Evaluation and Examination of Volume Fraction, Porosity, Microstructure and Computational Modeling of Hybrid Metal Matrix Composites to Reveal the Heat Flow Distribution Characteristics

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Abstract: Metal Matrix Composites (MMCs) are the competitive and proficient materials that possess natural opportunities for modern material science and development. The mechanical, tribological, thermal and machinability properties of composite materials are extensively pertinent for aerospace and automotive applications. In this paper, the determination of density, volume fraction and porosity has been carried out successfully. In the research, Al 6061 is the matrix alloy and Silicon Carbide and Graphite are the reinforcements considered, being fabricated using stir casting technique. Microstructural analysis has been carried out using Scanning Electron Microscope to examine the distribution of the reinforcements. Finite Element Analysis (FEA) has been used to simulate the thermal and mechanical behaviour of Metal Matrix Composites. Computational simulation for the investigation of thermal properties of hybrid metal matrix composites has been performed depending on the variation in volume fraction of hybrid MMCs. To carry out computational modelling, the experimental values have been used to show the temperature distribution and heat flow distribution characteristics, being considered as the salient thermal properties of composite materials.

Key words: Metal matrix composites, material science, volume fraction, porosity, microstructural analysis, finite element analysis, computational modelling and heat flow distribution.

1. Introduction

A composite material is a macroscopic combination of two or more dissimilar materials having an identifiable interface between them. A composite material exhibits a significant proportion of the properties of both constituent phases such that a superior amalgamation of properties is realized. Composite materials comprises of two phases: one is the matrix, which is continuous and surrounds the other phase, often called the dispersed phase or reinforcement [1]. The main purpose of the reinforcement is to offer strength and stiffness to the composite. A matrix is used to combine the reinforcement together by virtue of adhesive and cohesive characteristics, and provides a solid form to the composite material. The matrix strongly holds the reinforcements in proper orientation and position and distributes the loads consistently among the reinforcements. The matrix material surrounds and supports the reinforcement materials by maintaining their comparative proportions. The reinforcements convey their incomparable mechanical and physical properties to augment the matrix properties. A synergism produces material properties unavailable from the individual constituent materials, while the wide assortment of matrix and intensifying materials allows the designer of the product or structure to choose a most constructive condition [2, 3].

Metal Matrix Composites have materialized as a category of productive materials for advanced structural, electrical, thermal management, electronic packaging and wear applications. MMCs reveal remarkable improvement in physical and mechanical properties compared with unreinforced Aluminium alloys. Aluminium is the most popular matrix for MMCs. Aluminium alloys are attractive due to their low density, their capability to be strengthened by precipitation, good corrosion resistance, high thermal and electrical conductivity and damping capacity. MMCs based on Aluminium alloys have received greater interest since they coalesce with low weight, high mechanical strength, excellent wear properties, and becoming potential as a material for many engineering applications [3].

Metal Matrix Composites are generally distinguished by characteristics of the reinforcement namely particle reinforced MMCs, short fiber or whisker reinforced MMCs and continuous fiber or layered MMCs. Metal Matrix Composites (MMCs) covers an extensive range of materials to simple reinforcements of castings with low cost refractory wool, to complex continuous fires lay-ups in foreign alloys. The properties of MMCs are controlled and supported by the matrix, the reinforcement and the interface. The characteristics of metal matrix composites are determined by their microstructure and internal interfaces, which are influenced by their production and thermal mechanical prehistory. The microstructure covers the structure of the matrix and the reinforced phase. The chemical composition, grain or sub-grain size, texture, precipitation, behaviour and lattice defects are important to the matrix. The second phase is characterized by its percentage of volume, variety, size, distribution and orientation. Local varying internal tension due to the thermal expansion behaviour of the two phases is an additional influencing factor [2]. The reinforcement is striking because it is accountable for the assessment and optimization of mechanical properties, cost and performance of a given composite. In particular, many of the considerations arising due to fabrication, processing and service performance of composites are related exclusively to the metallurgical aspects that take place in the interfacial region between matrix and reinforcement [3, 4, and 5].

Metal Matrix Composites (MMCs) have been transformed from a theme of scientific and intellectual attention to a material of broad technological and commercial implication over the past few decades. There is an augmented demand for better materials in the area of dynamic structures, which demand high strength and light weight. Metal Matrix Composites assure to serve the intended purpose in this regard. They possess high toughness, excellent impact and fatigue strength, good thermal shock resistance, high thermal stability and high surface durability. The challenge and demand for developing metal matrix composites for use in high performance structural and functional applications including aerospace industries, automobile sector and defence. The objective of developing these composite materials is to agglomerate the desirable properties of metal and particulates. Metal Matrix Composites consists of at least two chemically and physically distinct phases, suitably distributed to provide properties not obtainable with either of the individual phases. For many researchers, MMCs is often equated with the term light metal matrix composites. Considerable progress in the development of MMCs has been achieved in decent decades, so that they could be introduced into the most imperative applications [2, 3 and 4].

Finite Element Method (FEM) supplies an institutional investigation considering the advantages of graphical and computational post-processes. It helps for the methodical analysis of material behaviours and properties, including the examination 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 comprehensively 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 or numerical simulations concerning with the thermal analysis of metal matrix composites composed of Aluminium and Silicon Carbide has been performed in extended areas of Silicon Carbide 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, meticulously and automatically [6, 7].

2. Literature Review

Literature review related to mechanical and thermal properties, microstructural analysis and computational modelling of the composite materials has been carried out. The research papers concerning with the thermal characterization and computational modelling of composite materials has been discussed in this section.

J. Zhang *et al.* [8] have investigated the effect of Silicon Carbide and Graphite particulates on the resultant damping behavior of 6061 A1 metal matrix composites to develop a high damping material. The microstructural analysis has been performed using scanning electron microscopy, optical microscopy and image analysis. It was shown that the damping capacity of Al 6061 could be significantly improved by the addition of either Silicon Carbide or graphite particulates through spray deposition processing.

M L Ted Guo *et al.* [9] in their research paper have studied the tribological behavior of self-lubricated Aluminium/Silicon Carbide/Graphite hybrid composites with various amount of graphite addition synthesized by the semi-solid powder densification (SSPD) method. It has been found that the seizure phenomenon which occurred with a monolithic aluminium alloy did not occur with the hybrid composites. The amount of graphite released on the wear surface increased as the graphite content increased, which reduced the friction coefficient. Graphite released from the composites bonded onto the wear surfaces of the counter faces.

R F Cooper and K Chyung [10] in their study have presented Silicon Carbide continuous fibre-reinforced glass and glass-ceramic matrix composites showing high strength and fracture toughness using thin-foil transmission electron microscopy and scanning transmission electron microscopy (AEM). The outstanding mechanical behaviour of these materials is directly correlated with the formation of a cryptocrystalline carbon (graphite) reaction-layer interface between the fibers and the matrix. AEM results are used to comment upon a possible mechanism for the high-temperature embrittlement behavior noted for these materials when they undergo rupture in an aerobic environment.

Yongzhong Zhan [11] has analyzed the role of graphite particles and copper hybrid composites against steel. Copper matrix composite reinforced with Silicon Carbide and Graphite particles were prepared by a powder metallurgy method. Microstructural analysis showed that a uniform graphite microcrystals layer on the top of worn surface helped to decrease the plastic deformation in subsurface region and alleviate adhesion wear. It showed that graphite particle was an effective addition agent for copper matrix composite applied in high-temperature sliding wear condition.

L C Davis and B E Artz [12] in their research thesis have explained the thermal conductivity of metal matrix composites, which are potential electronic packaging materials, has been calculated using effective medium theory and finite element techniques. It has been found that Silicon Carbide particles in Al must have radii in excess of 10 μm to obtain the full benefit of the ceramic phase on the thermal conductivity. Comparison of the effective medium theory results to finite element calculations for axisymmetric unit cell models in three dimensions and to simulation results on disordered arrays of particles in two dimensions confirms the validity of the theory.

S Cem Okumus *et al.* [13] in their paper have studied on thermal expansion and thermal conductivity behaviours of Al/Si/SiC hybrid composites. It clearly highlights that Aluminium-Silicon based hybrid composites reinforced with silicon carbide and graphite particles has been prepared by liquid phase particle mixing and squeeze casting. The thermal expansion and thermal conductivity behaviours of hybrid composites with various graphite contents (5.0; 7.5; 10 wt.%) and different silicon carbide particle sizes (45 μm and 53 μm) has been investigated. Results indicated that increasing the graphite content improved the dimensional stability, and there was no obvious variation between the thermal expansion behaviour of the 45 μm and the 53 μm silicon carbide reinforced composites.

R A Saravanan and J Narciso [14] have investigated on thermal expansion behaviour of particulate metal matrix composites explains that Aluminium-matrix composites containing thermally oxidized SiC particles of controlled diameter ranging from 3 to 40 μm have been produced successfully by vacuum assisted high-pressure infiltration. Their thermal-expansion coefficients (CTEs) has been measured between 25°C and 500°C with a high-precision thermal mechanical analyser (TMA), and compared with the predictions of various theoretical models. The thermal-expansion behavior of the three-phase Al/SiC/SiO2 composite shows no significant deviation from the predictions of elastic analysis, since the measured CTEs lie within the elastic bounds derived by Schapery's analysis.

Tran Nam and G Requena [15] have studied on effect of thermal cycling on the expansion behaviour of Al/SiC composites is carried out where the coefficient of thermal expansion (CTE) and accumulated plastic strain of the pure aluminium matrix composite containing 50% SiC particles (Al/SiCp) during thermal cycling (within temperature range 298–573 K) were investigated. The composite was produced by infiltrating liquid aluminum into a preform made by SiC particles with an average diameter of 14 microns. Experiment results indicated that the relationship between the CTE of Al/SiCp and temperature is nonlinear; CTE could reach a maximum value at about 530 K. The theoretical accumulated plastic strain of Al/SiC composites during thermal cycling has also been calculated and compared with the experimental results.

S X Xu [16] has investigated the temperature profile and specific heat capacity in temperature modulated Differential Scanning Calorimeter with a low sample heat diffusivity. The paper explains about a specific numerical model that is used to analyze the effects of thermal diffusivity on temperature distribution inside the test sample and specific heat measurement by TMDSC. The sample test results are presented to demonstrate the effects of material thermal diffusivity.

E Morintale and A Harabou [17] have described the use of heat flows from DSC curve for calculation of specific heat of the solid materials. On the basis of the second law of thermodynamics, they have established a procedure for calculating the specific heat of solid materials using heat flow in the sample studied, and the rate of heating of the sample.

B Karthikeyan *et al*. [18] have elucidated specific heat capacity measurement of Al/SiC_P composites by Differential Scanning Calorimeter. Good thermal control systems have been considered for various materials applicable for spacecraft applications. Differential Scanning Calorimeter has been employed to determine the specific heat capacity of 7075 Al /SiC_P composites.

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.

M Grujicic *et al.* [20] has accomplished the computational investigation of structural shocks in Al/SiC particulate metal matrix composites. In this paper, the propagation of planar, longitudinal, steady structured shock waves within MMCs has been studied computationally. The purpose of this paper has been helpful to advance the use of computational engineering analyses and simulations in the areas of design and application of the MMCs protective structures. This approach has been applicable to a prototypical 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.

D Saraev and S Schmauder [21] have emphasized the finite element modelling of Al/SiC metal matrix composites with particles aligned in stripes based on two and three dimensional comparison. Three-dimensional finite element calculations comparing to axisymmetric calculations have been performed to predict quantitatively the tensile behaviour of composites reinforced with ceramic particles in stripes. The analyses are based on a unit cell model, which assumes the periodic arrangement of reinforcements. The results have been presented in such a manner that varying the distance between the stripes when particle volume fraction is kept constant significantly influences the overall mechanical behaviour of composites.

3. Microstructural Analysis of Hybrid Metal Matrix Composites

The evaluation of effective properties of composite materials is of paramount significance in the effectual design and application of composite materials. One of the imperative factors that strongly influence the properties of a composite material is the examination of microstructure. Microstructure refers to the shape, size distribution, spatial distribution and orientation distribution of the reinforcements in the matrix. Microstructural analysis of hybrid metal matrix composites has been carried out using Scanning Electron Microscope. The specimens have been polished 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 and presence of porosity. This helps to comprehend 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 [13]. Fig. 1, 2, 3, 4 and 5 show the micrographs of the different compositions of the hybrid MMCs.

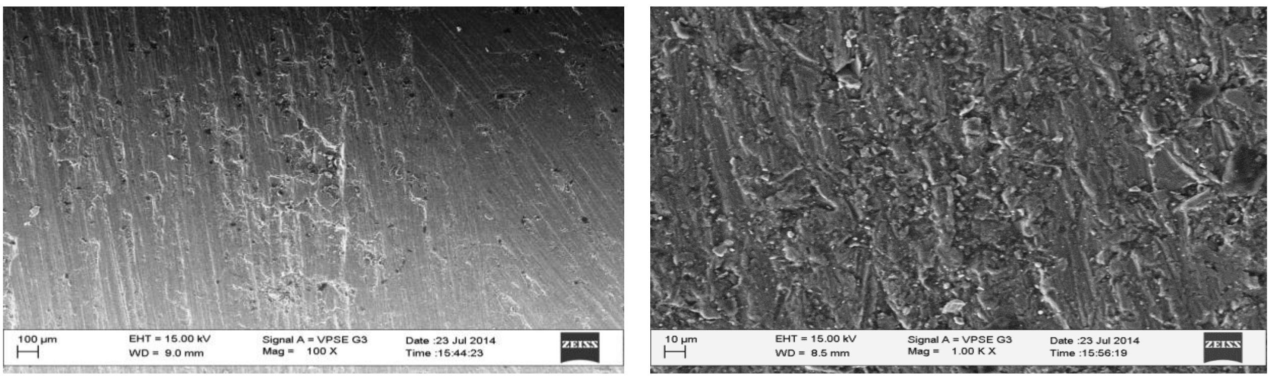

Fig. 1. SEM microstructures of Al 6061 sample

Fig. 1 depicts the micrographs of Al 6061 with no reinforcements. Fig. 2, 3, 4 and 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%. The dark patches indicate the presence of Graphite and white patchy layer specify the presence of Silicon Carbide. It can be observed that, with the addition of Silicon Carbide and Graphite with varying volume fraction, the distribution of the reinforcements is uniform with the absence of cracks and deleterious pores. Also, due to the variation in volume fraction of the reinforcements by performing constant stirring, the dispersoid concentration is uniform with minimum porosity. It has been reported in the literature that, by increasing Graphite content in the composite matrix leads to grain refinement for Aluminium and eutectic Silicon and porosity. It has been stated that, due to the increase in volume fraction of the reinforcements, the distribution is more reliable with negligible porosity. From the literature, it has been investigated that, porosity can severely degrade the thermal and mechanical properties of MMCs [13, 15, 16 and 17].

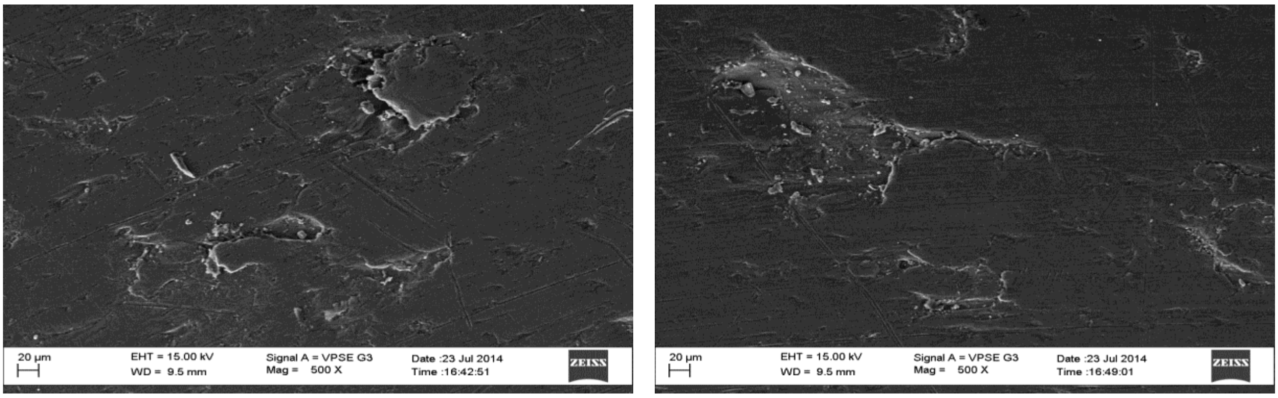

Fig. 2. SEM microstructures of Al 6061 with 1.25% Silicon Carbide and 1.25% Graphite

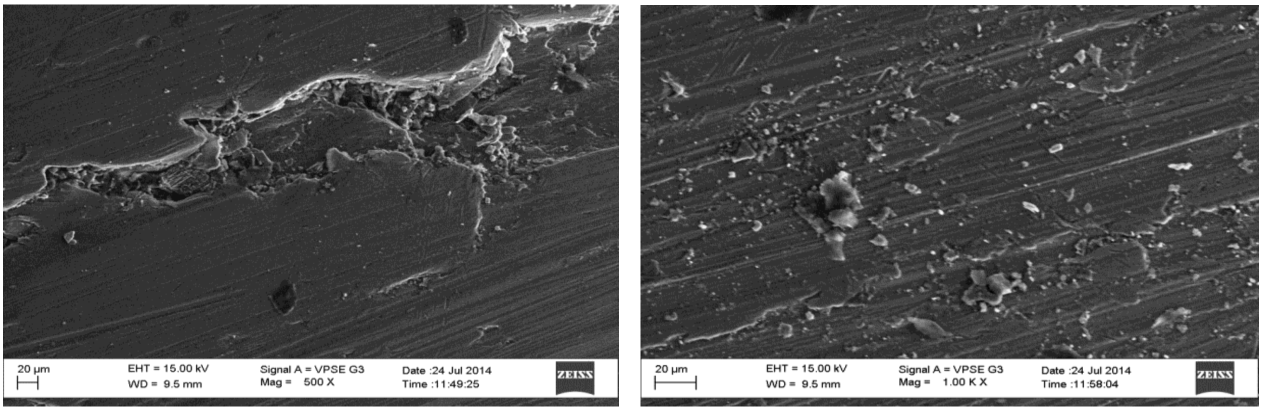

Fig. 3. SEM microstructures of Al 6061 sample with 2.5% Silicon Carbide and 2.5% Graphite

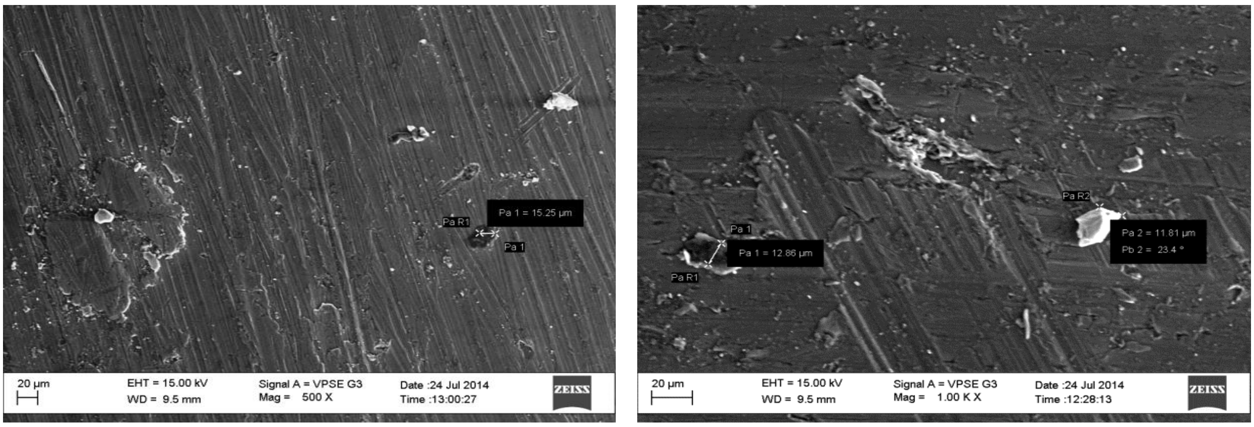

Fig. 4. SEM microstructures of Al 6061 with 3.75% Silicon Carbide and 3.75% Graphite

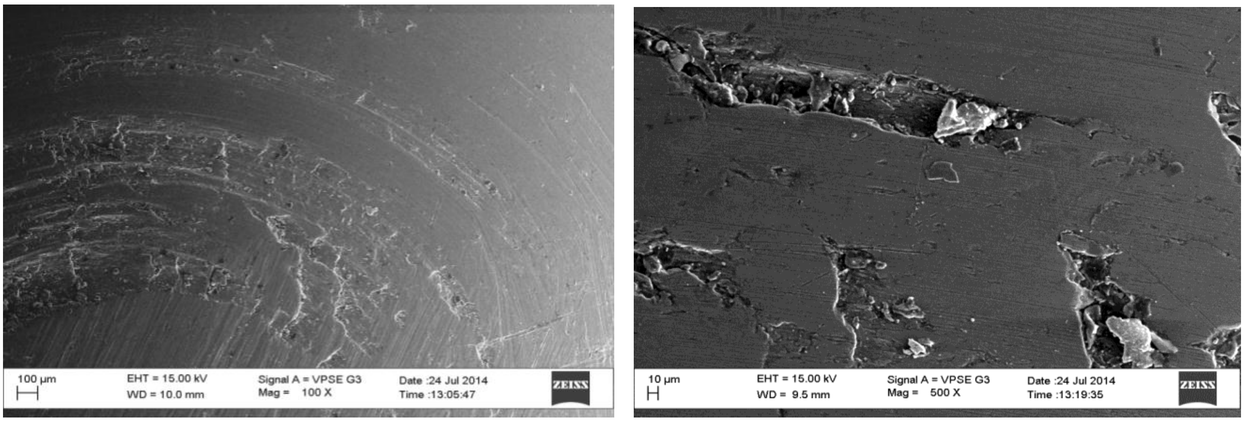

Fig. 5. SEM microstructures of Al 6061 with 5% Silicon Carbide and 5% Graphite

4. Evaluation of Density, Porosity and Volume Fraction of the Hybrid Metal Matrix Composites

It is essential to examine the salient factors of the composite materials namely density, porosity and volume fraction to characterize the properties of composite materials. These parameters will benefit in the clear determination of mechanical, tribological, machinability and thermal properties of composite materials. The density of a Metal Matrix Composite material has been determined using the relationship between volume and mass. A special technique for the determination of the density where pores are taken into account is the determination by using water displacement method. This method allows the determination of the density in air compared to its displacement in water or other liquid of known density. Depending upon the nature of the specimen (e.g., open or closed cell), the resultant value may deviate from the true mass. A clean specimen is weighed accurately in air using a laboratory balance. The same specimen is weighed while suspended in water or other liquid of such density that the specimen will sink. Deducting the mass of the suspension wire from the weight in liquid, the volume of the specimen is calculated from the effect of displacement by a liquid of known density (Archimedean principle). This allows the determination of density of specimens with irregular shapes, uneven surfaces, or porosity. Caution must be exercised to assure that no air is trapped within the specimen. Placing the specimen in a vacuum while submerged in the displacement liquid will usually avoid error. Table 1 depicts the comparison of experimental and theoretical densities of the hybrid metal matrix composites.

Table 1. Comparison of Experimental and Theoretical Densities of the Hybrid MMCs

Serial Number	Material Compositions	Experimental values (g/cc)	Theoretical values (g/cc)
1	Al-6061	2.7	2.7
2	Al-6061 + 1.25% SiC + 1.25% Graphite	2.696	2.6976
3	Al-6061 + 2.5% SiC + 2.5% Graphite	2.6836	2.6845
4	Al-6061 + 3.75% SiC + 3.75% Graphite	2.674	2.673
5	Al-6061 + 5% SiC + 5% Graphite	2.664	2.666

The presence of porosity in composite materials will greatly affect the strength and related properties. It is essential to evaluate the presence of porosity in the composite materials which is beneficial to determine the mechanical and thermal properties. In the present research, the porosity of hybrid metal matrix composites has been investigated based on the determination of density of hybrid MMCs. Using water displacement method based on Archimedes principle, experimental values of the density of the hybrid composites have been evaluated and using rule of mixtures, theoretical values of the density of the composites have been accomplished. It has been noticed that, the difference in the theoretical and experimental densities of the composites is very marginal and porosity is very minimum. Experimentally, the presence of porosity in composite materials has been determined using ultrasonic testing method.

The volume fractions of composite materials play an important role in the thorough evaluation of properties of composites. In the present study, the evaluation of volume fraction from weight fraction has been carried out. The lower and higher volume fractions of the composites will result in the consistent variation in the properties of the materials, thus possible to carry out the characterization of the materials effectively. The conversion of volume fraction from weight fraction can be calculated using the following relation:

$$V_f = \frac{W_p/\rho_p}{\frac{W_p}{\rho_p} + (1-W_p)/\rho_m} \tag{1}$$

where, W_p is the weight of the reinforcements, ρ_p is the density of the reinforcements and ρ_m is the density of the matrix alloy. The densities of Al 6061 are 2.7 g/cc, Silicon Carbide (SiC) is 3.21 g/cc and Graphite (Gr) is 1.93 g/cc.

From equation (1), the volume fraction of the hybrid metal matrix composites has been calculated and tabulated in Table 2. Table 2 indicates the evaluation of volume fraction of hybrid metal matrix composites.

Table 2. Evaluation of Volume Fraction of Hybrid Metal Matrix Composites Based on Weight Fractions

Serial Number	Material Compositions	Weight fractions	Volume fractions
1.		-----------------	--------------
2.	Al-6061 + 1.25% SiC + 1.25% Graphite	1.25% SiC + 1.25% Gr	1.2%
3.	Al-6061 + 2.5% SiC + 2.5% Graphite	2.5% SiC + 2.5% Gr	2.55%
4.	Al-6061 + 3.75% SiC + 3.75% Graphite	3.75% SiC + 3.75% Gr	3.7%
5.	Al-6061 + 5% SiC + 5% Graphite	5% SiC + 5% Gr	4.6%

Volume fraction or fiber volume ratio is an important mathematical element in composite engineering. Voids are often formed in a composite structure throughout the manufacturing process and must be calculated into the fiber volume fraction of the composite. The calculation of volume fraction is very important in determining the overall mechanical properties of a composite. A higher volume fraction typically results in better mechanical properties of a composite. The volume fraction can be calculated using a combination of weights, densities, elastic moduli, stresses in respective sections, Poisson ratios, and volumes of the matrix, fibers and voids. Adding too little fiber reinforcement in the composite will actually deteriorate the properties of the material and too much fiber volume may decrease the strength of the composite due to lack of space for the matrix to fully surround and bond with the fibers.

5. Computational Modelling of Hybrid Metal Matrix 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 MMCs fabrication to be fruitful with empirical results and computational investigation. For the analysis of metal matrix composite, many researchers have suggested the analysis of unit cell of composite. Generally, there are computational difficulties to obtain reasonable results based on a small single unit owing to a lack of interaction between reinforcement and matrix. On the contrary, the computation with multiple unit cells allows reliable results due to considerable material interaction [9, 10 and 11].

In this research work, ANSYS 12 software has been used in the finite volume analysis to carry out the thermal analysis of the different compositions of hybrid metal matrix composites. In the finite element solution of engineering problems, the predominant tasks of mesh generation, processing and graphical representation of the results are usually assigned to independent computer programs. These programs can either be embedded under a common shell or interface to enable the user to interact with all parts in a single environment, or they can be implemented as separate sections of a software package. Discretization of the solution domain into appropriate mesh is the first step in the finite element simulation of field problems. Some of the major factors in the selection of a particular mesh design for a problem are domain geometry, type of the finite elements used in the discretization, accuracy and computational cost. In the present work, using experimental values of hybrid metal matrix composites namely thermal conductivity, specific heat capacity and enthalpy, the computational parameters namely temperature distribution and heat flow have been accomplished. Fig. 6 to Fig. 15 indicates the contour plots concerning with temperature distribution and heat flow obtained computationally.

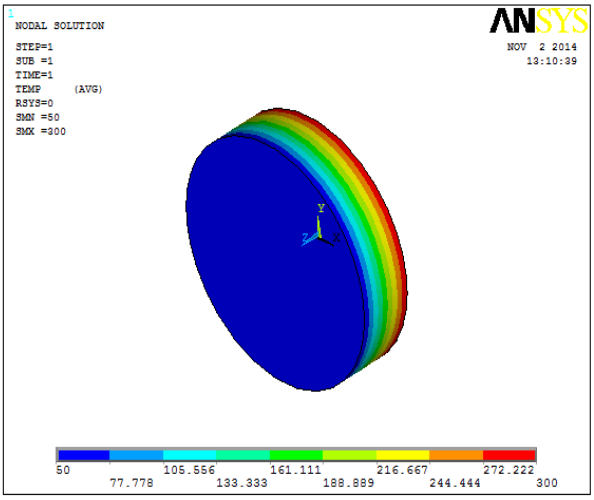

Fig. 6. Temperature distribution for Al 6061

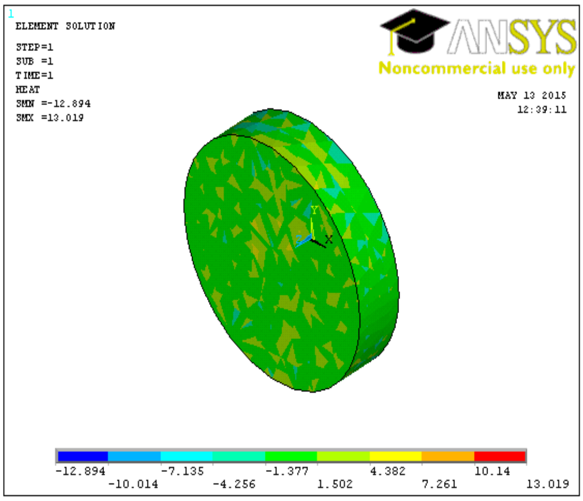

Fig. 7. Heat flow distribution for Al 6061

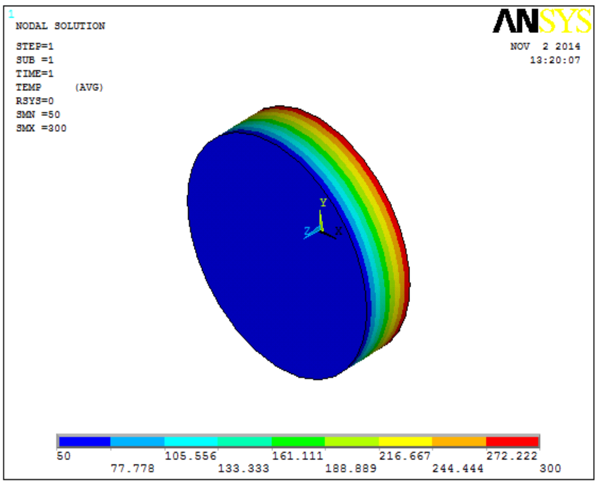

Fig. 8. Temperature Distribution for Al 6061 + 1.25% SiC +1.25% Gr

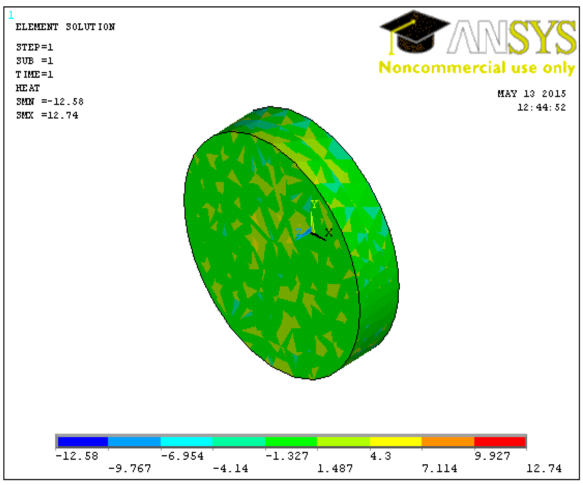

Fig. 9. Heat flow for Al 6061 + 1.25% SiC +1.25% Gr

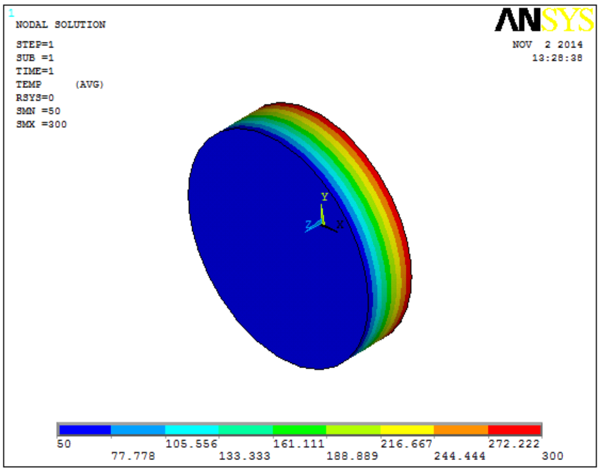

Fig. 10. Temperature Distribution for Al 6061 + 2.5% SiC +2.5% Gr

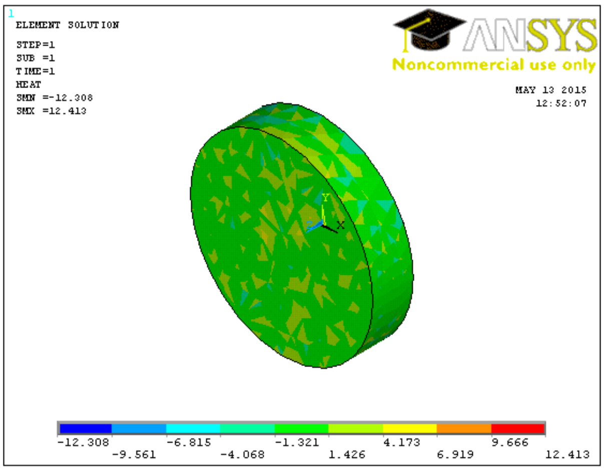

Fig. 11. Heat flow for Al 6061 + 2.5% SiC +2.5% Gr

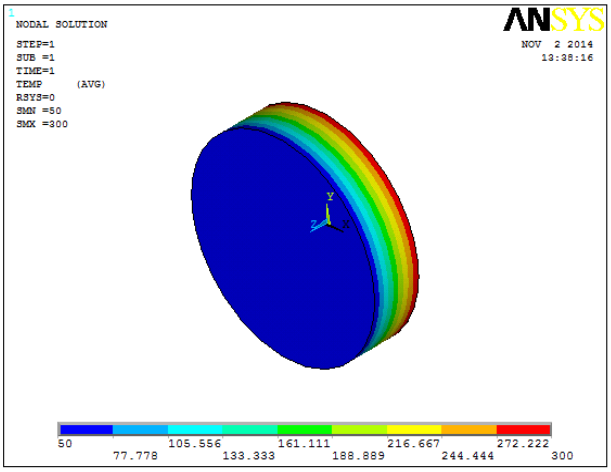

Fig. 12. Temperature Distribution for Al 6061 + 3.75% SiC + 3.75% Gr

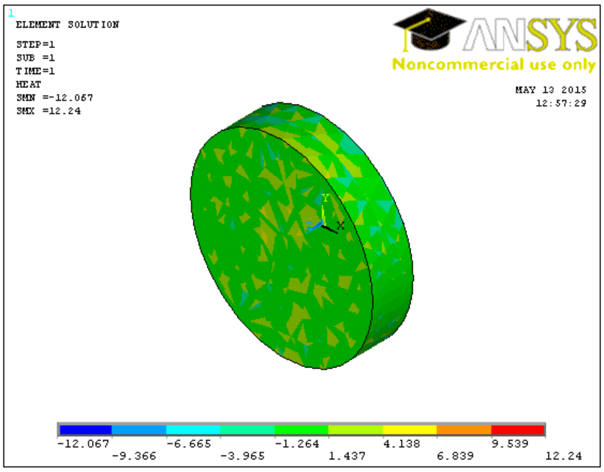

Fig. 13. Heat flow for Al 6061 + 3.75% SiC + 3.75% Gr

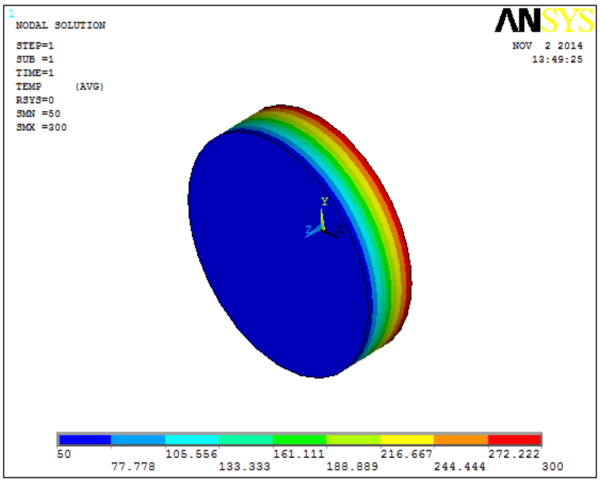

Fig. 14. Temperature Distribution for Al 6061 + 5% SiC + 5% Gr

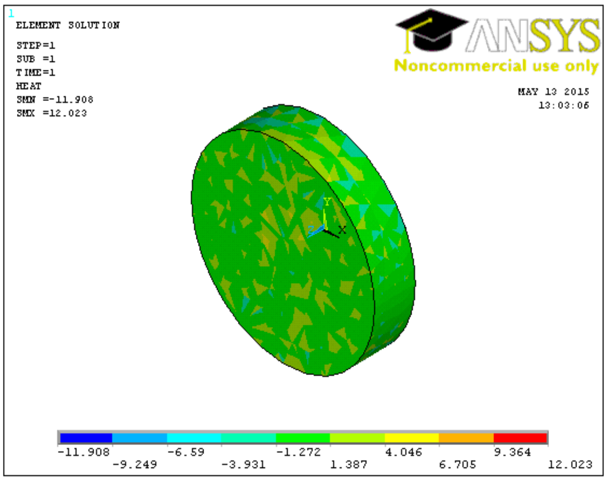

Fig. 15. Heat flow for Al 6061 + 5% SiC + 5% Gr

Table 3. Experimental Values of Thermal Conductivity, Specific Heat Capacity and Enthalpy for Different Percentage Compositions of the Hybrid Metal Matrix Composites at 300 C

Percentage composition of composites	Thermal Conductivity (W/m K)	Specific Heat Capacity (kJ/kg K)	Enthalpy (kJ/kg)
Al 6061	168	0.980	561
Al 6061 + 1.25% SiC + 1.25% Gr	167.4	0.967	552
Al 6061 + 2.5% SiC + 2.5% Gr	166.78	0.955	539
Al 6061 + 3.75% SiC + 3.75% Gr	164.3	0.925	528
Al 6061 + 5% SiC + 5% Gr	163	0.910	518

Fig. 6 to Fig. 15 emphasizes the various contour plots showing the distribution patterns of temperature and heat flow distribution. Table 3 emphasizes the experimental values of Thermal Conductivity, Specific Heat Capacity and Enthalpy for different hybrid composites obtained based on experimentation. In the present work, using experimental values of hybrid metal matrix composites namely thermal conductivity, specific heat capacity and enthalpy, the computational parameters temperature distribution and heat flow has been accomplished. Fig. 16 depicts the variation of heat flow with temperature. Heat flow distribution is beneficial for the evaluation of the thermal effects of the composite materials. From the principles of heat transfer, the heat flow can be evaluated based on Fourier's law of conduction. Fig. 7, 9, 11, 13 and 15 represent the contour plots depicting heat flow patterns depending on temperature distribution. From Fig. 16, it has been observed that, Al 6061+ 5% SiC + 5% Gr exhibits minimum heat flow, whereas Al 6061 exhibits maximum heat flow. It has been be noticed that, with the addition of reinforcements Silicon Carbide and Graphite to Al 6061, there has been variation in heat flow for the different percentage compositions of hybrid metal matrix composites. Addition of Graphite with Aluminium matrix alloy and Silicon Carbide with varying volume fraction resulted in the variation in heat flow of the hybrid metal matrix composites. Generally, due to the decrease in thermal conductivity of the material, heat flow gradually decreases. It has been perceived experimentally that, Al 6061 exhibits maximum thermal conductivity and Al 6061 + 5% SiC+ 5% Gr exhibits minimum thermal conductivity. It has been observed that, the thermal flux of the different compositions of the hybrid metal matrix composites decreases drastically resulting in decrease in heat flow of the hybrid composites.

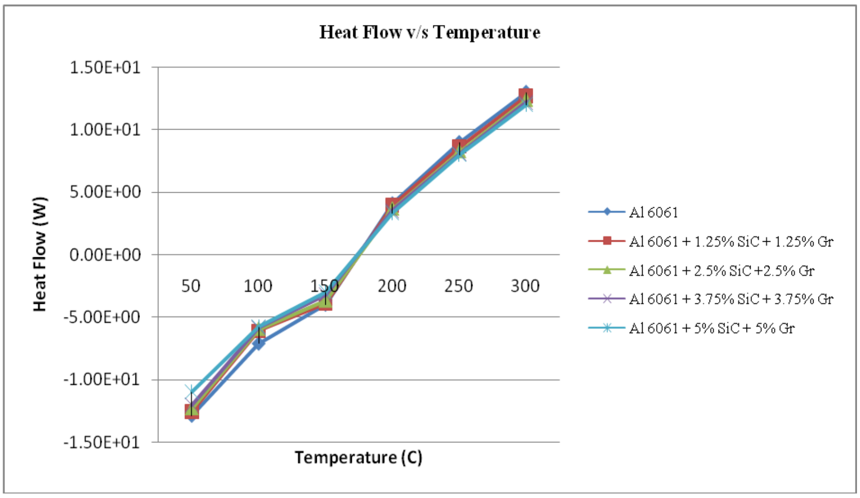

Fig. 16. Variation of heat flow v/s temperature for the different percentage compositions of hybrid metal matrix composites

6. Conclusions

The following conclusions are drawn based on the results obtained:

1. Al 6061 exhibits maximum heat flow and Al 6061 + 5% SiC + 5% Gr reveals minimum heat flow based on the values of thermal conductivity at maximum temperature. Al 6061 possesses maximum value of thermal conductivity 167.4 W/m K, whereas Al 6061 + 5% SiC + 5% Gr possess minimum values of thermal conductivity at 300°C.

2. The heat flow and thermal conductivity of the hybrid composites reduces due to the enhancement of graphite content.

3. The values of heat flow and thermal conductivity decreases over the range of temperatures, with variation in density, variation in volume fraction of SiC and porosity of hybrid composites. With the addition of reinforcements of low volume fraction, thermal conductivity of hybrid has been observed to be low.

4. Al 6061 exhibits maximum density value of 2.7 g/cc. By the addition of Graphite with Al 6061 and Silicon Carbide, the values of density gradually decrease.

5. It can be observed that, with the addition of Silicon Carbide and Graphite with varying volume fraction, the distribution of the reinforcements is uniform with the absence of cracks and deleterious pores. Also, due to the variation in volume fraction of the reinforcements by performing constant stirring, the dispersoid concentration is uniform with minimum porosity.

6. The conversion of weight fraction into volume fraction has been beneficial in the evaluation of thermal properties of composite materials, also led to the computational investigation of the hybrid metal matrix composites. Due to lower percentage volume fraction, the values of heat flow and thermal conductivity are very optimum.

7. The volume fraction, density and porosity greatly influence in the thermal characterization of composites.

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