Computational modelling and mesh independence studies for the investigation of thermal conductivity behaviour for aluminium hybrid composites

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Abstract
The thermal characterization of composite materials has been increasingly important in a wide range of applications. Thermal conductivity is one of the most important properties of metal matrix composites. Since nearly all metal matrix composites are used in various temperature ranges, measurement of thermal conductivity as a function of temperature is necessary in order to know the behaviour of the material. In this paper, determination of thermal conductivity has been accomplished for Al 6061, silicon carbide and graphite hybrid metal matrix composites from room temperature to 300°C. Aluminium based composites reinforced with silicon carbide and graphite particles have been prepared by stir casting. The thermal conductivity behaviour of hybrid composites with different percentage compositions of reinforcements has been investigated by using laser flash technique. The results have indicated that the thermal conductivity of the different compositions of hybrid metal matrix composites decreases by the addition of graphite (Gr) with silicon carbide (SiC) and Al 6061. Few empirical models have been validated concerning with the evaluation of thermal conductivity of composites. Mesh independence studies or numerical convergence test has been accomplished.

Keywords: Thermal characterization, thermal conductivity, thermal gradient, thermal flux, mesh independence studies and numerical convergence.

1 Introduction

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 equipments and components. Particularly in automotive industry, metal matrix composites have been used commercially in fibre reinforced pistons and aluminum 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 [8]. 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 [26]. 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.

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Aluminium based metal matrix composites are advanced materials having the properties viz., high specific strength and modulus, greater resistance, high elevated temperature and low coefficient of thermal expansion. 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 [5]. The addition of graphite particles to aluminium alloys and composites improves sliding wear and seizure resistance compared to non-reinforced aluminium alloys and composites that do not contain graphite. Aluminium graphite composites have been expansively used in a large number of automobile components like cylinder liners, pistons and various types of brakes, air diffusers and bushings. In the present work, anticipation has been made to investigate and characterize the thermal properties of hybrid composites involving Al 6061 and silicon carbide with the addition of graphite [2],[5],[6],[30].

2. Literature Review

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 viz., 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 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. Computational investigation of metal matrix composites has been accomplished by using finite element modelling.

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 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 [11],[12],[13],[17],[19],[27]. Few papers concerning with thermal conductivity behaviour of composite materials have been discussed.

Davis and Artz [9] in their paper have elucidated that the thermal conductivity of metal matrix composites has been regarded to be the most prospective properties 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 [7].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 [22] 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 [1] 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 [23] 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 [31] 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 [12] 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 metal matrix composites 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 metal matrix composites protective structures. This approach has been applicable to a prototypical composite 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 [19] 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. [17] 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.

Eusun Yu et al. [11] 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 composite has been emphasized. It has been proved that, as the volume fraction of SiC increases, the stress turned to be compressive.

It is evident from the literature review that, aluminium matrix composites needs greater emphasis. However, investigations concerning thermal characterization and analysis of composite materials of aluminium matrix composites are inadequate. The summary of literature review can be structured as follows. Many experimental investigations have been carried out in the field of thermal analysis and characterization of aluminium-silicon carbide composites, but limited work has been accomplished pertaining to aluminium-silicon carbide-graphite hybrid MMCs.

The literature review 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 aluminium matrix composites 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 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. 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 percentage reinforcements [2]-[4],[7],[8],[15],[16]. But, limited work has been carried out on thermal characterization 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 varying percentage reinforcements at lower proportions 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.

3. 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 average particle size around 25 microns and particulates of graphite of average particle size 60 to 70 microns have been added as reinforcements. To study the influence of thermal parameters comprehensively, specimens of aluminium 6061-silicon carbide-graphite hybrid metal matrix composites having various percentage reinforcements (2.5%, 5%, 7.5% and 10%) have been fabricated. Hybrid metal matrix composites specimens have been cast by mixing equal proportions of Silicon Carbide and Graphite reinforcements maintaining the total percentage of reinforcements same (2.5%, 5%, 7.5% and 10%). A specimen of matrix alloy Al 6061 has been cast without the inclusion of any reinforcements. The evaluation of thermal properties viz., thermal conductivity, thermal diffusivity and specific heat capacity has been accomplished. Different sample sizes have been considered as per ASTM standards. The sample sizes for the evaluation of thermal conductivity is diameter 12.7 mm and thickness 3 mm. The sample size for estimation of specific heat capacity is powder form or pellets, approximately 20 mg. The dimensions chosen agree well with the available literature. The samples have fabricated to the required sizes. In all, five specimens of aluminium-silicon carbide-graphite hybrid composites with varying weight fraction has been stir cast. Five specimens have been separately considered for the determination of thermal conductivity and specific heat capacity behaviour with different sample sizes.

4. Experimental Investigation on Thermal Diffusivity and Thermal Conductivity of Hybrid Composites

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

\[
\rho_c = \rho_m V_m + \rho_p V_p
\]  

(1)

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Hybrid composites</th>
<th>Density (g/cc)</th>
<th>Density (g/cc)</th>
<th>Percentage Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(Water displacement method)</td>
<td>(Rule of mixtures)</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Al 6061</td>
<td>2.7</td>
<td>2.7</td>
<td>0</td>
</tr>
<tr>
<td>2.</td>
<td>Al 6061 + 1.25% SiC + 1.25% Gr</td>
<td>2.694</td>
<td>2.696</td>
<td>0.07%</td>
</tr>
<tr>
<td>3.</td>
<td>Al 6061 + 2.5% SiC + 2.5% Gr</td>
<td>2.685</td>
<td>2.692</td>
<td>0.26%</td>
</tr>
<tr>
<td>4.</td>
<td>Al 6061 + 3.75% SiC + 3.75% Gr</td>
<td>2.676</td>
<td>2.679</td>
<td>0.11%</td>
</tr>
<tr>
<td>5.</td>
<td>Al 6061 + 5% SiC + 5% Gr</td>
<td>2.661</td>
<td>2.668</td>
<td>0.26%</td>
</tr>
</tbody>
</table>

Table 1. Density of Hybrid Composites with Varying Percentage Reinforcements

It has been reported in the literature that, the density of Al 6061 is 2.7 g/cc, Silicon Carbide is 3.21 g/cc and Graphite is 2 g/cc. Table 1 refers to the density of hybrid composites for the various percentage compositions (1.25%, 2.5%, 3.75% and 5%, equal proportions of SiC and Graphite particles) with precipitation hardening matrix alloy Al 6061. Eq. (1) has been beneficial to evaluate the density of composite materials and they have been validated with experimental results. The difference between the theoretical and experimental density of hybrid composites is very marginal and has been proved to have negligible porosity. The thermal diffusivity has been measured by using a NETZSCH LFA 447 Nano Flash diffusivity apparatus.

For the determination of thermal conductivity and thermal diffusivity, the sample should be disc shaped and size is as per American Society for Testing and Materials (ASTM) standards. 5 samples have been considered with different percentage compositions. Al 6061 is the base alloy and reinforcements silicon carbide and graphite with different percentage compositions 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 fraction [7],[9]-[12],[17]. 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.

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

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Hybrid Composites</th>
<th>Heat Capacity (J/kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Al 6061 (Sample 1)</td>
<td>980</td>
</tr>
<tr>
<td>2.</td>
<td>Al 6061 + 1.25% SiC + 1.25% Gr (Sample 2)</td>
<td>968</td>
</tr>
<tr>
<td>3.</td>
<td>Al 6061 + 2.5% SiC + 2.5% Gr (Sample 3)</td>
<td>947</td>
</tr>
<tr>
<td>4.</td>
<td>Al 6061 + 3.75% SiC + 3.75% Gr (Sample 4)</td>
<td>924</td>
</tr>
<tr>
<td>5.</td>
<td>Al 6061 + 5% SiC + 5% Gr (Sample 5)</td>
<td>918</td>
</tr>
</tbody>
</table>

Table 2. Specific Heat Capacity of Hybrid Composites with Varying Percentage Reinforcements at 300°C
Fig. 1 depicts the variation of thermal diffusivity with temperature for different compositions of hybrid metal matrix composites. Fig. 2 indicates the variation of thermal conductivity and 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. 2, it has been observed that, Al 6061 has high thermal conductivity with 168 W/m K. Generally, the thermal conductivity varies as the temperature changes significantly. It has been be noticed that, by 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. 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 [13]-[17]. From the literature, it is clear that, the addition of Silicon Carbide with Aluminium will increase the thermal conductivity gradually. But form 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. 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.

![Thermal Diffusivity vs Temperature](image)

**Fig. 1** Variation of Thermal Diffusivity and Temperature for different compositions of MMCs

5. Mathematical validation of thermal conductivity models

Theoretical prediction of effective thermal conductivity for multi-phase composite materials is very constructive for analysis and optimization of the material performance and for new material designs. The correct and accurate modelling for thermal coefficients of composite materials has a great value due to their excellent thermal and mechanical properties and their use in industrial applications and technological fields. 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 [18]-[23].
The empirical models that have been considered for the validation of thermal conductivity are Rule of Mixtures (ROM), Series, Maxwell and Geometric models. Fig. 3 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 ROM, Series and Maxwell models, whereas the values of thermal conductivity slightly deviate from Geometric model. It can be inferred that, experimental data are in good agreement with ROM, Series and Maxwell models. It has been observed from the experimental investigation that, the thermal conductivity of hybrid composites with varying weight fraction has been gradually decreasing. Volume fraction of matrix and reinforcements of hybrid composites commensurate ROM, Series and Maxwell models. But in Geometric model, thermal conductivity is marginally deviating from experimental results due to the small variation in volume fraction of matrix and reinforcements. Table 3 illustrates the validation of thermo-elastic models based on the thermal conductivity behaviour of hybrid composites.

6. Computational analysis of the hybrid composites

In the present work, using experimental values of hybrid metal matrix composites viz., thermal conductivity, specific heat capacity and enthalpy as material properties, the computational investigation viz., thermal gradient and thermal flux have been accomplished. 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 for different hybrid MMCs. (a), (b), (c), (d), (e) and (f) illustrates the computational contour plots concerning the computational thermal properties viz., thermal gradient and thermal flux based on thermal conductivity behaviour for the temperature ranging from 50°C to 300°C. Mesh independence studies or numerical convergence test has been carried out for sample 2 (Al 6061 +1.25% SiC + 1.25% Gr). The convergence test has been carried out to check the accuracy of numerical solutions with theoretical values for the computational thermal properties thermal strain and thermal stress for the different elemental
Table 3. Validation of Thermo-Elastic Models based on Thermal Conductivity

<table>
<thead>
<tr>
<th>Hybrid Composite Specimens</th>
<th>Experimental values</th>
<th>Series model</th>
<th>ROM</th>
<th>Maxwell model</th>
<th>Geometric model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>168.2</td>
<td>168</td>
<td>167.5</td>
<td>168</td>
<td>167</td>
</tr>
<tr>
<td>Sample 2</td>
<td>167.4</td>
<td>166.1</td>
<td>166.4</td>
<td>167</td>
<td>166</td>
</tr>
<tr>
<td>Sample 3</td>
<td>166.8</td>
<td>165.4</td>
<td>165.8</td>
<td>165.3</td>
<td>165.1</td>
</tr>
<tr>
<td>Sample 4</td>
<td>165.3</td>
<td>164.7</td>
<td>165</td>
<td>164.7</td>
<td>164.23</td>
</tr>
<tr>
<td>Sample 5</td>
<td>164.2</td>
<td>164</td>
<td>164</td>
<td>164</td>
<td>163.5</td>
</tr>
</tbody>
</table>

Fig. 3. Comparison of Experimental Values of Thermal Conductivity with Empirical Models

Fig. 4 depicts the mesh generation of hybrid composites based on thermal expansion behaviour. Fig. 5 and 7 distributions. Five refinements have been achieved to achieve convergence for the number of the computational elements viz., 13086, 22240, 42959, 100669 and 172867.

The computational contour plots depicted in fig. 5 and 6 describes the magnitude of thermal gradient and thermal flux for Al 6061 + 1.25% SiC + 1.25% Gr with five refinements for different element distributions. It has been observed that, thermal gradient and thermal flux have been computed for the varying temperature. In the computational contour plots, the thermal gradient and thermal flux have been indicated with reference to the temperature distribution band illustrated in fig. 5 and 6. The computational values viz., thermal gradient and thermal flux have been determined by using Von Mises computational theory, where temperature has been depicted as the boundary condition. The computational spectrums depict the variation in thermal gradient and thermal flux at all temperatures based on the behaviour of thermal expansion.

Fig. 7 and 8 depicts the variation of thermal gradient and thermal flux with different computational elements to carry out mesh independence studies for the sample Al 6061 + 1.25% SiC + 1.25% Gr (Sample 2). It has been observed that, the thermal gradient and thermal flux for sample 2 have been varying for the different computational elements.
Fig. 4. Mesh Generation of Hybrid Metal Matrix Composites based on Thermal Conductivity Behaviour of Hybrid Composites
Fig. 5 (a), (b), (c), (d) (e) and (f) Temperature Distribution and Thermal Gradient for Al 6061 + 1.25% SiC + 1.25% Gr with Five Refinements for Different Element Distributions- 13086, 22240, 42959, 100669 and 172867

The meshing mode of the software, the element edge length or finer mesh density depending on the length of the sample has been varied to achieve finer mesh. It has been noticed that, for the computational elements (172867), the computational values of thermal gradient and thermal flux have been converged with the theoretical values of thermal gradient and thermal flux. Mesh independence has led to utmost accuracy in the computational solution after finer mesh refinement is attained. Also, there has been no substantial variation in the numerical solution after finer mesh refinement. The similar procedure can be adopted for the remaining samples also.
Table 4 emphasizes the experimental values of thermal conductivity, specific heat capacity and enthalpy for different hybrid composites obtained based on experimentation. Table 5 and 6 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. 5 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 [24]-[28]. Fig. 9 to 13 depicts the computational contour plots concerning thermal gradient and thermal flux that have been obtained computationally for the different percentage compositions of hybrid metal matrix composites using...
ANSYS 12. Fig. 14 and 18 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. From fig. 19 and 20, it has been observed that, displacement refers to thermal gradient. Al 6061+ 5% SiC + 5% Gr exhibits high thermal gradient and low thermal flux, whereas Al 6061 exhibits low thermal gradient and high thermal flux. It has been 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 heat 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 [28]-[31].

7. Conclusions

The following conclusions are drawn based on the results obtained:

(i) Al 6061 exhibits maximum value of thermal conductivity, whereas there is a decline in thermal conductivity 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 of hybrid composites reduces due to the increase of graphite content.

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

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

(v) The variation in thermal conductivity depends on porosity, temperature variation, volume fraction, internal structure of the composites, dispersoid concentration of reinforcements and density of composites.
It has been observed that, Al 6061+ 5%SiC + 5% Gr exhibits high thermal gradient and low thermal flux, whereas Al 6061 exhibits low thermal gradient and high thermal flux.

Fig. 7 Variation of Thermal Gradient with Computational Elements for Sample 2.

Fig. 8. Variation of Thermal Flux with Computational Elements for Sample 2

Fig. 9 (a) and 10 (b) Thermal Gradient and Thermal Flux for Al 6061
Fig. 11 (a) - 12 (b) Thermal Gradient and Thermal Flux for Al 6061 + 1.25% SiC + 1.25% Gr

Fig. 13 (a) - 14 (b) Thermal Gradient and Thermal Flux for Al 6061 + 2.5% SiC + 2.5% Gr
Fig. 15 (a)-16 (b) Thermal Gradient and Thermal Flux for Al 6061 + 3.75% SiC + 3.75% Gr

Fig. 17 (a)-18 (b) Thermal Gradient and Thermal Flux for Al 6061 + 5% SiC + 5% Gr
Fig. 19 Variation of Thermal Gradient v/s Temperature for different compositions of hybrid composites

Fig. 20 Variation of Thermal Flux v/s 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

<table>
<thead>
<tr>
<th>Percentage composition of composites</th>
<th>Thermal Conductivity (W/mK)</th>
<th>Specific Heat Capacity (kJ/kg K)</th>
<th>Enthalpy (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al 6061 (Sample 1)</td>
<td>168.2</td>
<td>0.980</td>
<td>561</td>
</tr>
<tr>
<td>Al 6061 + 1.25% SiC + 1.25% Gr (Sample 2)</td>
<td>167.4</td>
<td>0.967</td>
<td>552</td>
</tr>
<tr>
<td>Al 6061 + 2.5% SiC + 2.5% Gr (Sample 3)</td>
<td>166.8</td>
<td>0.955</td>
<td>539</td>
</tr>
<tr>
<td>Al 6061 + 3.75% SiC + 3.75% Gr (Sample 4)</td>
<td>165.3</td>
<td>0.925</td>
<td>528</td>
</tr>
<tr>
<td>Al 6061 + 5% SiC + 5% Gr (Sample 5)</td>
<td>164.2</td>
<td>0.910</td>
<td>518</td>
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</table>

Table 5: Comparison of computational and theoretical values of thermal gradient of hybrid composites

<table>
<thead>
<tr>
<th>Percentage composition of composites</th>
<th>Computational values (using ANSYS)</th>
<th>Theoretical Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50°C 100°C 150°C 200°C 250°C 300°C</td>
<td>50°C 100°C 150°C 200°C 250°C 300°C</td>
</tr>
<tr>
<td>Sample 1</td>
<td>81202 82145 83587 84129 85472 86414</td>
<td>81208 82150 83592 84139 85479 86422</td>
</tr>
<tr>
<td>Sample 2</td>
<td>81215 82180 83813 85178 86580 87833</td>
<td>81225 82190 83823 85182 86580 87835</td>
</tr>
<tr>
<td>Sample 3</td>
<td>81251 82211 83826 85372 86917 88462</td>
<td>81255 82224 83827 85375 86920 88463</td>
</tr>
<tr>
<td>Sample 4</td>
<td>81292 82244 84000 85403 87120 88561</td>
<td>81292 82244 84002 85404 87123 88565</td>
</tr>
<tr>
<td>Sample 5</td>
<td>81300 82264 84364 85415 87516 88566</td>
<td>81310 82268 84366 85418 87520 88569</td>
</tr>
</tbody>
</table>

Table 6: Comparison of computational and theoretical values of thermal flux of hybrid composites

<table>
<thead>
<tr>
<th>Percentage composition of composites</th>
<th>Computational values (using ANSYS)</th>
<th>Theoretical Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50°C 100°C 150°C 200°C 250°C 300°C</td>
<td>50°C 100°C 150°C 200°C 250°C 300°C</td>
</tr>
<tr>
<td>Sample 1</td>
<td>0.133 0.134 0.135 0.136 0.137 0.138</td>
<td>0.135 0.134 0.135 0.138 0.137 0.138</td>
</tr>
<tr>
<td></td>
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<td>E8  E8  E8  E8  E8  E8</td>
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<tr>
<td>Sample 2</td>
<td>0.130 0.131 0.132 0.134 0.135 0.136</td>
<td>0.132 0.131 0.133 0.135 0.135 0.136</td>
</tr>
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<td>E8  E8  E8  E8  E8  E8</td>
</tr>
<tr>
<td>Sample 3</td>
<td>0.128 0.129 0.130 0.132 0.134 0.135</td>
<td>0.131 0.130 0.132 0.132 0.133 0.135</td>
</tr>
<tr>
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<tr>
<td>Sample 4</td>
<td>0.126 0.128 0.129 0.130 0.132 0.132</td>
<td>0.129 0.129 0.130 0.130 0.132 0.131</td>
</tr>
<tr>
<td></td>
<td>E8  E8  E8  E8  E8  E8</td>
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</tr>
<tr>
<td>Sample 5</td>
<td>0.125 0.127 0.128 0.129 0.132 0.131</td>
<td>0.130 0.128 0.128 0.128 0.131 0.130</td>
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<tr>
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<td>E8  E8  E8  E8  E8  E8</td>
<td>E8  E8  E8  E8  E8  E8</td>
</tr>
</tbody>
</table>

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References


