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RESEARCH ARTICLE

A COMPREHENSIVE EXPERIMENTAL INVESTIGATION ON THERMAL PROPERTIES AND CHARACTERIZATION OF HYBRID METAL MATRIX COMPOSITES

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ABSTRACT

The thermal characterization of hybrid metal matrix composites is increasingly important in a wide range of applications. Thermal Analysis of Metal Matrix Composites is required to clearly examine the thermal properties viz., Thermal Conductivity, Temperature Difference, Thermal Capacity or Heat Difference, Coefficient of Thermal Expansion (CTE) and Rate of Heat Transfer. Thermal studies of composite materials are gaining greater impetus in the present scenario. This will help to understand the properties of materials as they change with temperature. It is often used as a term for the study of heat transfer through structures. The assessment of thermal parameters of composites will benefit to evaluate heat capacity, variation in the intensity of heat, heat diffusion and heat release rate. In the present scenario, research work is accomplished on hybrid composites based on thermal expansivity and specific heat capacity using Dilatometer and Differential Scanning Calorimeter, as limited research has been carried out on hybrid composite based on thermal properties. The coefficient of thermal expansion is one of the most important properties of MMCs. Since nearly all Metal Matrix Composites are used in various temperature ranges, measurement of CTE as a function of temperature is necessary in order to know the behaviour of the materials. The heat flow and heating rate are beneficial in the estimation of specific heat capacity for different percentage compositions of the hybrid composites. This technical paper emphasizes the experimental evaluation of CTE and specific heat capacity using encomiastic experimental techniques. .

INTRODUCTION

The term Metal Matrix Composites (MMCs) covers a very wide 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 by the matrix, the reinforcement and the interface. In particular many of the considerations arising due to fabrication, processing and service performance of composites are related of processes that take place in the interfacial region between matrix and reinforcement. The applications of these materials are absolutely appreciative and applicable in almost all areas of mechanical engineering. Aluminium Silicon alloys in particular finds extensive and increased applications in industries due to their properties viz., high fluidity, low melting point, high strength, corrosion resistance, good casting characteristics and lower coefficient of thermal expansion [1]. Aluminium Silicon alloys in particular are being extensively finding increased applications in industries due to their properties viz., high fluidity, low melting point, high strength, corrosion resistance, good castability characteristics and lower coefficient of thermal expansion [2]. Among modern composite materials, particle reinforced Aluminium Matrix Composites are finding increased application due to their favorable mechanical properties and good wear resistance. Aluminum-Silicon Carbide and Aluminium-Graphite are used as reinforced composites to study its unique characteristics and behaviour. But in the present situation, it is pertinent to carry out research work on hybrid composites for their mechanical and thermal characteristics [2].

The thermal behaviour of composite materials is often sensitive to changes in temperature. This is mainly because, the response of the matrix to an applied load is temperature dependent and changes in temperature can cause internal stresses to be set up as a result of differential thermal contraction and expansion of the constituents. Thermal analysis of hybrid composites is a pragmatic approach to clearly study its thermal characteristics. Most of the thermal studies are mainly concerned with Aluminium matrix composites but minimum information is available on hybrid composites [3].

Literature Review

The necessity of thermal analysis of hybrid metal matrix composites must be comprehensively discussed. The behaviour of composite materials is often sensitive to changes in temperature. This is mainly because, the response of the matrix to an applied load is temperature dependent and changes in temperature can cause internal stresses to be set up as a result of differential thermal contraction and expansion of the constituents. Thermal analysis of hybrid composites is a

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pragmatic approach to clearly study its thermal characteristics. Most of the thermal studies are mainly concerned with Aluminium matrix composites but minimum information is available on hybrid composites [4].

The assessment of thermal parameters of composites namely thermal expansivity and specific heat capacity are given emphasis for the meticulous characterization of the composites. The literature survey based on the determination of specific heat capacity and thermal expansivity are as follows:

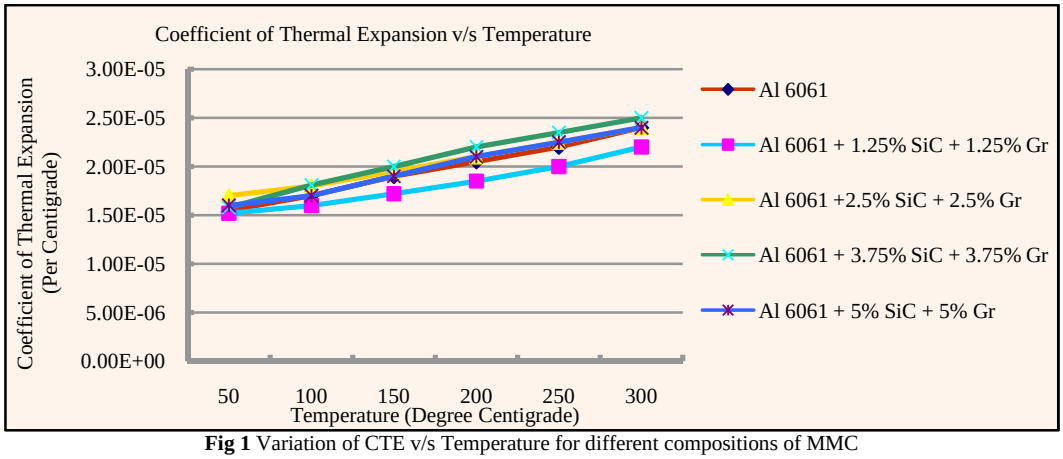

Fig 1 Variation of CTE v/s Temperature for different compositions of MMC

S Cem Okumus, Sardar Aslam *et al* [5] in their paper have studied on Thermal Expansion and Thermal Conductivity behaviour of Al/Si/SiC hybrid composites clearly highlights that Aluminium-Silicon based hybrid composites reinforced with silicon carbide and graphite particles were prepared by liquid phase particle mixing and squeeze casting. The thermal expansion and thermal conductivity behaviour of hybrid composites with various graphite contents (5.0; 7.5; 10 wt.%) and different silicon carbide particle sizes (45 µm and 53 µm) were 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 Arpon, E Louis *et al* [6] have analyzed that thermal expansion behaviour of Aluminium/SiC composites with bimodal particle distributions where it summarizes that The thermal response and the coefficient of thermal expansion (CTE) of Aluminium matrix composites having high volume fractions of SiC particulate have been investigated. The composites were produced by infiltrating liquid Aluminium into preforms made either from a single particle size, or by mixing and packing SiC particulate of two largely different average diameters (170 and 16 µm, respectively).

The experimental results for composites with a single particle size indicate that the hysteresis in the thermal strain response curves is proportional to the square root of the particle surface area per unit volume of metal matrix, in agreement with current theories. Instead, no simple relationship is found between the hysteresis and any of the system parameters for composites with bimodal particle distributions. On the other hand, the overall CTE is shown to be mainly determined by the composite compactness or total particle volume fraction; neither the particle average size nor the particle size distribution seems to affect the overall CTE. This result is in full agreement with published numerical results obtained from finite element analyses of the effective CTE of Aluminium matrix composites. The results also indicate that the CTE varies with particle volume fraction at a pace higher than predicted by theory.

R A Saravanan, J Narciso *et al* [7] have investigated on thermal expansion behaviour of particulate metal matrix composites explains that Aluminium-matrix compositescontaining 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) were measured between 25°C and 500°C with a high-precision thermal mechanical analyzer (TMA), and compared with the predictions of various theoretical models. The thermal-expansion behavior of the three-phase Al/SiC/SiO_2 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. The effect of particle size is quite evident in the pressure-infiltrated composites: the larger the particles, the greater the thermal expansion of the composite. The observed behavior of these composites is discussed in terms of particle size, silica layer formed during oxidation, and thermal stresses developed as a result of the CTE mismatch between the reinforcement and the matrix.

Tran Nam, Requena *et al*. [8] 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 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/SiC 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.

N Chawla, X Deng *et al* [9] comprehensively describes thermal expansion behaviour of Aluminium matrix composites with densely packed SiC particles where the coefficient of thermal expansion (CTE) of Al-based metal matrix composites containing 70 vol.% SiC particles (Al/SiC) has been measured based on the length change from room temperature to 500°C. In the research work, the instantaneous CTE of Al/SiC was

studied by thermo-elastic models and micromechanical simulation using finite element analysis in order to explain abnormalities observed experimentally. The CTE was predicted according to analytical thermo-elastic models of Kerner, Schapery and Turner. The CTE was modeled for heating and cooling cycles from the temperature range 20^0C to 500^0C considering the effects of microscopic voids and phase connectivity. The finite element analysis is based on a two-dimensional unit cell model comparing between generalized plane strain and plane stress formulations. The thermal expansion behaviour is strongly influenced by the presence of voids and confirms qualitatively that they cause the experimentally observed decrease of the CTE above 250^0C.

S X Xu, Y Li *et al* [10] have investigated the temperature profile and specific heat capacity in temperature modulated Differential Scanning Calorimeter with a low sample heat diffusivity. One important application of temperature modulated DSC (TMDSC) is the measurement of specific heat of materials. When the sample has very good thermal conductivity as in the case of metals, the temperature gradient is not normally an important factor and can be ignored most of the time. In this paper, a round analytical solution is given and a numerical model is used to analyze the effects of thermal diffusivity on temperature distribution inside the test sample and specific heat measurement by TMDSC, PET sample test results are presented to demonstrate the effects of material thermal diffusivity.

Bedrich Smetana, Monica Zaludova *et al* [12] have summarized the possibilities of heat capacity measurement of metallic system. The paper deals with the study possibilities of heat capacities, mainly of metallic systems (alloys) on the basis of Fe (Fe-C). Possibilities of theoretical calculations dependencies of heat capacities on temperature are presented in this work in a wide temperature region. Theoretical basis of heat capacities determination using Neumann-Kopp rule is discussed. Experimental possibilities of heat capacities acquisition are determined by the experimental base. Various methods of heat capacities measurement and calculations are presented in the paper (continuous, stepped and DROP method, theoretical Neumann-Kopp rule).

E Morintale, A Harabor *et al* [13] have described the use of heat flows from DSC curve for calculation of specific heat of the solid materials. On basis of the second law of thermodynamics, has 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. Heat flow is obtained from DSC curve, the portion of the curve that does not cause thermal effects and gravimetric effects. For example, the specific heat has been calculated for lysozyme (globular protein) in the temperature range 139-190°C, when the measurements were made in air and argon. Specific heat values of solid organic material are of great interest in the stability and functionality of the material.

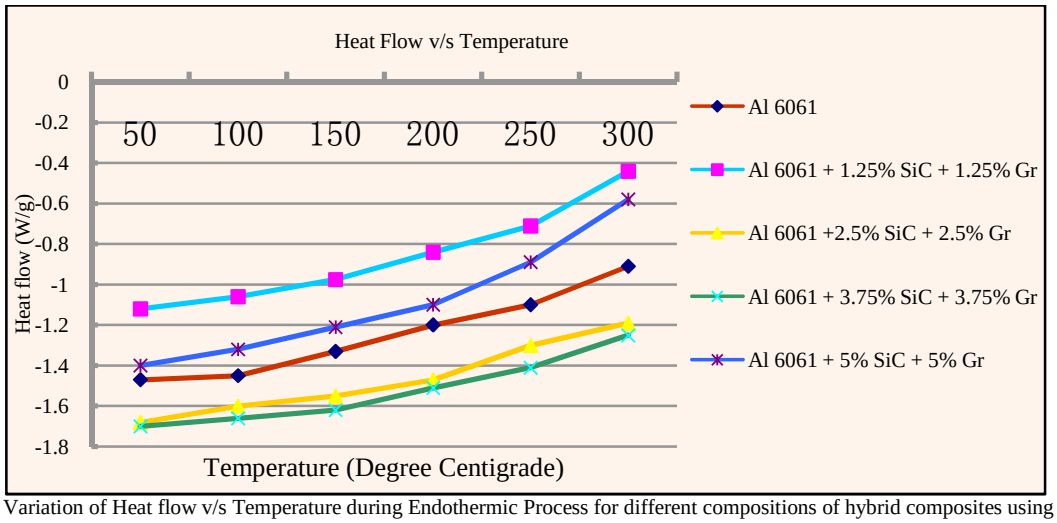

Fig 2 Variation of Heat flow v/s Temperature during Endothermic Process for different compositions of hybrid composites using DSC

N R Pradhan, H Duan *et al* [11] have examined the specific heat and effective thermal conductivity of composites containing single and multi wall carbon nanotubes. The specific heat and effective thermal conductivity in anisotropic and randomly oriented multi-wall carbon nanotube (MWCNT) and randomly oriented single-wall carbon nanotube (SWCNT) composites from 300 to 400 K was studied. Measurements on randomly oriented MWCNTs and SWCNTs were made by depositing a thin film of CNTs within a calorimetric cell. Anisotropic measurements were made on MWCNTs grown inside the highly ordered, densely packed nanochannels of anodic Aluminum oxide. The specific heat of randomly oriented MWCNTs and SWCNTs showed similar behavior to the specific heat of bulk graphite powder. However, the specific heat of aligned MWCNTs is smaller and has weaker temperature dependence than that of the bulk above room temperature.

M J O'Neill [14] has explained the measurement of specific heat functions by Differential Scanning Calorimeter. When a sample material is subjected to a linear temperature program, the heat flow rate into the sample is proportional to its instantaneous specific heat. By recording this heat flow rate as a function of temperature, and comparing it with the heat flow rate into a standard material under the same conditions, the specific heat of the sample is determined as a function of temperature. The method is illustrated by measurements on various samples in the temperature range 340"K to 510" K and agreement with literature specific heat values is demonstrated. The ultimate precision of the method is 0.370 or better, which approaches the precision of adiabatic Calorimetry. However, measurements may be made with samples which are four orders of magnitude smaller, and program rates two orders of magnitude larger, than those typical of conventional Calorimetry.

Experimental Procedure

Thermal expansion is the tendency of matter to change in volume in response to change in temperature. The degree of expansion to the change in temperature is called the material's coefficient of thermal expansion and generally varies with temperature. Coefficient of Thermal Expansion is one of the most important properties of MMCs. Since nearly all Metal Matrix Composites are used in various temperature ranges, measurement of CTE as a function of temperature is necessary in order to know the behaviour of the material. Several different systems for measurement of CTE can be used depending on the temperature conditions. One of the most common systems used is a dilatometer. A dilatometer measures the length or the volume changes of the sample, when the sample follows a temperature program and submits a small force. In a push rod dilatometer, the change in length of the sample is detected by an inductive displacement transducer. Calibration and corrections of measurements are done by using various standards and comparison with materials of known expansion. The measurement of the coefficient of thermal expansion (CTE) can be carried out in the temperature range from approximately – 150°C to 1500°C. Linesis 75 Platinum Horizontal Dilatometer comprises of Thyristor controlled unit, Linear Variable Differential Transformer (LVDT), automatic pressure control unit, variety of sample holders and RCS (Rate Controlled Sintering) software. The coefficient of thermal expansion (CTE) can be controlled by two parameters simultaneously namely wall thickness and volume fraction comprehensively. 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 are shown for different percentage composition. It is obvious that the CTE of the composites and matrix increases with increase in temperature. For the determination of CTE of the composites, Dilatometer was used comprehensively.

Differential Scanning Calorimeter (DSC) thermal analysis is an important tool in the experimental characterization of composite materials. It is used to evaluate polymers and polymer matrix composites for diverse applications such as automobiles, aircrafts, space vehicles, containers, and piping systems for the marine and petrochemical industries. Fundamentally, DSC measures the heat capacity of a sample by recording the heat flow rate into the sample and comparing it to a reference sample. From the DSC curve one can determine materials transition points such as the glass transition temperature and melting temperature. The DSC can also quantify the degree of crystallinity for thermoplastic matrices and the residual heat of reaction for thermosetting resins. Additionally, the curing characteristics of thermosetting matrices can be modeled from limited DSC curves to develop a mathematical cure kinetic model that can be used for process optimization and curing simulations [15].

In Differential Scanning Calorimetry (DSC), the sample material is subjected to a linear temperature program, and the heat flow rate into the sample is continuously measured; this heat flow rate is proportional to the instantaneous specific heat of the sample. Two sample holders are mounted symmetrically inside an enclosure which is normally held at room temperature. A primary temperature control system controls the average temperature of the two sample holders, using platinum resistance thermometers and heating elements embedded in the sample holders. A secondary temperature control system measures the temperature difference between the two sample holders, and adjusts this difference to zero by controlling a differential component of the total heating power. This differential power is measured and recorded [15, 16].

In the present research work, the type of DSC proposed is heat flux for the determination of heat flow distribution and specific heat capacity. The procedure described above was carried out with Q100 DSC, on a number of samples for which specific heat functions have been measured. A temperature interval from room temperature to 300° C was used for all but one of the measurements to be discussed, where a slightly smaller interval was used. The nominal program rate was 10°*C* per minute. All samples were encapsulated in the Aluminum foil dishes supplied with the instrument, which weigh approximately 20 mg with their covers. It was verified by calculation that the small weight variations between these dishes would contribute a negligible error to the measurement.

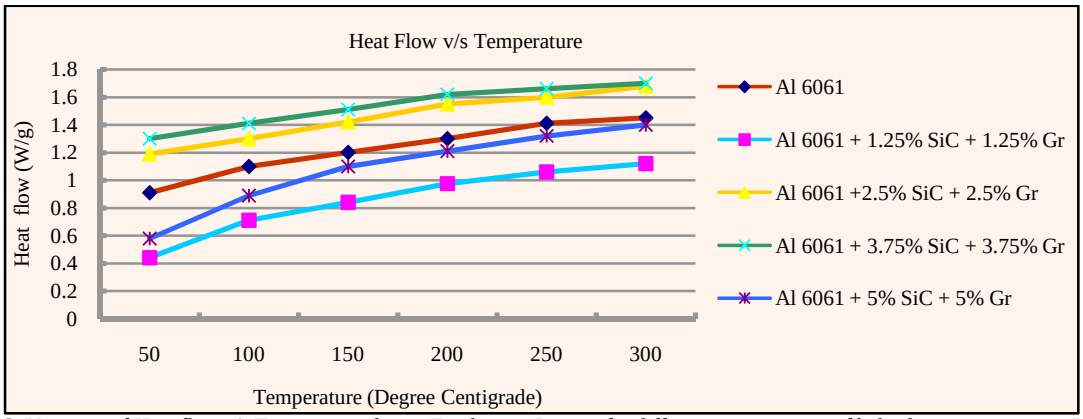

Fig 3 Variation of Heat flow v/s Temperature during Exothermic Process for different compositions of hybrid composites using DSC

RESULTS & DISCUSSION

For the determination of CTE, the size of the cylindrical sample is diameter 5 mm and length 10 mm, as per ASTM standards. 5 samples are considered with different percentage compositions. Al 6061 is the base alloy and reinforcements SiC and Gr with different percentage compositions 1.25%, 2.5%, 3.75% and 5% are selected. All the specimens were tested from room temperature to 360°C. This temperature range was selected so as to include the entire usable range of

the composites, without the formation of liquid phase in the matrix. The data were 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. Rate Controlled Sintering (RCS) is an asset for standard dilatometer software. During measurement using dilatometer, the change in length of the sample for the required temperature range is considered. The purpose of RCS is to determine the optimal sinter process, especially the optimal temperature-time profile. 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 was limited to 360 °C, as there is greater possibility of reaching molten condition.

The evaluation of CTE of hybrid metal matrix composites 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 [6]. The thermal expansion behavior of Al alloy reinforced with Silicon Carbide and Graphite were measured at prominent temperatures varying from 20°C to 350°C.

samples are considered with different percentage compositions. Al 6061 is the base alloy and reinforcements SiC and Gr with different percentage compositions 1.25%, 2.5%, 3.75% and 5% are selected. All the specimens were tested from room temperature to 300°C. This temperature range was selected so as to include the entire usable range of the composites, without the formation of liquid phase in the matrix. The data were obtained in the form of per cent linear change versus temperature.

Differential Scanning Calorimetry is thermo analytical technique in which the difference in the amount of heat required to increase the temperature of a sample and reference is measured as a function of temperature. Both the sample and reference are maintained at nearly the same temperature throughout the experiment [17]. There is significant need for determining the specific heat capacity in order to perform thermodynamic calculations. Historically, specific heat capacity is measured at room temperature and presumed not to change with temperature. Figures 4.1 and 4.2 shows the variation of heat flow and temperature for different compositions of hybrid MMC based on endothermic and exothermic processes. It is noticed that the heat flow of the hybrid composites with different percentage compositions varies with the increase in temperature. There is consistency in the variation of heat flow for different temperatures recorded at regular intervals.

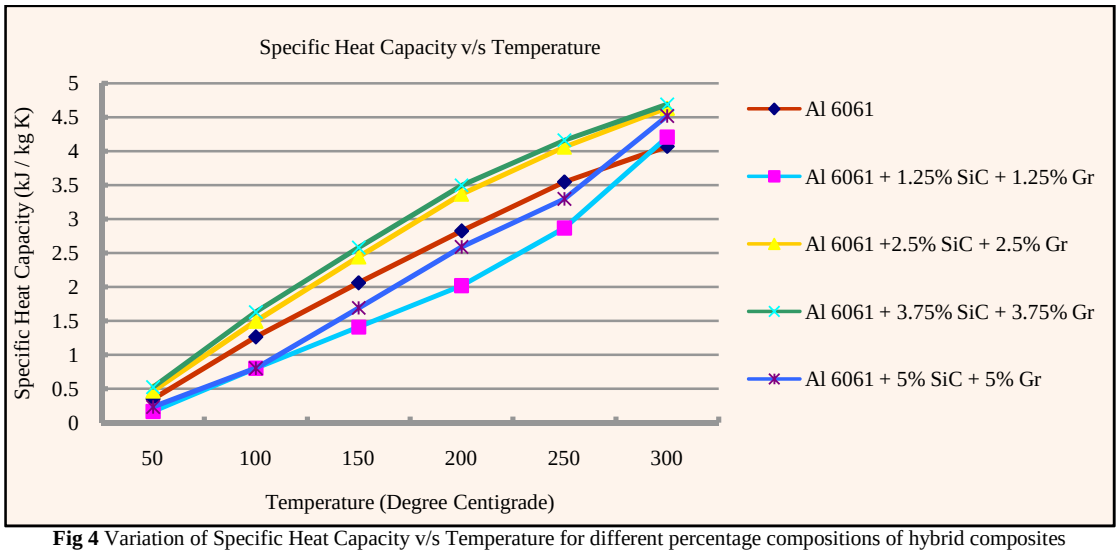

Fig 4 Variation of Specific Heat Capacity v/s Temperature for different percentage compositions of hybrid composites

Fig 4.1 shows the variation of CTE and temperature for different compositions of hybrid MMC. It is noticed that, the CTE of the hybrid composites with different percentage compositions increases with the increase in temperature. There is consistency in the increase of CTE for different temperatures recorded at regular intervals. During the testing of different samples, the elongation was observed to be low, as such the increase in the values of CTE of the mentioned compositions of hybrid MMCs were in endurable limits ranging from 15 $\times 10^{-6}$/°C to 26 $\times 10^{-6}$/°C. Al 6061 + 3.75% SiC + 3.75% Gr exhibited the maximum value of CTE, whereas Al 6061 + 1.25%SiC + 1.25% Gr exhibited lower magnitude of CTE and Al 6061 exhibited normal value of CTE.

For the determination of Specific Heat Capacity and enthalpy, the sample should be in powder form of about 20 mg. 5

and temperature for different compositions of hybrid MMC. It can be observed that the magnitude of specific heat capacity is high for Al 6061 + 3.75% SiC + 3.75% Gr and low for Al 6061. For the other samples, the values of specific heat capacities are moderate. It was observed that with increasing the percentage volume fraction of the reinforcement material Silicon Carbide, the heat capacity of the MMCs increases. With the increase in the content of Silicon Carbide, the heat capacity also increases for the given range of temperature. The variation in heat flow was observed to be consistent, as such the values of specific heat capacities of all compositions were in first order ranging from 0.3 kJ/kg K to 4.7 kJ/kg K.

CONCLUSIONS

1. It is noticed that, the CTE and Specific Heat Capacities of the hybrid composites with different percentage compositions increases with the increase in temperature. There is consistency in the increase of CTE for different temperatures recorded at regular intervals.
2. During the testing of different samples, the elongation was observed to be low, as such the increase in the values of CTE of all compositions were in endurable limits. Similarly, during the testing of different samples, the heat flow was observed to be consistent, as such the increase in the values of specific heat capacities of all compositions were in appreciative limits.
3. The percentage volume fraction of SiC estimated was low, facilitating CTE to increase drastically and exhibits the expected trend.
4. The hybrid composites have lower volume fractions of SiC than conventional Al-SiC composites with the same CTEs.
5. In Al-SiC composites, the thermal expansion behavior will be influenced by Aluminium and the tightened restriction of SiC particles.
6. Al 6061 + 3.75% SiC + 3.75% Gr exhibited the maximum value of CTE, whereas Al 6061 + 1.25%SiC+ 1.25% Gr exhibited lower magnitude of CTE and Al 6061 exhibited normal value of CTE. The variation in specific heat capacity was observed to be steady; as such the values of specific heat capacities of all compositions were in first order ranging from 0.3 kJ/kg K to 4.7 kJ/kg K.
7. The theoretical and experimental values of density of composites were compared and it proved to have negligible porosity.

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References

1. "Introduction to composites", Composites ASM Hand Book, Vol 21, May 2002.
2. Bedrich Smetana, Monica Zaludova et al [6], "Possibilities of Heat Capacity Measurement of Metallic systems", METAL 12, 23 – 25, 2012, Czech Republic, EU.
3. D. Hull, T.W. Clyne, "An Introduction to Composite Materials", Cambridge Solid State Science Series, Second Edition.
4. E Morintale, A Harabou et al [7], "Use of heat flows from DSC curve for calculation of specific heat of the solid materials", Physics AUC, Volume 23, 89-94, 2013.
5. H K D H Bhadeshia, "Differential Scanning Calorimeter", University of Cambridge, Materials Science & Metallurgy.
6. Leonard C Thomas, "Making accurate DSC and MDSC Specific Heat Capacity measurements with Q 1000 DCS", TA Instruments, 109 Lukens Drive, New Castle, USA.
7. M J O'Neill, "Measurement of specific heat functions by Differential Scanning Calorimeter", The Parker-Elmer corporation, Norwalk.
8. N Chawla, X Deng et al, "Thermal expansion anisotropy in extruded SiC particle reinforced 2080 aluminium alloy matrix composites", Material Science and Engineering, A 426 (2006) 314-322.
9. N R Pradhan, H Duan et al [5],"The specific heat and effective thermal conductivity of composites containing single and multi wall carbon nanotubes", IOP Publishing, May 2009, USA.
10. N. R. Habbu "Use of Aluminium Silicon Alloys in Automobile Application" proceedings of one day Industry Institute Interactive Meet on Al-Si alloys, Development and Application for transport sector, IISC Bangalore, September 2000.
11. R A Saravanan, J Narciso et al, "Thermal expansion studies on aluminium-matrix composites with different reinforcement architecture of SiC particles" Volume 51, Issue 11, 27 June 2003, Pages 3145-3156.
12. R Arpon, E Louis et al, "Thermal expansion behaviour of aluminium/SiC composites with bimodal particle distributions", Volume 51, Issue 11, 27 June 2003, Pages 3145-3156.
13. S Cem Okumus, Sardar Aslam et al, "Thermal Expansion and Thermal Conductivity Behaviors of Al-Si/SiC/graphite Hybrid Metal Matrix Composites (MMCs)", Volume 18, No 4 (2012).
14. S X Xu, Y Li et al, "Study of temperature profile and specific heat capacity in temperature modulated DSC with a low sample heat diffusivity", Elsevier, May 2000, pp 131-140.
15. S.S. Joshi, N. Ramakrishnan & P. Ramakrishnan, "Micro Structural Analysis of Chip formation during Orthogonal Machining of Al/ SiCp Composites" Journal of Engg. Metals. Technology, July 2001, Volume 123, pp 315 – 321.
16. Suchitra Mutlur, "Thermal Analysis of Composites using DSC."
17. Tran Nam, Requena et al, "Thermal expansion behaviour of aluminium matrix composites with densely packed SiC particles", Applied Science and manufacturing, Part A 39 (2009) 856-865.

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