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Research Article

An Experimental Study of the Effects of Ceramic Composition on the Electrical and Thermal Properties of Al/SiC Composites

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Abstract

Al/SiC metal-matrix composites were investigated through Differential Thermal Analysis device as a function of volume fraction of SiC particles and sample temperature ranging 273 K to 373 K. It was found that electrical resistivity increased with increasing sample temperature and volume fraction of SiC. In contrast to electrical resistivity, electrical conductivity decreased with increasing sample temperature and volume fraction of SiC. Electrical conductivity decreased from $1,8x10^7$ 1/ohm.m to $2x10^6$ 1/ohm.m as the volume fraction of SiC increased to 60%. On the other hand, thermal conductivity decreased with increasing volume fraction of SiC particles, while being almost insensitive to temperature change between 273 K to 373 K. Thermal conductivity decreased from 120 W/mK to 10 W/mK as the volume fraction of SiC increased to 60%.

Keywords: Metal-Matrix composites, Electrical conductivity, Thermal conductivity, Al/SiC

Al/SiC Kompozit Malzemelerde Seramik Bileşenin Hacimsel Oranının Elektriksel ve Isıl Özellikler Üzerindeki Etkilerinin Deneysel İncelemesi

Öz

Bu çalışmada Al/SiC metal matris kompozit malzemelerde, seramik bileşenin hacimsel değişiminin elektriksel ve ısıl iletkenlik üzerindeki etkileri 273K- 373K sıcaklık aralığında, deneysel olarak ile incelenmiştir. Test sonuçlarında, sıcaklığın ve seramik bileşenin hacimsel oranının artmasıyla elektriksel direncin arttığı ve elektriksel iletkenliğin azaldığı görülmüştür. Seramik bileşenin yapı içerisindeki hacimsel oranı %60'a artması ile elektriksel iletkenlik $1,8x10^7$ 1/ohm.m değerinden $2x10^6$ 1/ohm.m değerine düşmüştür. Ayrıca metal matris kompozit malzemelerde seramik bileşenin artması ile termal iletkenliği azalmış olup 273 ila 373K arasındaki sıcaklık değişiminin ısıl iletkenlik üzerinde önemli bir etkisi olmamıştır. Seramik bileşenin hacimsel oranının %60'a çıkması ile ısıl iletkenlik 120 W/mK değerinden 10 W/mK değerine düşmüştür.

Anahtar Kelimeler: Metal-Matris kompozitler, Elektriksel iletkenlik, Isıl iletkenlik, Al/SiC

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1. Introduction

Metal matrix composites (MMCs) are class of metal that combines both metal and another material to improve current performance. These composites can be classified based on their matrix metals such as Cu-based, Al-based, Mg-based etc. while they can be named based on reinforcement type such as fiber reinforced, whisker reinforced, particle reinforced etc. (Mortensen & Llorca, 2010). MMCs have been attractive engineering materials due to many factors including having tailorable properties (e.g. Elastic modulus, strength etc.), being the only way to introduce ceramic particles such as carbide and oxide into metals for better performances for harsh environments. These advantages have led researches on MMCs to date starting from the late 1980s (Evans et al., 2003; Mortensen & Llorca, 2010).

Amongst MMCs, Al-matrix composites have been extensively studied due to low density and high ductility of Al. Addition of ceramic particles to Al metal generally increased mechanical properties in addition to corrosion and wear resistance of pure Al (Sahin & Murphy, 1996; Torres et al., 2002). Al_2O_3 and SiC have been the most widely used reinforcements introduced into Al to form Al-matrix MMCs (Lavernia et al., 1995). Owing to low cost and better mechanical properties in addition to high temperature stability (Khadem et al., 2011), SiC has been more attractive as a reinforcement material (Ünlü, 2008; Xiong et al., 2011). Effects of SiC particles on the mechanical properties of Al/SiC MMCs have been extensively studied. It was found that strength and hardness levels increased with increasing volume fraction of SiC, while impact toughness is inversely proportional (Ozben et al., 2008). It was also shown that impact properties of Al/SiC MMC are strongly affected by matrix-reinforcement bonding and particle cracking (Ozden et al., 2007). Aging process was found to be effective on the fatigue life of Al/SiC MMCs. It was observed that peak aged MMCs showed less fatigue life degradation compared to under-aged conditions (Srivatsan et al., 2005). Effect of particle clustering and random distribution of SiC studies showed that microstructures having clustered particles experienced more extensive particle fracture compared to the microstructures with randomly distributed SiC particles under tensile loading (Peng & Fuguo, 2010).

Besides mechanical properties, thermal and electrical properties have utmost importance for engineering applications pointing to thermal and electrical management. One of these engineering applications is electronic packaging owing to lightweight, low cost and good physical properties (Lee, 2000). Additionally, pliable manufacturing creates advantages on tailoring physical properties such as thermal and electrical conductivity. Up to date, many electronic packaging applications have been realized using MMCs (Guo et al., 2014; Zweben, 1992) such as microwave housing with Al/SiC. For tailorable thermal and electrical properties, it is critical to control volume fraction of SiC particles in the microstructure. Because these properties are highly sensitive to the volume fraction of ceramic and metal in an MMC. In general, thermal, and electrical conductivity values of Al/SiC MMCs decreased with increasing volume fraction of SiC particles (Lee, 2000; Weber et al., 2010). High volume fraction (e.g. > 50%) of SiC particles is important to reduce the coefficient of thermal expansion (CTE) for having a material that has comparable thermal properties with conventional thermal controlling materials such as alumina and semiconductors (Lee, 2000).

This study aims to contribute to the research literature on the thermal and electrical properties of Al/SiC metal matrix composites. Al/SiC MMCs with volume fractions of ceramic particles ranging from 0-60%. Electrical and thermal properties were characterized through Differential Thermal Analysis. It was found that electrical resistivity increased with increasing volume fraction of SiC. On the other hand, electrical and thermal conductivity values decreased with increasing volume fraction of SiC particles. A maximum electrical conductivity of 1,8 x 107 1/ohm.m was achieved for pure Al, where the maximum thermal conductivity was 120 W/mK. As the volume fraction of SiC increased to 60%, the electrical conductivity and thermal conductivity values decreased to 2 x 106 1/ohm.m and 10 W/mK, respectively. Electrical conductivity decreased with increasing sample temperature, while a slight increase was observed in thermal conductivity with increasing temperature.

2. Experimental Procedure

The MMC composites were produced by a powder stacking-hot pressing method using Al and SiC powders. Maximum particle diameter of Al spherical powders was 44µm, where maximum powder diameter of spherical SiC powders was 10µm The metal and ceramic powders were mechanically blended for 3 hours to obtain a homogeneous mixture followed by pouring the mixture into sintering mold. The sintering process was conducted at 600ºC under 100MPa for 90min. A vacuum and argon atmosphere were used to prevent oxidation during sintering. Figure 1 shows the processing steps of Al-SiC metal matrix composites.

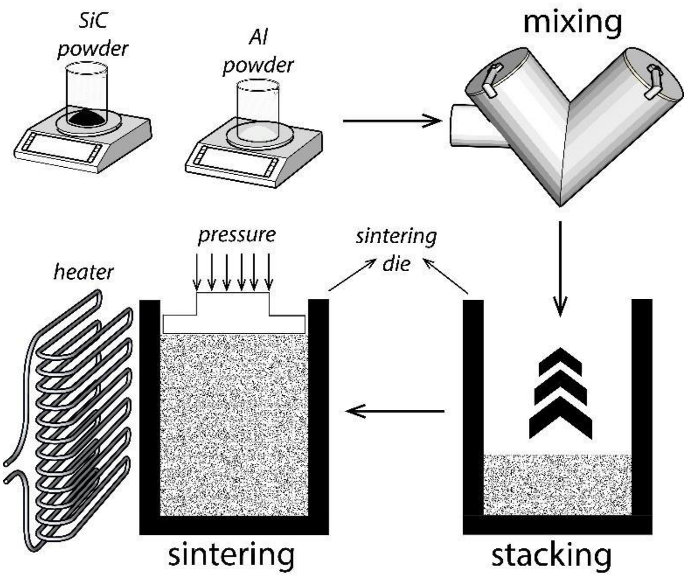

Figure 1. The production process of metal matrix composites by powder stacking hot pressing technique.

The high temperature phase analysis of Al-SiC composites were made by using the Perkin Elmer Diamond Differential Thermal Analysis device. All thermal analysis was made at the heating rate of 20 K/min. in pure nitrogen atmosphere. The electrical resistivity vs. temperature was carried out for the samples using (CRYO Industries of America Model No: REF-2261-202HT) with 4 K/min heating rate under vacuum between 273K and 373K temperature range.

3. Results and Discussion

Figure 2 shows microstructures of Al/SiC composites as a function of volume fraction of SiC. It is clear that as the volume fraction of SiC increases, white areas (Al matrix) decrease compared to dark areas (SiC particles). Al and SiC areas are marked on the image.

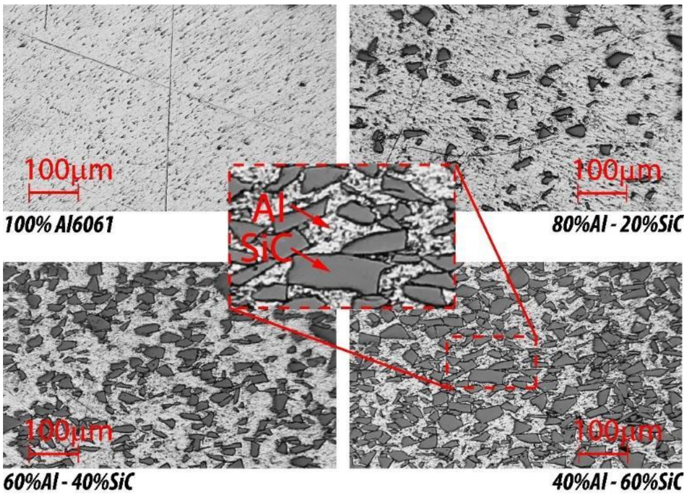

Figure 2. Microstructure of Al/SiC composites as a function of SiC

Figure 3 shows differential thermal analysis results of all composite materials. The samples were thermally cycled under zero stress between temperatures of 293 and 1073K. It is evident that aluminum phase conversion value decreased as the volume fraction of SiC particles increased. When the SiC ratio was 60%, it was determined that there were two phase transformations in succession. The first of these two-phase transformations was the eutectoid Si phase transformation and the other phase transformation was a phase transformation from solid to liquid (Ravi et al., 2007; B. Singh et al., 2013; V. K. Singh et al., 2014).

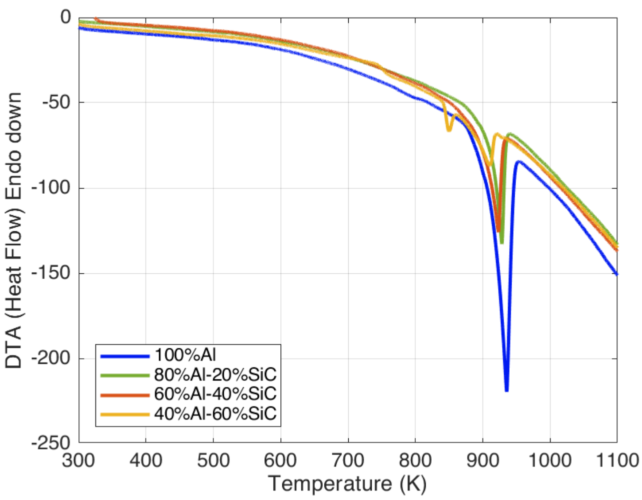

Figure 3. DTA termograms of Al/SiC composite materials

Table 1 shows the melting temperature and phase transformation enthalpy values of the Al/SiC composites related to chemical compositions. It is clear that the melting temperatures and phase transformation enthalpy values decreased with increasing volume fraction of SiC particles. The decrease of the melting temperatures with increasing SiC content is in good agreement with the literature. Singh et al. also saw that the value of melting temperature decreased with the contribution of SiC in Al-SiC composite (V. K. Singh et al., 2014).

The enthalpy values also decreased with increasing SiC. This might be due to the decrease in Al content in the composites. Since the only phase transformable material is Al in the studied temperature range, the phase transformation enthalpy is directly linked to the amount of Al metal in the composites. Decreased Al content resulted in a decrease in the enthalpy values.

Table 1. DTA results of Al/SiC composite materials.

Composition	***Melting point (K)***	***Enthalpy (µV.s/mg)***
%100 Al	*935.1*	*374.0*
%80 Al-%20 SiC	*928.3*	*312.0*
%60Al-%40 SiC	*923.6*	*218.3*
%40Al-%60 SiC	*909.7*	*90.6*

Figure 4 shows electrical resistivity values of Al/SiC composites as a function of temperature ranging 273K to 373K. Electrical resistivity (ρ) value was measured directly by using a cryostat system. The electrical resistivity value increases with increasing SiC ratio in the Al-SiC composite. This increase has gained significant momentum with the SiC ratio being a matrix. If we examine the variation of the electrical resistance with temperature for each composite, it was concluded that the resistance value between 273K and 373K did not vary significantly.

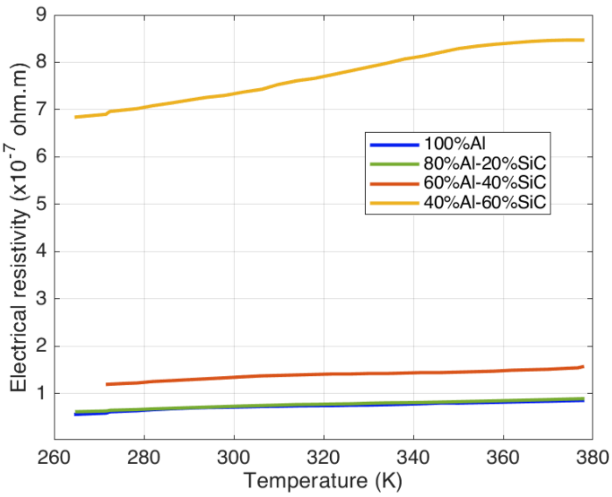

Figure 4. Electrical resistivity of Al/SiC composites as a function of temperature.

Figure 5 shows the electrical conductivity change of Al/SiC composites by temperature. The electrical conductivity (σ) value was calculated by the formula (σ=1/ρ). In contrast to the electrical resistance of composites, their electrical conductivity and thermal conductivity have been shown to decrease with increasing SiC contribution. Since the SiC particles are non-conducting parts of the Al/SiC composites, the dependence of the electrical conductivity on the volume fraction of SiC ceramic particles can be explained based on the differential effective medium scheme, which is widely used in modeling of conductivity of metal matrix composites reinforced by non-conductive particles such as SiC (Weber et al., 2003). Differential effective medium scheme can be to explain the relationship between volume fraction of matrix and electrical conductivity as follows:

$$\sigma_c = \sigma_m V_m^n$$

where σ_c is conductivity of composite, σ_m is conductivity of matrix, V_m is volume fraction of matrix and n is a parameter related to particle shape. Therefore, as the volume fraction of metal matrix increases in a composite, electrical conductivity increases. In other words, electrical conductivity decreases as the volume fraction of non-conductive reinforcement increases based on the formula above.

As mentioned above, electrical resistivity is strongly dependent on temperature change in metallic materials. Electrical resistivity increases with increasing sample temperature. This fact is usually expressed by (Kahveci et al., 2019):

$$\rho_s = \rho_o[1 + \alpha(T - T_o]$$

where ρ_s is electrical resistivity at temperature T, ρ_o is electrical resistivity at room temperature, α is electrical resistivity coefficient and T_o is room temperature. Based on the formula, electrical resistivity increases with increasing temperature as shown in Figure 4. Since the thermal conductivity is calculated by taking the inverse of electrical resistivity, it is expected that electrical conductivity decreased by increasing temperature.

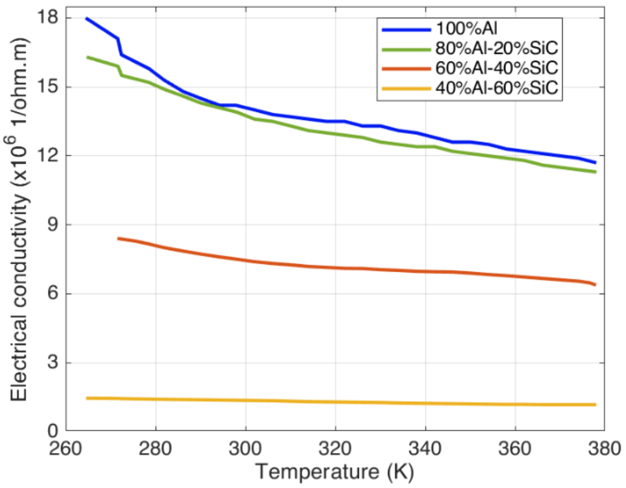

Figure 5. Electrical conductivity of Al/SiC composites as a function of temperature.

Figure 6 shows thermal conductivity values as a function of temperature in Al/SiC composites. The thermal conductivity values were calculated using Wiedemann-Franz law.

Wiedemann-Franz law is a law derived from the kinetic theory of gases, but it is applied for solid materials. According to this law, there is a relation between thermal conductivity and electrical conductivity as follows.

$$\sigma = \frac{K}{LT}$$

In this equation, K is the thermal conductivity of the sample, L is Lorenz number, T is the temperature in kelvin and σ is the electrical conductivity of that sample. L is almost equal to 2.44x10-7 WΩ/K2 for metals and semiconductors (Bevington & Han Kim, 1979; Krishnamachar, 2018; Patel et al., 2013; Yi et al., 2020).

It is clear that thermal conductivity values decreased by increasing volume fraction of SiC particles. In contrast to electrical conductivity results in Figure 6, thermal conductivity values were not generally sensitive to change of sample temperature.

It is known that heat is conducted through two main mechanisms, which are electrons mobility and phonon vibrations (Polat et al., 2019). In metals, electrons mobility is more dominant mechanism in heat conduction compared to phonon vibrations. In ceramics, the responsible mechanism for heat conduction is phonon vibration, since there are no free electrons to conduct heat from one place to another. On the other hand, ceramic materials are known to have lower thermal conductivity compared to metals, due to scattering of phonon vibrations in ceramics (Salaway et al., 2008). Thus, thermal conductivity values decreased with increasing volume fraction of SiC in the current Al/SiC composites.

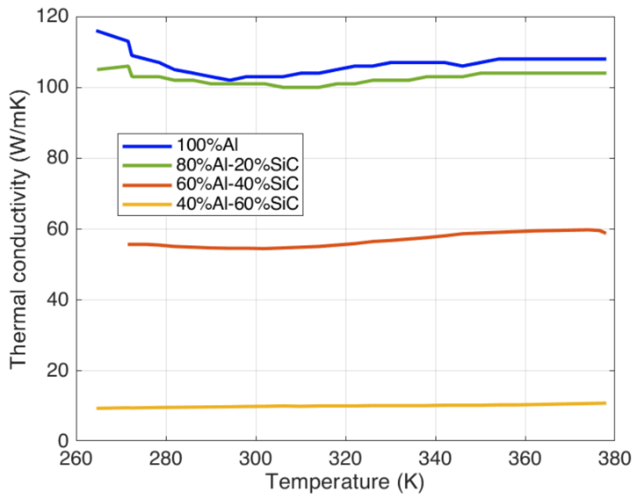

Figure 6. Thermal conductivity of Al/SiC composites as a function of temperature.

On the other hand, it's previously reported that an increase in the volume fraction of porosity in metal matrix composites resulted in a decrease of thermal conductivity values. The volume fraction of voids is expected to increase with increasing volume fraction of SiC particles in the current Al/SiC composites. Since none of the two heat conductive mechanisms, electrons mobility or phonon vibration, operates in voids, an increase of voids in microstructure results in a decrease in thermal conductivity values in Al/SiC composites as previously observed (Cem Okumus et al., 2012). The relationship between porosity and thermal conductivity can be expressed by the following formula (Kobayashi et al., 2013).

$$k_m^p = k_m \left[\frac{1 - V_p}{1 + V_p}\right]$$

where k_m^p *and* k_m are thermal conductivities of matrix with and without porosity, respectively and Vp is the volume fraction of porosity in microstructure. As clear from the formula, as the volume fraction of porosity increases in a microstructure of composite, the thermal conductivity of the matrix decreases. Additionally, the occurrence of interface reactions with increasing SiC ratio may cause the thermal conductivity value to decrease with the SiC additive in Al-SiC composites. The same reasons are thought to be the factors that decrease the electrical conductivity of the composite and increase the electrical resistance.

4. Conclusions

Differential Thermal Analysis method was used to characterize thermal and electrical properties of Al/SiC composites with volume fraction of SiC particles reaching to 60% as a function temperature ranging 273K to 373K. Based on the experimental results, it was observed that electrical resistivity increased with increasing sample temperature and volume fraction of SiC ceramic particles. On the contrary, electrical conductivity was found to be decreased with increasing sample temperature and volume fraction of SiC. Electrical conductivity decreased to 2x106 1/ohm.m as the volume fraction of SiC increased to 60%. Thermal conductivity was observed to be decreased with increasing volume fraction of SiC ceramic particles and was nearly not dependent on temperature change between 273K to 373K. A minimum thermal conductivity of 10 W/mK was observed as the volume fraction of SiC was 60%.

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