

Research Article

Evaluation of the Effective Thermal Properties of Aluminum Metal Matrix Composites Reinforced by Ceramic Particles

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Abstract

The effective thermal properties of aluminum metal matrix composites (AMMCs) reinforced by ceramic particles were explored. The importance of AMMCs reinforced by ceramic particles lies in their properties are characterized by and which is difficult to availability combined in other engineering material. Synthesis and development of AMMCs with different properties increased dramatically due to development of technology and increasing modern industry requirements in an engineering applications. By selection a suitable reinforcements in AMMCs, a new composite could be synthesized which meets the requirements of the required engineering applications. Various types of ceramic particles such as oxides, carbides, nitrides, as well as carbon nanotubes can be used as reinforcements in AMMCs. Thermal properties of AMMCs consisting of an aluminum as continuous matrix phase and ceramic particles as reinforcements are directly affected by type, size, geometry, RVR and modulus of elasticity of dispersions. Also the difference in the heat transfer mechanisms in the constituents of composites plays an important role, as well as an interfacial thermal barrier resistance influence effectively on heat transfer inside the composite and thus the thermal properties. In the present study, based on the literature review, the effective thermal properties of AMMCs reinforced with ceramic particles were discussed.

Keywords: Thermal properties, Aluminum metal matrix composites and Ceramic particles.

1. Introduction

Composite materials do play a great significance and an effective role in many engineering industries applications because of the physical properties that are characterized by. Thermal properties is one of prime physical properties of composites, which also include electrical, magnetic and optical properties. Thermal property of a material is its physical property related to application of heat energy and explain its response. As a solid body absorbs energy in the form of heat, its temperature increases and its dimensions increase. Heat capacity, thermal expansion, and thermal conductivity are properties that are often critical in the practical utilization of solids. Heat is transferred at a higher rate across materials of high thermal conductivity than across materials of low thermal conductivity. The reciprocal of thermal conductivity is called thermal resistivity [Physical property, *et al*, 2013].

There are different types of engineering materials (metals, ceramics, polymers and composites), so the driving mechanism for thermal conductivity depends on type of material. Generally, the thermal conductivity

mechanism in materials is attributed to electrons and phonons. Because of large numbers of free electrons with high free mean paths and velocities in high pure metals, the electron mechanism of heat transfer is much more efficient than the phonon contribution. These free electrons are also not as easily scattered as phonons. The thermal conductivity in pure metals remains approximately constant with rising temperature. Metals with crystal structure type of face center cubic "FCC" are characterized by the highest thermal conductivity. Metals have crystal structure of body center cubic "BCC" show an order of magnitude lower thermal conductivity. Alloying metals with impurities result in a reducing in the thermal conductivity. Atoms of different metals have different sizes, act with impurities as scattering centers and lead to lowering the efficiency of electron motion. Figure 1.1 shows the thermal conductivity versus composition for copper-zinc alloys.

Nonmetals, such as glass, ceramics and polymers, are thermal isolating materials as much as they lack numbers of free electrons. Because the phonons are primarily responsible for thermal conduction in nonmetallic materials and phonons are scattered much more than electrons by lattice imperfections, so they are not as effective as free electrons in the transport of heat energy.

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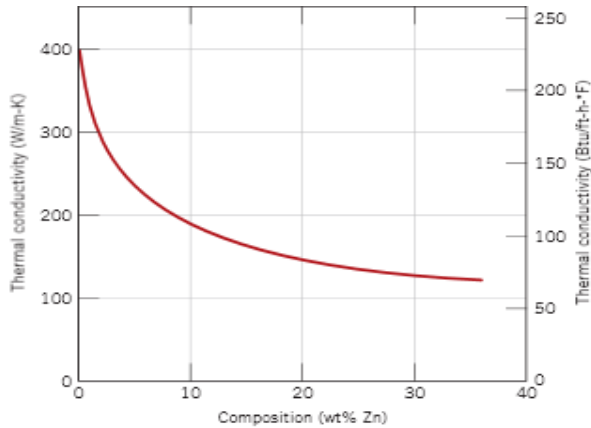


Fig. 1.1: Thermal conductivity versus composition for copper-zinc alloys

Crystalline ceramics have higher conductivities than glass and other amorphous ceramics, since the phonon scattering is much less than effective when the atomic structure is little disordered and irregular. With rising temperature, increases the scattering of lattice vibrations. As a result, the thermal conductivity of most ceramic materials normally decreases with increasing temperature, especially at relatively low temperatures (Figure 1.2).

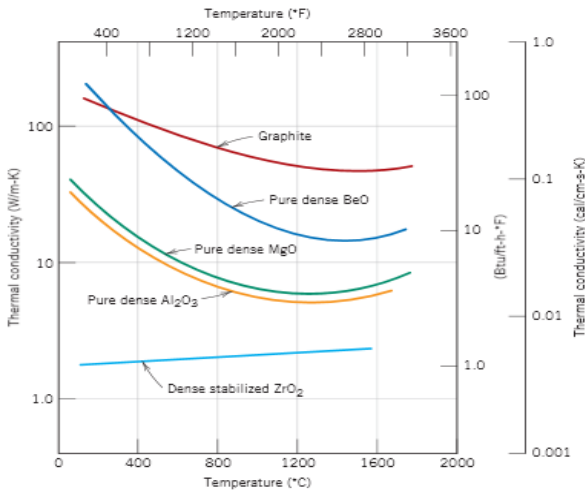


Fig. 1.2: Dependence of thermal conductivity on temperature for several ceramic materials

Figure 1.2 shows that the conductivity starts to increase at higher temperatures, this is because of radiant heat transfer. Significant quantities of infrared radiant heat may be transported through a transparent ceramics. This process becomes more efficiency with rising temperature.

Porosity may have a dramatic impact on thermal conductivity of ceramic materials. Increasing the pore volume will lead to a reduction of the thermal conductivity [Callister, *et al* 2007; Composite materials handbook, *et al* 2002; Kainer, *et al*, 2006].

An interfacial thermal resistance, it is also known as “the thermal boundary resistance” or “Kapitza resistance”, is defined as a measure of an interface's resistance to thermal flow. Because of the differences

in electronic and vibrational properties in different materials. The heat energy carrier (phonon or electron, depending on the type of material) will scatter at the interface when it attempts to travel through the interface. The probability of transmission after scattering will depend on the available energy states on both the sides of interface. There are two primary models that are used to understand the thermal resistance of interfaces, which are: the acoustic mismatch and diffuse mismatch models. The two models are based only on phonon transport, with ignoring of the electrical contributions. So they should be applied for interfaces where at least one of the materials is electrically insulating. The thermal resistance then will result from the transfer of phonons across the interface. Heat energy is transferred when higher energy phonons exist in higher density in the hotter material propagate to the cooler materials, which in turn transmits lower energy phonons, creating a net energy flux. The decisive factor in determining the thermal resistance at an interface is the overlap of phonon states, as illustrated in figures 1.3-a and -b [Interfacial thermal resistance, *et al* 2015].

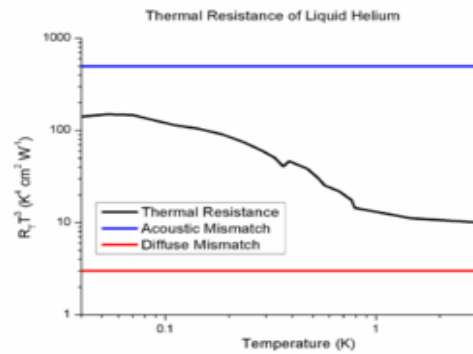


Fig. 1.3 (a) Typical Interfacial Resistance of liquid Helium With metals. Resistance has been multiplied by T^3 to remove the expected T^{-3} dependence

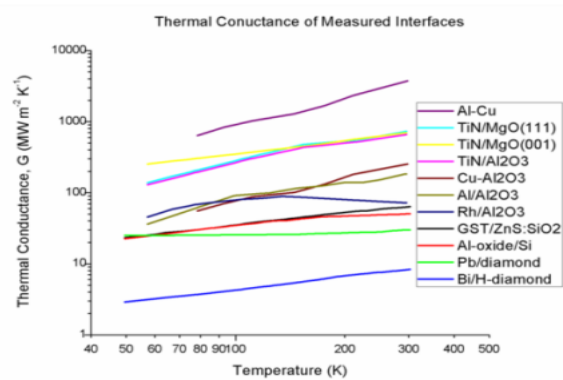


Fig. 1.3 (b) Thermal conductance of measured interface of some Composites (Composites and alloys)

An expressions for the effective thermal conductivity of composites consisting of a continuous matrix phase with dilute concentrations of dispersions with

spherical, cylindrical and flat plate geometry with a thermal barrier resistance at the interface between the components were derived by a modification of the original theories of Rayleigh and Maxwell. Because of the existence of an interfacial thermal barrier resistance in composites, it was found that, the effective thermal conductivity not only depends on the volume fraction of the dispersed phase but also on the dispersion size. However, interfacial thermal barriers are expected to be effective only if they are non-parallel to the direction of heat flow. This suggests that for non-spherical dispersions with preferred orientation, the existence of a thermal barrier resistance can serve as an additional mechanism for introducing anisotropy in thermal conductivity even when K_d (dispersion conductivity) = K_m (matrix thermal conductivity) [Hasselman, *et al*, 1987].

By analyzing of the role of aggregation and interfacial thermal resistance on the effective thermal conductivity of nanofluids and nanocomposites, three-level homogenization theory, validated by monte carlo simulation of heat conduction on model fractal aggregates was used. It was concluded that the thermal conductivity of nanofluids and nanocomposites can be significantly improved by the aggregation of nanoparticles into clusters. The conductivity improvement due to aggregation is also a strong function of the chemical dimension of the aggregates and the radius of gyration of the aggregates. This developed model accounts for aggregation kinetics and the impact of chemistry of the system through their dependence of the radius of gyration. By including the effect of interfacial thermal resistance in the homogenization model. It was also found that any enhancement in the thermal conductivity will be degraded, however, this degradation can be limited by large aggregate sizes [Evans, *et al*, 2008].

The thermal resistance "reciprocal to the thermal conductivity" is caused by various types of phonon scattering processes such as phonon-phonon scattering, boundary scattering, scattering from static point imperfections, dislocations of atoms, stacking faults and grain boundaries. In some cases was found that phonon-boundary scattering effects dominate the thermal conduction processes and reducing thermal conductivity. Because of the large band gap between the valence and conduction bands, most ionically and covalently bonded materials exhibit very low thermal conductivity, but covalently bonded solids tend to have higher thermal conductivities than thus of ionically bonded solids.

The distance between phonon scattering centers represents the relevant mean free path. Collisions between phonons are not relevant because they do not change the net momentum of the phonons involved in transport whereas so-called umklapp processes, in which two phonons interact with the lattice to yield a third scattered phonon. Phonons travel at the speed of sound and for maximizing the thermal conductivity, these phonon scattering processes must be minimized. In composites, the scattering of phonons is mainly due

to the interfacial thermal barriers, resulting from acoustic mismatch and flaws associated with the filler-matrix interface. There are four criteria must be met in the solid nonmetallic material in order to be high thermal conductive: low atomic mass, chemical bonding, simple crystal structure and low anharmonicity in the molecular vibrations [Andritsch, *et al*, 2010; Kochetov, *et al*, 2012].

Monte Carlo simulation was carried out for studying of the phonon transport in random composite materials made from nanoparticles of two different materials with large thermal conductivity contrast ratio.

The effective thermal conductivity of nanoparticle composites was obtained based on the RVE with 1000 or more nanoparticles randomly stacked in space. The effects of interface scattering on thermal conductivity percolation of random nanoparticle composites were examined for the constituents with large thermal conductivity contrast ratio. Because of the interface scattering, it was found that the geometrical percolating network formed by the high thermal conductivity particles is not effective for the thermal conductivity improvement of nanocomposites when the nanoparticle size is comparable or smaller than the phonon mean free path of the high thermal conductivity constituent. The minimum thermal conductivity for composite materials made from small nanoparticles occurs when the volumetric concentration of high thermal conductivity constituent is around 0.5 because of the dominance of the phonon-interface scattering. The thermal conductivity of the composites can be improved by increasing the thermal conductivity contrast ratio only when the volumetric concentration of the high thermal conductivity constituents is large. Because of the dominance of interface scattering, this effect can saturate with further increasing the contrast ratio having no effect on the composite thermal conductivity. The effective thermal conductivity of the nanoparticle composites was found to moderately increase with the transmissivity and specularity of the interface scattering, figures :1.4- a, -b, -c and -d [Tian, *et al*, 2008].

Heat capacity, it is also named as the thermal capacity, is the ratio of the heat added to "or subtracted from" an object to the resulting temperature change. as a measurable physical quantity. Heat capacity can also be defined as the amount of heat required to change the temperature of a substance or system one degree.

Mathematically, it is expressed as: $C = dQ/dT$, J/mol-K or Cal/mol-K, where dQ is the energy required to produce a temperature change equal to dT . Because the total heat a material can absorb depends on its volume / mass, the heat capacity is not an intrinsic property. Hence another parameter named specific heat, C , it is defined as heat capacity per unit mass (J/kg.K, Cal/kg.K). Increasing internal energy of material may lead to geometrical changes. As a result, heat capacity can be measured either at constant volume, C_v , or at constant external pressure, C_p . Generally, the magnitude of C_p is always greater than C_v but only marginally.

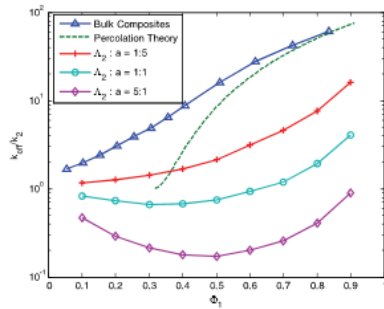


Fig. 1.4-a: Effect of the nanoparticle size on the nondimensionalized effective thermal conductivity of nanoparticle composites. The thermal conductivity contrast $K_1 : K_2 = \varpi_1 : \varpi_2$, $k_1:k_2 = \varpi_1 : \varpi_2$ between the nanoparticles is assumed to be 100

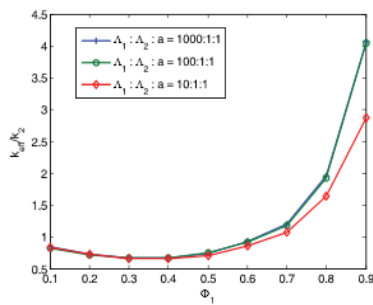


Fig. 1.4-b: Effect of the constituents intrinsic thermal conductivity contrast ratio on the nondimensionalized effective thermal conductivity of nanoparticle composites. $\varpi_2 : a = 1 : 1$ is used in this simulation

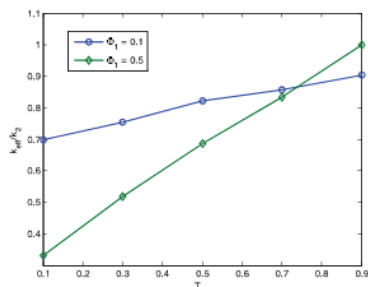


Fig. 1.4-c: Effect of the phonon-interface transmissivity on the nondimensionalized effective thermal conductivity of the nanocomposites. $\varpi_1 : \varpi_2 : a = 100 : 1 : 1$ is used in this simulation

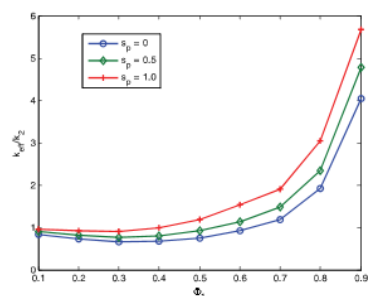


Fig. 1.4-d: Effect of the specularity of phonon interface scattering on the nondimensionalized effective thermal conductivity of nanoparticle composites. $\varpi_1 : \varpi_2 : a = 100 : 1 : 1$ is used in this simulation.

Heat energy a material absorbs exists in form of thermal energy vibrations of constituent atoms or molecules. A part from other mechanisms of heat absorption such as electronic contribution. Atoms and molecules vibrate at higher frequencies with increase of heat energy. Due to the vibrations of adjacent atoms are coupled through atomic bonding, lattices may move. This can be represented as elastic waves “phonon” or sound waves. Vibrational contribution of heat capacity of solid materials varies with temperature and can be determined through the equation: $C_v = AT^3$.

C_v represents increased ability of atomic vibrations or enhanced energy of lattice waves with rising temperature. It is equal to zero at 0K, but ascends very quickly with increasing temperature.

Dependence of volumetric heat capacity value reaches saturation above a temperature named Debye temperature “ θ_d ”. This saturation value is approximately equal to $3R$ ($\approx 6 \text{ cal/mol.K}$), where R is the universal gas constant. For many solids, value of “ θ_d ” is below room temperature. Figure 1.5 shows The dimensionless heat capacity divided by three, as a function of temperature as predicted by the Debye model and by Einstein’s earlier model. The horizontal axis is the temperature divided by the Debye temperature. Note that, as expected, the dimensionless heat capacity is zero at absolute zero, and rises to a value of three as the temperature becomes much larger than the Debye temperature. The red line corresponds to the classical limit of the Dulong–Petit law. [Wiley, et al, 2002; Heat capacity, et al, 2015].

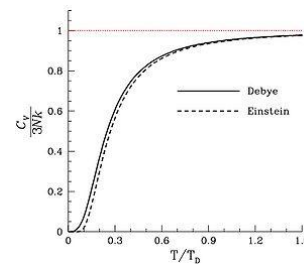


Fig. 1.5

Selection of materials for usage at high temperature and/or temperature changes need an engineer to determine and understand their thermal properties. Because of an increasing of new industrial demands in modern engineering applications, particulate reinforced light metals have become of vital importance. The main objective of fabrication and utilizing metal matrix composites (MMCs) is to accomplish the excellent strength to weight and weight to stiffness ratios in a less cost light material.

Aluminum and its alloys are the most commonly used matrix materials in the production of MMCs because of their preferred properties such as lightness, good corrosion resistance, high strength to weight ratio, good electrical and thermal conductivity, high stiffness, good abrasion resistance, ductility and good

heat reflectivity [Wiley, *et al*, 1992]. Figure 1.6 shows examples of composite reinforcements.

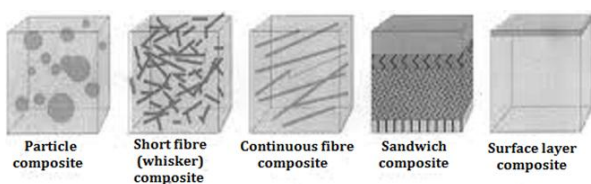


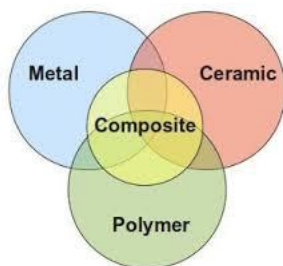
Fig. 1.6: Examples of composite reinforcements

2. Metal Matrix Composites (MMCs)

Composite materials are combinations of two materials in which one of the material is called the reinforcement, is in the form of fibers, sheets or particles, and is embedded in the other material named the matrix phase. At a recent times, fabrication and an evolution of composite materials with different properties increased very significantly due to development of technology and increasing new demands of industry in modern engineering applications. Technology of composite materials combines the most great significant properties of the components together in order to get a material with overall properties appropriate for the manufacture of the engineering part required.

Modern techniques used to fabricate a composite structure are dependent upon material performance requirements, structure configuration, and production rates [ASM International Handbook, *et al*, 1989].

Composites can be classified by their matrix material into metal matrix composites (MMC's), ceramic matrix composites (CMC's) and polymer matrix composites (PMC's), or sometimes referred to as organic matrix composites (OMC's).



A metal matrix composite (MMC) is a type of composites with at least two constituents, one being a metal. The other constituent part may be a different metal or another material, such as a ceramic or organic material. When the composite contains more than two constituent parts at least three materials are present, it is named a hybrid composite.

There are various industrial techniques used to produce different composite materials. Metal Matrix Aluminum and its alloys are the most commonly used matrix materials in the production of (AMMCs) because of their preferred properties.

2.1 AMMCs Reinforced with Ceramic Particles

The combination of lightweight, environmental resistance and adequate mechanical and physical properties has made aluminum and its alloys composites very popular. The melting point of aluminum is high enough to satisfy many application requirements. [Wiley, *et al*, 1992].

There are several types of ceramic materials such as SiC, SiO₂, Al₂O₃, MgO, ZnO, BeO, MnO₂, TiO₂, TiC, etc. are used as reinforcement elements. Superior properties of these materials such as refractoriness, high compressive strength and hardness, excellent wear resistance, etc. make them appropriate for use as reinforcements in metal matrix composites [Khedera, *et al*, 2011; Ramesh, *et al*, 2010; Surappa, *et al*, 2003]. Various techniques such as casting, melt stirring, powder metallurgy, in-situ and infiltration can be used to fabricate and produce MMCs. Melt stirring method has a good potential in all-purpose applications as it is a low cost MMCs production method [Calin, *et al*, 2012; Jit, *et al*, 2009].

Selection of the suitable technique and material is the most important and an effective criterion for fabrication of MMCs. Furthermore, in case of MMCs fabrication with melt stirring method, increased Reinforcement Volume Ratio (RVR) and reduced particle size resulted more difficult production process and increased porosity and particle agglomeration [Suresh, *et al*, 2011; Mazahery, *et al*, 2012].

2.1.1 Thermal properties of AMMCs reinforces by ceramic particles

High-performance thermal materials are classified into monolithic carbonaceous materials, carbon / carbon composites (CCCs), metal matrix composites (MMCs), ceramic matrix composites (CMCs) and polymer matrix composites (PMCs). Figure 2.1 illustrate values of thermal conductivities and coefficients of thermal expansion of semiconductors, ceramics and thermal materials used in microelectronic, optoelectronic, and MEMS packaging.

Metal matrix composites can be synthesized for an optimization of thermal and physical properties in an engineering electronic applications. For these applications, the thermal expansion can be controlled with a negligible penalty in thermal conductivity. Thermal expansion coefficient decreases with increasing volume fraction of silicon carbide in a 2080/SiCp composite. Due to the thermal conductivity of SiC which is similar to those of Al, aluminum metal matrix reinforced with SiC will not lose much in the way of thermal conductivity. In particular, a bimodal distribution of the particles was used, because small reinforcement particles fit in the space between large particles. Enhanced thermal conductivity and lightweight in a CTE - matched material are the features being exploited in using Al/SiC and Al/C metal matrix composites in electronic industrials., Continuous boron fiber-reinforced aluminum

composites made by diffusion bonding were also used as heat sinks in chip carrier multilayer boards. Al/carbon fiber composites are characterized by high thermal conductivity along the fiber direction, the conductivity transverse to the fibers is two-third those of aluminum. C/Al composites are useful in heat transfer applications where lightweight is required. These composites are also useful to use in high speed airplanes for dissipation of heat from the leading edges of wings. Also, the importance of metal matrix composites lies in its use for covers of inertial guidance system for a missile system [Chawla, *et al*, 2013].

Figure 2.1 illustrate the thermal conductivities and coefficients of thermal expansion of semiconductors, ceramics and thermal materials used in microelectronic, optoelectronic, and MEMS packaging [Zweben, *et al*, 2006].

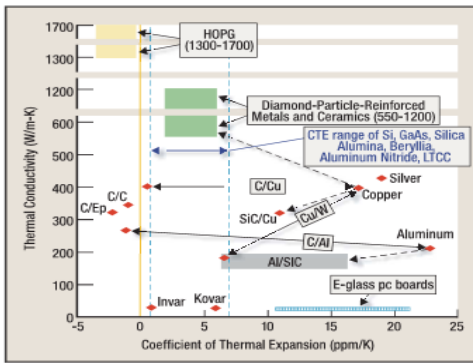


Fig. 2.1: Thermal conductivities and coefficients of thermal expansion of semiconductors, ceramics and thermal materials used in microelectronic, optoelectronic and MEMS packaging.

Figures 2.2-a, -b and -c represent an effective transverse thermal conductivity of carbon / Aluminum composite, boron / Aluminum composite and Silicon Carbide / Aluminum composite [Tang, *et al*, 2007].

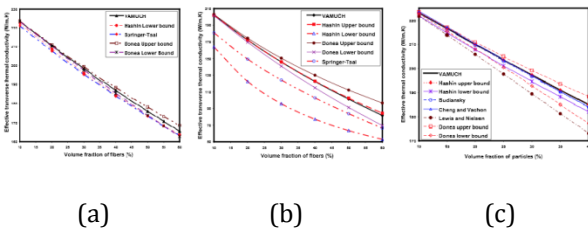


Fig. 2.2: Effective transverse thermal conductivity of (a):carbon/Al composite, (b):boron/Al composite and (c):SiC/Al composite

H. Lee and S. Hong fabricated a high volume fraction SiCp/Al metal matrix composites via pressure infiltration casting technique, they found that the TC of SiCp /Al composites were sensitively dependent on the RVR of SiC particles, the inorganic binder content, and the residual pores at the interfaces of SiC/Al. CTE of SiCp /Al composites were dependent on the RVR of SiC

particles, but were independent of the inorganic binder content and amount of residual pores. Their results are represented in figures 2.3-a, -b and -c. [Lee, *et al*, 2003].

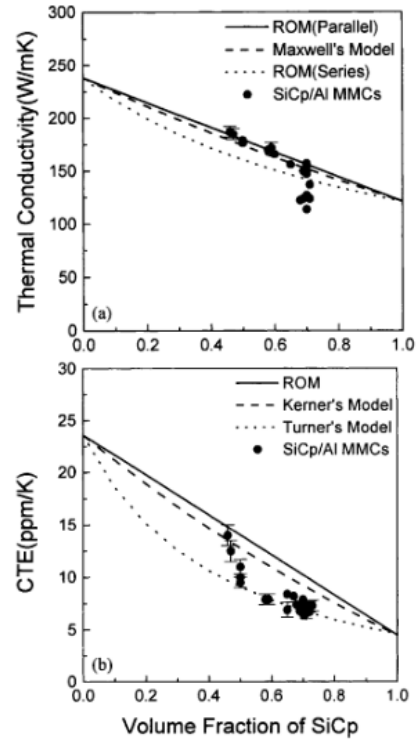


Fig. 2.3- (a): Variation of TC & CTE of SiCp/Al composites with increasing volume fraction of SiC particles

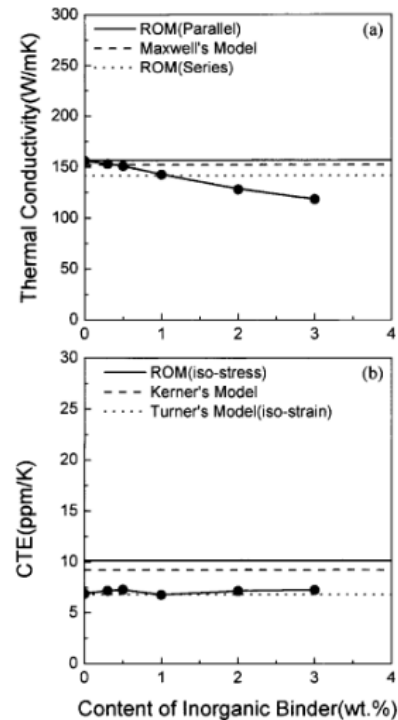


Fig. 2.3- (b): Variation of TC & CTE of SiCp/Al composites with varying content of SiO₂ inorganic binder

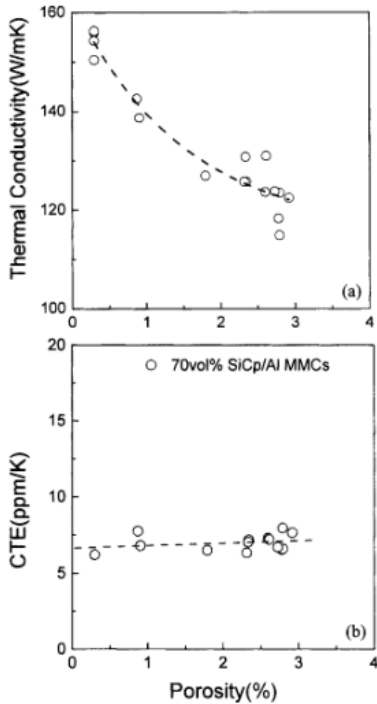


Fig. 2.3- (c): Variation of TC & CTE of SiCp/Al composites with varying porosity in 70 vol. % SiCp/Al composites

Ceramic particles as reinforcements can be used for synthesis of aluminium metal matrix composites either in microparticles or in nanoparticles to produce nanocomposites. The thermal conductivity of composites containing microparticles can be determined by taking into account the shape and volume of the incorporated particles, assuming diffusive heat conduction in both phases. This approach cannot be applied to a system with nanoparticles inside. In case of nanostructures, phonons have a considerable impact and are usually dominant. As a result, the phonon properties of the structure become of a distinct significance for thermal conductivity. Several factors have to be taken into account for nanocomposites, which can be ignored when dealing with microscale particles. Generally, in case of nanoscale particles, interface resistance and phonon scattering have an effective influence on thermal properties of composites. [Andritsch, *et al*, 2010; Kochetov, *et al*, 2012].

A commercial pure aluminum as matrix material and fly ash as reinforcements were used for fabrication of metal matrix composite by using stir casting process. The particle size of the fly lies in the range from 0.1 to 100 μm .

As illustrated in figure 2.4, results of the experimental investigation showed that the thermal conductivity of composites decreased with increasing the amount of ash [Chittaranjan, *et al*, 2014].

Aluminum-silicon as matrix was used for fabrication of hybrid composites reinforced with silicon carbide and graphite particles by using melt stirring and squeeze casting.

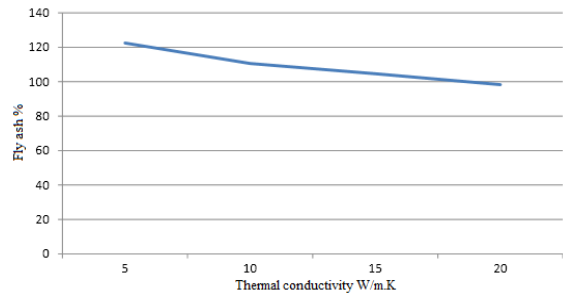


Fig 2.4: Graph showing variations in fly ash vs. thermal conductivity

For investigation of thermal conductivity, the hybrid composites were manufactured with various graphite content and different SiC particle sizes. Results showed that an addition of graphite particles to a hybrid composite with 20 vol.% SiC particles resulted in reduced thermal expansion, this is attributed to that SiC has lower CTE than that of aluminum matrix. Introducing high amount of graphite led to more dimensional stability of SiC reinforced Al-Si based hybrid MMCs. Because of the layered structure of graphite, the thermal was absorbed by the graphite particles. Increasing graphite content led to reduce the CTE of composites and shift the maximum temperature of the CTEs, due to the relaxation of compressive stresses in the matrix. With increasing of reinforcement content and the temperature decreases TC (figures 2.5-a, -b and -c).

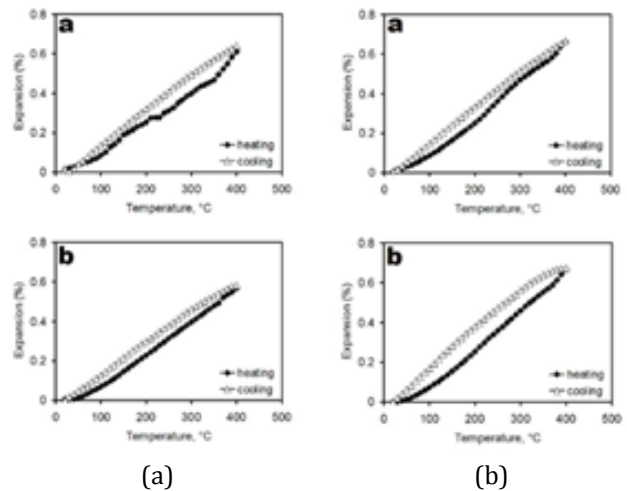


Fig. 2.5 (a): 53 μm SiC particles size (b): 45 μm SiC particles size Thermal strain response curves recorded during the heating and cooling between 20 $^{\circ}\text{C}$ and 400 $^{\circ}\text{C}$ for the hybrid Al- Si-20 vol.% SiC /graphite composites, 7.5 wt.% graphite (a) and 10 wt.% graphite (b)

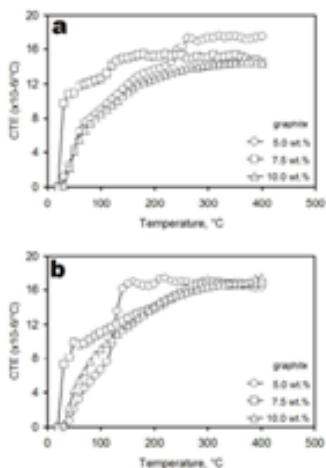


Fig. 2.5 (c): Coefficient of thermal expansion as a function of temperature for the Al-Si-20 vol% SiC 53 μm/graphite composites (a), and Al-Si-20 vol % SiC (45 μm)/graphite composites (b)

This is attributed to the lower TC values of reinforcements than that of matrix and because of increased temperature reduces the TC [Okumus, *et al*, 2012].

The thermal conductivity of plasma sprayed Al-12 wt.% Si containing 10 wt.% multiwall carbon nanotubes (CNTs) was computed at micro- and macro-length scales by utilizing an object oriented finite element method (OOF). The values of the experimental results at 50 °C indicated that CNT addition diminished the thermal conductivity of Al-Si matrix from 73 W.m⁻¹.K⁻¹ to 25.4 W.m⁻¹.K⁻¹ which is attributed to the presence of CNT clusters. OOF computations at micro-length scale predicted an 81% enhancement in the thermal conductivity of Al-Si matrix because of existence of well dispersed CNTs inside the matrix. Due to the extremely thermal conductivity of CNT clusters at larger lengths scale, reduced the overall conductivity. Results indicated that thermal conductivity of CNT clusters could be up to three orders of magnitude lower than individual CNTs, as shown in figures 2.6-a and -b.

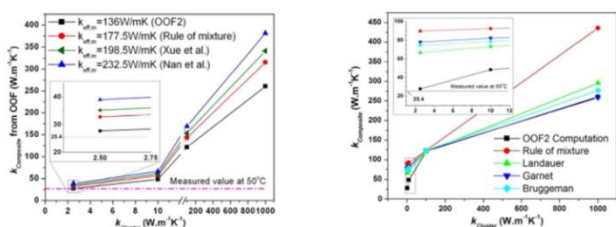


Fig. 2.6-(a): Variation of the overall thermal conductivity of the Al-10CNT composite ($K_{composite}$) with the conductivity of CNT cluster ($K_{cluster}$). Inset shows the plot for small $K_{cluster}$ values, (b): Variation of the overall thermal conductivity of the composite ($K_{composite}$) with conductivity of the CNT clusters ($K_{cluster}$) as calculated by various theoretical models for two-phase materials and OOF2. Inset is the same plot at small $K_{cluster}$ values

This is due to the diminish in length efficiency, presence of porosity and the inefficient heat transfer between CNT interfaces. Thus, good dispersion of CNTs becomes an unavoidably for thermal property enhancement. The experimental results match well the values were calculated using OOF [Bakshi, *et al*, 2010]. Lm13/MGOP metal matrix composites by varying the reinforcement content from 0 wt.% to 10 wt.% using stir-casting route was fabricated. The thermal conductivity of as-cast and heat treated alloy and its composites were tested.

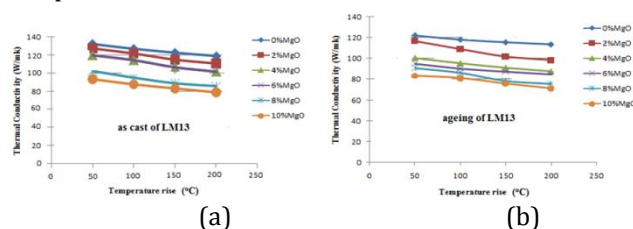


Fig. 2.7: Effect of Temperature Rise on Thermal Conductivity for Different Wt% of reinforcement

Result exhibited that the thermal conductivity of as-cast and heat treated alloy and its composites was decreases as the reinforcement content increases, figures 2.7-a and -b. [Ananda, *et al*, 2012].

The effect of the dispersion of Al₂O₃ nanoparticles into A356 Al alloy on the thermal conductivity was assessed. A356/Al₂O₃ metal matrix nanocomposites (MMNCs) were fabricated using a combination of rheocasting and squeeze casting techniques. Two different sizes of Al₂O₃ nanoparticles were dispersed into the A356 Al alloy, typically, 60 and 200 nm with volume fractions up to 5 vol.%. The results indicated that the A356 monolithic alloy exhibited better thermal conductivity than the MMNCs. The A356/Al₂O₃ MMNCs containing up to 3% of 60 nm Al₂O₃ nanoparticles showed better thermal conductivities than the MMNCs containing 200 nm nanoparticles, figures 2.8-a, -b and c.

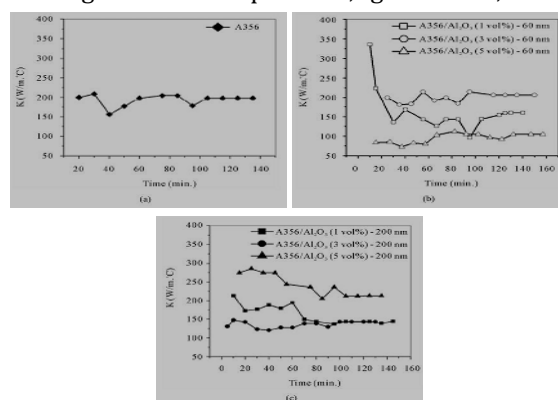


Fig. 2.8: Variation of average thermal conductivity with the time for (a) the A356 monolithic alloys; (b) A356/Al₂O₃ 60 nm) MMNCs and (c) A356/Al₂O₃ (200 nm) MMNCs

The maximum reduction percent in the thermal conductivity, according to the A356 monolithic alloy, were about 47%. This percentage was exhibited by A356/Al₂O₃ MMNCs containing 5 vol.% of nanoparticles having 60 nm [El-Kady, *et al*, 2011].

Effects of reinforcement volume ratios on the thermal conductivity of Al-MgO reinforced metal matrix composites (MMCs) of 5%, 10% and 15% RVR produced by melt stirring technique were examined. EN AW 1050A aluminum alloy as matrix material and MgO powders with particle size of $\sim 105 \mu\text{m}$ as reinforcement material, are used for synthesis of the composite. Results indicated that the porosity increases with increasing the RVR, which leads to reducing the effective thermal conductivity of Al-MgO composites. Figure 2.9 shows that the magnitude of the thermal flux is greater in the Al matrix while it is much lower with respect to this value in MgO particles [Calin, *et al*, 2012].

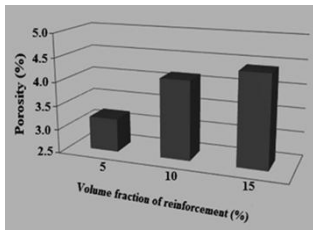


Fig. 2.9: RVR and porosity value relationship of composite samples

J. Molina, J. Narciso and others investigated on the thermal conductivity of aluminum matrix composites having a high volume fraction of SiC particles by comparing data for composites fabricated by infiltrating liquid aluminum into preforms made either from a single particle size, or by mixing and packing SiC particles of two largely different average sizes. Results showed that the thermal conductivity of Al/SiC composites based on bimodal powder mixtures can be attributed to using the differential effective medium scheme in which the two particle populations are treated as two distinct types of inclusion, figures 2.10-a and -b.

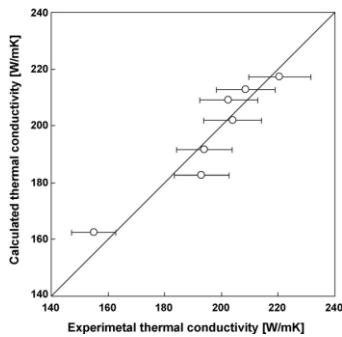


Fig. 2.10-(a): Experimental thermal conductivity of the SiC/Al composites produced by infiltration of aluminum into preforms of monomodal SiC particles of variable average size compared to predicted values based on the differential effective medium scheme including correction to find effective inclusion conductivities according to Eq. (1). The values taken for the intrinsic thermal conductivity of the inclusion, K_r^{in} , and the thermal interface conductivity, h , are 253 W/m.K and $7.5 \text{ W/m}^2 \text{ K}$, respectively

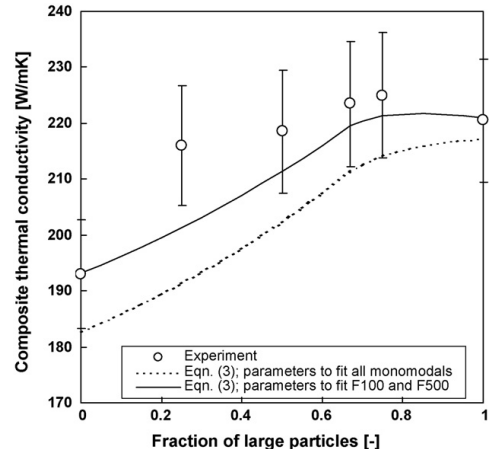


Fig. 2.10- (b): Thermal conductivity of the SiC/Al composites produced by infiltration of aluminum into preforms of bimodal SiC mixtures (SiC-500/SiC-100 vs the percentage of coarse particles). The circles are the experimental results; the dashed line is the calculation using the values of K_r^{in} and h derived fit all composites with monomodal particle size distribution, while the full line represents the prediction based on the deterministic pair $K_r^{in} 10^7$ the h that fits the conductivity of monomodal composites with particle sizes used in the bimodal mixture.

The finite interface thermal conductance at the particle / matrix interface is taken into account for the different sizes a distinct effective thermal conductivity [Molina, *et al*, 2008] .

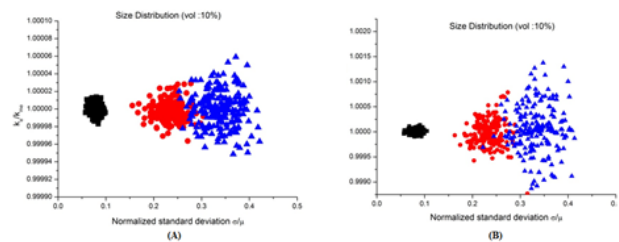


Fig. 2.11-a: For the particle size distribution, (A) the effective thermal conductivities (k_e/k_m) and (B) the effective CTE (α_e/α_m) are plotted as a function of normalized deviation (σ/μ)

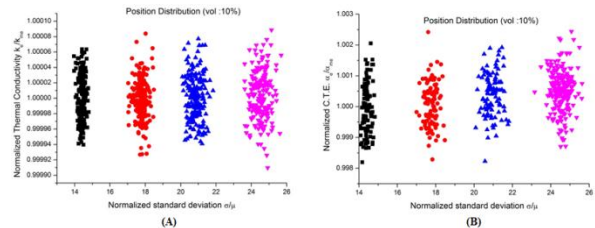


Fig. 2.11-b: For the spatial position distribution, (A) the effective thermal conductivities (k_e/k_m) are plotted as a function of normalized deviation (σ/μ), and (B) the effective CTE (α_e/α_m) are plotted as a function of normalized deviation (σ/μ)

The study exhibited that the MMC 35Al-65SiC has a very good thermal conductivity and 25Al-75SiC has the least CTE. Results showed that the specific heat capacity increases with increased in the volume percentage of the aluminum from 25 to 35, as shown in figures 2.15-a, -b and -c.

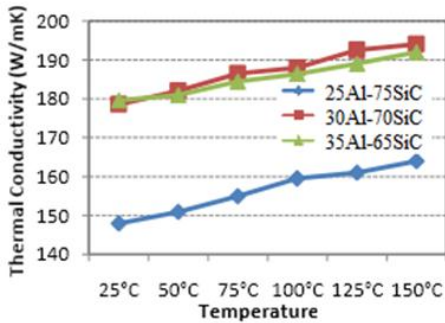


Fig. 2.15-(a): Variation of TC with respect of Temperature

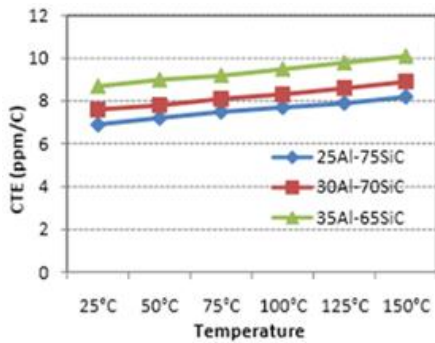


Fig. 2.15- (b): Variation of CTE with respect to temperature

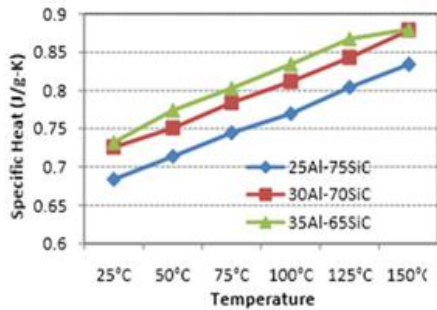


Fig. 2.15- (c): Variation of Specific Heat with respect to Temperature

However, the relationship is not linear. It is observed that by increasing the percentage of aluminum content the specific heat of MMC increases [Reddy, *et al*, 2014]. A356(Al-7Si-0.3Mg) powder as matrix material and Si particles with an average size of 13 μm were mixed with the same total volume fraction containing 0, 4%, 8% and 12% of SiC particles, which has a similar particle size with silicon particles. Composite were fabricated by gas pressure infiltration technique.

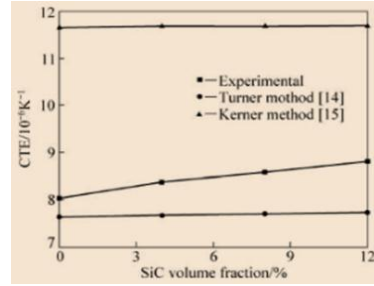


Fig. 2.16- (a): CTEs of Al/Si/SiC composites and comparison between theoretical predictions and experimental data versus SiC volume fraction

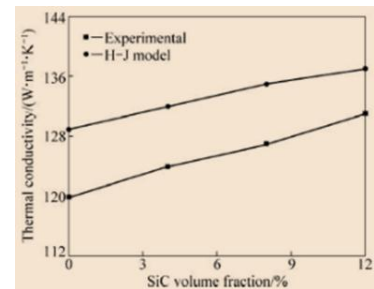


Fig. 2.16- (b): Experimental data of thermal conductivity ones predicted by H-J model as function of volume fraction of SiC

As illustrated in figures 2.16-a and -b, results showed that produced composites have higher thermal conductivity (TC). Meanwhile, coefficient of thermal expansion (CTE) changed smaller than TC. The predicted results by H-J models are in good agreement with the experimental data [Xiao-min, *et al*, 2012].

A356 aluminum alloy as matrix and nano SiC with 50 nm of particles size are used for manufacturing of composite via stir casting technique.

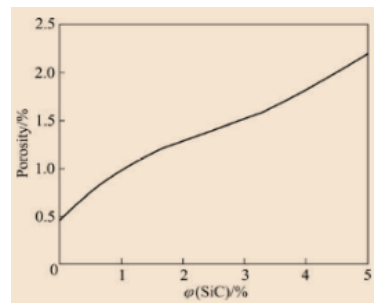


Fig. 2.17: Variation of porosity with volume fraction of nano SiC

Results showed that the composites contain little porosity, but the porosity increased with increasing RVR of silicon carbide nanoparticles. These would lead to reduce the thermal conductivity of composite, figure 2.17, [Mazahery, *et al*, 2012].

A 356 alloy was reinforced with different weight percentage of abundantly available industrial waste quarry dust to produce composites using stir casting technique. The weight percentage of quarry dust were

0.5, 7.5 and 10%. As illustrated in figures 2.18-a, -b and -c, results showed that increasing the weight percentage of the reinforcement lead to increasing the porosity and decreasing the density of composite. TC of the composite with 7.5 wt. % of quarry dust is lower than those of the 356 alloy [Ramesh, *et al*, 2014].

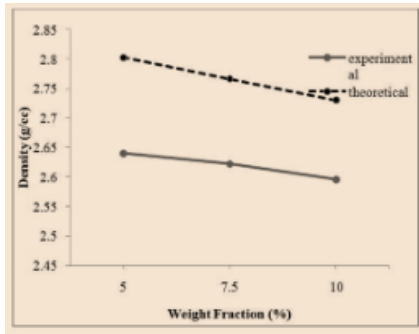


Fig. 2.18- (a): Variation of experimental and theoretical density of the composite

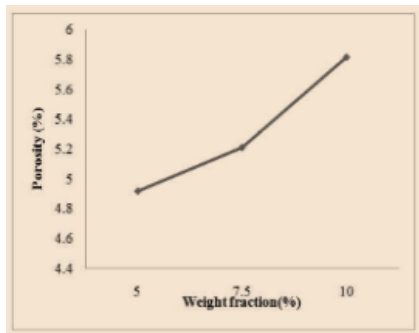


Fig. 2.18- (b): Variation of porosity with weight fraction of the Composites

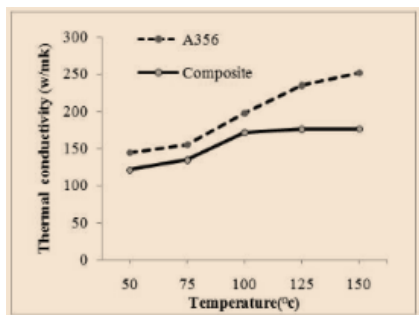


Fig. 2.18- (c): Variation of thermal conductivity A356 and composite with temperature.

Aluminum powder as matrix and vapor grown carbon fiber as reinforced were used for fabrication of the composite by spark plasma sintering (SPS) technique. The 10wt% of Al-Si alloy was added to the aluminum powder for the improvement of the interface adherence between VGCF and Al. Carbon nanotube (CNT) is also dispersed on VGCF fillers for further improvement of the thermal conductivity of the composite. Results indicated that the TC of the VGCF/Al composites is about two to three times higher

than the pure aluminum and it increases by the dispersion of a small amount of CNT. The SEM observation and FEM analysis showed that the VGCF-CNT network may play an important role to increase the TC of composite. The TC of the direction corresponded to the axial direction of VGCF is larger than that of other directions of the composites, figures 2.19-a, -b, -c, -d and -e, [Sasaki, *et al*, 2011].

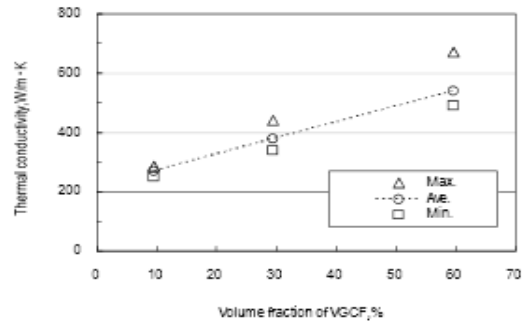


Fig. 2.19- (a): The relationship between TC and RVR

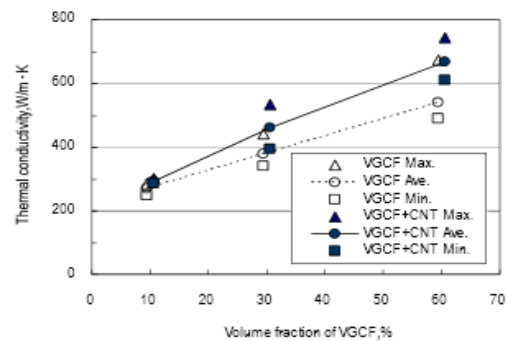


Fig. 2.19- (b): The relationship between TC and RVR of VGCF for confirm the effect of CNT dispersion

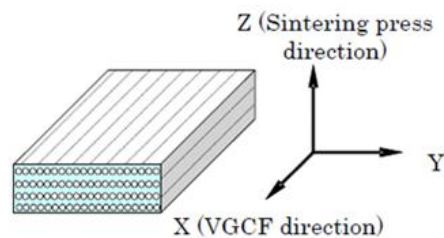


Fig. 2.19- (c): TC obtained by FEM (H type)

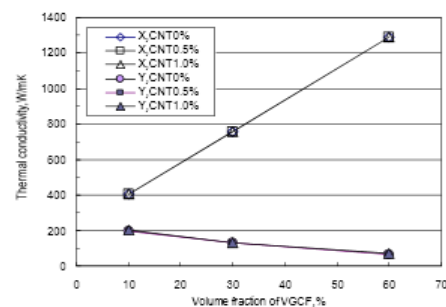


Fig. 2.19- (d): TC obtained by FEM (I type)

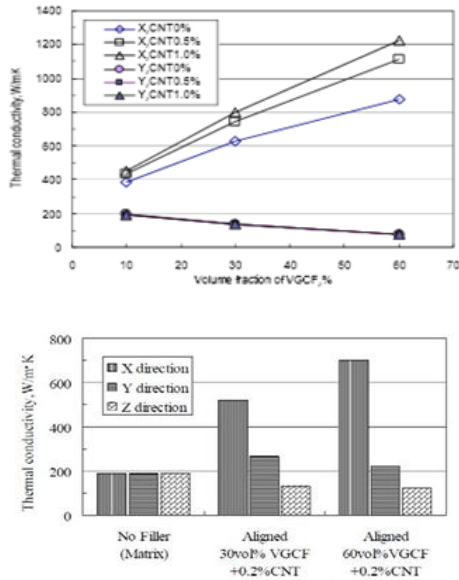
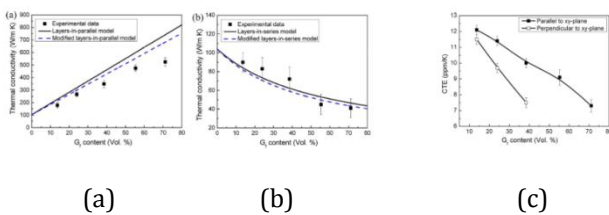


Fig. 2.19- (e): Thermal anisotropy of composite

An AlSi7Mg0.3 alloy and Gf & Si powder were used to fabricate composites using an optimized pressure infiltration process. In the produced composites, Gf layers were spaced apart by Si particles and oriented perpendicular to the pressing direction. This offered the opportunity to tailor the TC CTE of the composites. Thermal properties of the composites as a function in RVR of Gf were studied. As shown in figures 2.20-a, -b and -c, results showed an enhanced longitudinal TC and an increasing the global TC with an increase of the RVR of Gf, while it showed an decreasing the CTE in the directions parallel and perpendicular to the xy-plane [Zhou, *et al*, 2014].



(a) (b) (c)

Fig. 2.20-(a): Comparison of experimental data with theoretical predictions: the longitudinal TC, (b): the transversal TC of the composites with different Gf volume fractions and (c): CTE values of the composites with different Gf volume fractions

Conclusion

The above introduced extensive literature survey shows that worthwhile comprehensive efforts have been reported to evaluate thermal properties of AMMCs reinforced with ceramic particles to meet the requirement modern industrial applications. Thermal properties of AMMCs reinforced with ceramic particles mainly depend on existence of an interfacial thermal barrier caused by the difference in elastic moduli of constituents of composite. Because of largely different

elastic moduli of Al and ceramic particles, the interface between them will permit scattering of phonons. The energy of phonons is not easily transferred to the aluminum, so the ceramic particles have less contribution to the thermal conducting of AMMCs. As a result, the energy transfer between phonons in AMMCs is not systematic. TC of AMMCs with large ceramic particles shows a negative temperature dependence, but they have an effect over this temperature dependence. TC of AMMCs with smallest particle size is almost independent of temperature. The porosity of AMMCs increases with increasing the volume fraction of ceramic reinforcements (RVR) causes reducing its effective thermal conductivity. Thermal flux magnitude in ceramic particles is much lower than those in Al and Al alloys. For the controlled thermal properties of AMMCs, control size of reinforcements is more importance than the control of spatial position. Aluminum/graphite composites reveal a high efficiency to utilize as thermal management material because of the combination of high TC and low CTE. The graphite absorb the thermal because of its layered structure and increasing graphite content lead to reducing CTE of AMMCs. TC diminishes with increasing graphite content and temperature, this can be attributed to the lower TC values of graphite than those of matrix and because of increased temperature reduces the TC. Using of Gf as reinforcements in AMMCs lead to enhancement of longitudinal TC and increasing the global TC with increasing volume fraction, but it cause reducing the CTE. Thermal conductivity value of VGCF/Al composites is three times higher than that of pure Al and it becomes more by the dispersion of a small amount of CNT. The TC of the direction corresponded to the axial direction of VGCF is larger than that of other directions of the composites. Specific heat of AMMCs depends on the properties of constituents parts, so it increases with increasing the volume fraction of the higher specific heat constituent.

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