Effect of addition of Si on thermal and electrical properties of Al-Si-Al$_2$O$_3$ composites

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Abstract. Al-5wt.%Si-Al$_2$O$_3$, Al-10wt.%Si-Al$_2$O$_3$, Al-20wt.%Si-Al$_2$O$_3$ composites were fabricated by powder metallurgy and in-situ reactive synthesis technology. The impact of the addition of Si on the thermal and electrical properties was tested and analysed for vary in silicon content in Al-Si-Al$_2$O$_3$ composites. Results show that both thermal expansion coefficient and thermal conductivity decreased as silicon content increased because Si and Al$_2$O$_3$ dispersed in the Al matrix uniformly to suppress the high thermal expansion of Al to a large extent as well as the interfacial thermal resistance which led to the decline in thermal conductivity. Electrical resistivity increased when silicon content was increased because low thermal expansion coefficient particles of Si and Al$_2$O$_3$ severely damaged the continuity of the Al matrix which hindered movement of electron in the matrix.

Keywords: Al-Si-Al$_2$O$_3$ composites; Microstructure; Thermal properties; Electrical properties.

1. Introduction
Particle reinforced aluminum matrix composites have been recently developed due to the excellent performance of aluminum alloy combined with enhanced particles. With their high strength, wear resistance, thermal fatigue resistance and relatively inexpensive cost, Al-based composite materials are applied widely in the manufacture of optical and electronic parts, especially in the transport sector for price-sensitive automotive industry [1-3]. Particle reinforced Al matrix composites are also favored in the aerospace and military sectors. Due to the requirement for satellite waveguide of small thermal expansion coefficient, Cr/Al composites have been manufactured [1, 4]. Thus, particle reinforced aluminum matrix composites have a significant development potential and application prospects [5]. One advantage of Al-based composite materials the ability to obtain excellent performance through proper control of the composition. Kasprzak W [6] has performed research on the properties of cast Al–Si based alloy, with the addition of Zr–V–Ti, which showed that this improved yield strength and cyclic yield strength at room temperature, while slightly improving hardness at elevated temperature. Mazahery Ali [7] fabricated aluminum matrix composites reinforced...
with boron carbide particles and found that the abrasion resistance of the composites increased with increasing volume fraction. Al-Si/SiCp (15 vol.%SiC particulate) composite was synthesized by WeiLi [8] and samples with high micro-hardness and low porosity volume fraction showed superior thermal fatigue resistance. At present, many countries have entered the stage of development and application of particle reinforced aluminum matrix composites. Also, many investigations have focused on the effect of the addition of Si on the properties of Al-based composites. Gao Ying [9] has discussed the mechanical properties of two kinds of Al-Si-Al2O3 composites with different Si content. The study by Wang Yongjin [10] indicated that the tensile strength of as-cast and as-extruded alloys could be improved with the increase in Si content. In this paper, the impact of the addition of Si on the thermal and electrical properties of Al-Si-Al2O3 composites were tested and discussed on the basis of analysis of the thermodynamic as well as the electrical properties of Si and microstructure of material, from the perspective of relation between the physical, chemical, and structural properties of composites. Al-Si-Al2O3 composites with different Si content exhibit much different properties. The effects of the addition of Si on the thermal and electrical properties of Al-Si-Al2O3 composites have been reported in very few studies. This investigation proposes to study the performance of Al-Si-Al2O3 composites as function of content of silicon.

2. Preparation of material
Al-based composites were fabricated by powder metallurgy and in-situ reactive synthesis technology, in which Al power with diameter of 5µm and nano-SiO2 powder of purity 99.99% were used. Al-5wt.%Si-Al2O3, Al-10wt.%Si-Al2O3, Al-20wt.%Si-Al2O3 composites were fabricated based on the reaction formula[11]:

\[(4+m)\text{Al} + 3\text{SiO}_2 = 2\text{Al}_2\text{O}_3 + 3\text{Si} + m\text{Al}\]

(1)

The mixture ratios are shown in Table 1.

| Si (wt. %) | Al : SiO2 (g) |
|-----------|---------------|
| 5         | 9.5:1         |
| 10        | 4.8:1         |
| 20        | 2.5:1         |

The process sequence for the composites, in this study, is as follows: Mixing→Freeze-drying→Cold hydraulic pressing→Vacuum degassing→Hot hydraulic pressing. Hot hydraulic pressing process parameters are: 700 °C× 50Mpa × 1h.

The thermal expansion coefficient of the composite was tested by ZRPY-1400 coefficient of thermal expansion tester; the thermal conductivity of the composite was tested by DRH thermal conductivity tester, and the electrical resistivity of the composite was tested by WSP-53 digital four probe tester.

3. Experimental results and analysis

3.1. Analysis of the microstructure of material
The microstructures of Al-Si-Al2O3 composite, with varying mass fraction of Si particles are shown in Figure 1.
The Al-5wt.%Si-Al₂O₃ composite (Figure 1a) is hypoeutectic. α-Al is firstly separated during condensation, and then the co-crystallized Al-Si alloy follows. As shown in Figure 1a, the Si and Al₂O₃ reinforced phases have sheet-like appearance, and there are some pores located in the composite. The Al-10wt.%Si-Al₂O₃ composite (Figure 1b) has more homogeneous distribution of Al₂O₃ particles generated in situ in the Al matrix. Si, that is replaced, disperses uniformly in the mixture matrix of Al and Al₂O₃. It is apparent that the composite has high structural homogeneity and density without pores. In some areas, Al particles are agglomerated in large area as shown in Figure 1b, forming Al-Si eutectic microstructure in strip-like appearance. It may be caused by poor uniformity of the mixing or the existence of large aluminum particles.

Increasing the Si mass fraction to 20wt.% (Figure 1c) leads to some large pores created in the Al matrix. As shown in the micrograph, Si is of long strip and bulk shape, and the quantities and scale of primary Si increase, which is in accordance with the Al-Si binary phase diagram. The presence of eutectic Si around the Al₂O₃ particles shows that the nucleation and growth of eutectic Si are attached to alumina particles.

From the above SEM results, Al-Si-Al₂O₃ composites which are fabricated by in-situ reactive synthesis technology show good microstructure uniformity and high density with the homogeneous distribution of the reinforced Al₂O₃ phase in the Al matrix. Si and Al, was fabricated by in-situ reactive synthesis technology, form Al-Si eutectic structure. From these microstructures, bulk primary
silicon is observed by increasing the Si content from 5wt.% to 20wt.%, and the crystal morphology of particles is generally a polyhedron.

3.2. Effect of addition of Si on thermal expansion coefficient of composites

The linear expansion coefficient of the composites, with varying mass fraction of Si, is shown in Figure 2.

![Figure 2. Coefficient of linear expansion versus Siwt.%](image)

As seen from Figure 2, with increasing Si content, the thermal expansion coefficient of composites decreases. This may be due to the following factors: (1) Physical properties of reinforcement and matrix: From Turner’s model [12], the thermal expansion coefficient of composites mainly depends on the thermal expansion coefficient of the matrix and the degree of restraint on the matrix from reinforcement through the matrix/reinforcement interface. The high thermal expansion of Al is restrained to a large extent as silicon has low thermal expansion coefficient and Al2O3 particles disperse in Al matrix. The main factor influencing the thermal expansion coefficient is the volume content of reinforcement particles [13]. (2) Interfacial stress: Due to the mismatch in the expansion coefficients of the reinforcement and the matrix, within the constraints of the interface, this will result in residual stress in the matrix near the interface region which can lead to the occurrence of corresponding elastic strain in the matrix alloy. This is because when the composites solidify, a large number of dislocations occur at the Si-Al interface due to the stress, which causes diffusion along dislocation. The essence of thermal expansion is that the average distance in the lattice structure of particle increases with rising temperature [13], and the existence of the dislocation impedes expansion. (3) Binding force between atoms: The nature of thermal expansion in solids is that the average distance between atoms in the lattice structure increases with increasing temperature. In Al-Si-Al2O3 composites, there is a large area of Al accumulation in some areas resulting in a non-uniform composition distribution and particle size, so that the micro-structure is even worse and the binding energy among Al, Si and Al2O3 is reducing. The coefficient of thermal expansion increases.(4) Effect
of grain size: Atoms restrain the expansion of the matrix mainly by the transfer of the interface zone. When the volume fraction is certain, the reinforcement/matrix interfacial area mainly depends on the particle size. With increasing Si from 5 wt.% to 20 wt.%, the restraints to matrix deformation reduces due to the increase in size of primary silicon. As a result, the variation in thermal expansion coefficient with change in composition [14] is not linear. (5) Impact of porosity: Pores could destroy the continuity of material microstructure so that the binding force between matrix alloys can be reduced. In this way, thermal vibration amplitude increases which can lead to poor thermal stability.

3.3. Effect of addition of Si on thermal conductivity of composites

The thermal conductivity value of the composites, with varying mass fraction of Si, is shown in Figure 3.

![Figure 3. Thermal conductivity versus wt.% of Si.](image)

From Figure 3, with increasing Si content, the thermal conductivity of the composites decreases. Heat in solid is conducted by lattice vibrations (phonon) and the movement of free electrons [13]. With the addition of Si and Al₂O₃ particles, the thermal conductivity of Al-Si-Al₂O₃ composites decreases. This is due to increase in heat conduction via phonons, decrease in heat conduction due to free electrons, and the influence of free electrons on thermal conductivity being higher than that of phonons. At the same time, the increase in volume content of the particles causes an increasing interfacial area per unit volume of the composites, and the interfacial thermal resistance increases, which leads to the decline in thermal conductivity [15]. In addition, the porosity of composites has a complex effect on thermal conductivity. The pores can be considered as dispersed phase and the increase in the porosity will decrease the thermal conductivity if the temperature and the porosity are not high, the pore size is very small and pores distribute uniformly. The presence of many pores in 20wt.%Si composite is one of the reasons for the decrease in thermal conductivity[13, 16]. Otherwise, the dislocation in the Al matrix increases scattering, which decreases the thermal conductivity to some extent [17].
3.4. Effect of addition of Si on electrical resistivity of composites

The electrical resistivity of the composites with varying mass fraction of Si is shown in Figure 4.

![Graph showing variation of electrical resistivity with weight % of Si.](image)

**Figure 4.** Variation of electrical resistivity with weight % of Si.

As can be seen from Figure 4, the electrical resistivity of the Al-Si-Al2O3 composites rises with increasing silicon content. The electrical resistance of a metal represents the integrity of the crystal lattice is due to the scattering of the electron wave [13]. In the conductive properties of Al-Si-Al2O3 composites, Al is in a highly conductive continuous phase which plays a leading role. Therefore, the continuous Al matrix directly determines the conductivity of the Al-Si-Al2O3 composite. With increase in the content of Si, Si and Al2O3 particles severely damage the continuity of the Al matrix, which destroys the periodic potential field of the matrix lattice, hinders the movement of electrons in the matrix and increases the scattering of the electrons. As a result, the electrical conductivity deteriorates and the electrical resistivity increases. The electric resistivity of the composite materials will increase with the addition of Si and Al2O3contentas Si and Al2O3 have high electrical resistivity, especially the electrical resistivity of Al2O3 is up to 1013Ω•m. The electric resistivity is a micro structure-sensitive property; the degree of order and microstructure of particle has significant effect on the resistivity of materials and the change in resistivity often reflects the change in the inner microstructure of the materials [18]. The more uniform distribution of the microstructure of the composites, the smaller scattering of the electrons appear due to free electrons. This could lead to smaller resistivity. For the Al-20wt.%Si-Al2O3 composite, there are more porosities; pores reduce the average distance of the electrons and increase the electron scattering so that the resistance could be increased. Additionally, dislocations in the Al matrix cause lattice distortion and increase electron scattering. But it has a little influence on the increase in resistivity. In the reaction process between Al and SiO2 the interface area will increase, and the interface can scatter electrons, to increase the electrical resistivity of the composites significantly [18].
4. Conclusions

(1) With increasing Si content, the coefficient of thermal expansion of Al-Si-Al$_2$O$_3$ composites decreases. This is because the coefficient of thermal expansion of the composite mainly depends on the coefficient of thermal expansion of the matrix and the degree of restraint on the matrix from reinforcement through the matrix/reinforcement interface. The high thermal expansion of Al is restrained to a large extent as Si has low thermal expansion coefficient and Al$_2$O$_3$ particles disperse in the Al matrix.

(2) With the addition of Si and Al$_2$O$_3$ particles, the thermal conductivity of Al-Si-Al$_2$O$_3$ composites decreases due to the increase in the heat conduction via phonons, the decrease in heat conduction by free electrons, and the effect of the free electrons on the thermal conductivity being far higher than that of phonons. At the same time, the increase in volume content of the particles causes an increase in the interfacial area per unit volume in the composites, and the interfacial thermal resistance increases, which leads to the decline in thermal conductivity.

(3) With increasing Si content, Si and Al$_2$O$_3$ particles severely damage the continuity of the Al matrix, which destroys the periodic potential field of the matrix lattice, hinders the movement of electrons in the matrix and increases the scattering of the electrons. As a result, the electrical conductivity deteriorates and the electrical resistivity increases.

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