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Experimental Investigation, Numerical Analysis and Validation of Empirical Models for Thermal Behaviour of Al 6061–SiC–Graphite Hybrid Metal Matrix Composites

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ABSTRACT

Metal matrix composites (MMCs) have been regarded as one of the most principal classifications in composite materials. The thermal characterization of hybrid MMCs has been increasingly important in a wide range of applications. The coefficient of thermal expansion (CTE) and thermal conductivity are regarded as the most important properties of MMCs based on thermal behaviour. Since nearly all MMCs are used in various temperature ranges, measurement of 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 expansivity and thermal conductivity has been accomplished for Al 6061, silicon carbide and graphite hybrid MMCs from room temperature to 300°C. Aluminium-based composites reinforced with silicon carbide and graphite particles have been prepared by stir casting technique. The thermal expansivity and thermal conductivity of hybrid composites with different percentage compositions of reinforcements have been investigated. The results have indicated that the thermal expansivity of the different compositions of hybrid MMCs decreases by the addition of graphite with silicon carbide and Al 6061. Few empirical models have been validated for the evaluation of thermal expansivity and thermal conductivity of composites. Using the experimental values, namely modulus of elasticity, Poisson ratio and thermal expansivity, computational investigation has been carried out to evaluate the thermal parameters, namely thermal displacement, thermal strain and thermal stress. The thermal conductivity of hybrid composites with different percentage compositions of reinforcements has been investigated using laser flash technique. The results have indicated that the thermal conductivity of the different compositions of hybrid MMCs decreases by the addition of graphite with silicon carbide and Al 6061. Using the experimental values, namely density, thermal conductivity, specific heat capacity and enthalpy at varying temperature ranges, computational investigation has been carried out to evaluate the thermal gradient and thermal flux.

Keywords: *computational, reinforcements, thermal characterization, thermal conductivity, thermal expansivity, thermal flux and thermal gradient, thermal strain, thermal stress*

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INTRODUCTION

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

Aluminium alloy is generally used in automotive sector as it encompasses with excellent mechanical properties, better corrosion resistance and wear, low melting point compared to other materials. The most prominent property of this material is lightweight and low production cost, which will attract the researchers from all perspectives [2, 3]. Among modern composite materials, particle-reinforced aluminium matrix composites (AMCs) are finding increased application due to their resourceful mechanical properties and good wear resistance. 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 composites. Particle or discontinuously reinforced AMCs have become very important because they are economical when compared to continuous-fibre-reinforced composites, and they have relatively good isotropic properties compared to fibre-reinforced composites [3, 4]. These materials have captivated the attention of researchers and manufacturers all over the world because of their outstanding properties such as high-strength-to-weight ratio, improved wear and elevated temperature resistance, and low density. These materials are comparatively easier to manufacture than the continuously reinforced composites and have a great potential to be available at low cost [1–5].

MMCs have been exceedingly constructive 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 numerical post-processes. It helps 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 behaviours of MMCs. Aluminium is well known as a matrix material that possesses high magnitude of CTE. Thus silicon carbide (SiC) particles in aluminium matrix have been considered as a role of CTE reduction in Al/SiC system. 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. 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 realized if big series of numerical experiments for different materials and microstructures can be carried out quickly, systematically and automatically [5–9]. Some of the important papers concerning with computational investigation of composites have been discussed in this section:

Aluminium–silicon carbide composites are attractive with many exceptional features, including higher thermal conductivity, lower thermal expansivity and low density. With any aluminium matrix alloy, the addition of silicon carbide will augment thermal conductivity and flexural strength [6]. The addition of graphite particles to aluminium alloys and composites improves sliding wear and seizure resistance compared to non-reinforced aluminium alloys and composites that do not contain graphite. Aluminium–graphite composites have been expansively used in a large number of automobile components like cylinder liners, pistons and various types of brakes, air diffusers and bushings [6–8]. In the present work, anticipation has been made to investigate and characterize the thermal properties of HMMCs involving Al 6061 and silicon carbide with the addition of graphite [9–11].

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 parameters of composites, namely thermal conductivity and thermal diffusivity will benefit to evaluate heat capacity, variation in the intensity of heat, heat diffusion and heat release rate. For aerospace and automotive applications, low CTE, 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 HMMCs is laser flash apparatus. Computational investigation of MMCs has been accomplished using finite element modelling using ANSYS.

Nam et al. [5] have explored the modelling and numerical computation of thermal expansion of AMC with densely packed SiC particles. In this paper, the physical CTE of AMC 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° to 500°C using FEA based on two-dimensional (2D) unit-cell models. A comparison of physical CTE with the experimental results showed better and satisfactory results.

Yu et al. [6] have carried out investigation on thermal properties of Al/SiC MMC 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.

Mishnaevsky [7] 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.

Grujicic et al. [8] have accomplished the computational investigation of structural shocks in Al/SiC particulate MMCs. 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 MMC protective structures. This approach has been applicable to a prototypical MMC 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.

Saraev and Schmauder [9] have emphasized the finite element modelling of Al/SiC MMCs with particles aligned in stripes based on 2D and 3D comparisons. 3D 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.

Davis et al. [10], in their paper, have elucidated that the thermal conductivity of MMCs 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 FEA. 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.

Okumus et al. [11] have explored the behaviour of thermal expansion and thermal conductivity of aluminium–silicon/silicon carbide/graphite hybrid MMCs. It has been emphasized that aluminium–silicon-based hybrid composites reinforced with the particles of silicon carbide and graphite have 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 and 53 μm silicon-carbide-reinforced composites.

Molina and Rheme [12] 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 scheme considering a finite interfacial thermal resistance.

Parker et al. [13] 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.

Chen et al. [14] have carried out a detailed investigation on the behaviour of thermal conductivity of MMCs 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 have been presented. Major factors controlling the thermo-physical properties have been discussed in detail.

Weidenfeller and H [15] 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 with different fillers of varying volume fractions have 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.

It is evident from the literature review that AMCs possess extensive applications. However, investigations concerning with the thermal analysis and characterization of composite materials of AMCs are inadequate. The summary of literature review can be summarized as follows. Many experimental investigations have been carried out in the field of thermal analysis and characterization of aluminium–silicon carbide composites, but very limited work has been accomplished pertaining to aluminium–silicon carbide–graphite hybrid MMCs.

The literature review has indicated clearly the potential prospects of further investigations on thermal analysis and characterization of AMCs. From the literature review, it is absolutely clear that the investigation pertaining to AMCs 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. In the present scenario, research work accomplished on hybrid composites based on mechanical and tribological properties has been accomplished substantially, but extremely inadequate research has been carried out on aluminium–silicon carbide–graphite hybrid composites concerning with thermal analysis and characterization. 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 fractions [10]. But, very limited work has been carried out on thermal analysis and characterization of Al 6061 with silicon carbide (SiC) and graphite (Gr) based on low- and high-weight fractions of HMMCs. Hence, graphite (Gr) has been reinforced concurrently with silicon carbide considering lower weight fractions of the 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.

MICROSTRUCTURAL ANALYSIS OF COMPOSITES

Microstructural analysis of HMMCs has been carried out using scanning electron microscope. The specimens have been polished and etched as per standard metallographic procedure. The microstructure of the hybrid composites has been carried out for Al 6061 and reinforcements, namely silicon carbide and graphite, by varying the volume fraction. The microstructural analysis of the hybrid composites has been advantageous to study the morphology, cohesive interfacial bonding, particle size and presence of porosity. This helps to understand the distribution of reinforcements, namely silicon carbide and graphite, with the matrix alloy Al 6061. It has been accounted in the literature that the evaluation of the distribution of reinforcements and porosity is favourable to carry out thermal analysis and characterization of composites [10]. Figures 1–5 show the micrographs of the different compositions of the HMMCs.

Figure 1 depicts the micrograph of Al 6061 with no reinforcements. Figures 2–5 represent the micrographs of Al 6061 with the addition of reinforcements, silicon carbide, of varying weight fractions 1.25%, 2.5%, 3.75% and 5%. It has been observed that the dark patches indicate the presence of graphite and white patchy layers reveal the presence of silicon carbide. It has been examined that, with the addition of silicon carbide and graphite of varying weight fractions, the distribution of the reinforcements has been homogeneous with the absence of cracks, non-existence of parallel striations and detrimental pores. It has been reported in the literature that, when the volume fraction of the reinforcements is higher, the uniform dispersoid distribution has been obtained by melt stirring for a slightly longer time [11–13].

In this research, the porosity has been investigated both experimentally and theoretically. Using water displacement method based on Archimedes principle, experimental values of the density of the hybrid composites have been evaluated and the theoretical values of the density have been computed using Rule of Mixtures (ROM). It has been noticed that the difference of the experimental and theoretical densities of the composites is very marginal and hence the porosity has been negligible. Figures 2–5 characterize that strong cohesive interfacial bonding between the matrix alloy and reinforcements has been accomplished due to the variation in the weight fractions of the reinforcements. Also, due to the variation in weight fractions 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 eventuate due to the deficient stirring speed and duration of stirring, and the presence of porosity may be featured to the amount of dissolved gases [6, 9]. The particle sizes of the hybrid composites with varying weight fractions 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. 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 has severely deteriorated the thermal and mechanical properties of MMCs [9]. It has been stated that, due to the increase in volume fraction of the reinforcements, the distribution is more reliable with negligible porosity [18]. It has been illustrated in the literature that the microstructures of aluminium–silicon carbide–graphite HMMCs have been beneficial for mechanical characterization [19–21]. It has been proved that, by the addition of silicon carbide with aluminium can noticeably improve the flexural strength, modulus of elasticity, thermal conductivity and distribution of stress [22, 23].

EXPERIMENTAL INVESTIGATION ON COEFFICIENT OF THERMAL EXPANSION USING DILATOMETER

In this research work, the coefficient of thermal expansion (CTE) is determined using Linesis 75 Horizontal Platinum Dilatometer. The CTE has been considered as one of the most important properties of MMCs. The CTE values have a stronger dependence on particle volume fraction than the wall thickness in the range of temperatures explored. The thermal expansion results with the variation of temperature for the composites and the matrix has been shown for different percentage composition. It is obvious that the CTE of the composites and matrix increases with the increase in temperature.

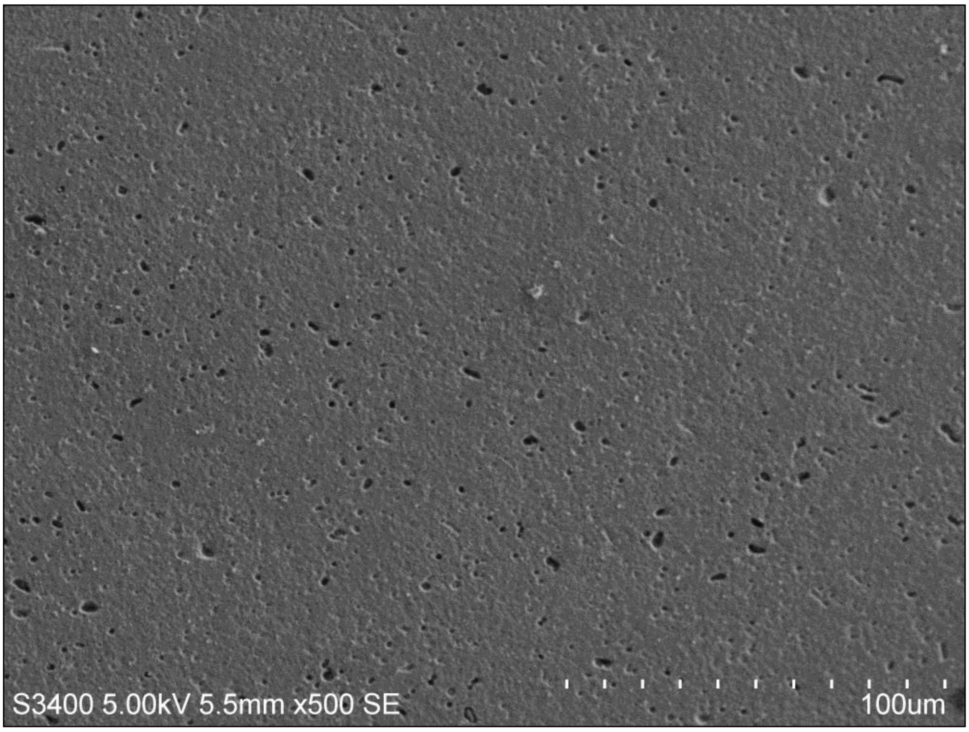

Fig. 1. *Microstructure of Al 6061.*

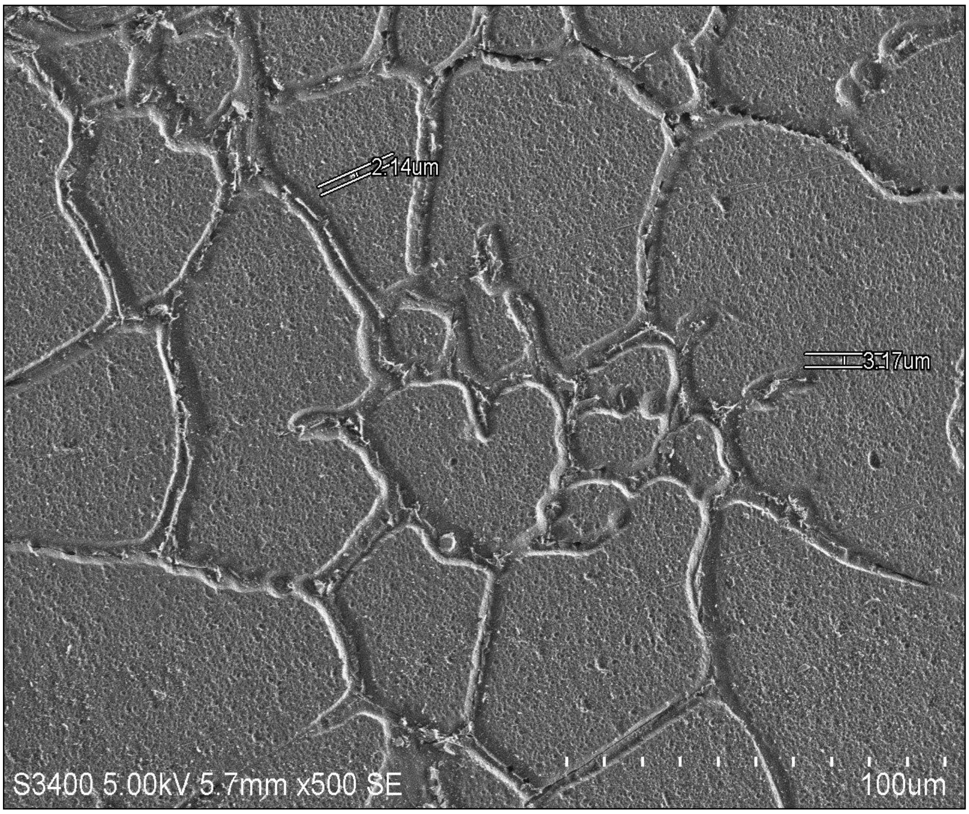

Fig. 2. *Microstructure of Al 6061 with 1.25% silicon carbide and 1.25% graphite.*

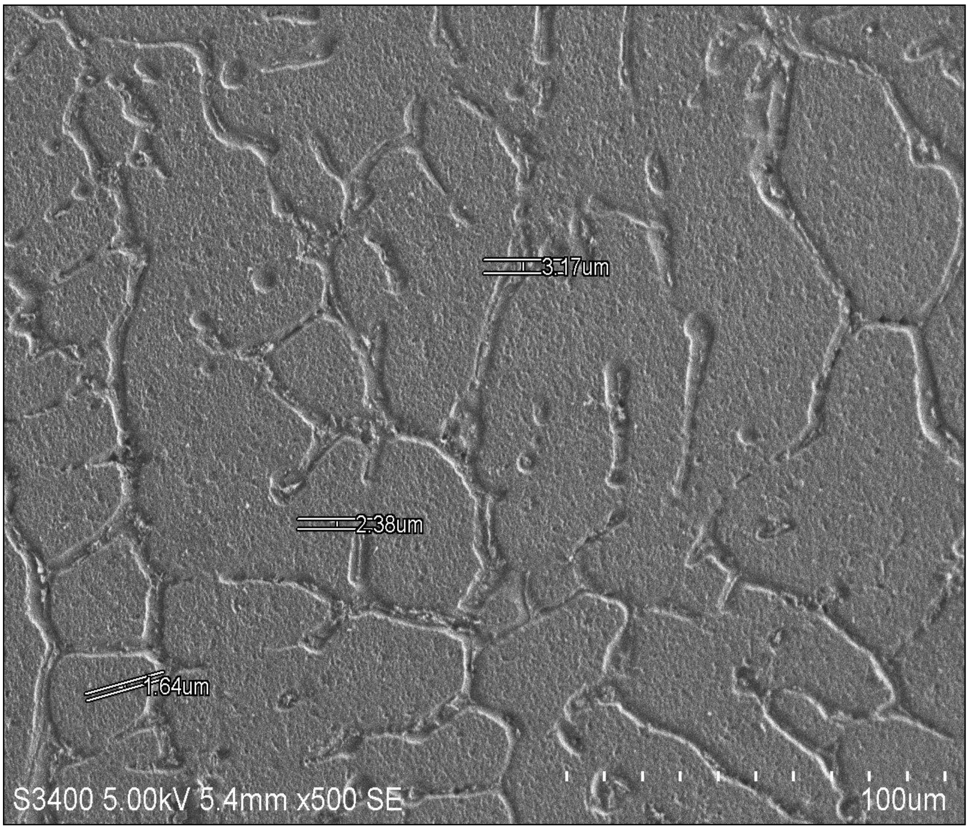

Fig. 3. *Microstructure of Al 6061 with 2.5% silicon carbide and 2.5% graphite.*

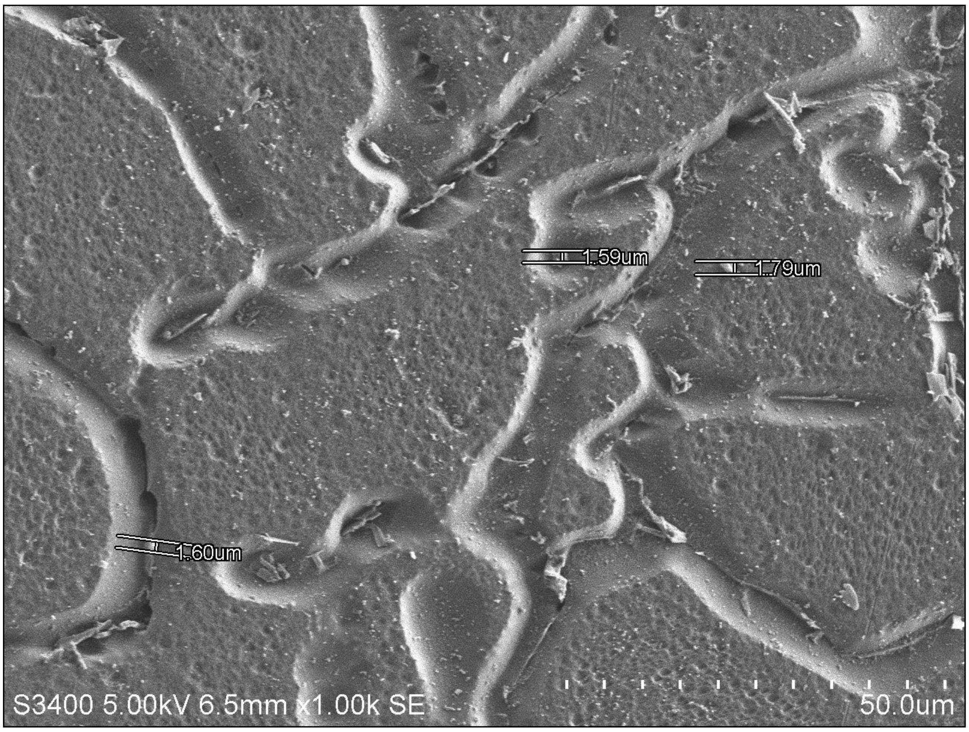

Fig. 4. *Microstructure of Al 6061 with 3.75% silicon carbide and 3.75% graphite.*

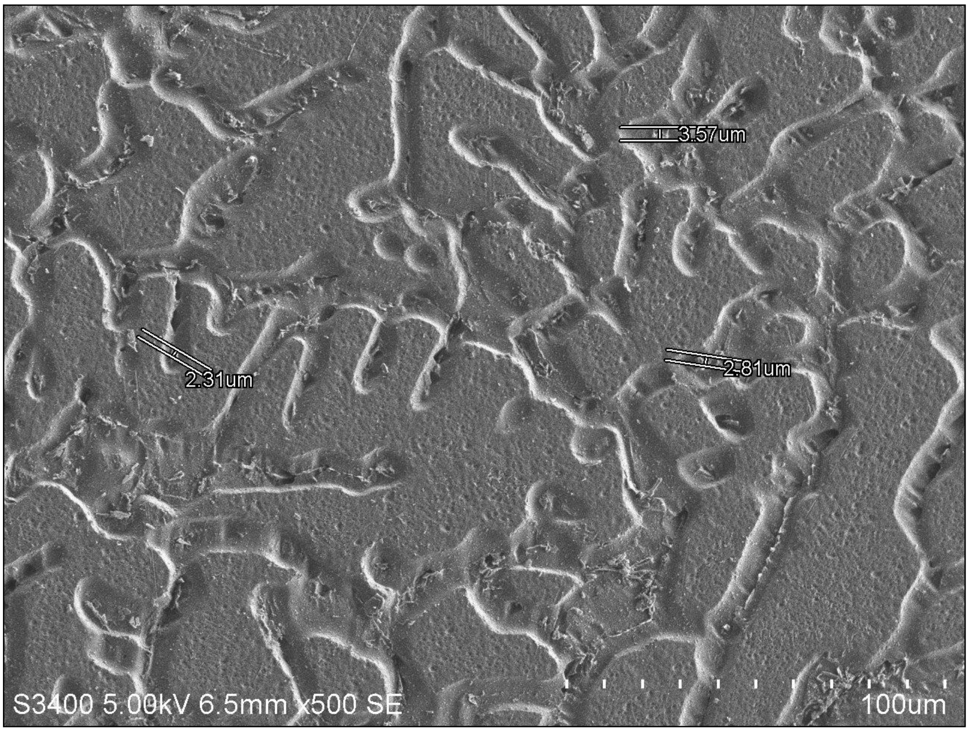

Fig. 5. *Microstructure of Al 6061 with 5% silicon carbide and 5% graphite.*

For the determination of CTE, the size of the cylindrical sample is diameter 5 mm and length 10 mm. Five samples are considered with different percentage compositions. Al 6061 is the base alloy and reinforcements, silicon carbide (SiC) and graphite (Gr), with different percentage compositions 1.25%, 2.5%, 3.75% and 5% are selected. 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 fractions [18, 25]. But, very limited work has been carried out on thermal analysis and characterization of Al 6061 with silicon carbide and graphite based on low- and high-weight fractions of HMMCs. Hence, graphite (Gr) has been reinforced concurrently with silicon carbide considering lower weight fractions of the hybrid composites. All the specimens have been tested from room temperature to 300°C. This temperature range has been selected so as to include the entire usable range of the composites, without the formation of liquid phase in the matrix. The data has been obtained in the form of per cent linear change versus temperature. Standard data analysis software was used to evaluate the CTE of the composites tested and was determined at intervals of 20°C. Some of the salient parameters considered during the determination of CTE are sample length, relative density of the samples and sintering temperature. The melting point of aluminium is 560°C. But during the testing process, it has been limited to 300°C, as there is greater possibility of reaching molten condition.

Figure 6 depicts the variation of CTE and temperature for different compositions of hybrid MMC. It has been noticed that the magnitude of CTE of the hybrid composites with different percentage compositions increases with the increase in temperature. From Figure 6, it has been observed that Al 6061 exhibits maximum thermal expansivity. Generally, the thermal expansivity increases as the temperature increases 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 expansivity at maximum temperature for the different percentage compositions of HMMCs. Addition of graphite with aluminium matrix alloy and silicon carbide with varying volume fraction resulted in the reduction in thermal expansivity of the HMMCs. The magnitude of CTE of graphite is very low compared to Al 6061 and silicon carbide. It has been reported in the literature that the thermal expansivity for HMMCs considerably increases by reinforcing silicon carbide over the different range of temperatures [21]. It has been inferred in the experimentation that the reinforcement of graphite with aluminium–silicon and silicon carbide does not enhance thermal expansivity, thermal conductivity and thermal diffusivity significantly [10]. It has been examined that addition of silicon carbide and graphite reinforcements with high volume fraction results in higher values of thermal capacity, thermal expansivity and thermal conductivity [8, 10, 26–28].

EXPERIMENTAL INVESTIGATION ON THERMAL DIFFUSIVITY AND THERMAL CONDUCTIVITY OF HYBRID COMPOSITES

The thermal diffusivity has been measured using a NETZSCH model LFA 447 Nano Flash diffusivity apparatus. The unit used in this work has been equipped with a furnace, capable of operation from 25° to 300°C. The system has been equipped with a software-controlled automatic sample changer allowing measurement of up to four samples at the same time. The temperature rise on the back face of the sample is measured using an infrared detector. Data acquisition and evaluation have been accomplished using a comprehensive 32-Bit MS-Windows software package. Various analysis models have been integrated in the software. The instrument has been designed to carry out tests fully automatically [29, 30]. The LFA

447 operates in accordance with national and international standards such as ASTM E-1461, DIN 30905 and DIN EN 821.

For the determination of thermal conductivity and thermal diffusivity, the sample should be disc-shaped and the 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 different percentage compositions or weight fractions 1.25%, 2.5%, 3.75% and 5% have been selected. 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 fractions [10, 21–23]. All the specimens have been tested from room temperature to 300°C. This temperature range have 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 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.

Figure 7 depicts the variation of thermal conductivity and temperature for the different compositions of HMMCs. Figure 8 indicates the variation of thermal diffusivity and temperature for the different compositions of HMMCs. The different samples have been tested from room temperature to 300°C using laser flash apparatus. From Figure 7, it has been observed that Al 6061 exhibits maximum thermal conductivity with 168 W/mK. Generally, the thermal conductivity increases as the temperature increases 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 conductivity and thermal diffusivity at maximum temperature 300°C for the different percentage compositions maintaining low-weight fractions of HMMCs. It has been reported in the literature that the thermal conductivity considerably increases by reinforcing silicon carbide with aluminium alloy over the different range of temperatures [10]. From the literature, it is clear that the addition of silicon carbide with aluminium will increase the thermal conductivity gradually [10]. But from the present experimental investigation, it has been comprehended that, by the addition of graphite with silicon carbide and Al 6061, there is no substantial variation in thermal conductivity.

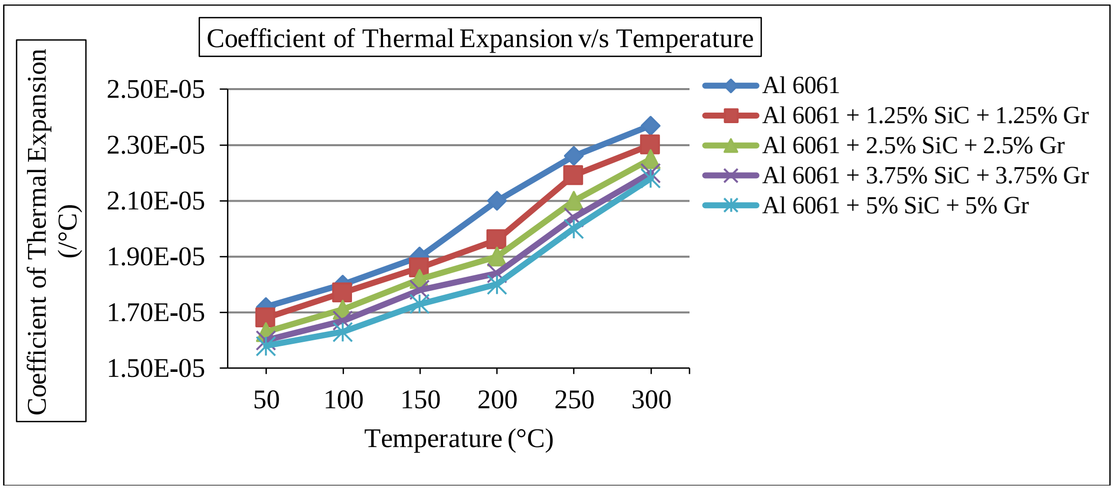

Fig. 6. *Variation of CTE vs. temperature for different compositions of hybrid composites.*

This has proved that, the addition of reinforcements, silicon carbide and graphite, has insignificant influence in the increase of thermal conductivity. It has been reported that the thermal conductivity of graphite is very low compared with aluminium and silicon carbide. The result indicated that graphite content improves the dimensional stability, and there will be no variation in the thermal behaviour of hybrid composites. The term "dimensional stability" refers that the thermal strain and particle sizes of the hybrid composites, namely Al–Si/SiC/graphite has been increased depending on the amount of graphite added and has benefitted in achieving better dimensional stability [10]. Based on these investigations, it can be concluded that the thermal conductivity of hybrid composites reduces due to the enrichment of graphite content. It can be concluded 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 with almost negligible porosity. The volume fraction of silicon carbide is indeed the main factor contributing to the thermal conductivity of MMC. When the MMC undergoes heating process, expansion and deformation processes occur steadily. From literature, aluminium–silicon carbide composites are attractive with many outstanding features, including higher thermal conductivity, lower thermal expansivity and low density. With any aluminium matrix alloy, the addition of silicon carbide will enhance thermal conductivity and flexural strength [11, 13, 23].

It has been reported in the literature that the dependence of the overall thermal conductivity on the particle diameter for spherical particles of equal size has been investigated with several predictions. This is due to the decrease of the thermal conductivity values with the decreasing grain size of different compositions of silicon carbide, which can be attributed to the interfacial properties between the aluminium matrix and silicon carbide. It is apparent that decreasing the grain size results in a larger surface area between aluminium matrix and 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 MMCs, SiC and graphite particles that 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 diminishes thermal diffusivity. The decrease in thermal diffusivity dominates the temperature dependence of thermal conductivity in the high-temperature region. The specific heat decreases strongly at temperatures below room temperature and dominates the temperature dependence of thermal conductivity [10].

MATHEMATICAL VALIDATION OF EMPIRICAL MODELS

Theoretical prediction of thermal expansivity and effective thermal conductivity for multi-phase composite materials is very constructive for analysis and optimization of the material performance and for new material designs. Numerous experimental studies have been carried out to investigate the thermal expansivity of MMCs reinforced with isolated particles. Many empirical models, namely ROM, Turner, Kerner and Schapery, have been developed to understand the thermal expansion behaviour of MMCs. Although these models can be used to predict the dependence of CTE of particle-reinforced metals on the reinforcement content, they do not take into consideration the case for which the reinforcing particles are interconnected or the presence/effects of voids generated during the processing of the composites [28–32].

To understand the behaviour of thermal expansion of the hybrid composites, several existing theoretical models of composites have been compared. When the interfaces are free to slide and the constituent phases are free to flow, the CTEs of the composites can be expressed by ROM. For a composite with perfect interfacial bonding between particles and matrix, Kerner's model is suitable for predicting the CTEs of composites. In Turner's model, each component of a composite undergoes a homogeneous strain throughout the composite [17]. In the present research, some of the empirical models considered in the evaluation of thermal expansivity are ROM, Kerner's model and Schapery's model. Figure 8 represents the comparison of experimental values of thermal expansivity at maximum temperature with the mathematical models. Figure 9 clearly indicates that the experimental values of thermal expansivity with varying weight fraction of composites closely match with ROM, Kerner's model and Schapery's model. It has been be inferred that, experimental data are in good argument with all mathematical models. It has been observed that, ROM exhibited the highest CTE, whereas Kerner and Schapery models exhibited lower values of CTE. It can be clearly inferred that, ROM can be adjudged as the best empirical model for the evolution of CTE.

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 [7, 8, 32–34]. 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.

In the present research, some of the empirical models considered in the evaluation of thermal conductivity are series model, Maxwell model, geometric mean model, Russell model and Rayleigh model. Figure 9 represents the comparison of experimental values of thermal conductivity at maximum temperature with the mathematical models. The experimental values of thermal conductivity of different compositions of HMMCs are compared with various mathematical models. Figure 9 clearly indicates that the experimental values of thermal conductivity with varying volume fraction of composites closely match with series model, Maxwell and Rayleigh models, whereas the values deviate with reference to geometric model. It has been inferred that experimental data are in good agreement with series model, Maxwell and Rayleigh models, but deviated from geometric model. The thermal conductivity of the hybrid compositions based on the variation in percentage volume fraction is gradually decreasing.

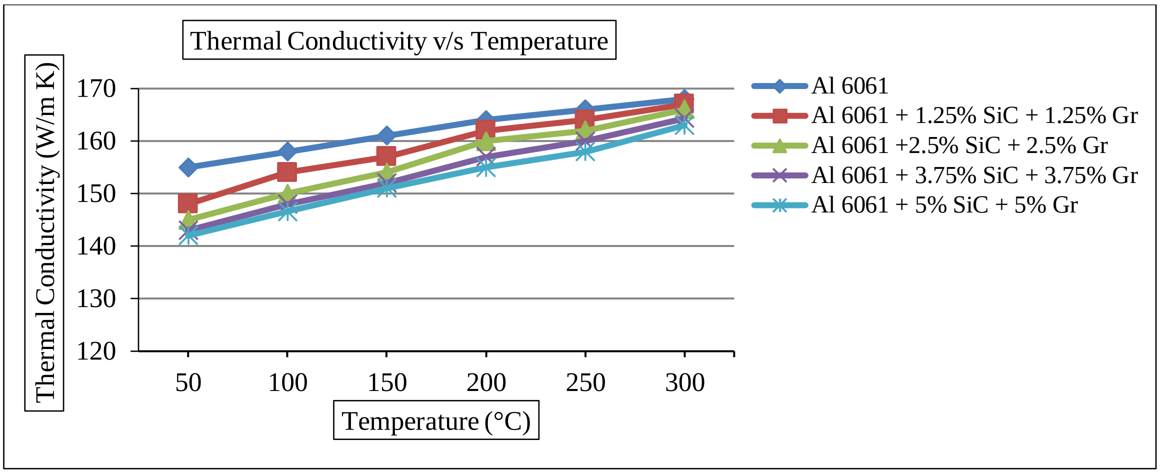

Fig. 7. *Variation of thermal conductivity and temperature for different compositions of MMCs.*

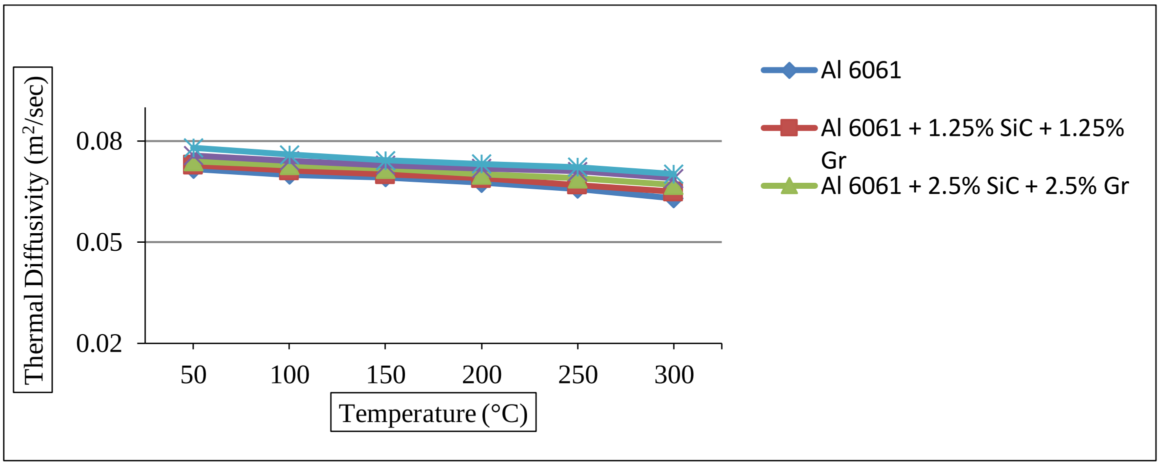

Fig. 8(a). *Variation of thermal diffusivity and temperature for different compositions of MMCs.*

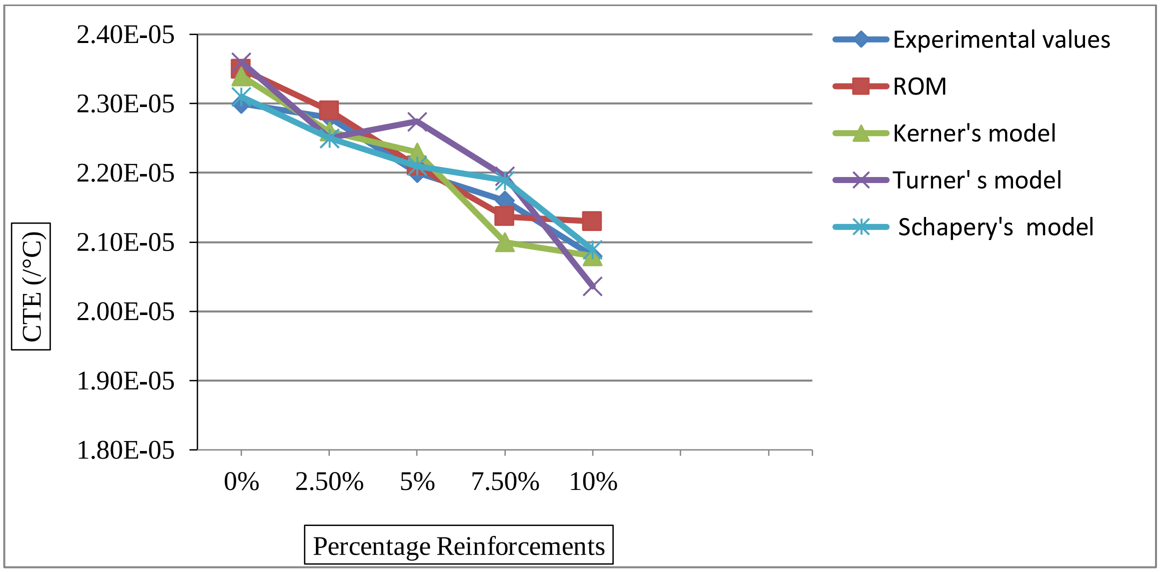

Fig. 8(b). *Comparison of the values of CTE based on experimental results and empirical models.*

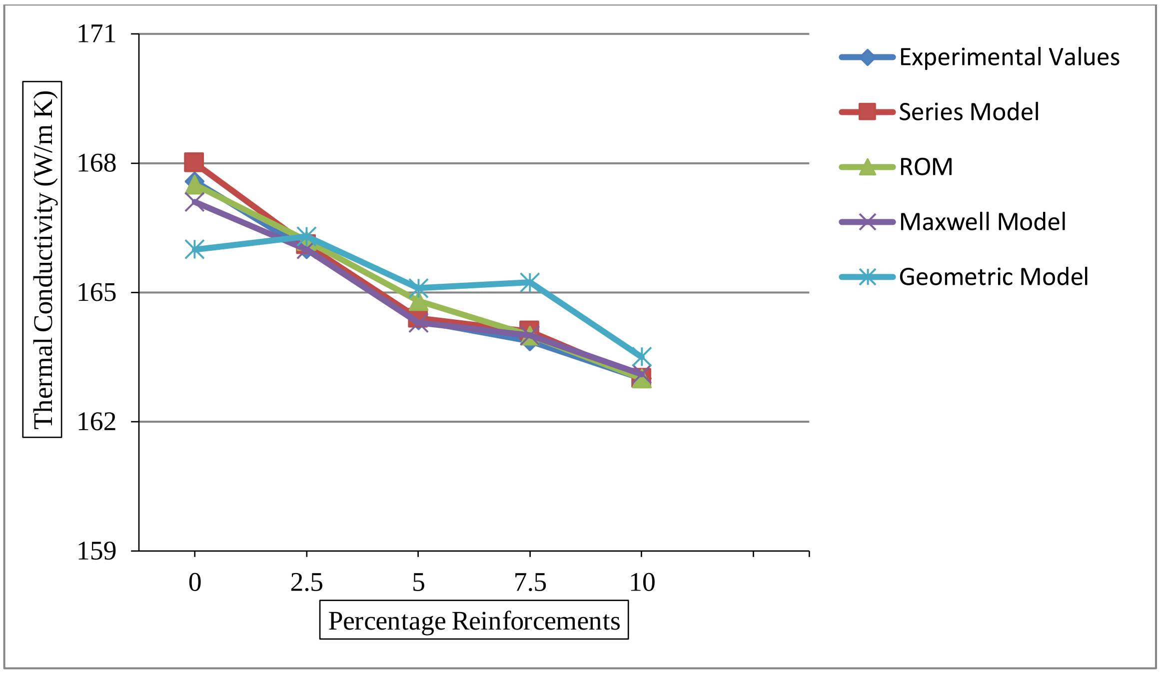

Fig. 9. *Comparison of experimental values of thermal conductivity with empirical models.*

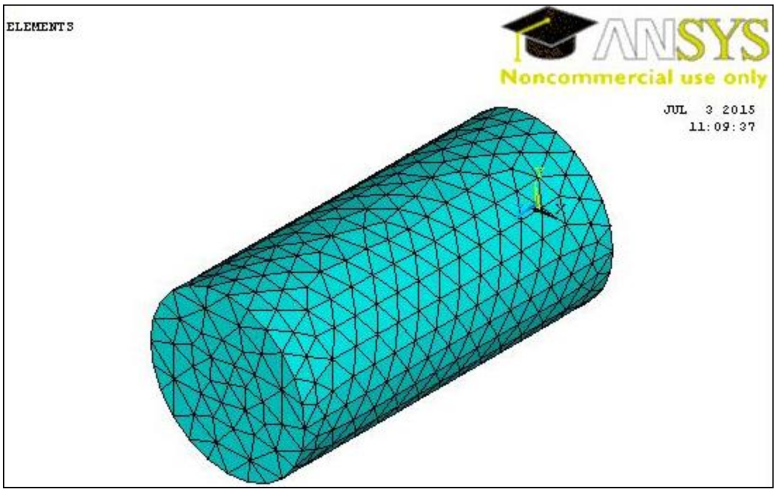

Fig. 10. *Mesh refinement/generation of the hybrid composites.*

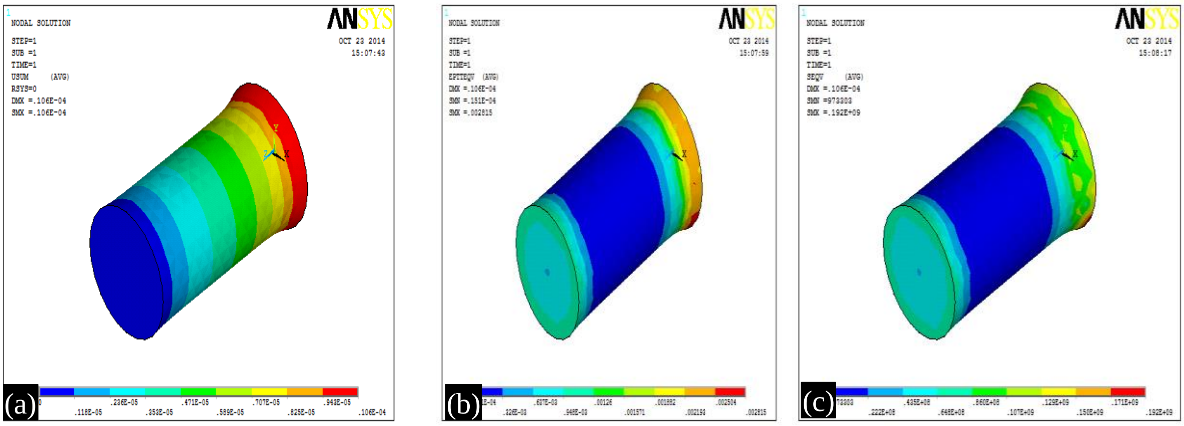

Fig. 11(a–c). *Thermal displacement, thermal strain and thermal stress for Al 6061.*

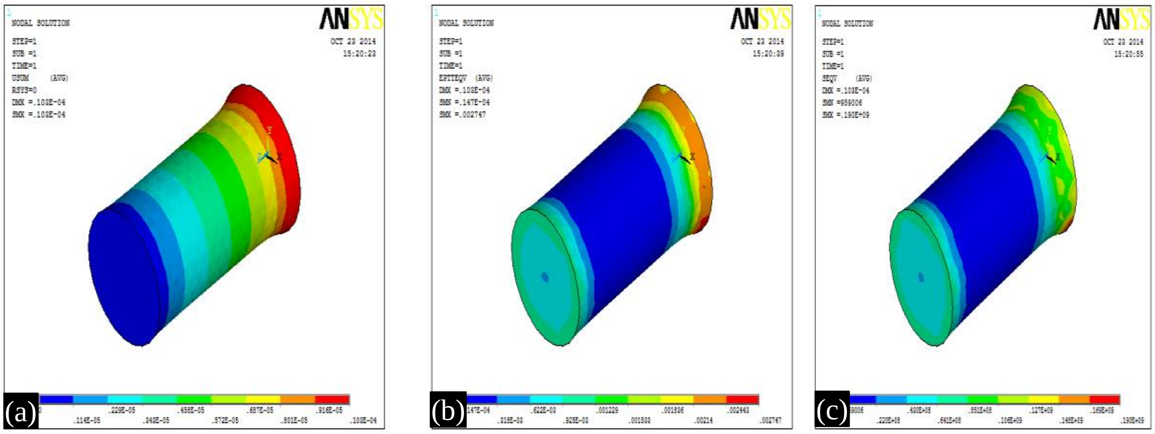

Fig. 12(a–c). *Thermal displacement, thermal strain and thermal stress for Al 6061 + 1.25% SiC + 1.25% Gr.*

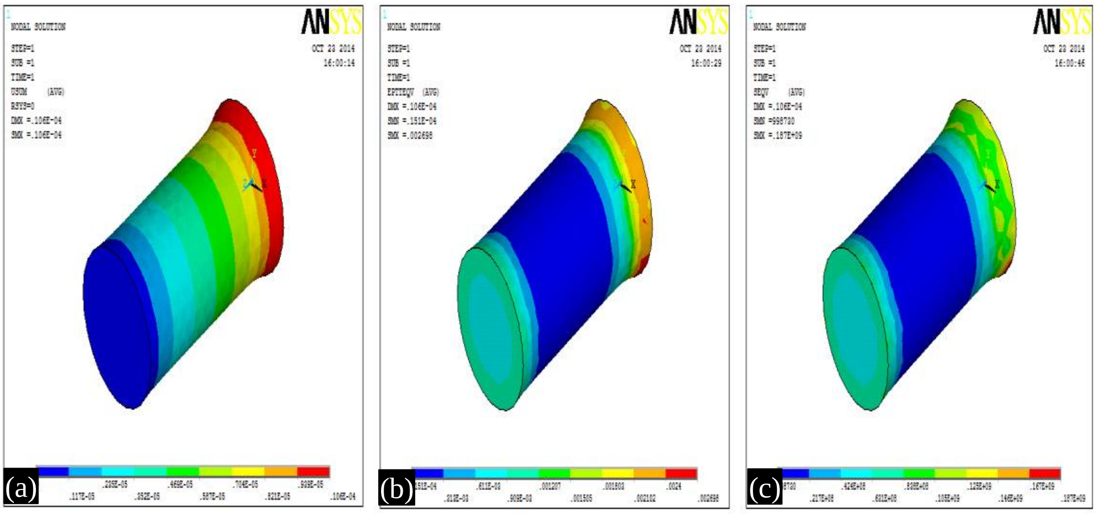

Fig. 13(a–c). *Thermal displacement, thermal strain and thermal stress for Al 6061+ 2.5% SiC + 2.5% Gr.*

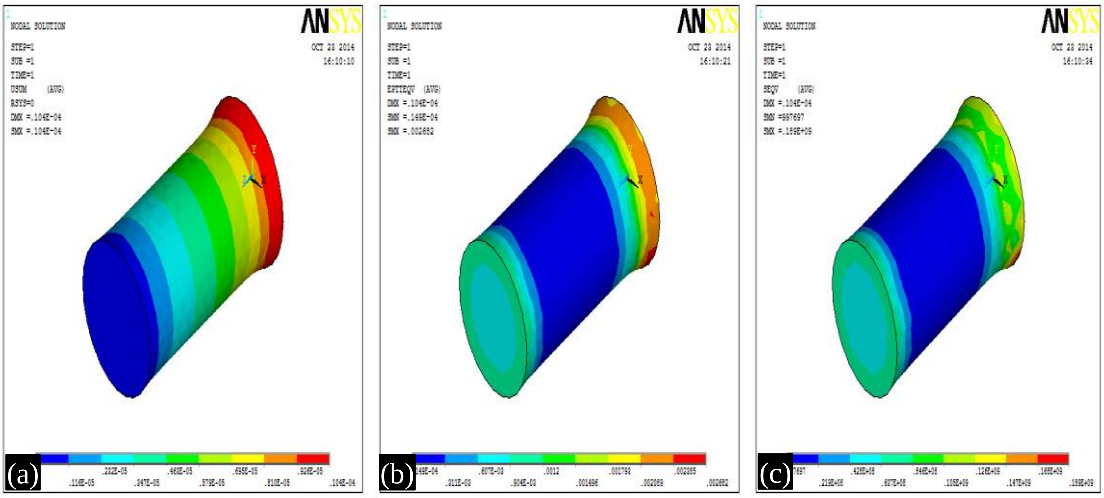

Fig. 14(a–c). *Thermal displacement, thermal strain and thermal stress for Al 6061+ 3.75% SiC + 3.75% Gr.*

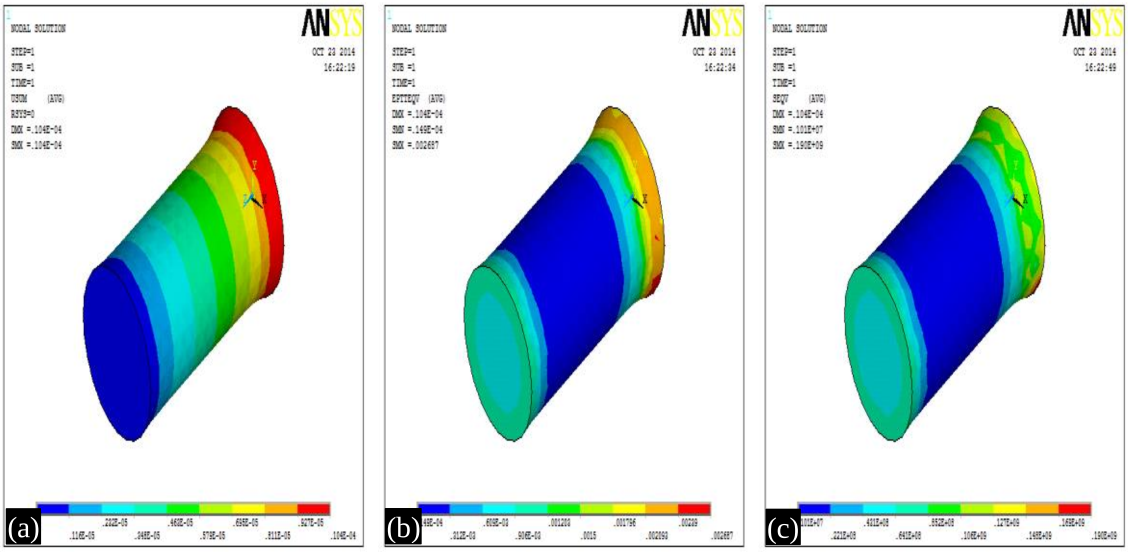

Fig. 15(a–c). *Thermal displacement, thermal strain and thermal stress for Al 6061+ 5% SiC + 5% Gr.*

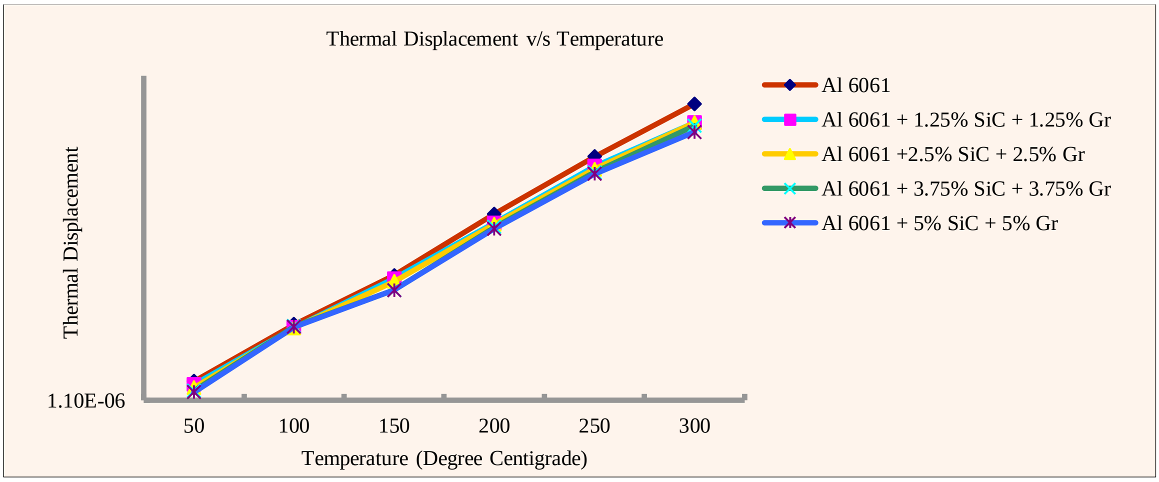

Fig. 16. *Variation of thermal displacement vs. temperature for different compositions of hybrid composites.*

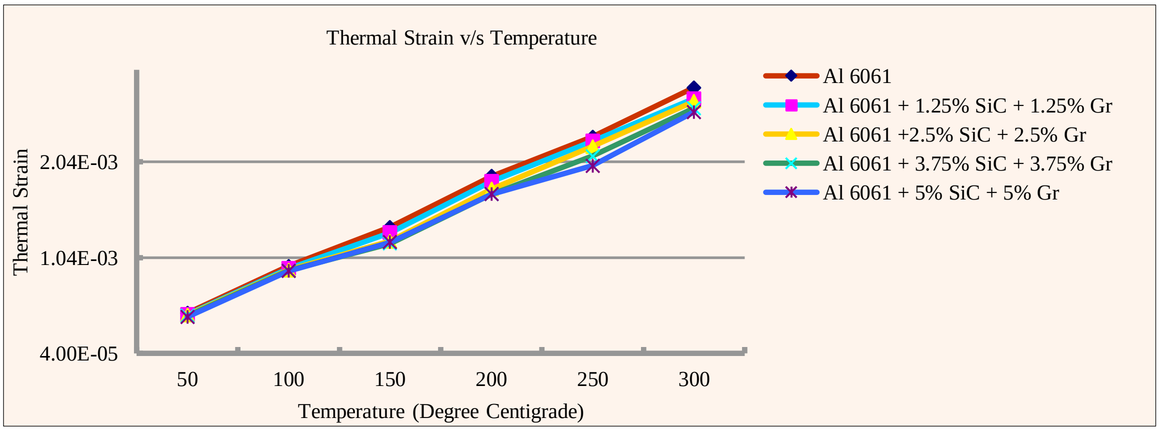

Fig. 17. *Variation of thermal strain vs. temperature for different compositions of hybrid composites.*

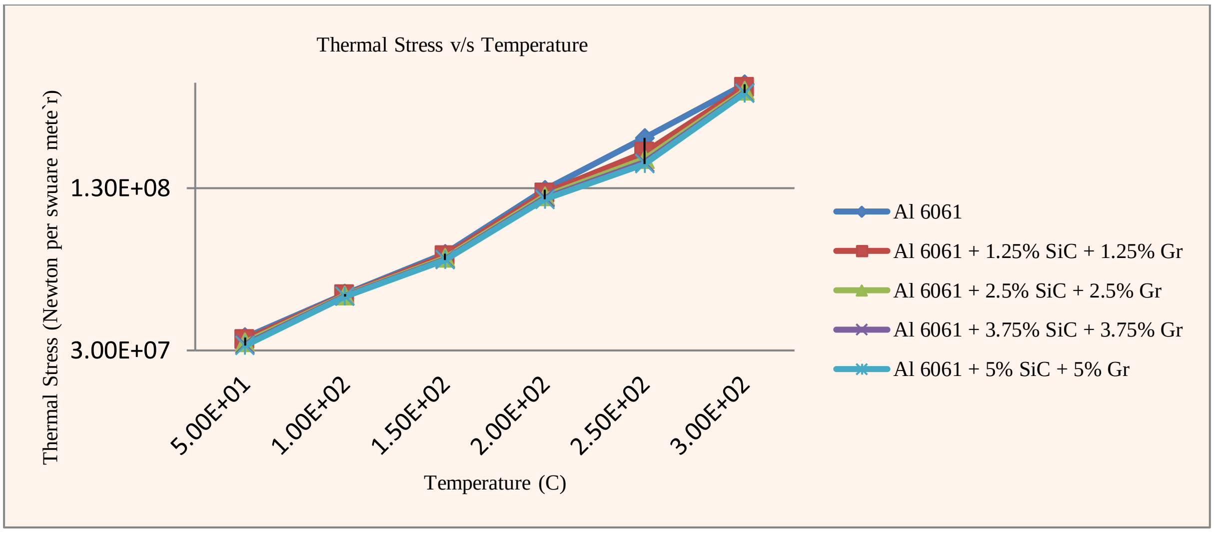

Fig. 18. *Variation of thermal stress vs. temperature for different compositions of hybrid composites.*

Table 1. *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	72
Al 6061 + 3.75% SiC + 3.75% Gr (Sample 4)	2.673	0.2945	73
Al 6061 + 5% SiC + 5% Gr (Sample 5)	2.66	0.2913	74

Table 2. *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 3. *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

The experimental values of thermal conductivity at 300°C have been referred for different hybrid compositions depending on the variation of percentage volume fraction. The thermal conductivity values are gradually decreasing with the variation in percentage volume fraction concerning with Series, Maxwell and Rayleigh models. But in geometric model, thermal conductivity is marginally deviating from experimental results due to small variation in the volume fractions of matrix and reinforcements.

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 can accomplish both thermal and stress enhancers. 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 MMC, 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.

A flourishing application of MMCs 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 has led a systematic way to many numerical and analytical techniques. FEM has been regarded as an efficient technique for the prediction and computation of the properties based on the mechanical and thermal behaviour of composites [6, 8].

In the present work, using the experimental values based on the evaluation of HMMCs, namely modulus of elasticity, Poisson ratio and thermal expansivity, the computational investigation has been accomplished to evaluate the thermal parameters, namely thermal displacement, thermal strain and thermal stress.

Figures 11–15 emphasize the various contour plots showing the distribution patterns of thermal displacement, thermal strain and thermal stress. Table 1 shows the experimental values of density, Poisson ratio and modulus of elasticity for the different percentage compositions of HMMCs. 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 has been evaluated by ROM. Tables 2 and 3 depict the comparison of computational and theoretical values of thermal strain and thermal stress of HMMCs, 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. Figure 10 depicts the mesh generation of the 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. 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 [25, 4]. From Tables 2 and 3, it has been proved that the numerical and theoretical values of thermal strain and thermal stress are almost identical, 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 MMC undergoes heating process, expansion and deformation processes occur steadily. Indeed, thermal stress will be induced by the difference of lattice constants between the matrix and the particles [4, 25–27]. Figures 16–18 depict 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 the maximum thermal displacement, thermal strain and thermal stress. Generally, the thermal displacement, thermal strain and thermal stress increase as the temperature increases 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 the maximum temperature for the different percentage compositions of HMMCs. It has been comprehended that, due to the gradual decrease in thermal expansivity, the values of thermal displacement, thermal strain and thermal stress decrease. 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 HMMCs.

It has been reported in the literature that the evaluation of CTE of HMMCs is relatively difficult to predict because several factors, namely volume fraction, morphology and distribution of the reinforcements, matrix plasticity, interfacial bondage, and the internal structure of the composites, may influence the results. During the evaluation of CTE, thermal strain can be attributed to thermal stress and higher thermal stress can lead to the generation of strain between the heating and cooling cycles. The CTE of the hybrid composites is 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 [20–23].

From the literature, it has been reported that the hybrid composites have lower volume fractions of SiC than conventional Al–SiC composites with the same CTEs. The decrease in the maximum temperature for CTE values for graphite-reinforced composites is considered as a result of relaxation of the compressive stress in the matrix. The reduction in CTE values can be attributed to the lower CTE value of graphite compared to Al–Si matrix alloy and SiC reinforcement, and the ability of the reinforcements to effectively constraint the expansion of the matrix [6, 10]. 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 CTE of AMCs 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 [27–29].

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 fabrications of MMCs. In this regard, computational FEM analysis has been carried out for silicon carbide in Al 6061, which can accomplish both thermal and stress enhancers. To extend experimental information, the computational FEM on a variety of composite material systems allows MMC fabrication to be productive with empirical results and computational investigation. For the analysis of MMC, 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 [6–11].

In the present work, using experimental values of HMMCs, namely thermal conductivity, specific heat capacity and enthalpy, the computational investigation, namely thermal gradient and thermal flux, is accomplished. The mode of computational investigation adopted is “thermal” with hyperbolic-type characterization and the element type selected is Solid Brick 8node 70. Some of the major boundary conditions considered are densities, thermal conductivities, specific heat capacities and enthalpies of the different HMMCs.

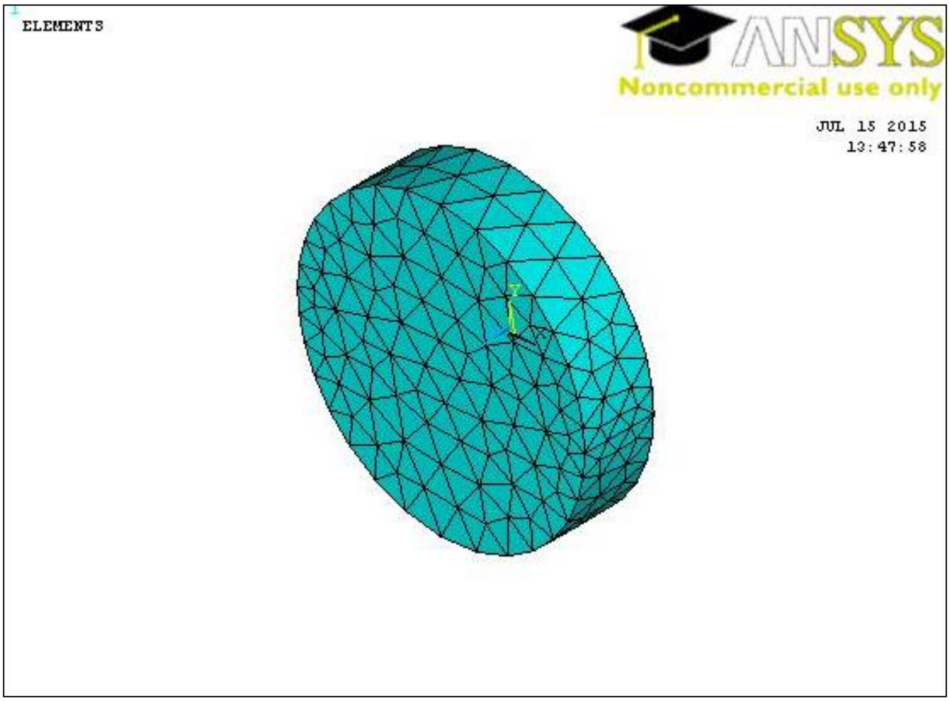

Fig. 19. *Mesh generation of hybrid metal matrix composites.*

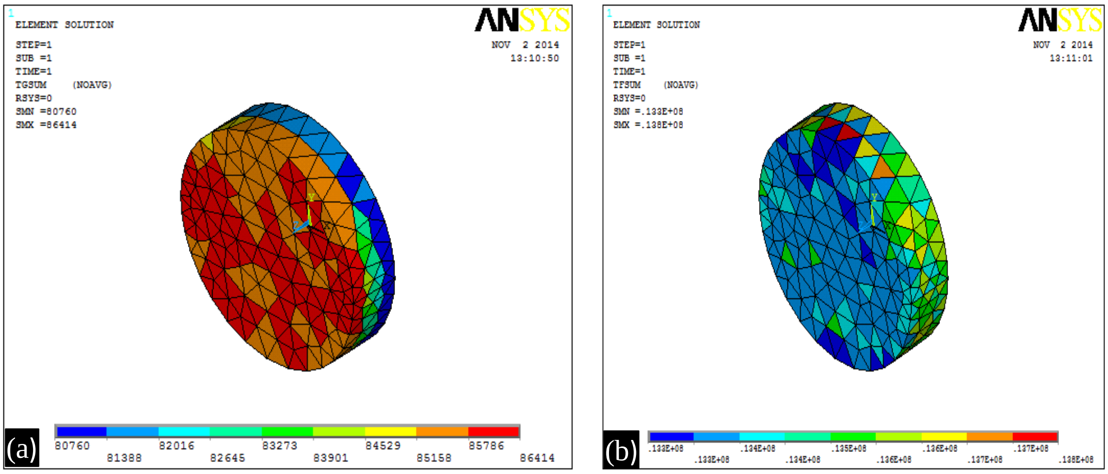

Fig. 20(a, b). *Thermal gradient and thermal flux for Al 6061.*

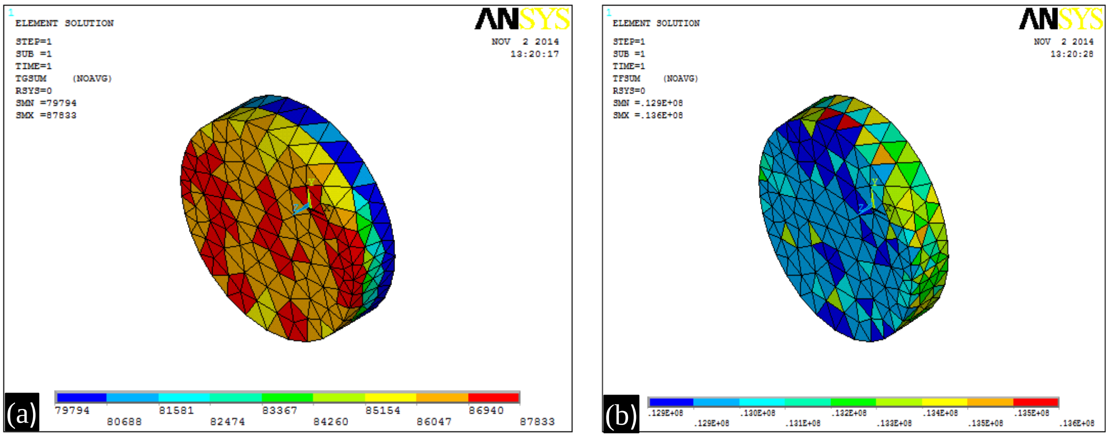

Fig. 21(a, b). *Thermal gradient and thermal flux for Al 6061 + 1.25% SiC + 1.25% Gr.*

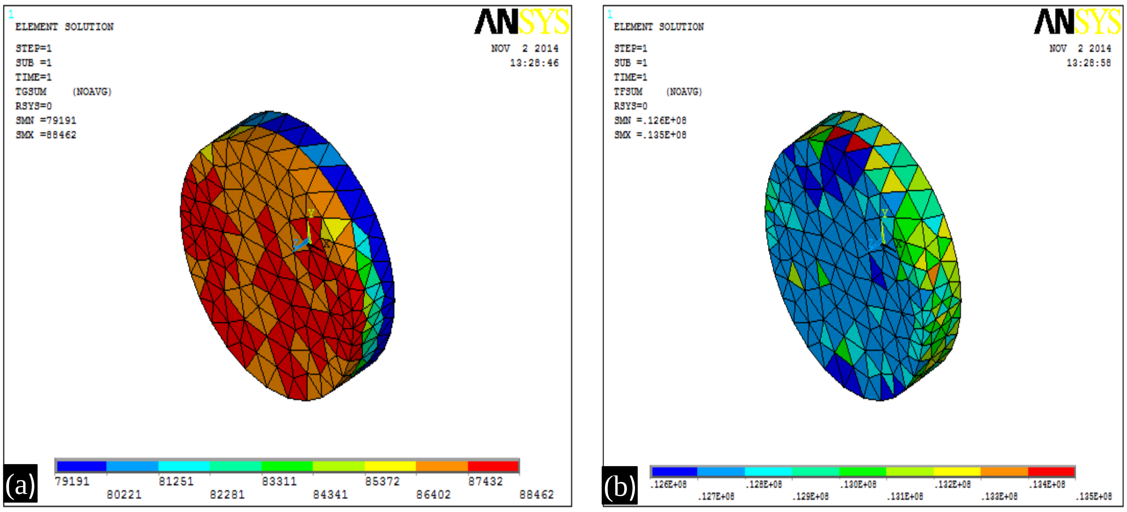

Fig. 22(a, b). *Thermal gradient and thermal flux for Al 6061 + 2.5% SiC + 2.5% Gr.*

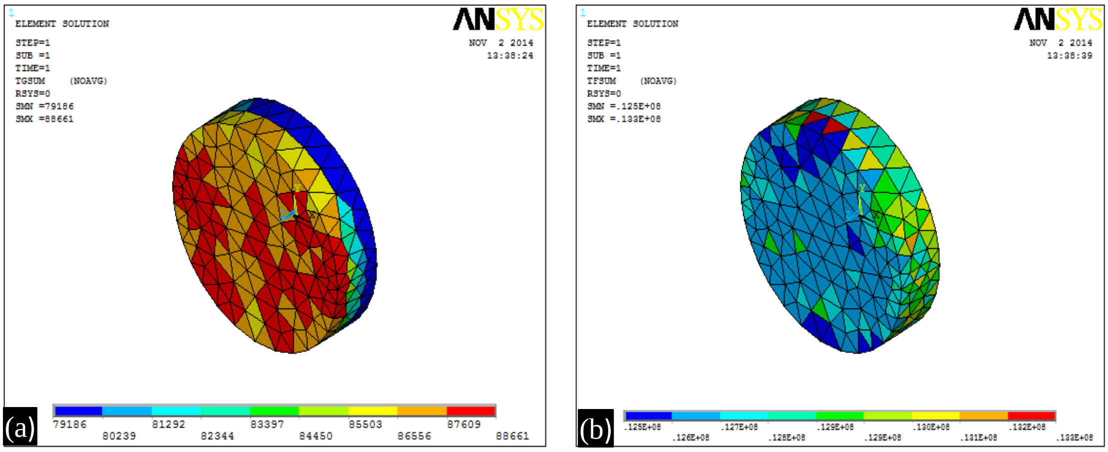

Fig. 23(a, b). *Thermal gradient and thermal flux for Al 6061 + 3.75% SiC + 3.75% Gr.*

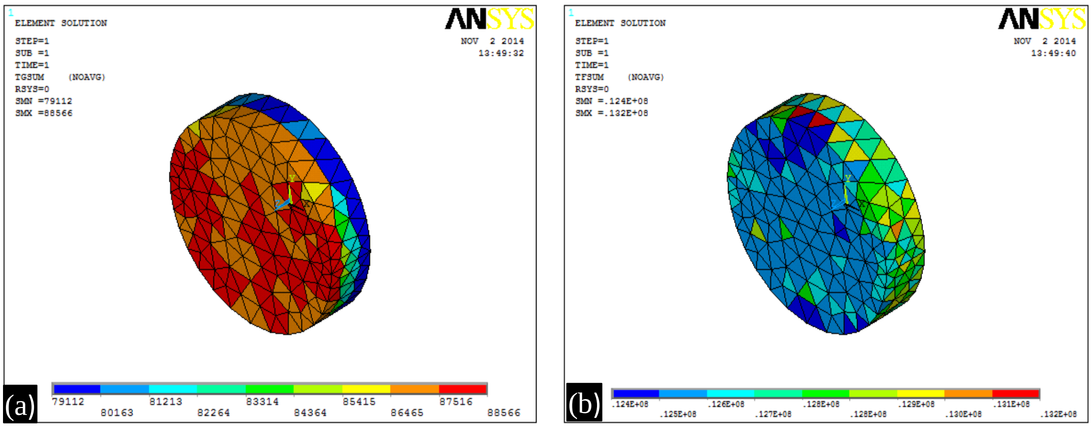

Fig. 24(a, b). *Thermal gradient and thermal flux for Al 6061 + 5% SiC + 5% Gr.*

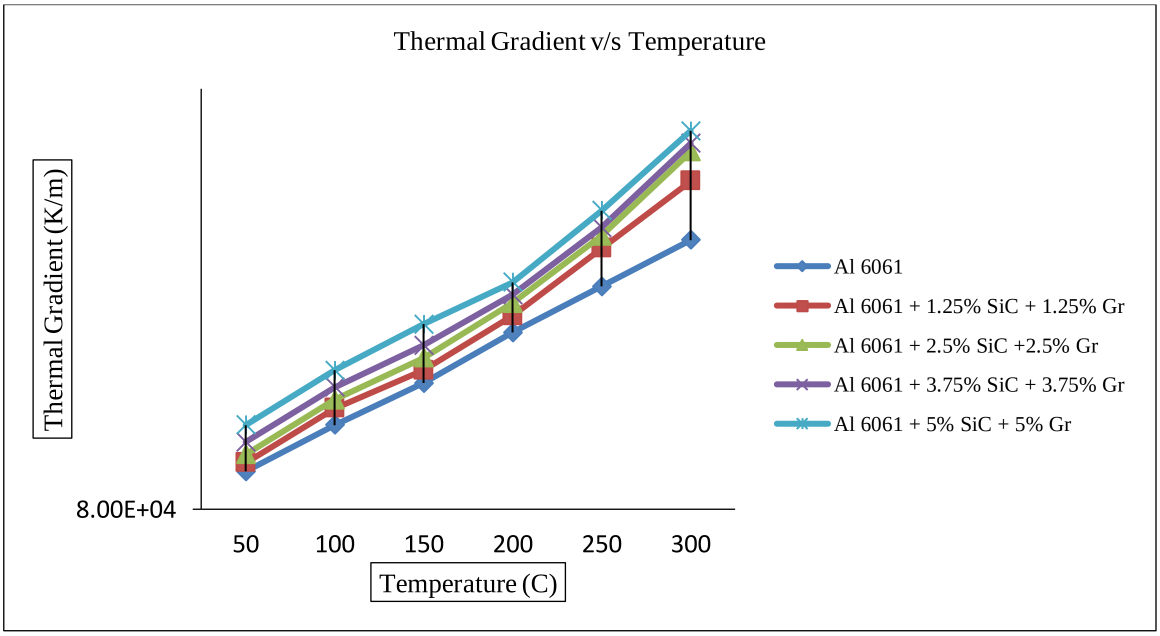

***Fig. 25**. Variation of thermal gradient vs. temperature for different compositions of hybrid composites.*

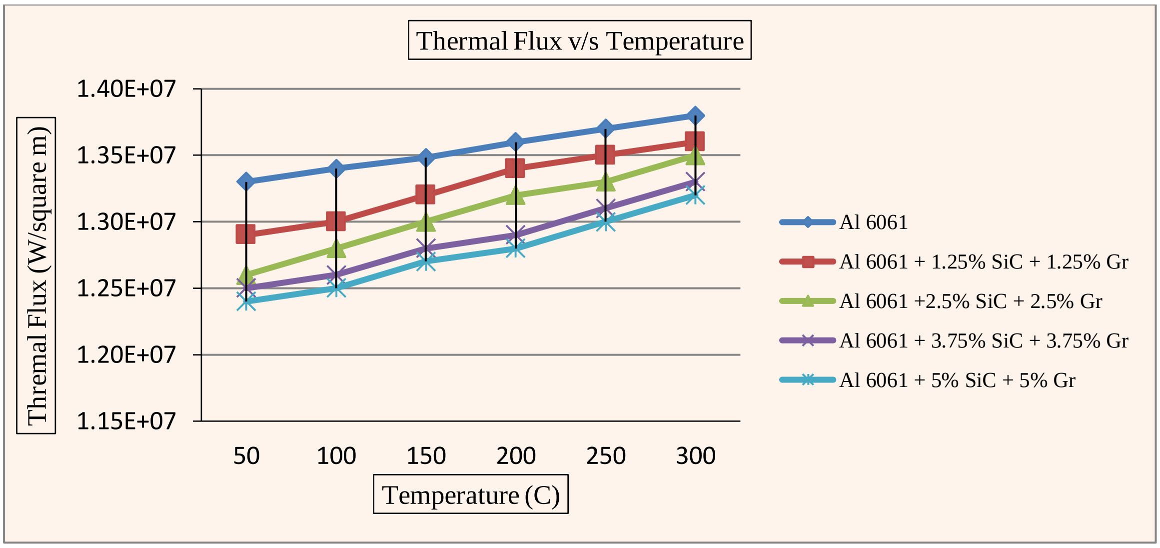

Fig. 26. *Variation of thermal flux vs. temperature for different compositions of hybrid composites.*

Table 4. *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 5. *Comparison of computational and theoretical values of thermal gradient of hybrid composites.*

Percentage composition of composites	**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 6. *Comparison of computational and theoretical values of thermal flux of hybrid composites.*

Percentage composition of composites	**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 4 emphasizes the experimental values of thermal conductivity, specific heat capacity and enthalpy for different hybrid composites obtained based on experimentation. Tables 5 and 6 depict the comparison of computational and theoretical values of thermal gradient and thermal flux of HMMCs, respectively. To enhance the computational accuracy of the results, a finer mesh density has been used, which has been arrived through numerical convergence. Figure 19 depicts the mesh generation of the 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. 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 [31, 32]. Figures 20–24 indicate the contour plots concerning with thermal gradient and thermal flux that have been obtained computationally for the different percentage compositions of HMMCs using ANSYS 12. Figures 25 and 26 depict 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 the thermal gradient [6, 8]

From Figures 25 and 26, it has been observed that, displacement refers to 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 HMMCs. 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 HMMCs decreases drastically resulting in the 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 HMMCs, 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 [6,].

CONCLUSIONS

In this research work, experiments have been carried out to investigate the salient thermal characteristics of HMMCs with percentage reinforcements, namely 2.5%, 5%, 7.5% and 10% of silicon carbide and graphite with aluminium matrix alloy Al 6061. Microstructural studies on hybrid composites have been performed. The experimental results have been analysed. Thermo-elastic models have been used to validate the thermal expansion and thermal conductivity behaviour of HMMCs. Computational investigation and modelling of hybrid composites have been carried out to determine the prominent computational thermal properties. Based on the experimental and computational results, the following conclusions have been drawn:

- The microstructural examination by employing optical micrographs reveals that the fine precipitates of alloying elements have been dispersed along the grain boundary in the matrix of aluminium. The uniform distribution of the reinforcements has led to the continuous dispersion along the grain boundary.
- The particles of silicon carbide and graphite have been dispersed in the matrix alloy Al 6061 and they are homogeneous with no parallel striations and detrimental pores. Interdendritic segregation has been observed near the grain boundaries which may be attributed to the solidification process. The presence of silicon carbide and graphite particles in the matrix substantially improved the microstructure, impeding the coarsening of the initial phase of dendrites during solidification.
- From the surface morphological studies, it appears that cohesive interfacial bonding has been accomplished between the matrix alloy and reinforcements. Also, due to constant stirring, the dispersoid concentration of the reinforcements is found to be uniform with minimum porosity and without any clustering.
- For each of the combinations having equal proportions of silicon carbide and graphite reinforcements, namely 2.5%, 5%, 7.5% and 10%, the thermal expansion and thermal conductivities of the hybrid composites tend to increase with the increase in temperature for the chosen range of temperature. For all the temperatures in the chosen range, the CTE and thermal conductivity of the 10% reinforcement combination appears to be less when compared to the thermal conductivity values of other percentage combinations. The thermal conductivity of the 10% reinforcement combination seems to be lower when compared to other combinations at 300°C. This may be due to the presence of graphite, which has lower thermal conductivity when compared to silicon carbide and matrix aluminium. It has been reported in the literature that the interfacial thermal resistance will have a remarkable effect on the effective thermal conductivity of composite materials and the volume proportion of silicon carbide is indeed the main factor contributing to the thermal conductivity of MMCs.
- It has been mentioned in the literature that graphite generally improves the dimensional stability. In this research work, the inclusion of silicon carbide and graphite reinforcements with AMCs does not exhibit substantial variation in thermal conductivity and thermal expansion behaviour of hybrid composites. The thermal strain for aluminium–silicon carbide–graphite HMMCs has been increased depending on the amount of graphite added to the matrix aluminium and has benefitted in achieving the dimensional stability.
- The experimental values of thermal expansivity of aluminium–silicon carbide–graphite hybrid composites seem to closely match with the thermal expansivity values obtained by ROM, Kerner’s model and Schapery’s model. It can be inferred that, experimental data are in agreement with the theoretical values obtained from

thermo-elastic models, with the exception of Turner's model wherein minor deviation from the experimental data has been observed. In Turner's model, the bulk moduli of hybrid composites tend to increase with the decrease in Poisson's ratio. Turner's model presumes that the reinforcements and the matrix undergo expansion at the uniform rate depending on the increase in volume proportions of the reinforcements. The analytical predictions by Turner are slightly imprecise for increasing volume proportions of the reinforcements.

- The values based on experimentation pertaining to thermal conductivity behaviour of aluminium–silicon carbide–graphite hybrid composites seem to match with the thermal conductivity values obtained by ROM, Series and Maxwell models. Further, it can be observed that, experimental data tend to marginally deviate from thermal conductivity values obtained by geometric mean model. This small variation may be attributed to the decrease in volume proportions of silicon carbide and graphite reinforcements and matrix aluminium.
- The thermal gradient of the hybrid composites appears to increase with increase in temperature for each of the combinations of equal proportions of silicon carbide and graphite reinforcements, namely 2.5%, 5%, 7.5% and 10%. For the chosen range of temperature, the 10% reinforcement combination exhibits higher thermal gradient when compared to the computational values of thermal gradient of other percentage combinations at all temperatures. When compared to other combinations at 300°C, the thermal gradient of the 10% reinforcement combination seems to be higher. The decrease in the values of thermal conductivity, thermal elongation or change in thickness and rate of heat flow may be the reasons for the increase the thermal gradient. Analogously, the computational values of thermal flux for the 10% reinforcement combination seem to be lower when compared to the thermal flux of other combinations at all temperatures in the chosen limit.

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