened restriction of SiC particles. The CTE of the particle reinforced MMCs is usually affected by a variety of factors namely interfacial reactions, plasticity due to CTE mismatch between particle and matrix during heating or cooling, and residual stresses [Zhang and Wu, 2004; Elomari and San Marchi, 1997].

9 THEORETICAL VALIDATION OF THERMAL EXPANSIVITY MODELS

Theoretical prediction of thermal expansivity for multi-phase composite materials is very constructive for analysis and optimization of the material performance. The correct and accurate modelling for thermal coefficients of composite materials has a great value due to their excellent thermal and mechanical properties. The challenges in modelling complex materials arise mainly from the inherent variety and randomness of their microstructures. Several attempts have been made to develop expressions for thermal expansivity by different researchers viz., Kerner, Schapery, Turner and Hashin-Shtrikman [Grujicic et al., 2011; Leon Mishnaevsky, 2006; Kush Kumar Dewangan et al., 2010; Eusun Yu et., 2008; Saraev and Schmauder, 2000; Sehrat Durmaz, 2004]. Thermo-elastic models have been developed over the last century to predict the thermal expansivity behaviour of two-phase composites for which dispersion of a second phase in a continuous medium of the first phase is assumed. The models either assume or require as input a specific dispersion of second phase and these have been reviewed by numerous researchers.

The thermo-elastic models considered for the validation of thermal expansivity are rule of mixtures, Kerner, Turner and Schapery models. Fig. 15 illustrates the comparison of experimental values of thermal expansivity with the thermo-elastic models. Fig. 15 depicts that, the experimental values of thermal expansivity with varying weight fraction of hybrid composites closely matches with all theoretical models. It has been observed that, rule of mixtures exhibited the best CTEs, whereas Kerner, Turner and Schapery models exhibited endurable values of CTEs. The experimental data has been in the broad range between Kerner and Schapery predictions. Kerner’s model has been close to the experimental values, although the Turner model predictions have been slightly higher than the experimental results. It has been attributed that, Kerner’s model has been close to rule of mixtures approximation when the constraint term is small. It has been reported in the literature that, if the reinforcements are in particulate form, the constraint will not too large as that from the fibre reinforcement. The experimental results are closer to the lower bound of the Schapery model. It can be clearly inferred that, rule of mixtures can be adjudged as the best empirical model for the evaluation of CTEs.

In rule of mixtures, it has been observed that, the coefficients of thermal expansion of hybrid composites with varying weight fraction have been decreasing. This is because, the volume fraction of matrix alloy and reinforcements are low. In Kerner and Schapery models, it has been observed that, bulk and shear moduli of hybrid composites have been increasing. But Poisson ratio and volume fraction of hybrid composites are low. Hence, the CTEs of hybrid composites decrease on these factors. In Turner model, the bulk moduli of hybrid composites have been increasing due to variation in Poisson ratio. The Poisson ratio of hybrid composites with varying weight fraction has been determined by using rule of mixtures. The bulk and shear moduli of hybrid composites have been calculated by using principles of mechanics of composite materials. Table 3 depicts the material properties of hybrid composites with varying weight fraction. Table 4 illustrates the validation of thermo-elastic models with experimental results.

Table 3. Material Properties of Hybrid Composites with Varying Weight Fraction

Hybrid Composite Specimens	Poisson ratio	Moduli of Elasticity (GPa)	Bulk Moduli (GPa)	Shear Moduli (GPa)
Sample 1	0.3	70	58.33	27
Sample 2	0.2984	71.5	59	27.7
Sample 3	0.2945	73	59.2	28.3
Sample 4	0.2935	74.5	60	29

Sample 5	0.2912	76	61	29.6

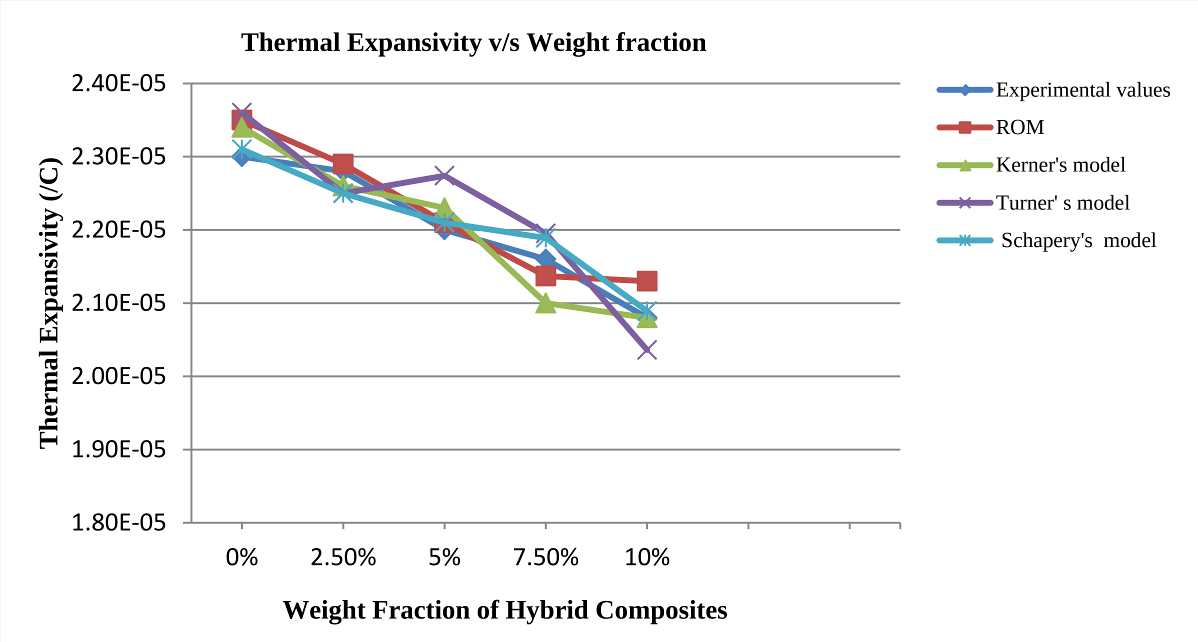


Fig. 15. Validation of the Thermo-elastic Models with Experimental Results

Table 4. Validation of Thermo-Elastic Models with Experimental Results

Hybrid Composite Specimens	CTE/°C (Experimental values)	CTE/°C (Rule of Mixtures)	CTE/°C (Kerner's model)	CTE/°C (Turner's model)	CTE /°C (Schapery's model)
Sample 1	23.6×10^{-6}	23.6×10^{-6}	23.4×10^{-6}	23.4×10^{-6}	23.6×10^{-6}
Sample 2	22.8×10^{-6}	22.9×10^{-6}	22.6×10^{-6}	22.58×10^{-6}	22.61×10^{-6}
Sample 3	22×10^{-6}	22.1×10^{-6}	22.3×10^{-6}	22.54×10^{-6}	22.1×10^{-6}
Sample 4	21.6×10^{-6}	21.57×10^{-6}	21×10^{-6}	21.95×10^{-6}	21.5×10^{-6}
Sample 5	20.8×10^{-6}	20.6×10^{-6}	20.8×10^{-6}	20.36×10^{-6}	20.9×10^{-6}

10 COMPUTATIONAL ANALYSIS OF HYBRID COMPOSITES

In the present scenario, the control manner of Silicon Carbide in Aluminium matrix is not only stipulated over a large regime due to interaction between reinforcements and matrix but also cannot show representative nature owing to limited controlled regime over all possible fabrication of MMCs. In this regard, Computational FEM analysis has been carried out for Silicon Carbide in Al 6061, which is beneficial for the computation of thermal properties viz., thermal stress, thermal strain, thermal displacement, thermal gradient, thermal flux and heat flow. To extend experimental information, the computational FEM method on a variety of composite materials systems allows MMC fabrication to be fruitful with empirical results and computational investigation. For the analysis of metal matrix composite, many researchers have suggested the analysis of unit cell of composite. Generally, there are computational difficulties to obtain reasonable results based on a small single unit owing to a lack of interaction between reinforcement and matrix. On the contrary, the computation with multiple unit cells allows reliable results due to considerable material interaction [Davis and Artz, 2009; Cem Okumus et al., 2012; Molina and Rheme, 2008].

A flourishing application of metal matrix composites in the topic of engineering design necessitates an elaborate categorization of mechanical and thermal properties. The properties based on thermal expansion of composite materials play a significant role in evaluating the thermal strain and thermal stresses in components or structures of MMCs. The association of numerous expensive, monotonous and other factors in the process of characterization of materials have led a systematic way to many numerical and analytical techniques. Finite element method has been regarded as an efficient technique for the prediction and computation of the properties based on mechanical and thermal behaviour of composites [Schapery, 1968; Lu et al., 2011; Elomari and San Marchi, 1997].

Using experimental values of hybrid metal matrix composites as materials properties viz., density, thermal conductivity, specific heat capacity and enthalpy, the computational investigation viz., thermal gradient and thermal flux have been accomplished based on the thermal conductivity behaviour of hybrid composites.

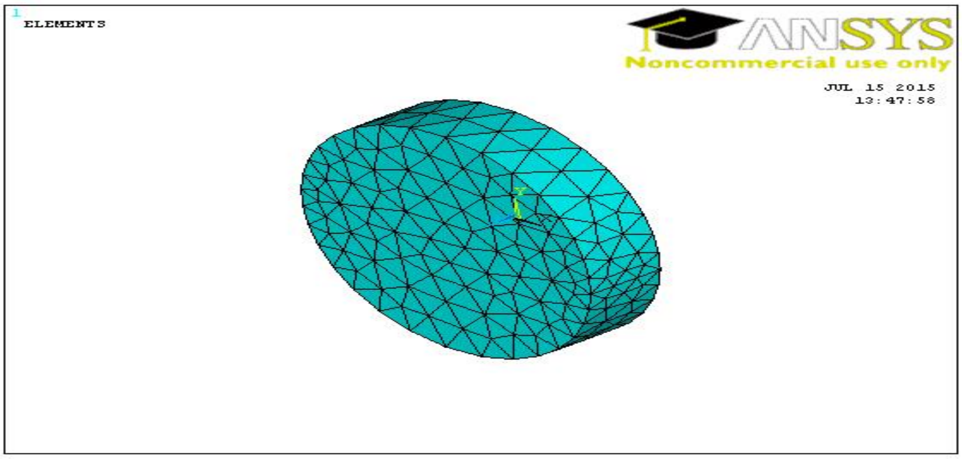


Fig. 16. Mesh generation of hybrid metal matrix composites

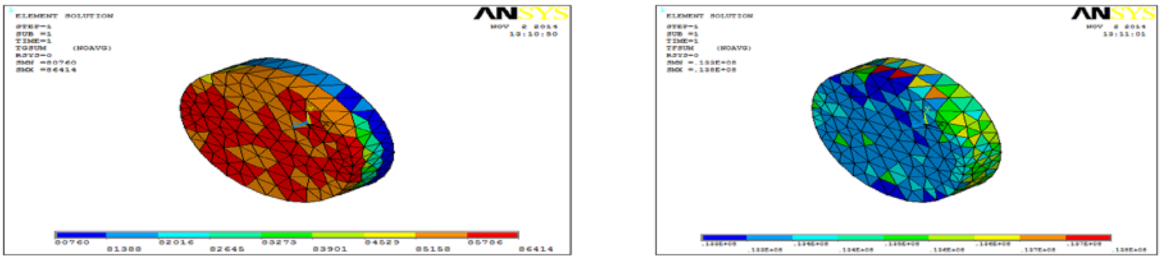


Fig. 17 (a) and 17 (b) Thermal Gradient and Thermal Flux for Al 6061

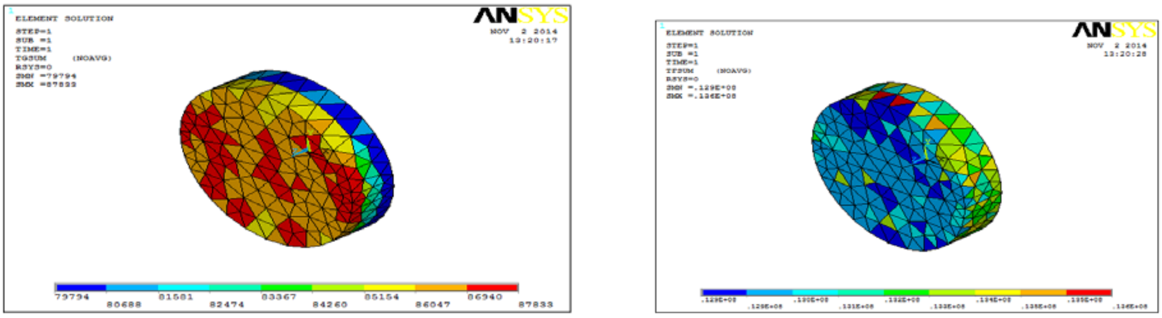


Fig. 18 (a) and 18 (b) Thermal Gradient and Thermal Flux for Al 6061 + 1.25% SiC + 1.25% Gr

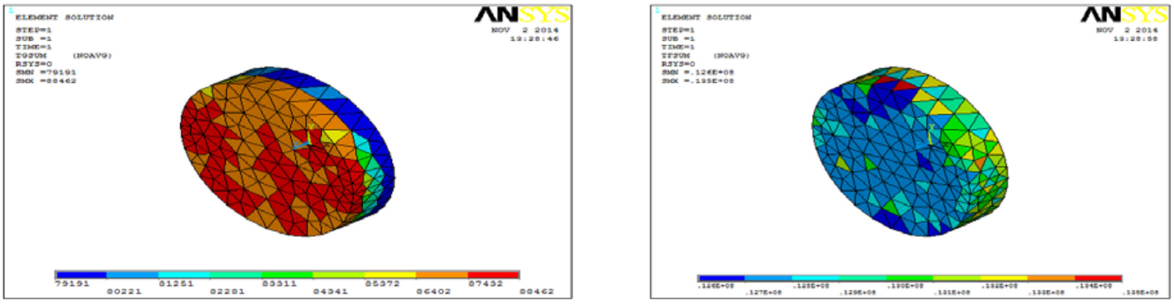


Fig. 19 (a) and 19 (b) Thermal Gradient and Thermal Flux for Al 6061 + 2.5% SiC + 2.5% Gr

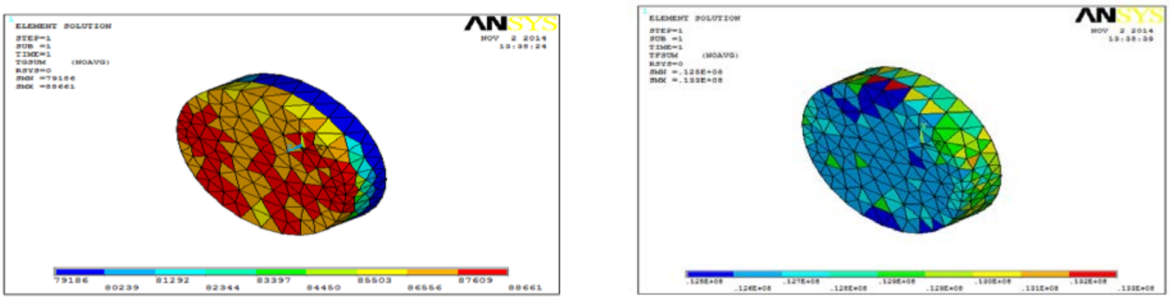


Fig. 20 (a) and 20 (b) Thermal Gradient and Thermal Flux for Al 6061 + 3.75% SiC + 3.75% Gr

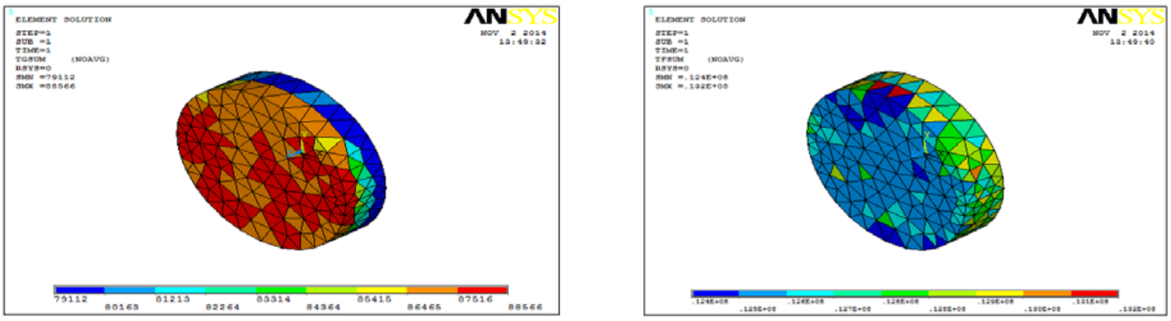


Fig. 21 (a) and 21 (b) Thermal Gradient and Thermal Flux for Al 6061 + 5% SiC + 5% Gr

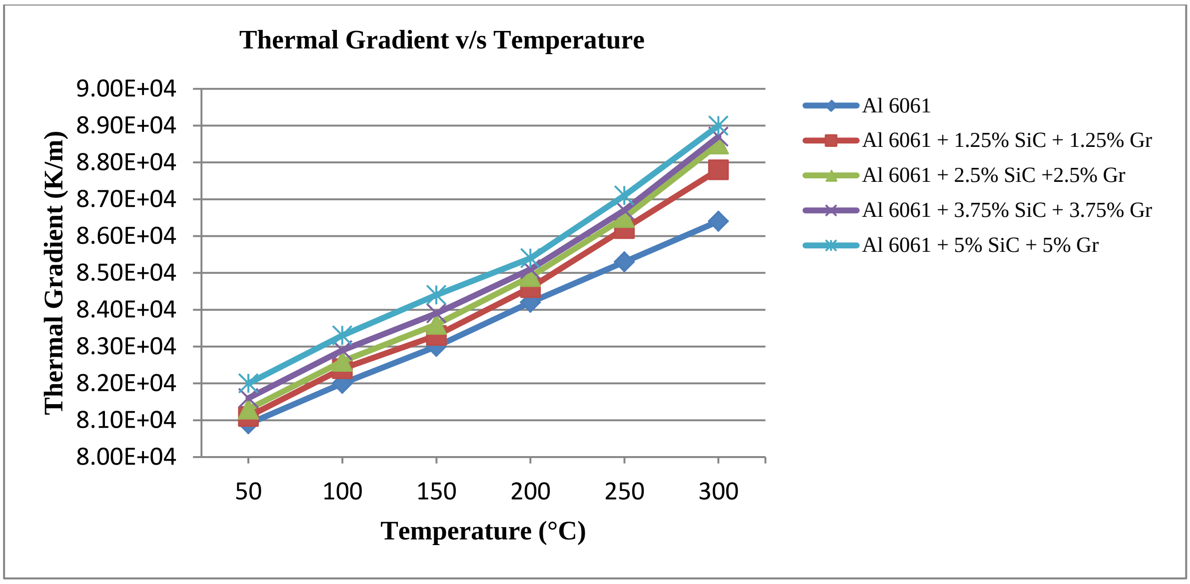


Fig. 22. Variation of Thermal Gradient with Temperature for different compositions of hybrid composites

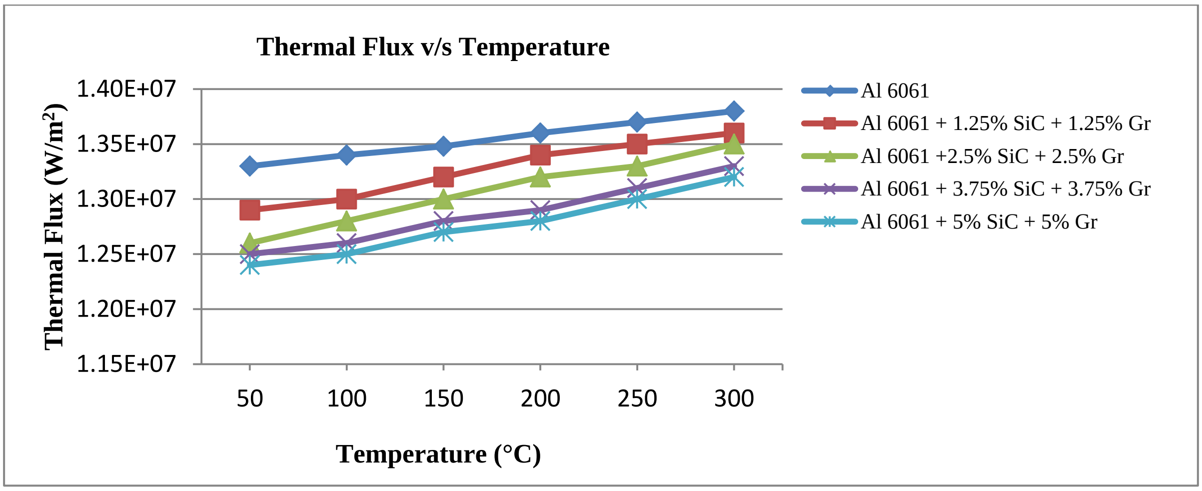


Fig. 23. Variation of Thermal Flux with Temperature for different compositions of hybrid composites

Table 5. Experimental values of Thermal Conductivity, Specific Heat Capacity and Enthalpy for different percentage compositions of the hybrid metal matrix composites at maximum temperature 300°C

Percentage composition of composites	Thermal Conductivity (W/mK)	Specific Heat Capacity (kJ/kg K)	Enthalpy (kJ/kg) and Density in g/cc
Al 6061 (Sample 1)	168.2	0.980	561 and 2.7
Al 6061 + 1.25% SiC + 1.25% Gr (Sample 2)	167.4	0.967	552 and 2.693
Al 6061 + 2.5% SiC + 2.5% Gr (Sample 3)	166.8	0.955	539 and 2.684
Al 6061 + 3.75% SiC + 3.75% Gr (Sample 4)	165.3	0.925	528 and 2.675
Al 6061 + 5% SiC + 5% Gr (Sample 5)	164.2	0.910	518 and 2.66

Table 6. Comparison of computational and theoretical values of thermal gradient of hybrid composites

Hybrid Composite Specimens	Thermal Gradient (K/m)											
	Computational values (using ANSYS)						Theoretical Values					
	50°C	100°C	150°C	200°C	250°C	300°C	50°C	100°C	150°C	200°C	250°C	300°C
Sample 1	81202	82145	83587	84129	85472	86414	81208	82150	83592	84139	85479	86422
Sample 2	81215	82180	83813	85178	86580	87833	81225	82190	83823	85182	86580	87835
Sample 3	81251	82221	83826	85372	86917	88462	81255	82224	83827	85375	86920	88463
Sample 4	81292	82244	84000	85403	87120	88561	81292	82244	84002	85404	87123	88565
Sample 5	81300	82264	84364	85415	87516	88566	81310	82268	84366	85418	87520	88569

Table 7. Comparison of computational and theoretical values of thermal flux of hybrid composites

Hybrid Composite Specimens	Thermal Flux (W/m^2)											
	Computational values (using ANSYS)						Theoretical Values					
	50°C	100°C	150°C	200°C	250°C	300°C	50°C	100°C	150°C	200°C	250°C	300°C
Sample 1	0.133e8	0.134e8	0.135e8	0.136e8	0.137e8	0.138e8	0.135e8	0.134e8	0.135e8	0.138e8	0.137e8	0.138e8
Sample 2	0.130e8	0.131e8	0.132e8	0.134e8	0.135e8	0.136e8	0.132e8	0.131e8	0.133e8	0.135e8	0.135e8	0.136e8
Sample 3	0.128e8	0.129e8	0.130e8	0.132e8	0.134e8	0.135e8	0.131e8	0.130e8	0.132e8	0.132e8	0.133e8	0.135e8
Sample 4	0.126e8	0.128e8	0.129e8	0.130e8	0.132e8	0.132e8	0.129e8	0.129e8	0.130e8	0.130e8	0.132e8	0.131e8
Sample 5	0.125e8	0.127e8	0.128e8	0.129e8	0.132e8	0.131e8	0.130e8	0.128e8	0.128e8	0.128e8	0.131e8	0.130e8

Table 5 emphasizes the experimental values of thermal conductivity, specific heat capacity and enthalpy for different hybrid composites obtained based on experimentation. Table 6 and 7 depicts the comparison of computational and theoretical values of thermal gradient and thermal flux of hybrid metal matrix composites respectively. To enhance the computational accuracy of the results, a finer mesh density has been used, which has been arrived through numerical convergence. Fig. 16 depicts the mesh generation of hybrid composites, where it has been noticed that, the accuracy in the results has been maintained and there has been no substantial variation in the results, even though finer mesh refinement has been attained. The mode of computational investigation adopted is "thermal" with hyperbolic type characterization and the element type selected is Solid Brick8node 70 and some of the major boundary conditions considered are densities, thermal conductivities, specific heat capacities and enthalpies of the different hybrid MMCs. Computationally, numerical convergence or mesh independence study has been vital to reduce the cost of computation and maintain utmost accuracy in the results based on computational analysis [Schapery, 1968; Lu et al.].

Fig. 17 to 21 indicates the contour plots concerning with thermal gradient and thermal flux that have been obtained computationally for the different percentage compositions of hybrid metal matrix composites by using ANSYS 12. Fig. 22 and 23 depicts the variation of thermal gradient and thermal flux with temperature. Thermal flux and thermal gradient are beneficial for the evaluation of the thermal effects of the composite materials. The evaluation of thermal flux depends on the ratio of net rate of heat transfer with respect to unit area. Analogously, the ratio of change in temperature to change in displacement determines thermal gradient.. Al 6061+ 5% SiC + 5% Gr exhibits maximum thermal gradient and minimum thermal flux, whereas Al 6061 exhibits minimum thermal gradient and maximum thermal flux. It has been be noticed that, with the addition of reinforcements Silicon Carbide and Graphite to Al 6061, there has been variation in thermal gradient and thermal flux at maximum temperature for the different percentage compositions of hybrid metal matrix composites. From the experimentation, it has been observed that, with the increase in percentage volume fractions of the hybrid composites, the thermal conductivity decreases by the addition of Graphite with Silicon Carbide and Al 6061. It has also been observed that, the thermal displacement of the different compositions of the hybrid metal matrix composites decreases drastically resulting in increase in thermal gradient of the hybrid composites. In the computation of thermal gradient of the hybrid composites, the values of thermal displacement of the hybrid compositions are gradually decreasing, hence resulting in the increase of thermal gradient. Thermal gradient basically depends on the change in temperature. But, the thermal flux for Al 6061 is high compared to other hybrid MMCs, because gradually the thermal conductivity of these hybrid composites decreases with the increase in temperature by the addition of Graphite leading to the variation in the net hear transfer rate. The evaluation of the thermal properties namely thermal flux and thermal gradient may be useful to realize the advantages of Al 6061-SiC-Gr hybrid composites in structural applications, and to identify the locations with reasons where the temperature is critical to damage the interface [Zhang and Wu, 2004; Elomari and San Marchi, 1997].

In the present work, using the experimental values viz., modulus of elasticity, Poisson ratio and thermal expansivity, the computational investigation has been achieved to evaluate the thermal parameters viz., thermal displacement, thermal strain and thermal stress based on the thermal conductivity behaviour of hybrid metal matrix composites. The mode of computational investigation adopted is “structural” with hyperbolic type characterization and the element type selected is Solid Brick8node 45 and some of the major boundary conditions considered are densities, thermal expansivities, specific Poisson ratio and modulus of elasticity of the different hybrid MMCs.

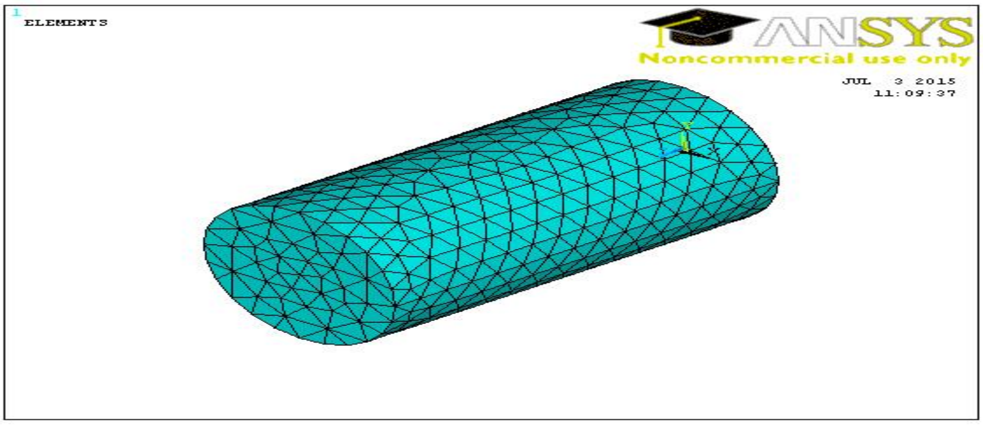


Fig. 24. Mesh refinement/generation of hybrid composites

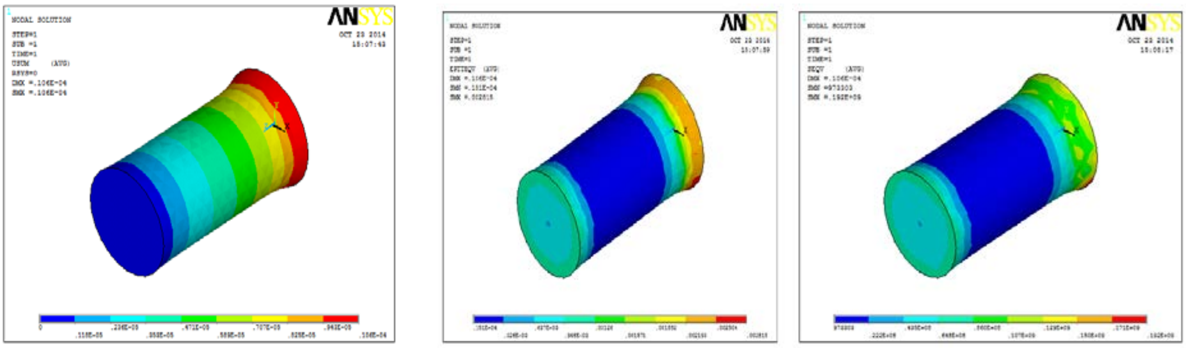


Fig. 25a, 25b and 25c. Thermal Displacement, Thermal Strain and Thermal Stress for Al 6061

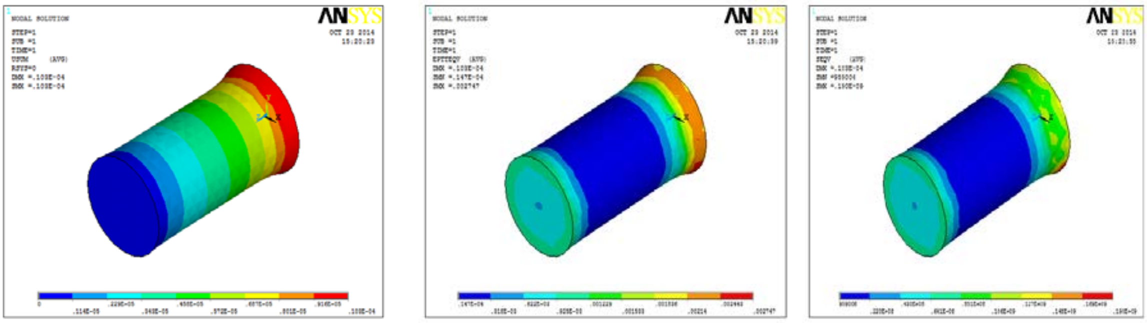


Fig. 26a, 26b and 26c. Thermal Displacement, Thermal Strain and Thermal Stress for Al 6061+ 1.25% SiC + 1.25% Gr

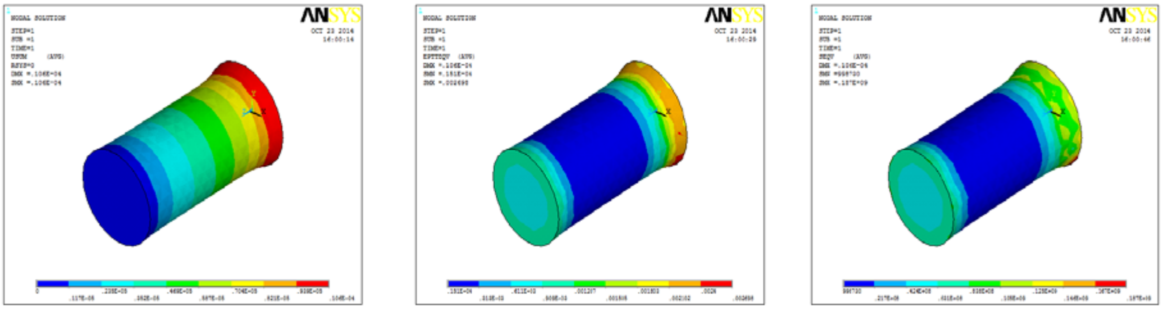


Fig. 27a, 27b and 27c. Thermal Displacement, Thermal Strain and Thermal Stress for Al 6061+ 2.5% SiC + 2.5% Gr

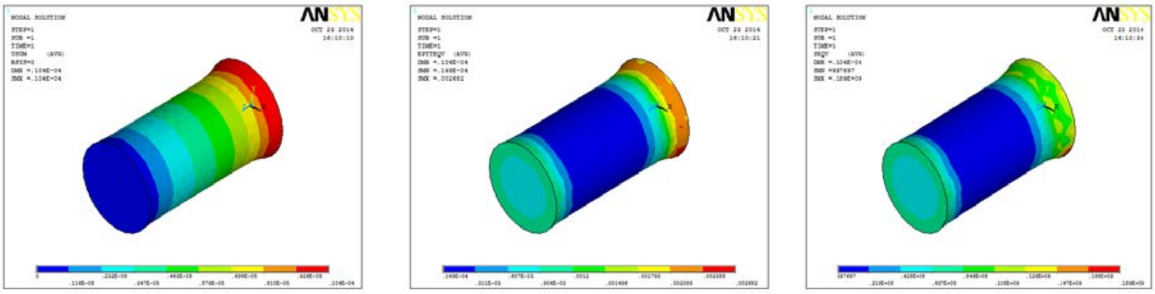


Fig. 28a, 28b and 28c. Thermal Displacement, Thermal Strain and Thermal Stress for Al 6061+ 3.75% SiC + 3.75% Gr

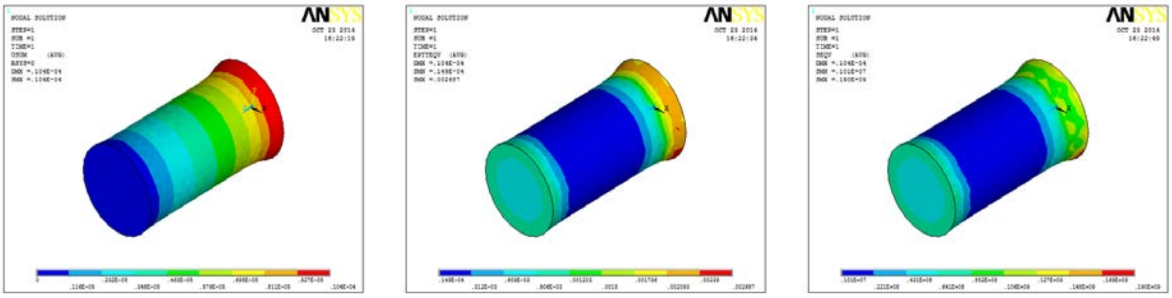


Fig. 29a, 29b and 29c. Thermal Displacement, Thermal Strain and Thermal Stress for Al 6061+ 5% SiC + 5% Gr

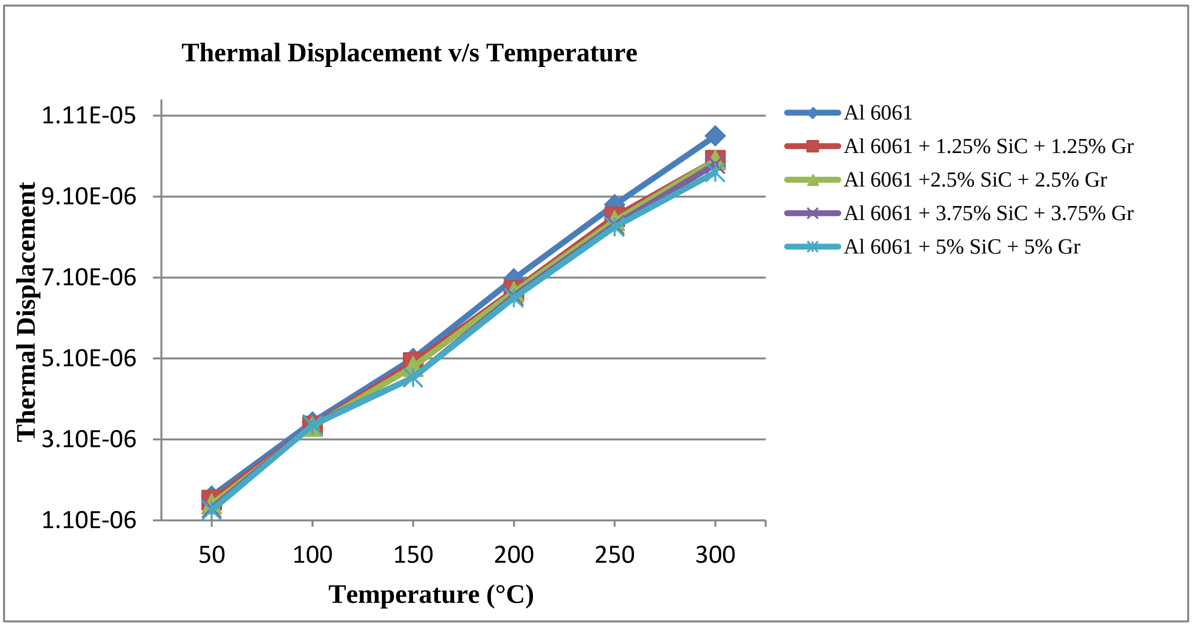


Fig. 30. Variation of Thermal Displacement with Temperature for different compositions of hybrid composites

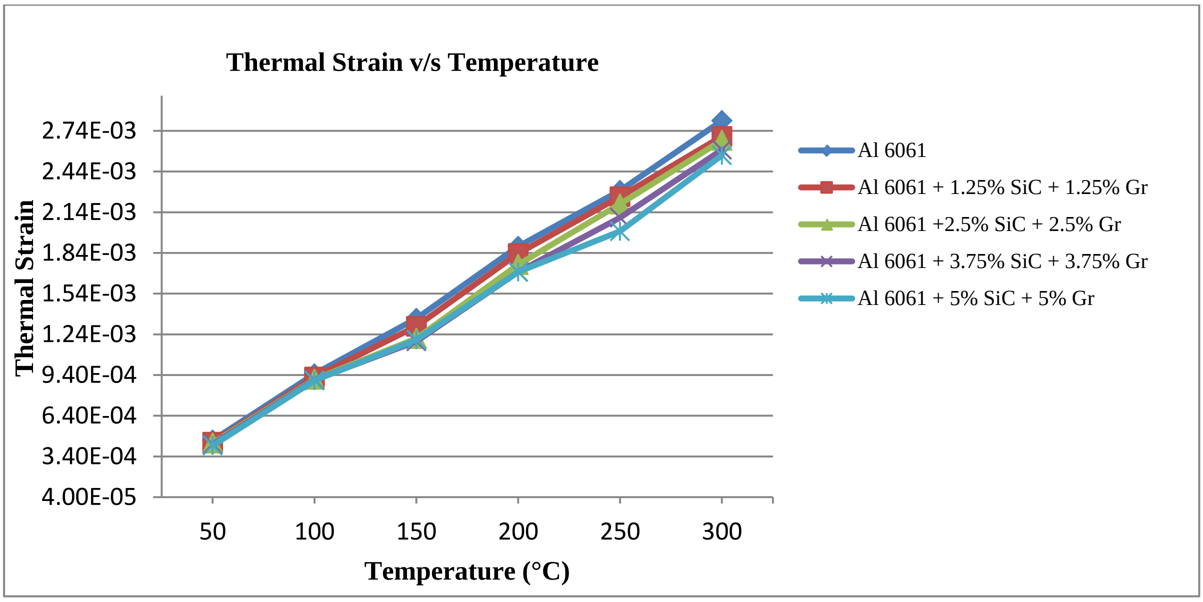


Fig. 31. Variation of Thermal Strain with Temperature for different compositions of hybrid composites

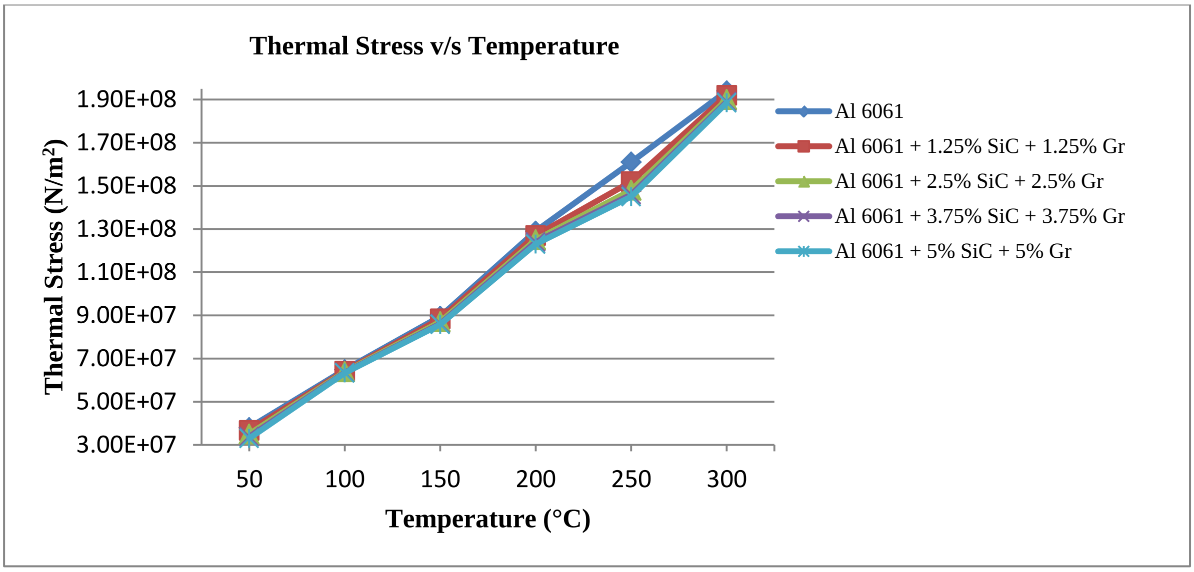


Fig. 32. Variation of Thermal Stress v/s Temperature for different compositions of hybrid composites

Table 8. Experimental values of Density, Poisson ratio and modulus of elasticity for the different percentage composition of the hybrid metal matrix composites

Percentage composition of composites	Density (g/cc)	Poisson ratio	Modulus of Elasticity (GPa)
Al 6061 (Sample 1)	2.7	0.3	70
Al 6061 + 1.25% SiC + 1.25% Gr (Sample 2)	2.691	0.2983	71.5
Al 6061 + 2.5% SiC + 2.5% Gr (Sample 3)	2.685	0.2967	73
Al 6061 + 3.75% SiC + 3.75% Gr (Sample 4)	2.673	0.2945	74.5
Al 6061 + 5% SiC + 5% Gr (Sample 5)	2.66	0.2913	76

Table 9. Comparison of computational and theoretical values of thermal strain of hybrid composites

Percentage composition of composites	Thermal Strain											
	Computational values (using ANSYS)						Theoretical Values					
	50°C	100°C	150°C	200°C	250°C	300°C	50°C	100°C	150°C	200°C	250°C	300°C
Sample 1	0.00048	0.00094	0.00141	0.00188	0.00234	0.00282	0.00048	0.00095	0.0014	0.00189	0.0023	0.0029
Sample 2	0.00047	0.00092	0.00138	0.00183	0.00229	0.00274	0.00047	0.00093	0.00138	0.00185	0.00229	0.00275
Sample 3	0.00046	0.00090	0.00123	0.00181	0.00215	0.00269	0.00046	0.00089	0.00123	0.00180	0.00216	0.00272
Sample 4	0.00045	0.00088	0.00116	0.00178	0.00206	0.00268	0.00045	0.00088	0.00116	0.00179	0.00208	0.00270
Sample 5	0.00045	0.00086	0.00106	0.00167	0.00193	0.00262	0.00044	0.00087	0.00106	0.00172	0.00196	0.00266

Table 10. Comparison of computational and theoretical values of thermal stress of hybrid composites

Percentage composition of composites	Thermal Stress											
	Computational values (using ANSYS)						Theoretical Values					
	50°C	100°C	150°C	200°C	250°C	300°C	50°C	100°C	150°C	200°C	250°C	300°C
Sample 1	0.33e8	0.648e8	0.965e9	0.129e9	0.161e9	0.192e9	0.32e8	0.65e8	0.97e9	0.129e9	0.161e9	0.193e9
Sample 2	0.31e8	0.641e8	0.954e9	0.127e9	0.159e9	0.190e9	0.31e8	0.64e8	0.95e9	0.127e9	0.159e9	0.191e9
Sample 3	0.29e8	0.63e8	0.945e9	0.125e9	0.157e9	0.188e9	0.30e8	0.62e8	0.94e9	0.125e9	0.157e9	0.189e9
Sample 4	0.27e8	0.612e8	0.93e9	0.123e9	0.155e9	0.186e9	0.28e8	0.61e8	0.92e9	0.123e9	0.155e9	0.186e9

Sample 5	0.25e8	0.60e8	0.91e9	0.121e9	0.153e9	0.184e9	0.26e8	0.60e8	0.91e9	0.121e9	0.153e9	0.184e9

Fig. 24 depicts the mesh generation of hybrid composites, where it has been noticed that, the accuracy in the results has been maintained and there has been no substantial variation in the results, even though finer mesh refinement has been attained. Fig. 25 to 29 emphasizes the various computational contour plots showing the distribution patterns of thermal displacement, thermal strain and thermal stress. Table 8 shows the experimental values of density, Poisson ratio and modulus of elasticity for the different percentage compositions of hybrid metal matrix composites. The experimental values of densities have been evaluated by water displacement method and modulus of elasticity has been determined by tension test. Poisson ratio of the hybrid composites have been evaluated by using rule of mixtures. Table 9 and 10 depicts the comparison of computational and theoretical values of thermal strain and thermal stress of hybrid metal matrix composites respectively. Finite element mesh generation has been accomplished for the hybrid composites using Solid Brick 8node 45. To enhance the computational accuracy of the results, a finer mesh density has been used, which has been arrived through numerical convergence. Computationally, numerical convergence or mesh independence study has been vital to reduce the cost of computation and maintain utmost accuracy in the results based on computational analysis [Schapery, R.A., 1968; Lu et al., 2011]. From table 9 and 10, it has been proved that, the numerical and theoretical values of thermal strain and thermal stress are almost same and convergence has been achieved. From the literature, it has been proved that, when Silicon Carbide was added to Aluminium matrix with increasing volume fraction of Silicon Carbide, the CTE value decreased linearly. However, the volume fraction of Silicon Carbide is indeed the main factor contributing to the CTE of MMC. When the MMCs undergoes heating process, expansion and deformation processes occurs steadily. Indeed, thermal stress has been induced by the difference of lattice constants between the matrix and the particles [Schapery, 1968; Lu et al., 2011; Elomari and San Marchi, 1997]. Fig. 30, 31 and 32 depicts the variation of thermal displacement, thermal strain and thermal stress with temperature. Theoretically, thermal strain has been calculated based on the product of thermal expansivity, change in temperature and initial length of the specimen; whereas thermal stress is the product of thermal expansivity, change in temperature and modulus of elasticity. It has been observed that, Al 6061 exhibits high thermal displacement, thermal strain and thermal stress. Generally, the thermal displacement, thermal strain and thermal stress varies as the temperature changes significantly. 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 displacement, thermal strain and thermal stress at maximum temperature for different percentage compositions of hybrid metal matrix composites. It has been comprehended that, due to the gradual decrease in thermal expansivity, the values of thermal displacement, thermal strain and thermal stress decreases. Addition of Graphite with Aluminium matrix alloy and Silicon Carbide with varying volume fraction resulted in the reduction in thermal displacement, thermal strain and thermal stress of the hybrid metal matrix composites.

12. CONCLUSIONS

(i) Al 6061 exhibits maximum values of thermal conductivity and thermal expansivity, whereas there has been a decline in thermal conductivity and thermal expansivity at maximum temperature for the different percentage compositions of hybrid metal matrix composites with the addition of reinforcements Silicon Carbide and Graphite to Al 6061.

(ii) The thermal conductivity and thermal expansivity of hybrid composites reduces due to the enhancement of Graphite content.

(iii) The thermal conductivity and thermal expansivity decreases over the range of temperatures, with variation in density, variation in volume fraction of Silicon Carbide and porosity of hybrid composites.

(iv) With the addition of reinforcements of low volume fraction, thermal conductivity and thermal expansivity of hybrid composites have been observed to be low.

(v) The variation in thermal conductivity and thermal expansivity depends on porosity, temperature variation, volume fraction, internal structure of the composites, dispersoid concentration of reinforcements and density of composites.

(vi) It has been observed that, Al 6061+ 5%SiC + 5% Gr exhibits maximum thermal gradient and minimum thermal flux, whereas Al 6061 exhibits minimum thermal gradient and maximum thermal flux.

(vii) Al 6061 exhibits maximum value of thermal displacement, thermal strain and thermal stress, whereas there has been a decline in thermal displacement, thermal strain and thermal stress at maximum temperature for the different percentage compositions of hybrid metal matrix composites with the addition of reinforcements Silicon Carbide and Graphite to Al 6061.

13. ACKNOWLEDGEMENTS

The authors wish to thank the prestigious company NETZSCH Technologies Private Limited, Chennai, India for providing Laser Flash apparatus facility to carry out the experimental work. They are greatly thankful to the prestigious organization National Aerospace Laboratories, Bengaluru, India for providing Dilatometer. They are indebted to Vignana Bhavan, University of Mysore, India for helping to carry out microstructural analysis using Scanning Electron Microscope. They are thankful to the prestigious Visvesvaraya Technological University, Belegavi, Karnataka, India for their support and cooperation during the research work.

REFERENCES

Abbott, G.L., Jenkins, R.J. and Parker, W.J. "Flash method of determining Thermal Diffusivity, Heat Capacity and Thermal Conductivity," *Journal of Applied Physics*, Vol. 31, Issue 9.

Achutha Kini, Gowri Shankar, M.C., Jayashree, P.K., Raviraj Shetty and Sharma, S.S. [2013] "Review on Effect of Silicon Carbide on Stir Cast Aluminium Metal Matrix Composites," *International Journal of Current Engineering and Technology,* ISSN: 2277-4106, Vol. 3, Number 3.

Anil Kumar, H.C., Hebbar, H.S. and Ravishankar, K.S. [2011] "Mechanical Properties of Fly Ash Reinforced Aluminium Matrix Alloy," *International Journal of Mechanical and Materials Engineering*, Vol. 6, 41-45.

Antonyraj Arockiaswamy, German, R.M., Wang, Suri and Park [2013] "DSC analysis of Al 6061 aluminium alloy powder by rapid solidification," *Journal of Thermal Analysis and Calorimetry*, 361-366.

Ashish Srivastava, Prayag Garg, Avdhesh Kumar, Yamini Krishna and Kanu Kumar Varshney [2014] "A Review on Fabrication and Characterization of Hybrid Metal Matrix Composites," *International Journal of Advance Research and Innovation*, ISSN: 2347-3258, Vol. 1, 242-246.

Belete Sirahbizu Yigezu, Manas Mohan Mahapatra and Pradeep Kumar Jha [2013] "Influence of Reinforcement Type on Microstructure, Hardness, and Tensile Properties of an Aluminium Alloy Metal Matrix Composites," *Journal of Minerals and Materials Characterization and Engineering*, 124-130.

Cem Okumus, S., Deniz Gultekin, Hatem Akbulat, Ramazan Karslioglu and Serdar Aslan [2012] "Thermal Expansion and Thermal Conductivity Behaviours of Al-Si/Silicon Carbide/Graphite Hybrid Metal Matrix Composites," *Materials Science*, ISSN: 1392-1320, Vol. 18, No. 4.

Cory A. Smith [2004] "Discontinuous Reinforcements for Metal Matrix Composites - Aluminium Composites," Vol. 121, *Composites ASM International ASM Hand Book*.

Davis, L.C. and Artz, B.E. [2009] "Thermal Conductivity of Metal Matrix Composites," *Journal of Applied Physics*, Vol. 77, 4954-4960.

Elomari, S. and San Marchi [1997] "Thermal expansion responses of pressure infiltrated SiC/Al MMC," *Journal of Material Science*, 2312-2140.

Eusun Yu, Jeong-Yun Sun, Hee-Suk and Kyu Hwan Oh [2008] "Investigation on Thermal Properties of Al/SiC Metal Matrix Composite Based on FEM Analysis."

Grujicic, M., Bell B.C. and B Pandurangan [2011], "Computational Investigation of Structured Shocks in Al/SiC particulate metal matrix composites."

Habbu, N.R. [2000] "Use of Aluminium Silicon Alloys in Automobile Application", *Proceedings of one day Industry Institute Interactive Meet on Al-Si alloys, Development and Application for transport sector*, IISC Bangalore.

Hai Duong, Papavassiliou, D., Mullen, K.J. and Muruyama, S. [2010] "Computational Modelling of Thermal Conductivity of Single Walled Carbon Nanotube Polymer Composites."

Hohenauer [2009] "Flash methods to examine diffusivity and thermal conductivity of metal foams," Pittsburg.

"Introduction to Composites," *Composites ASM Hand Book*, Vol.21, May 2002.

Karl Ulrich Kainer [2006] *Basics of Metal Matrix Composites* (Wiley-VcH Verlag GmbH, Weinheim)

Kush Kumar Dewangan, Vinod Naik and Durga Agarwal "Numerical Computation of Effective Thermal Conductivity of Polymer Composite Filled With Rice Husk Particle," *IOSR Journal of Mechanical and Civil Engineering*, ISSN: 2278-1684, 12-16.

Lee, H.S. and Hong, S.H. [2003] "Pressure Infiltration Casting Process and Thermophysical Properties of High Volume Fraction Al/SiC Particles Metal Matrix Composites," *Materials Science and Technology 19(8)*, 1057-1064.

Leon Mishnaevsky [2006] "Microstructural Effects on Damage in Composites – Computational Analysis," *Journal of Theoretical and Applied Mechanics*.

Lu, Hutchinson, T.J. and Hutchinson, J.W. "Effect of cracking and interface sliding on the thermal expansion of fiber reinforced composites," *Composites*, Vol. 26, No. 6, 403-414.

Maglic, K.D., Cezairliyan, A. and Peletsky, V.E. [1992] "Compendium of Thermophysical Property Measurement Methods – Recommended Measurement Techniques and Practices," Vol. 2, *Springer Science Business Media, LLC*.

Molina, J.M. and Rheme, M. [2008] "Thermal conductivity of Aluminum matrix composites reinforced with mixtures of diamond and Silicon Carbide particles", *Materials Science and Engineering*, Vol. 58, Issue 5, 393-398.

Na Chen and Zhang [2009] "Effect of Thermal cycling on the expansion behaviour of Al/SiC composites," *Journal of Materials Processing Technology*, 1471-1476.

Nam, T.H., Requena, G. and Degischer H.P. [2007] "Modelling and Numerical Computation of Thermal Expansion of Aluminium Matrix Composite," *Composites Part A*, 259-267.

Nanda Kumar, N. and Kanagaraj, P. [2011], "Study of Mechanical Properties of Aluminium Based Hybrid Metal Matrix Composites," *International Journal of Modern Engineering Research*, 166-172.

Naveen, G.J. and Ramesh, C.S. [2014] "Performance of Composite Materials using a Novel Technique," *International Journal of Engineering Science Invention*, ISSN: 2319-6734, Vol. 3, Issue 8, 25-29.

Parashuram Sonawane and Rajeshkumar Gangaram Bhandage [2013] "Preparation of Aluminium Matrix Composites using Stir Casting Method," *International Journal of Engineering and Advanced Technology*, ISSN: 2249-8958, Vol. 3.

Saraev, D. and Schmauder, S. [2003] "Finite Element Modelling of Al/SiC Metal Matrix Composites with Particles Aligned in Stripes – a 2D and 3D Comparison," *International Journal of Plasticity*, 733-747.

Schapery, R.A. [1968] "Thermal expansion coefficients of composite materials based on energy principles," *Journal of Composite Materials*, Vol. 2, 380-404.

Serhat Durmaz [2004] Ph. D thesis on "A Numerical Study on the Effective Thermal Conductivity of Composite Materials."

Ted Guo, M.L. and Tsao [2000] **"**Tribological behavior of self-lubricating aluminium/SiC/graphite hybrid composites synthesized by the semi-solid powder-densification method," *Composites Science and Technology*, Vol. 60, Issue 1, 65-74.

Weidenfeller and Hofer [2004] "Thermal conductivity, thermal diffusivity and specific heat capacity of particle filled polypropylene," *Applied Science and Manufacturing*, Part A 35, 423-429.

Zhang and Wu [2004] "Microstructure and thermal conduction properties of an Al-12 Si matrix composite reinforced with dual sized SiC particles," *Journal of Materials Science*, Vol. 39, 303-305.

Zhu Xiao-min, Yu Jia-kang and Wang Xin-yu [2012] "Microstructure and properties of Al/Si/SiC composites for electronic packaging," *Transactions of Nonferrous Metals, Society of China*, 1686-1692.