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Experimental Evaluation of Thermal Transport Characteristics of MMC's for heat Sink Material for Electronics Cooling

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Abstract - In this work, effort has been made in the evaluation and enhancement of thermal transport characteristics of metal matrix composites. The Thermal management systems are important in today's faster growing industrial needs which are demanding the high end processors with highest speed and reliability of performance. However, this work focuses on the development of new material for heat sink. Generally, the heat sink is attached to the CPU by the manufacturer mechanically. There is possibility of high stress inducement in the CPU due to mechanical fastening and the heat transfer is not effective as there will be a 100% surface to surface contact. Also there is a high possibility of shorting of electronic circuitry of the CPU due to the high conductivity of the heat sink material. In order to overcome these problems, effort is made to resolve the problem by developing the metal matrix composites to match with the required properties of the heat source. In this work, initially, the importance and motivation behind the evaluation of the thermal characteristics for the MMC's. The development of new MMC's was detailed along with the different compositions of the MMCs. For this, initially, baseline materials were explained in detail along their thermal properties. Six MMC's have been proposed with varying compositions of aluminum and silicon carbide. Aluminum was varied in percentage composition from 25% to 65% and Sic was varied between 35% to 75%. The MMC's were evaluated for the properties lie thermal conductivity, specific heat, thermal diffusivity, CTE. Also, the variation of these properties with respect to temperature is evaluated. Finally recommendations are given for the MMC's based on the required property criteria of the heat source material.

Keywords – Aluminum, Silicon carbide, Heat sink, Thermal conductivity, CTE, Specific heat.

I.INTRODUCTION

One of the challenges the industry facing today is the rate of heat dissipation from the micro electronics systems.

The higher and the fast heat removed, the better it is. However, there is a challenging situation that exists when the heat is removed from the electronic components. Generally, the heat sink is attached directly to the heat generating device so that

Heat is removed fast and device can be always kept cool. However, the requirement in such case is the selection of material for the heat sink. The coefficient of thermal expansion (CTE) of the heat sink material must be close enough to that of the semiconductor device. Most of the electronic devices like microprocessors are made out of silicon or its alloys. Hence the CTE of heat sink materials to be chosen should be close enough to that of silicon.

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This enables both the materials to expand by similar rates so that one can eliminate the fracture in the devices arising due to the differential thermal expansions. However, by choosing the heat sink materials with low CTE, there is a possibility that those materials can have the low thermal conductivities so that heat is not removed at a faster rate. This is conflicting situation where if one needs higher heat dissipation, it will result in device fractures or if one needs to protect the electronic device, it will be at the cost of higher heat dissipation. In generally highly conducting materials like copper or aluminum are chosen for manufacturing the heat sinks.

One can use interfacial materials which has got high thermal conductivity to increase the heat dissipation rate. But, there is a possibility that the high conducting pastes can short the built in electronic circuitry of the microprocessor or IC at the surface.

Hence it is required to develop solutions for increasing the heat transfer by developing new materials which has good thermal conductivity and good CTE.

A. Baseline Materials

Materials which are known for this kind of applications are:

- Fe-Ni alloys : It has got compatible CTE but offers low thermal conductivity
- Kovar: It has got compatible CTE but offers low thermal conductivity
- Cu-W alloys: It has got compatible CTE and Thermal conductivity, but has high density due to which the weight of the heat sink become high which cannot be sustained by the electronic devices like microprocessors or ICs. Moreover, the manufacturing and production cost of these metals are high
- Cu-Mo alloys: It has got compatible CTE and Thermal conductivity, but has high density due to which the weight of the heat sink become high which cannot be sustained by the electronic devices like microprocessors or ICs. Moreover, the manufacturing and production cost of these metals are high.

Table.1: List of heat sink materials and essential properties

Material	Thermal Conductivity (W/m K)	CTE(ppm/C)
Fe-Ni	13.2	9.8
Kovar	17.3	4.9
Silicon	124	2.49
Cu-Mo	180	7
Cu-W	190	7
SiC	210	2.7
Aluminum	240	24
Copper	385	16.4

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Since silicon is the material of the devices, the thermal conductivity of the chosen material should be above 124 W/m-K and the CTE must be very close to 2.49 ppm/C and the density should be close to 2.3 gm/cc. By looking at the other materials listed in Table 4.1, all materials except Fe-Ni and Kovar have thermal conductivities higher than Si [[158-160]. Of these materials, copper has the CTE very high compared to Si and hence cannot be chosen as heat sink materials due to the reasons listed above. So is the case with aluminum. Of the three remaining materials, SiC, Cu-W and Cu-Mo have CTE and density properties close to Si. Cu-W and Cu-Mo are not feasible again due to the reasons listed above. SiC may be chosen for this purpose. However, there are again cost, manufacturing and production issues with SiC. It is not easily moldable to required shapes and most of SiC parts are made using powder compaction.

The alternative is a composite with Aluminum as the matrix embedded with SiC particle to reduce the CTE from 24 to the values close enough to Si.

B. Proposed Materials

In this work, six different compositions of Aluminum and SiC were used for Devloping the specimens to determine the properties. The composition is varied by volume fraction. The specimens were made using the casting process by mixing the SiC powder of particle sizes up to 100 microns in the molten aluminum. The specimens were made with the dimensions 30mm x 100mm × 4 mm (Rectangular Specimen). Five specimens were made for each composition and data in the table 4.2 their volume fractions.

Table.2: Designation of the specimen composition and volume fractions

Designation	Aluminum %	SiC %
25Al-75SiC	25	75
30Al-70SiC	30	70
35Al-65SiC	35	65
45Al-55SiC	45	55
55Al-45SiC	55	45
65Al-35SiC	65	35%

II. EXPERIMENTAL PROCEDURE

A. Measurement of Thermal Conductivity:

Fig 1.shown above is equipment for measuring thermal conductivity

Consider a sample of cross section A across which a thermal gradient exists. T_2 and T_1 are the temperatures measured over a length ΔL. Let Q be the quantity of heat flowing through A as shown in Fig. 8.1 below.

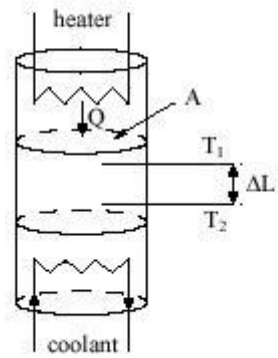

Figure 2: Set up for measuring Thermal Conductivity

Now, thermal conductivity K is given by the ratio of the heat flux Q/A to the thermal gradient ΔT / ΔL.

$$K = \frac{Q/A}{\Delta T/\Delta L}$$

B. Measurement of Heat Flux

The heat flux can be measured directly or indirectly. These methods are:

1. The absolute method where the electrical power supplied to the heater is measured and
2. The comparative method where a comparative measurement is made

The heat flux has to be uniaxial in all these methods and hence radial heat loss or gain must be minimized by methods such as insulation.

C. Thermal Conductivity and System Configuration

The length of a sample is influenced by the magnitude of the thermal conductivity. When the thermal conductivity of the sample is high, the amount of heat flowing is high and the heat lost from the sample's lateral surface is small. As a high temperature gradient is established in this case, it is possible to measure it accurately.

On the other hand, samples with low thermal conductivity (and correspondingly low heat flux) are usually of a smaller thickness, which is sufficient to generate an accurately measurable thermal gradient. Smaller thicknesses also mean less lateral losses. Sometimes, self-guarding is provided for lateral surfaces by the use of additional pieces of the sample material.

For low temperatures, the sample is packed inside insulation to minimize heat losses or heat gains along the radial direction. Installation of a guard, which can be controlled to have a temperature gradient same as that across the sample, is often required at high temperatures. At such high temperatures, heat losses are difficult to control. Therefore, the ratio of conductance of the sample to the conductance of lateral insulation becomes significant, as does the quality of guarding.

D. Measurement of Specific Heat Capacity

Basic experiment

1. Insert a thermometer and the immersion heater into their respective holes in the block. You may wish to drop a small amount of oil into the thermometer hole to improve the thermal contact between thermometer and block.
2. Allow the thermometer to reach thermal equilibrium

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and then write down the temperature.

3. Set up a suitable circuit that will enable you to measure the energy input to the heater.
4. Turn on the current, noting the time if you are measuring energy using an ammeter and a voltmeter to record power.
5. Energy = current, potential difference. Time. Monitor and note the meter readings as the energy is supplied. They may change slightly as things warm up.
6. Allow the block to heat up by about 10^0 C, then turn off the current and note the time again.
7. At this point, keep watching the thermometer. The temperature at the turn-off time is not the appropriate final temperature to record.
8. Use E = m c^2 to calculate the specific thermal capacity, c, of block.

III. RESULTS AND DISCUSSIONS

For composition, the five specimens are tested for the following properties.

❖ Thermal Properties

1. Thermal Conductivity
2. Specific Heat
3. Coefficient of thermal expansion (CTE)

Table 4. Properties of 25Al-75SiC

25Al-75SiC	Thermal Properties		
	Thermal Conductivity (W/m K)	Specific Heat (J/g K)	CTE (ppm/C)
Specimen 1	142	0.75	7.1
Specimen 2	148	0.6	6.7
Specimen 3	149	0.65	6.7
Specimen 4	148	0.72	7
Specimen 5	153	0.7	7.1
Mean	**148**	**0.684**	**6.92**

Table 4.3 shows the measured values of the properties of the new MMC 25Al-75SiC. The mean values of thermal conductivity is 148 W/m K, specific heat is 0.684 J/g K, CTE is 6.92 ppm/C, The thermal conductivity of the 25Al-75SiC is well above to that of Si which is a desirable property. Whereas CTE of the 25Al-75SiC is higher than that of Si, it is close enough.

Table 4.4: **Properties of 30Al-70SiC**

30Al-70SiC	Thermal Properties		
	Thermal Conductivity (W/m K)	Specific Heat (J/g-K)	CTE (ppm/C)
Specimen 1	**175**	**0.75**	**7.68**
Specimen 2	175	0.74	7.6
Specimen 3	178	0.71	7.59
Specimen 4	184	0.71	7.65
Specimen 5	181	0.72	7.68
Mean	**178.6**	**0.726**	**7.64**

Table 4. shows the measured values of the properties of the new MMC 30Al-70SiC. The mean values of thermal conductivity is 178.6 W/m K, specific heat is 0.726 J/g-K, CTE is 7.64 ppm/C, The thermal conductivity of the 30Al-70SiC is well above to that of Si and 25Al-75SiC which is a desirable property. Whereas CTE of the 30Al-70SiC is higher than that of Si, it is close enough to 25Al-75SiC.

Table .5: **Properties of 35Al-65SiC**

35Al-65 SiC	Thermal Properties		
	Thermal Conductivity(W/m K)	Specific Heat (J/g-K)	CTE (ppm/C)
Specimen 1	181	0.73	8.73
Specimen 2	182	0.75	8.9
Specimen 3	181	0.72	8.6
Specimen 4	176	0.7	8.8
Specimen 5	178	0.76	8.9
Mean	**179.6**	**0.732**	**8.786**

Table 4.5 shows the measured values of the properties of the new MMC 35Al-65SiC. The mean values of thermal conductivity is 179.6 W/m K, specific heat is 0.732 J/g K, CTE is 8.786 ppm/C. The thermal conductivity of the 35Al-65SiC is well above to that of Si and 25Al-75SiC and close to too 30Al-70SiC which is a desirable property. Where as CTE of the 35Al-65SiC is higher than that of Si, 25Al-75SiC and 30Al-70SiC.

Table 6: **Properties of 45Al-55SiC**

45Al-55SiC	Thermal Properties		
	Thermal Conductivity (W/mK)	Specific Heat (J/g K)	CTE (ppm/C)
Specimen 1	180	0.77	10.56
Specimen 2	179	0.79	11.1
Specimen 3	178	0.76	10.2
Specimen 4	178.5	0.79	10.8
Specimen 5	182	0.78	10.7
Mean	**179.5**	**0.778**	**10.672**

Table 6 shows the measured values of the properties of the new MMC 45Al-55SiC. The mean values of thermal conductivity are 179.5 W/m K, specific heat is 0.778 J/g K, CTE is 10.672 ppm/C. The thermal conductivity of the 45Al-55SiC is well above to that of Si and 25Al-75SiC and close to 30Al-70SiC and 35Al-65SiC which is a desirable property. Whereas CTE of the 45Al-55SiC is higher than that of Si, 25Al-75SiC, 30Al-70SiC and 35Al-65SiC

Table 4.7: Properties of 55Al-45SiC

55Al-45SiC	Thermal Properties		
	Thermal Conductivity (W/mK)	Specific Heat (J/g K)	CTE (ppm/C)
Specimen 1	177	0.78	10.7
Specimen 2	179	0.8	10.9
Specimen 3	176	0.77	10.6
Specimen 4	175	0.8	10.9
Specimen 5	176	0.79	10.8
Mean	**176.6**	**0.788**	**10.78**

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Table 7 shows the measured values of the properties of the new MMC 55Al-45SiC. The mean values of thermal conductivity is 176.6 W/m K, specific heat is 0.788 J/g K, CTE is 10.78 ppm/C, The thermal conductivity of the 55Al-45SiC is well above to that of Si and 25Al-75SiC and close to 30Al-70SiC and 35Al-65SiC, but close enough to 45Al-55SiC which is a desirable property. Whereas CTE of the 55Al-45SiC is higher than that of Si, 25Al-75SiC, 30Al-70SiC and 35Al-65SiC but close enough to 45Al-55SiC.

Table 4.8: Properties of 65Al-35SiC

65Al-35SiC	Thermal Properties		
	Thermal Conductivity (W/mK)	Specific Heat (J/g K)	CTE (ppm/C)
Specimen 1	169	0.78	11.3
Specimen 2	168	0.81	11.5
Specimen 3	172	0.78	11.2
Specimen 4	170	0.79	11.8
Specimen 5	168	0.81	11.7
Mean	**169.4**	**0.794**	**11.5**

Table 4.8 shows the measured values of the properties of the new MMC 65Al-35SiC. The mean values of thermal conductivity are 169.4 W/m K, specific heat is 0.794 J/gK, CTE is 11.5 ppm/C, The thermal conductivity of the 65Al-35SiC is well above to that of Si and 25Al-75SiC and less than 30Al-70SiC, 35Al-65SiC, 45Al-55SiC and 55Al-45SiC. Where as CTE of the 65Al-35SiC is higher than that of Si, 25Al-75SiC, 30Al-70SiC and 35Al-65SiC, 45Al-55SiC and 55Al-45SiC.

Table 4.9: Summary of Properties of New MMC's

	Thermal Properties		
	Thermal Conductivity (W/m K)	Specific Heat (J/g K)	CTE (ppm/C)
25Al-75SiC	148	0.684	6.92
30Al-70SiC	178.6	0.726	7.64
35Al-65SiC	179.6	0.732	8.786
45Al-55SiC	179.5	0.778	10.672
55Al-45SiC	176.6	0.788	10.78
65Al-35SiC	169.4	0.794	11.5

Table 4.9 shows the summary of the properties of the new MMCs developed. The values shown in the Table 4.9 are the mean values of the respective properties for the experiments conducted on five specimens. It can be concluded that the MMC 35Al-65SiC has a very good thermal conductivity and 25Al-75SiC has the least CTE, 65Al-35SiC has the highest Specific heat among all the MMCs. One has to choose the composition based on the requirement. For example, for the heat sink applications, one can choose 30Al-70SiC because it has got a good thermal conductivity and CTE both.

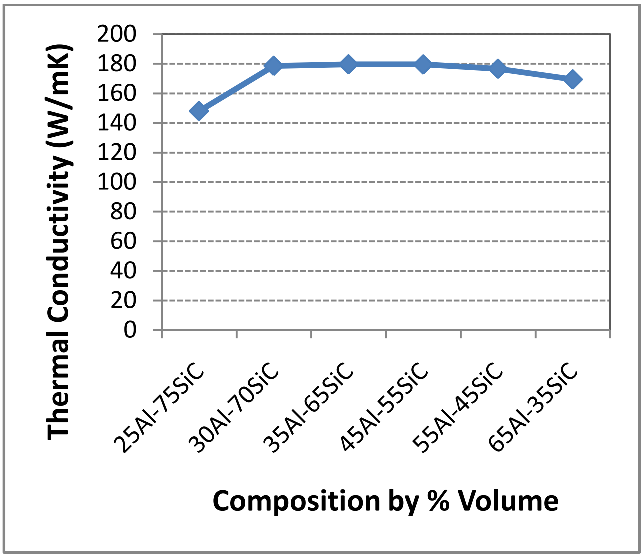

Figure 3: Thermal Conductivity v/s Volume Composition

Figure 3 shows the variation of thermal conductivity for different compositions. With increase in volume percentage of aluminum from 25% to 30%, the thermal conductivity increased gradually and later it becomes stagnant. This may be attributed to the reason that the SiC has a saturation effect when its percentage is less than 70%. The SiC may acts as a barrier to the thermal flow even though the percentage of Aluminum increases. From the above results, it is concluded that 50% of SiC acts as a deterrent for the thermal conductivity any amount of increase in the aluminum does not contribute to the enhancement of thermal conductivity. This is due to the reason that the distribution of the SiC particles occupies at least 50% of the volume so that it acts as a barrier for the heat flow.

The thermal conductivity of aluminum depends on the percentage composition. The thermal conductivity is maximum when percentage volume of aluminum is 100%, i.e. when aluminum is pure. If alloying elements in liquid form are added, the behavior of the alloy is different than when constituent is mixed in powder form. In alloys which are usually manufactured with casting technique, the base material and the alloy elements are uniformly and homogenously distributed and there will be a linear relationship between the thermal conductivity and the percentage composition of aluminum. But in case of powder mixing into the molten base material, the linear relationship between the thermal conductivity may not exist as SiC particles come in the way of continuous stream of aluminum. With increase in the volume percentage of the aluminum from 25% to 30%, the thermal conductivity increases and later it becomes stagnant. This may be attributed to the reason that the aluminum has a saturation effect when its percentage is more than 30%. The SiC may acts as a barrier to the thermal flow even though the percentage of aluminum increases. From the results, it can be concluded that 50 % of SiC acts as a deterrent for the thermal conductivity and any amount of increase in the aluminum does not contribute to the enhancement of thermal conductivity. This is due to the reason that the distribution of the SiC particles occupies at least 50% of the volume so that it acts as a barrier for the heat flow.

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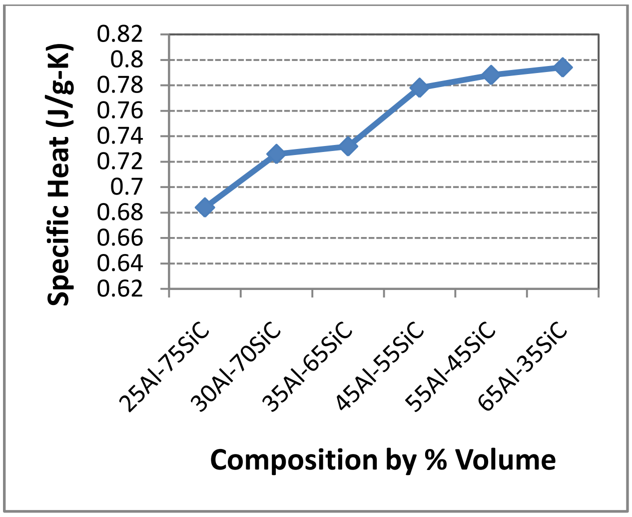

Fig. 4. Specific Heat V/s Volume Composition

Figure 4. shows the variation of specific heat for different compositions. With increase in the volume percentage of the aluminum from 25% to 65%, the specific heat of the composition increases. The relationship is not linear. Higher the specific heat, the better it is, as it absorbed more heat energy for a unit raise in temperature. Hence it removes large quantities of heat from the electronic devices. The specific heat of aluminum is 0.9 J/g K whereas the specific heat of SiC is 0.67 J/g K. Hence by increasing the percentage of aluminum content the specific heat of the MMC increased which is evident from the Fig. 4.

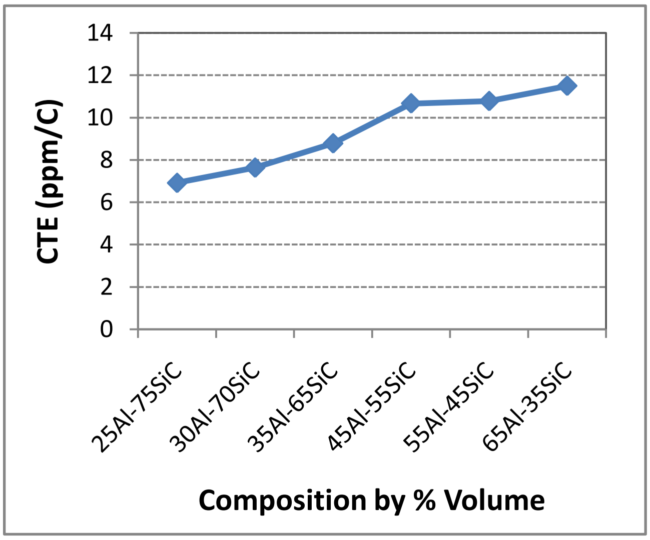

Fig. 5: CTE V/s Volume Composition

Figure 5 shows the variation of CTE for different compositions. With increase in volume percentage of the aluminum from 25% to 65%, the CTE of the composition increases. The relationship is not linear. Lower the CTE, the better it is as it does not expand much and hence the thermal stresses induced due to differential expansion is reduced. The material with CTE close enough to the electronic device should be chosen for better mechanical performances. CTE of aluminum is 24 ppm/C and that if SiC is 2.7 ppm /C. Hence it is clear that by increasing the percentage of aluminum content, the CTE of the MMC increased which is evident from the Fig. 5.

Table.10: Variation of thermal conductivity with respect to temperature

Thermal Conductivity (W/m k)	**25° C**	**50° C**	**75°C**	**100° C**	**125° C**	**150° C**
25Al-75SiC	148	151	155	159.5	161.1	164
30Al-70SiC	178.6	182	186.5	188	192.5	194
35Al-65SiC	179.6	181	184.5	186.3	189.1	192
45Al-55SiC	179.5	182.1	185.2	187.2	191	195
55Al-45SiC	176.6	179.2	182.1	186.2	189.1	192.1
65Al-35SiC	169.4	172.1	176.4	178.2	182.1	184.1

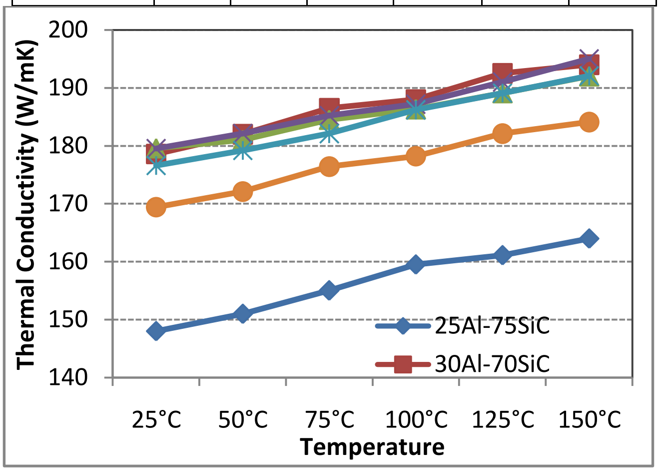

Fig. 6: Variation of thermal conductivity with respect to temperature

Table 10 & fig.6 shows the variation of thermal conductivity with respect to temperature. Due to practical limitations of the measurement facilities, the properties are not measured beyond 150°C. From the Fig. 4.6 it can be observed that the thermal conductivity of the MMCs increased with the temperature. The thermal conductivity profiles of 30Al-70SiC, 35Al65SiC, 45Al-55SiC and 55Al-45SiC are very closely spaced to each other in terms of the thermal conductivity at room temperature as well as at all other temperatures up to 150°C. When operating at temperatures up to 150°C, one can choose 30Al-70SiC if the thermal conductivity is a criteria for selection, since it performs well at all temperatures except near room temperature.

Table 11: Variation of CTE with respect to temperature

CTE (ppm/C)	25°C	50°C	75°C	100°C	125°C	150°C
25Al-75SiC	6.9	7.2	7.5	7.7	7.9	8.2
30Al-70SiC	7.6	7.8	8.1	8.3	8.6	8.9
35Al-65SiC	8.7	9	9.2	9.5	9.8	10.1
45Al-55SiC	10.6	10.9	11.2	11.6	11.8	12

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55Al-45SiC	10.8	11.2	11.4	11.7	12	12.4
65Al-35SiC	11.5	11.8	12.1	12.6	12.9	13.2

Figure 4.7: **Variation of CTE with respect to Temperature**

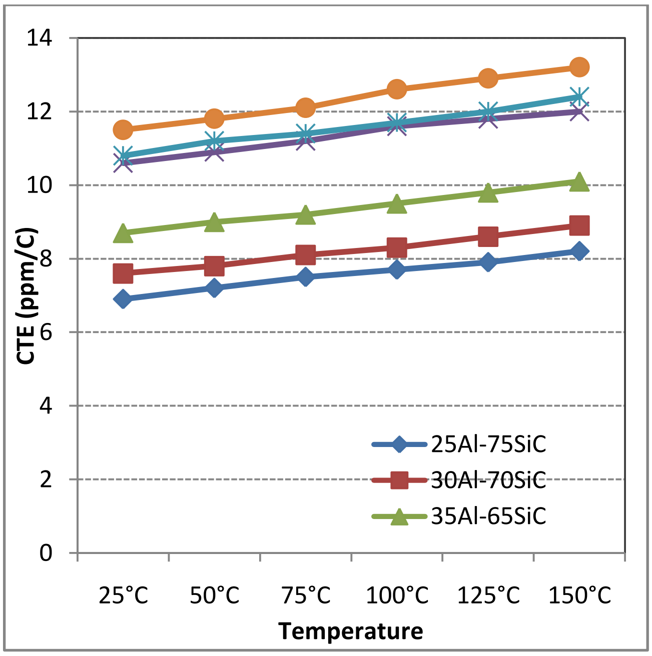

Table 11& Fig.7 shows the variation of CTE with respect to temperature. Due to practical limitations of the measurement facilities, the properties are not measured beyond 150°C. From the Fig. 4.7 it can be observed that the CTE of the MMCs increased with the temperature almost linearly. The CTE profiles of 45Al-55SiC, 55Al-45SiC and 55Al-45SiC are very closely spaced to each other in terms of the CTE at room temperature as well as at all other temperatures up to 150°C. Similarly, one can group the other three MMCs, namely, 25Al-72SiC, 30Al-70SiC and 35Al65SiC. When operating at temperatures up to 150°C, one can choose 25Al-75SiC if the CTE is criteria for selection, since it performs well at all temperatures.

Table 12: **Variation of specific heat with respect to temperature**

Specific Heat (J/g-K)	25°C	50°C	75°C	100°C	125°C	150°C
25Al-75SiC	0.684	0.714	0.745	0.77	0.804	0.834
30Al-70SiC	0.726	0.751	0.784	0.812	0.843	0.879
35Al-65SiC	0.732	0.774	0.803	0.834	0.8673	0.88
45Al-55SiC	0.778	0.809	0.836	0.87	0.899	0.946
55Al-45SiC	0.788	0.815	0.848	0.877	0.905	0.959
65Al-35SiC	0.794	0.827	0.863	0.889	0.92	0.958

Figure 4.8: Variation of Specific Heat with respect to Temperature

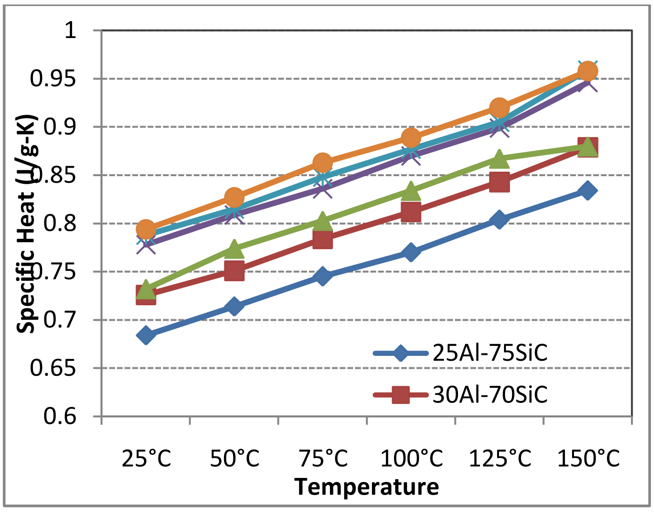

Table 4.12 & Fig.8 shows the variation of specific heat of MMC's with respect to temperature. Due to practical limitations of the measurement facilities, the properties are not measured beyond 150°C. From the Fig. 4.8 it can be observed that the specific heat of the MMCs increased with the temperature almost linearly. The specific heat profiles of 45Al-55SiC, 55Al-45SiC and 55Al-45SiC are very closely spaced to each other in terms of the specific heat at room temperature as well as at all other temperatures up to 150°C. Similarly, one can group the other three MMC's, namely, 25Al-72SiC, 30Al-70SiC and 35Al65SiC. When operating at temperatures up to 150°C, one can choose 65Al-35SiC if the specific heat is a criteria for selection, since it performs well at all temperatures.

IV.CONCLUSION

After review of the literatures available, it has been observed that there is not enough research work has been done to enhance the heat transfer by studying the effects of improving both the materials of heat sinks as well as the contact resistance models. In this work, the thermal characteristics are evaluated for a wide range of compositions of the MMC's. The effect of the composition on the thermal properties is studied in order to come out with a means to enhance the transport characteristics of heat sinks.

The experimental evaluation of the thermal characteristics of different composition of new MMC's developed in this work. It shows the summary of the properties of the new MMCs developed are presented. The study indicates that the MMC 35Al-65SiC has a very good thermal conductivity and 25Al-75SiC has the least CTE, 65Al-35SiC has the highest Specific heat among all the MMC's. One has to choose the composition based on the requirement. For example, for the heat sink applications, one can choose 30Al-70SiC because it has good thermal conductivity and CTE both.

The variation of thermal conductivity for different compositions. The specific heat capacity increases with increased in the volume percentage of the aluminum from 25% to 65%. However, the relationship is not linear. It is observed that by increasing the percentage of aluminum content the specific heat of MMC increases. The variation of thermal conductivity with respect to temperature. When operating at temperatures up to 150°C, one can choose

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30Al-70SiC if the thermal conductivity is criteria for selection, since it performs well at temperatures except near room temperature under study.

Overall, the thermal properties are evaluated for MMCs and based on the selection criteria, the composition of the MMCs can be chosen for the best performance.

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