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The Electrical Resistivity of a SiC_w/Al Alloy Composite with Temperature

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Abstract The electrical property of MMC is essentially important to some applications such as power transmission lines and cables, electronic and electrical components as well as electromagnetic shielding equipments. The behavior of electrical resistivity of SiC_w/Al alloy composites under as-extruded and annealed conditions has been investigated within the temperature range from room temperature to 450°C. It can be seen that within entire temperature range, the electrical resistivity of composites was higher than that of an unreinforced matrix alloy under the same condition of either as-extrusion or annealing. The temperature dependence of both exhibited positive incline like a typical metal. The variation of electrical resistivity of an unreinforced matrix alloy with temperature from ambient temperature to 450°C was nearly monotonous, while those of composites increased monotonously at low temperature and rose to a high level after about 250°C or 275°C. The difference of these temperature dependences on electrical resistivity can be interpreted as qualitatively the interfaces of SiC_w fibers and matrix, where act as nucleation sites.

Key words electrical resistivity, SiC_w/Al alloy composite, mean free path length, interface, nucleation site

1. Introduction

Up to date, there seem no much works focused on electrical property of discontinuously silicon carbide reinforced aluminum matrix (SiC/Al) composites which were primarily developed as advanced structural materials and is currently considered for applying in many fields,[1,2] the same as to other metal matrix composites(MMCs). In fact, the electrical resistivity of MMCs is very much important to some applications such as power transmission lines and cables, electronic and electrical components as well as electromagnetic shielding equipments.[3] It is generally known that electrical resistivity of pure metal and metallic alloys is greatly sensitive to the composition and microstructural features like solute atoms, crystal defects, and secondary phases.[4] After incorporation of ceramic reinforcement, the microstructural characteristics of matrix in composite would be quite different from that of an unreinforced matrix alloy.[5] Furthermore, the presence of reinforcement and reinforcement-matrix interfaces would have scattering effects to some extent on electrons that are dominative carriers in metallic materials. But there is only very limited information[3,6,7] on such a subject which depends considerably on careful experimental studies. In this investigation, the electrical resistivity of SiC_w/Al alloy composites and the corresponding unreinforced matrix alloy under as-extruded and annealed condition have been estimated, within the temperature range from room temperature to 450 . The reasonable interpretation to the obtained experimental phenomena has been provided.

2. Experimental Procedure

The starting experimental materials were a 20 vol.% SiC_w/Al-2.15Li-2.10Cu-1.15Mg-0.10Zr(wt.%) composite and its unreinforced matrix alloy fabricated by the same squeeze casting process under protection of Ar. The chemical analysis results showed that alloying element contents in the cast composite and unreinforced matrix were nearly identical. The cast materials were further processed into bars with diameter of 12.5 mm by hot extrusion at 480°C and 450°C for the composite and unreinforced matrix alloy, respectively. Microstructural analysis revealed that SiC whiskers were almost aligned along extrusion direction, and the aspect ratio of whiskers was about 4.

The specimens for electrical resistivity measurement, with the longest dimension parallel to the extrusion direction, were cut from the extruded bars by electrical spark machining. Two groups of samples were prepared, for either composites or an unreinforced matrix alloy. One

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group was directly employed for electrical resistivity measurement after surface polishing, while other group was subjected to an annealing treatment (held at 400°C for 4 hrs, furnace cooling, Ar protection) before measuring. Both samples were carefully surface polished, and the final dimension of specimens was 2×2×60 mm.

The electrical resistivity of prepared specimens was measured by using the standard four-probe method in an electric resistance-measuring instrument. High purity nickel wires with the diameter of 0.3 mm were used as electrical current and potential leads. A constant DC current of 100 mA was passed through specimens and the electrical resistivity of either SiC_w/Al composites or an unreinforced matrix alloy was determined using a Keithley Model 182 Sensitive Digital Voltmeter between room temperature (25°C) and 450°C. The specimens were heated in a quartz tube with the vacuum of 10^{-5} torr by an infrared furnace at the heating rate of 2°C/min. Five specimens were measured under as-extruded or annealed conditions. It was found the each five sets of readings of the data were approximately the same.

3. Results and Discussion

Fig. 1 illustrates the influence of testing temperature on the electrical resistivity of as-extruded and annealed SiC_w/Al alloy composites and the corresponding unreinforced matrix alloy. It can be seen that within the entire temperature range investigated, the electrical resistivity of composites was higher than that of an unreinforced matrix alloy under the same condition of either as-extrusion or annealing, and both of them increased with the increase of testing temperature. However, the variation of electrical resistivity of an unreinforced matrix alloy with temperature from ambient temperature to 450°C was nearly monotonous (see curves B in Fig. 1(a) and (b), respectively), while those of composites increased monotonously at low temperature and rose to a high level after about 250°C (for annealed sample, curve A in Fig. 1(b)) or 275°C (for as-extruded sample, curve A in Fig. 1(a)).

For metallic alloys, the increase of electrical resistivity with temperature is generally attributed to: (i) reduction of mean free path length of free electrons resulting from the larger amplitude of thermal vibration of lattices, and (ii) redissolution of solute atoms leading to scattering effects on free electrons.[4] Such case is also right as applying to the unreinforced matrix alloy described in Fig. 1(a) and

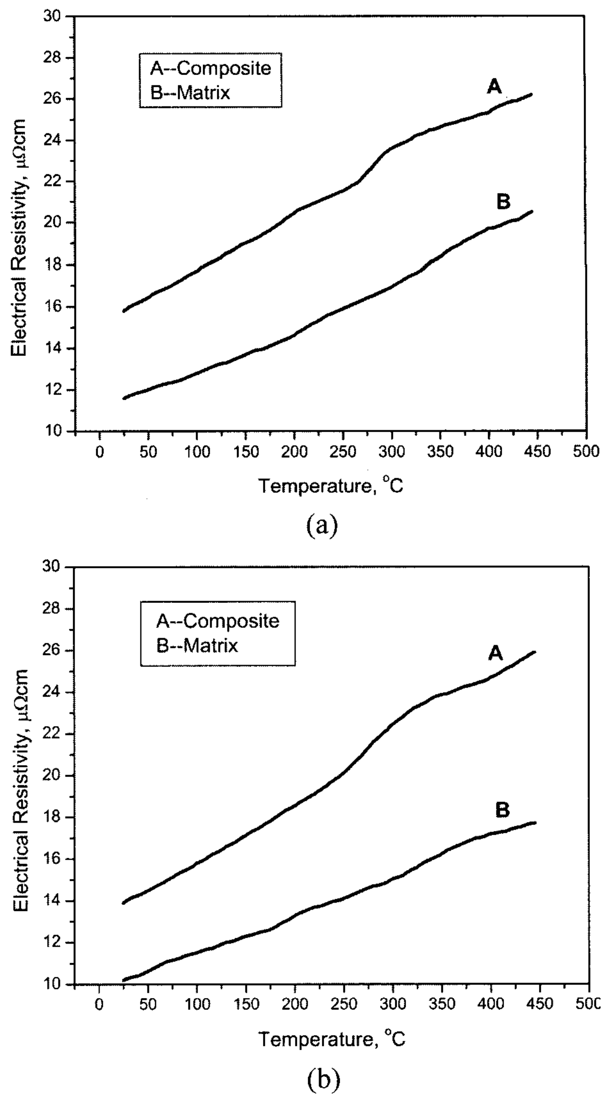

Fig. 1. Electrical resistivity as a function of testing temperature of (a) the as-extruded SiC_w/Al composite and its unreinforced matrix alloy and (b) the annealed SiC_w/Al composite and its unreinforced matrix alloy

(b). But for SiC_w/Al composites, other effects should be taken into consideration besides the above two factors. Clearly, since SiC whisker can be regarded as an insulator, the matrix of SiC_w/Al composites would consequently be the passing path of electrical current. Therefore, the electrical resistivity of SiC_w/Al composites would represent the microstructural feature of corresponding matrix in composites. The well-known microstructural characteristics of matrix in a composite, different from that of an unreinforced matrix, including high density dislocations, smaller grain size and presence of SiC-Al interface,[2,3,5] would undoubtedly cause scattering on free electrons and increase the resistivity of composites. With this in mind, it is easy to understand the electrical resistivity difference between composite samples and their corresponding unreinforced matrix samples, at either ambient or elevated temperatures, as shown in Table 1 and Fig. 1. However, the above microstructural effects that could increase the *in-situ* resistivity of matrix in composites seem not completely to explain the tendency of resistivity of composites varying with temperature. Further consideration will be presented below.

The increment in resistivity of as-extruded and annealed composites together with their corresponding matrix alloy with testing temperature was given in Fig. 2. It can be found that the resistivity variation ratio of composites was influenced by thermal treatment, while such an effect was less remarkable for an unreinforced matrix alloy. The matrix employed in the present study is a complex Al alloy system containing multiple elements such as Li, Cu, Mg, Zr that all could exist as solute atoms at high temperatures. For the unreinforced matrix alloy, the purification degree of an aluminum matrix from these excess solute atoms in an annealed sample before heating for resistivity measuring, should be higher than in the as-extruded sample since more equilibrium phases generated during annealing. And the crystal defect density in an annealed sample would probably be lower than in an as-extruded sample. Further, the grain size in an annealed sample would be probably larger than in an as-extruded sample as well due to the potential recovery and recrystallization during annealing. All these factors would lead to relatively lower electrical resistivity of an annealed sample compared with an as-extruded sample, as depicted in Table 1 and Fig. 1. It is also the same mechanism for annealed and as-extruded samples before heating.

Table 1. Electrical resistivity of SiC_w/Al composites and unreinforced matrix alloys at room temperature

Material	Electrical resistivity, mΩcm	Electrical resistivity, mΩcm
	Before heating for test	After heating for test
As-extruded composite	15.56	14.79
As-extruded matrix alloy	11.50	11.27
Annealed composite	13.91	14.83
Annealed matrix alloy	10.28	10.90

With increasing of temperature, the effects that dominate the resistivity increment of an unreinforced matrix alloy are reduction of mean free path length of free electrons and redissolution of solute atoms as described previously, despite the possible occurrence of recovery or recrystallization in an as-extruded sample during heating. Thus, the as-extruded and annealed matrix alloy samples exhibited similar resistivity variation behaviors as heated from ambient temperature up to 450°C. If followed the same mechanisms, the electrical resistivity of the as-extruded and annealed composite samples should also display similar tendency varying with temperature. But such suggestion is not consistent with the experimental

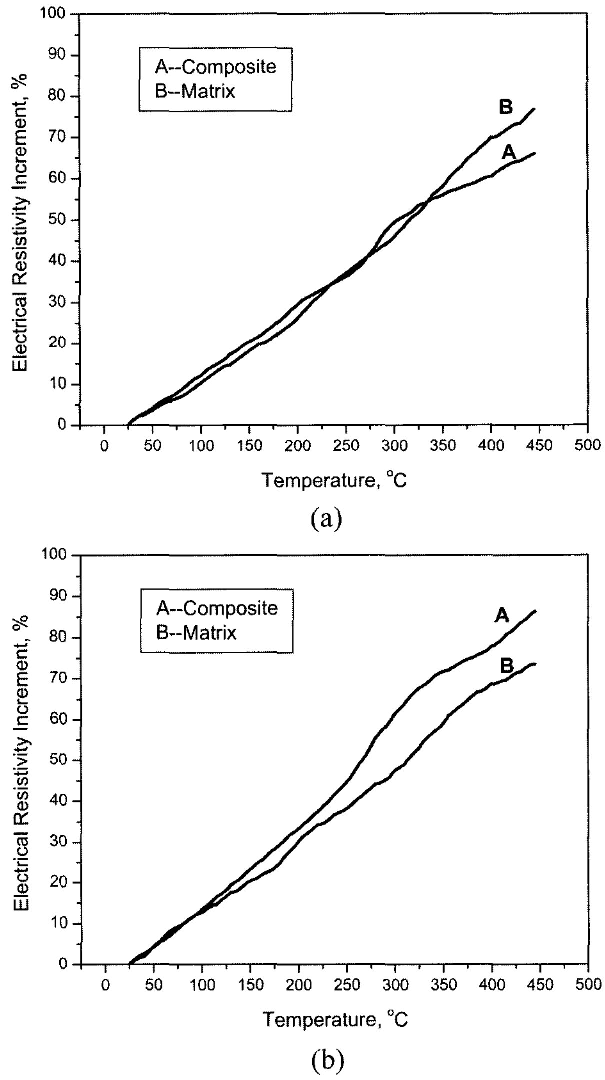

Fig. 2. Electrical resistivity increment varying with testing temperature for (a) the as-extruded SiC_w/Al composite and its unreinforced matrix alloy and (b) the annealed SiC_w/Al composite and its unreinforced matrix alloy

results as shown in Fig. 1 and Fig. 2. The thermal mismatch stresses in SiC_w/Al composites and the change of their states during heating are therefore to be taken into consideration.

It is generally acknowledged that there is significant residual thermal stress in MMCs, induced by primary processing because of the different coefficients of thermal expansion (CTE) of a matrix and reinforcement.[1,2] The residual stress in SiC_w/Al composites after cooled to room temperature usually presents as compressive stress to SiC fiber and tensile stress to matrix.[5,8] As increasing temperature of a composite, both whisker and matrix would expand. The expansion of matrix is constrained by whisker also due to their different CTE and elastic modulus, which leads to generation of misfit strain and related internal stress. According to the result of a recent study,[8] the internal stress in the matrix of SiC_w/Al composites would change from initial residual tensile stress to compressive thermal mismatch stress while heated to an appropriate temperature. The compressive internal stress applied to matrix can reduce the mean free path length of free electrons and hence the in crease of resistivity of composites. Meanwhile, a large amount of vacancy would generate in a matrix in order to accommodate the thermoelastic mismatch. Such effects should be responsible for the sharp rise in resistivity of SiC_w/Al composites varying with temperature as seen in Fig. 1. Since the initial residual stress is larger in an as-extruded sample than an annealed sample, the sudden variation of resistivity occurs at a higher temperature for the as-extruded SiC_w/Al composite.

With respect to the relative lower increment in resistivity of an as-extruded SiC_w/Al composite compared to an annealed composite at temperatures above 150°C as shown in Fig. 2, the recovery and recrystallization of matrix in as-extruded composite should account for this. It can also be found from Table 1, the resistivity of as-extruded SiC_w/Al or unreinforced matrix alloy samples at room temperature, after heated to 450°C for testing, was still a little higher than that of their corresponding annealed samples. Apparently, such difference is ascribed to the higher initial resistivity and internal energy as well as the lower stability of as-extruded samples.

In order to understand the abrupt jump for composite samples, compared to unreinforced matrix alloy around the temperature of 250 to 270°C as shown in Fig. 1 and 2, DVRC (Differentiation values of electrical resistivity change) treatment was performed and plotted in Fig. 3. We can clearly find several reaction peaks indicating the precipitation and reversion of meta-stable and stable phases while heating up. In case of extruded SiC_w/Al composite, 5 reaction peaks were observed. According to the reports[9-12] investigated on the aging process of Al-Li-Cu-Mg-Zr alloy, it is no doubt that the peaks indicate the precipitation of G.P. zone, the precipitation and reversion of δ', and the precipitation and reversion of d phase in sequence. While only two distinct reaction peaks were detected in an annealed sample, which speculated as the precipitation and reversion of d phase. As seen on Fig. 3(a), the reaction processes of G.P. Zone and meta-stable δ' phase disappeared due to the annealing treatment.

On the other hand, as seen on Fig. 3(b), the unreinforced

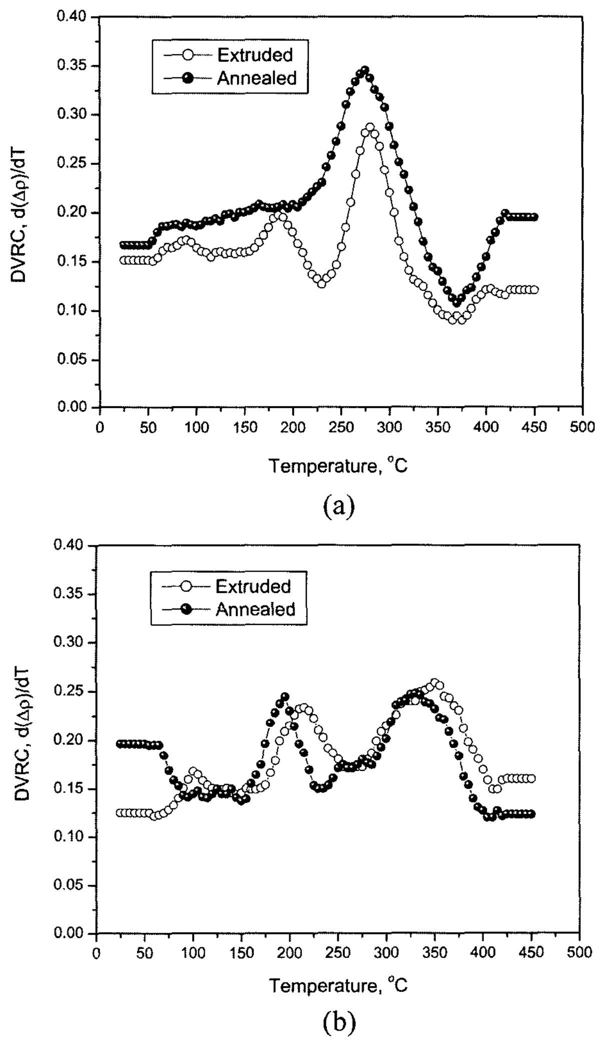

Fig. 3. Differentiation values of electrical resistivity changes (DVRC) against testing temperature for (a) the SiC_w/Al composite and (b) the unreinforced matrix alloy

matrix sample exhibited quite different behavior. Basically, both of the samples, that is, extruded and annealed condition, showed quite similar reaction behavior like the extruded curve of Fig. 3(a). Though 1 or 2 reaction peaks are not fully clear, it can be suggested that there appeared 5 reaction peaks in unreinforced matrix alloys, while the peak intensity was lower than those of (a). The peak intensity would provide very critical evidence in clarifying the abrupt jump mentioned before. Lets think about the difference. The only difference between (a) and (b) is the presence or absence of SiC_w fibers embedded in Al-ally matrix. Therefore, the difference of peak intensity can be attributed to the existence of SiC_w fiber. Especially, it seems that the interfaces would activate the reaction of precipitation and reversion of phase. This interpretation can be probably taken for granted in the view point of the theory of nucleation and growth. In conclusion, namely, the presence of SiC_w fiber in matrix caused the rapid increase around the temperature of 250 to 270°C by enhancing the reaction rate acting interfaces as nucleation sites.

4. Conclusions

The behavior of electrical resistivity of SiC_w/Al alloy composites under as-extruded and annealed conditions has been investigated. It can be seen that within the entire temperature range, the electrical resistivity of composites is higher than that of unreinforced matrix alloy under the same condition of either as-extrusion or annealing. Moreover both of them increased with the increase of testing temperature. However, the variation of electrical resistivity of an unreinforced matrix alloy with temperature from ambient temperature to 450°C is nearly monotonous, while that of composite increases monotonously at low temperature and rises to a high level after about 250°C or 275°C. This abrupt increase can be interpreted as qualitatively the interfaces of SiC_w fibers and matrix, where act as nucleation sites.

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