Coefficient of thermal expansion (CTE) study in metal matrix composite of CuSiC vs AlSiC

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Abstract. Metal matrix composites are widely used as advanced materials for thermal management applications. In view of the demands in higher temperature products application, materials with low coefficient of thermal expansion (CTE) and high thermal conductivity are required. Copper Silicon Carbide (CuSiC) is highly rated as the best materials selected for this application because it has good thermal characteristics especially in CTE, but its density is almost high for high temperature electronic device application. An aluminium silicon carbide (AlSiC) composite, on the other hand, is a new candidate for electronic device application since it has low density and good CTE characteristics. CuSiC and AlSiC composites were fabricated via powder metallurgy method through variety volume fractions such as 5%, 10%, 15% and 20%. In the present study, the comparison of CTE between CuSiC and AlSiC composites with different volume fraction of SiC particles has been carried out. The CTE of CuSiC and AlSiC composites were investigated and their responses between 25°C to 400°C were studied using horizontal dilatometer. Based on the experiment results, the density of CuSiC composites are decrease while the density of AlSiC composites is increase with increasing in SiC particles content. However, the porosity for both composites is increase with increasing in volume fraction of SiC particles. As of CTE, both composites showed decreased with increasing in SiC particles content that dispersed in their matrix. The experimental CTE values for both composites seem to be much lower than theoretical CTE value, which means that there has been excellent bonding between each particle after sintering process. The particles distribution has been observed to understand more on the aspect of SiC particles homogeneity in copper and aluminium matrix.

1 Introduction

In recent decades, scientists and engineers have been involved in designing a new generation of extraordinary materials from various combinations of properties that cannot be met by pure metal, ceramic and polymer to be used in modern technologies that called composite materials.

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Composite has been the most attracted materials to many researchers and become the materials of choice by many researchers due to its low cost, environment friendly and great performance [1]. The morphology, particle distribution, components, degree of crystalline and microstructure texture of the interphase between components can be engineered for various properties of composite materials [2].

Copper silicon carbide (CuSiC) and Aluminium silicon carbide (AlSiC) composites have been chosen due to their great heat properties such as heat dissipation, low CTE and good thermal conductivity. In thermal application, most metal matrix composites facing a mismatch issue in term of differences in CTE of two joining materials that produce stress and strain at the joining interface or in attachment surface. This will negatively affect the performance of the product which eventually lead to failure in operations [3]. Study has been conducted to analyse the effect of volume fraction in Silicon Carbide (SiC) particles reinforcement that will affect the CTE of the copper and aluminium.

CTE study of CuSiC composites were conducted and evaluated by many researchers in which the fabrication of CuSiC composites via powder metallurgy and angular shape SiC were commonly used [4-6]. Traditionally, copper is the good material for heat sink application but it suffers from high CTE and high density, therefore the incorporation of SiC particle into copper matrix will helps in reducing the CTE and density issues [7].

For AlSiC composites, the effect of SiC in aluminium matrix were conducted and evaluated through different fabrication methods [8-13]. Aluminium on the other hand, can resist oxidation under various conditions due to its stable film on its surface. The compatibility between aluminium and SiC has led to a new method development of AlSiC as a great material to be used in thermal application besides CuSiC.

2 Materials and procedures

In this study, powder metallurgy method was used to fabricate CuSiC and AlSiC composites. The powders went through a mixing process, compaction and sintering process. The effect of CTE on CuSiC and AlSiC composites are study with 5%, 10%, 15% and 20% volume percent of SiC reinforced in copper and aluminium.

The weighted powder was placed into a customized mixing container and several stainless steel balls were used to assist the mixing process. Two roll mill machines were used for this process. Since the customized mixing container was used, the mixing speed and mixing time were optimized through try-and-error method. Based on [14], to get best mixing, the optimal rotational speed, $N_o$ of cylindrical mixer is 75% form critical rotational speed where it represent a balance between centrifugal and gravitation forces and can be estimated as Equation (1);

$$N_o = \frac{32}{\sqrt{d}}$$

where $d$ is the cylindrical diameter in meters. So, the calculated mixing speed has been used was 160 rpm as shows in and 4 hours of mixing time for each sample.

Then the powders undergo plastic deformation by compacting them through cold isostatic pressing less than 5 tonnes of load by using hand press machine. These green compact samples were sintered in the tube furnace at 950°C for CuSiC and 580°C for AlSiC for 4 hours sintering time. The temperature of the furnace was slowly increased at 5°C per minute to minimize temperature gradient and prevent thermal shock on the samples. These samples were sintered in argon gas atmosphere. The samples for each volume fraction of SiC were prepared for CTE measurement. The Linseis L75HX1600 horizontal dilatometer was used to measure the CTE of the samples. The temperature range of this analysis was 20°C to 400°C and the heating rate was set at 5°C per minute. The inert gas argon was used...
to give gas shielding protection for samples from oxidation during the measurement process.

3 Results and discussion

Figure 1(a) shows the micrograph of copper powder at 500x magnification and it demonstrated that the powder particles are in irregular shape and size. However at 2000x magnification, the dendritic shape and non-uniform size of copper powder particle as shown (Figure 1(b)). According to [14], the dendritic shape of copper contributed to high green compact properties due to substantial mechanical interlocking during powder compaction process. It was reported that the density of the sintered product would be closest to theoretical density and low amount of porosity caused by dendritic structure fulfil gap between each particle [15].

Fig. 1. SEM micrograph of copper powder (a) at 500x magnification and (b) at 2000x magnification.

Figure 2 shows the micrograph of aluminium powder where (a) the image form under 200x magnification while (b) the image form under 500x magnification. Based on observation, the shape for aluminium powder is flake shape. The particle size of aluminium powder was discovered as non-uniform distribution of size between each particle. Unlike dendritic particle, flake shaped particles are more difficult to compact due to minimum contact surface area and low interlocking between each particles. Hence, it can be estimated that there are gaps formed in between aluminium and SiC particle and the total porosity are also high by increasing SiC content into aluminium matrix [14].

Fig. 2. SEM micrograph of aluminium powder (a) at 200x magnification and (b) at 500x magnification.

Based on Figure 3(a), the micrograph demonstrate SiC particles are in angular shape, finely separated particles and inconsistent in sizing. However, at 1000x magnification, SiC particles morphology was found irregular and sharp edge corner as illustrated in Figure
3(b). Theoretically, this type of surface particle of ceramic material is very suitable to fabricate with metal matrix in order to improve the green compact strength [16].

Figure 4 shows the comparison between true density and theoretical density of the CuSiC composites. Based on Figure 4, it found the true density of CuSiC composites was inversely proportional to the volume fraction of the SiC. The same result was reported by [17] which studies about SiC content effect on the properties of CuSiC composites produced by mechanical alloying. Nevertheless, the average true density of CuSiC composites were much more lower than theoretical density.

According to [18], the density of AlSiC composites were increased by increasing the volume fraction of SiC reinforcement. The increasing of AlSiC composite density is due to aluminium reinforced with other material that has higher density for SiC. Based on Figure 5, the true density of AlSiC composites were increased uniformly from 0% to 15% SiC reinforced aluminium matrix and approaching the theoretical density. However, the difference in density value between true density and theoretical density was lower that only 0.118 g/cm³ in average.
The porosity of composites with different volume fraction that calculated by using Equation (2);

\[ \rho_{\text{bulk}} = \left( \frac{D}{D-W} \right) D_W \]  

Figure 6 reveals that the porosity of both composites, CuSiC and AlSiC increased with increasing volume fraction of SiC reinforcement. The porosity of CuSiC composites were increasing from 1.7974% to 12.7285% by increment 20% SiC into copper matrix. An increasing of porosity for CuSiC composite also reported by [15] in their studies. The low amount porosity of dendritic CuSiC composite that was expected in characterization of copper powder before was proven after porosity evaluation. Besides CuSiC composites, the porosity of AlSiC composites also increased against increasing amount of SiC. It shows the same result as previous researches. However, the porosity of AlSiC composites is higher compared to CuSiC composites. What was expected in raw material analysis before, the amount of pore in AlSiC is higher due to flake shape of aluminium particles used and this expectation was proven after this evaluation.

Figure 7 shows the extracted CTE values of the CuSiC composites based on the raw CTE data. It has been noticed that the CTE of the composites with different compositions increases by increasing in temperature. Based on Figure 10, it shows that Cu-5vol%SiC composite exhibits maximum thermal expansivity compared to other compositions. Generally, the thermal expansivity increases as the temperature increase significantly. With
additional of SiC particles to copper matrix, there has been reduction in the thermal expansivity at maximum temperature for the different percentage composition of CuSiC composites. Addition of SiC particle with varying volume fraction resulted in the reduction in thermal expansivity of the CuSiC composites. This reduction proved that an additional of SiC particles might affect the expansion behaviour of copper matrix during heating condition. However, the experimental CTE value for each volume fraction of SiC was compared to theoretical CTE value and demonstrated in Figure 8.

![CTE behavior of CuSiC composites against Temperature](image)

**Fig. 7.** The CTE values of CuSiC with increasing volume fraction of SiC.

Based on Figure 8, the Cu-5vol%SiC shows highest experimental CTE value which is $14.37 \times 10^{-6}/^\circ\text{C}$ while the lowest is $11.67 \times 10^{-6}/^\circ\text{C}$. Since SiC particles impose significant constraint on the copper matrix, the CTE values of the CuSiC composite decreases with the increasing volume fraction of SiC. The decreasing CTE values of CuSiC composites logically as the CTE of SiC is lower than that copper [17]. It has been reported in literature review that the CTE of the CuSiC composites considerably increases by reinforcing SiC particles over [5].

Figure 8 also shows the experimental CTE are compliant with the theoretical dependence. Research [15] dealt if the experimental CTE plot of CuSiC composite shows much higher than theoretical CTE means that, CuSiC composites suffer by weak bonding between copper and SiC particle. But in this study, the experimental CTE was lower than theoretical CTE which mean the excellent interfacial bonding also imposes effective constraint on the expansion of the copper matrix. It can be say that the fabrication process was perfectly done on CuSiC composites due to existing of bonding between copper and SiC particles. This statement also related to shrinkage of CuSiC composite that discuss before. The shrunk of CuSiC composites is almost high because each powder particle undergo high neck growth while improving it properties [14].

An additional contribution to the decreasing CTE of the CuSiC composites also caused by the growth of porosity. Because of the different CTE between SiC and copper matrix, a CTE mismatch strain is induced when the composites are exposed to higher temperatures [19]. This CTE mismatch strain generates compression and tensile stress field in the matrix and reinforcement respectively. The pores undergo compression stress resulting in the shrinkage of the pore volume. Hence, the overall CTE of the composite decrease. The relationship between the CTE and porosity of the CuSiC composites was illustrated in Figure 9 where the CTE of composites was decreased with increasing porosity in composites.
Fig. 8. The average experimental and theoretical CTE of CuSiC composite against volume fraction of SiC.

Fig. 9. The relationship between the CTE and porosity of the CuSiC composite.

The extracted CTE values of the AlSiC composites come from raw CTE data is shown in Figure 10. From this figure, it shows the variation of CTE and temperature for different composition of AlSiC composites. It noticed that the CTE of the composites with different SiC particles content increases with the increases in temperature. However, the experimental CTE value for each volume fraction of SiC was compared to theoretical CTE value and illustrated in Figure 11. Back to Figure 10, there is almost consistency in the increase of CTE for different temperature recorded at regular intervals. The Al-5vol%SiC composite exhibited the maximum value of CTE whereas Al-20vol%SiC composite exhibited lowest magnitude of CTE behaviour.

It was stated that the low percentage of SiC content in AlSiC composites appearing CTE behaviour to increase drastically [20]. The reduction in CTE value of AlSiC composites can be attributed to the lower CTE value of SiC particles compared to aluminium matrix. Hence, the ability of SiC particles as reinforcement is effectively constraint the expansion of the aluminium matrix. It also supported by [21], the CTE behaviour will be influenced by the thermal expansion of aluminium and tightened restriction of SiC particles.

The experimental and theoretical CTE of various volume fractions of SiC reinforced aluminium matrix composites were shown in Figure 14. It showed that both CTE of the composites containing SiC particle were declined with the increasing volume fraction from 5% to 20% of SiC particles. The highest experimental CTE value is $18.98 \times 10^{-6}/^\circ\text{C}$ while the lowest is $16.93 \times 10^{-6}/^\circ\text{C}$. It agreed well with the accepted theory reported by [13] that the CTE of the composites is determined by the CTE of aluminium and the restriction of SiC particles through interfaces. This statement supported by [22] where increasing percentage content of SiC particles helped to increase the restriction on aluminium matrix,
then to reduce the CTE of the composites. However, the experimental CTE of AlSiC composites were much lower than theoretical CTE.

![CTE behavior of CuSiC composites against Temperature](image1.png)

**Fig. 10.** The CTE values of AlSiC with increasing volume fraction of SiC.

This CTE result indicated that the declines much more dependent on the high particles reinforcement content. Large particles size of ceramic material into metal matrix via powder metallurgy method also resulted in high pore area between reinforcement and matrix [14]. The increasing of porosity in AlSiC composites tends to decreasing of CTE of this composite as demonstrated in Figure 12.

![Comparison between experimental CTE and theoretical CTE](image2.png)

**Fig. 11.** The average experimental and theoretical CTE of AlSiC composite against volume fraction of SiC.

![CTE of CuSiC composites as function of porosity](image3.png)

**Figure 12:** The relationship between the CTE and porosity of the AlSiC composite.
4 Conclusions

The CTE behaviour of CuSiC and AlSiC composites was studied. The composites were fabricated via powder metallurgy method with different volume fraction of SiC particles content. Based on the experimental result and discussions, the following conclusions have been drawn.

i) The density for both composites is following the theoretical density trend. Density of CuSiC composites are decreases and AlSiC composites are increases with increment of SiC particles content. However, the porosity for these two composites is increase by increasing volume fraction of SiC particles.

ii) The use of dendritic particles shape absolutely good fabricated via powder metallurgy method due to best interlocking between powder particles. It also can be reduce the porosity of sintered product. Whilst the flake particles shape shows very high amount of porosity of sintered product and difficult to compact under cold isostatic pressure condition.

iii) The experimental CTE values of CuSiC and AlSiC composites were significantly lower that theoretical CTE values. This result shown CuSiC and AlSiC composites have an excellent bonding inter-particles because SiC particle can restrict the expansion of copper and aluminium matrix. The decreasing of experimental CTE values are also help by porosity of composite itself.

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