Effect of porosity and reinforcement content on the electrical conductivity of spray formed 2014-Al alloy + SiC_p composites

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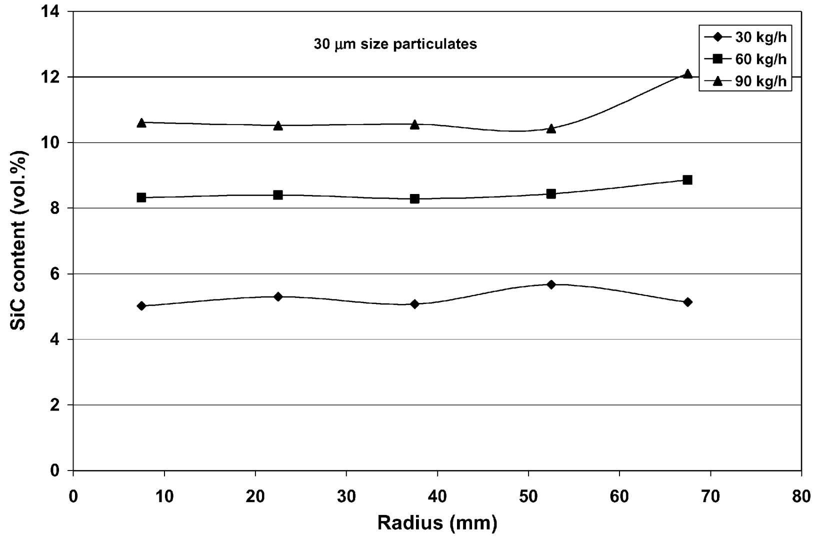
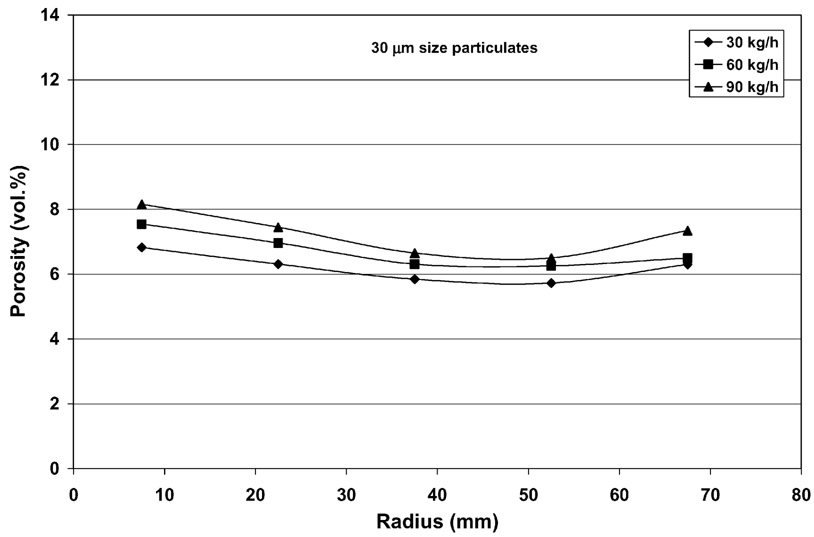
Metal matrix composites have attracted considerable interest, in recent years, due to their high electrical conductivity, high thermal conductivity and high mechanical strength. One of the most important properties required for the application of these composites in the electronic and electrical industries is electrical conductivity [1]. Electrical conductivity is drastically affected by the residual stresses and dislocations introduced during fabrication of metal matrix composites that arise due to the difference between the thermal expansion coefficients of the reinforcement and the matrix alloy [1–4]. The size, shape and volume fraction of reinforcements have also been known to affect the electrical conductivity of these materials by effecting the residual stresses near the reinforcement and matrix interface [5]. Porosity is one of the parameters which is introduced in the material during any process of fabrication. Porosity also introduces dislocations and stresses in the material and acts as the non-conducting void during electron conduction. However, there is no significant study on the effect of such parameters on the electrical conductivity of the metal matrix composite. Therefore, in the present study, attempt has been made to study the effect of size, volume fraction and the porosity on the electrical conductivity of a 2014-Al alloy composite reinforced by SiC_p particulates and produced by the spray forming process. Spray forming gives a better distribution of reinforcement phases and restrained interfacial reaction between reinforcement and matrix phases.

The nominal composition of the alloy used as the matrix in the present investigation was Al-4.5% Cu-1%Si-0.5%Mg (wt%). Metal matrix composites were produced with different mean sizes (6–58 μm) of reinforcements and different powders to melt mass flow rate ratio (10–30%). A gas to melt flow rate ratio of 2.47 (melt flow rate: 330 kg/h) was used in each experiment. The SiC_p particulate reinforcement was incorporated in the atomization zone by indigenously designed powder feeding system [6]. The porosity contents were measured by means of Archemedes buoyancy principle utilizing petroleum with a density of 0.7543 gcm^{-3}at room temperature. The measurement of SiC_p content was performed by estimation of carbon by carbon analysis and then the total SiC_p content was calculated based on the mass fraction of carbon in SiC_p. This method of SiC_p content measurement has been established by measuring and comparing SiC_p content by this method and image analysis method. The measurement of electrical conductivity was performed by a four point probe technique on SIGMASCOPE®SMP1 model equipment, at room temperature. Square samples were rotated head by head 90 degrees after each measurement to prevent the effect of anisotropy, if any, and then averaged. The samples were polished with 1000 grit emery paper prior to the measurements.

Fig. 1a shows a representative variation of SiC content (vol%)) with radial distance from the centre to the periphery of the spray formed composite billet, for three different powders to melt mass flow ratios of 10, 20 and 30% with the mean reinforcement size of 30 μm. This shows that the SiC content is uniform throughout the billet radius and varies from around 5 to 11vol%. The corresponding porosity content (vol%)) is shown in Fig. 1b. This shows that the porosity varies between 6–8 vol% for the above mentioned SiC contents. Porosity increases with increase in the reinforcement volume fraction. It has also been observed that the porosity increases with reduction in the reinforcement size. The decrease in reinforcemnt size increases the surface area of particles and, therefore, the variation of porosity with the equivalent surface area of particulates has been studied, as shown in Fig. 2. This shows that the amount of porosity of the composites increases with increase in effective surface area of the reinforced particulates. Fig. 3 shows a representative variation of electrical conductivity of composite with radial distance in the composite billet, for different volume fractions of SiC particulates with mean particle size of 30 μm corresponding to Fig. 1a. It is clearly shown that electrical conductivity decreases with increase in the volume fraction of reinforcement. There is little deviation from the centre to the periphery, which also depends upon the amount of porosity in the materials in that position. Fig. 4 shows the variation of electrical conductivity of the composites with the SiC particulate volume fraction for varying sizes of the reinforcement particulates. It seems that the electrical conductivity decreases with increasing volume fractions of the reinforcements. However, there is significant scatter of experimental data and it is difficult to say anything about correlation between the two parameters. This scatter seems to come from the fact that variation in the porosity has not



(a)



(b)

Figure 1 The variation of (a) SiC content and (b) porosity with the radius of billet for the particulate size of 30 μm at different powder mass flow rates.

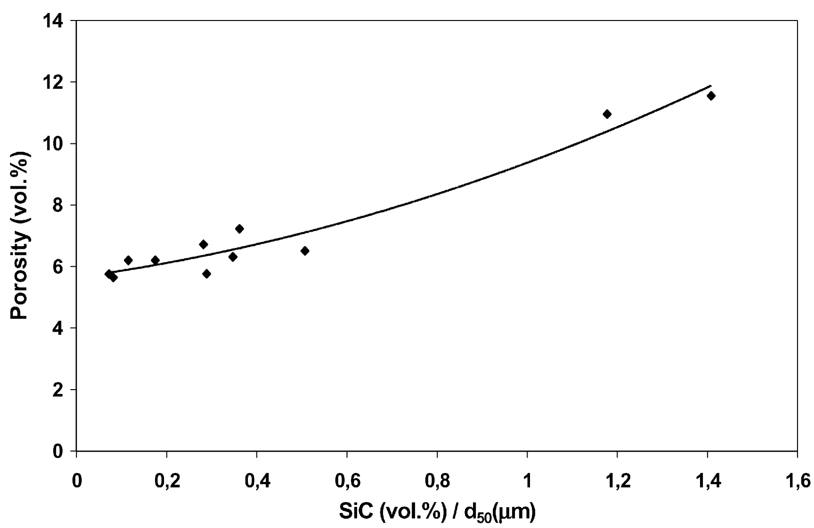


Figure 2 The variation of porosity with effective surface area of reinforced particulates.

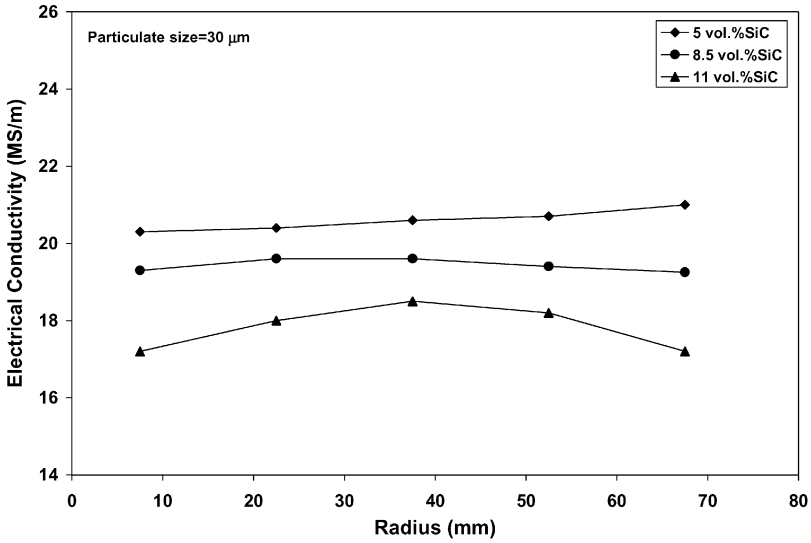


Figure 3 A representative variation of electrical conductivity of composites with the radius of billet for different volume fractions of SiC particulates.

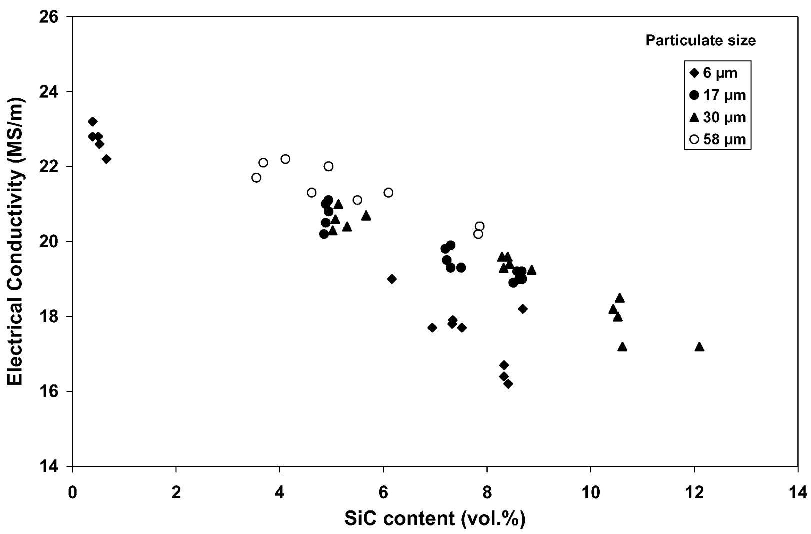


Figure 4 The variation of electrical conductivity of composites with SiC content for different particulate sizes.

been considered. However, when these parameters are combined together, the electrical conductivity seems to fit linearly with the sum of the porosity and SiC volume fractions, as shown in Fig. 5. This shows that the electrical conductivity of composites are affected both by the amount of porosity and the SiC content in the composite. Electrical conductivity is a linear function of the sum of porosity and SiC particulate volume fractions. In Fig. 5, data points are included from the composites having different reinforcement particle sizes. However, it seems that they follow a linear behavior irrespective of the size of reinforcement. It is apparent from Fig. 5 that electrical conductivity is lower for the composites with smaller size of reinforcements compared to their bigger size counterparts. The average electrical conductivity for 6 μm size reinforcements is 17.43 MS/m compared to 21.47 MS/m for the 58 μm reinforcement. The conductivity values for the above conditions have been calculated by considering the Rayleigh-Maxwell equation for the case that the electrical conductivity of the matrix is much higher than that of the reinforcement [7, 8]. The original equation (Equation 7, ref. [8]) has been modified considering the volume fraction of the porosity and the plastic zone around the SiC particulates. Plastic zone is defined as the volume of the matrix around SiC particilates that have dislocations and residual stresses. Therefore, the addition of all the three key parameters to effect the conductivity is incorporated in this equation.

The modified equation is shown as:

$$\sigma_{\mathrm{C}} = \sigma_{\mathrm{m}}\left(\frac{1-(V_{\mathrm{SiC}}+V_{\mathrm{P}}+V_{\mathrm{PZ}})}{1+\frac{(V_{\mathrm{SiC}}+V_{\mathrm{P}}+V_{\mathrm{PZ}})}{2}}\right)+\sigma_{\mathrm{PZ}}\times V_{\mathrm{PZ}} \tag{1}$$

Volume fraction of plastic zone has been assumed to be

$$V_{\mathrm{PZ}} = 3\times V_{\mathrm{SiC}} \tag{2}$$

where σ_{C}, σ_{m}, σ_{PZ}, V_{SiC}, V_{P}, V_{PZ} are electrical conductivity of composite, electrical conductivity of matrix, electrical conductivity of plastic zone, volume fraction

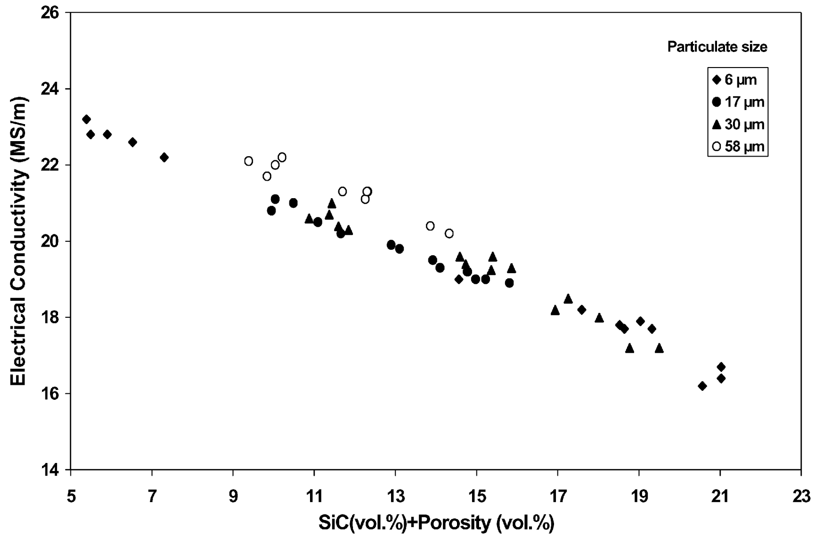


Figure 5 The variation of electrical conductivity of composites with sum of the SiC content and corresponding porosity volume fractions.

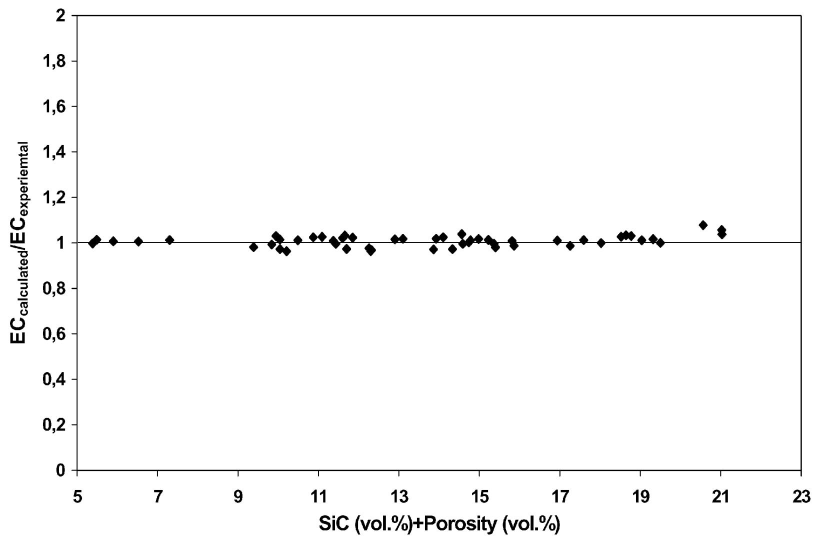


Figure 6 The ratio of calculated and measured values of electrical conductivities of composites.

of SiC, volume fraction of porosity and volume fraction of plastic zone respectively. The values for σ_m and σ_{PZ} are taken to be 2.51 and 1.62×10^5 $(\Omega\ \text{cm})^{-1}$ respectively. The ratio of the calculated and experimentally measured conductivity values is shown in Fig. 6. This shows that the values are close to 1, indicating a match between calculated and measured values.

The SiC particulates possess low electrical conductivity and the porosity acts as nonconducting voids for the electron flow. Therefore, both the parameters reduce the electrical conductivity the materials depending upon their respective content in the materials. There are several models both for the prediction of electrical conductivity of particulate reinforced metal matrix composite [1, 5, 9] and also for the materials with high porosity [10–12]. However, there is no literature which combines both the parameters. As porosity is one of the important factors which reduces the electrical conductivity, we have tried to correlate both the porosity and reinforcement content with the electrical conductivity. The effect of reinforcement comes due to a mismatch between the thermal expansion coefficient of the matrix and the reinforcement. This introduces residual stresses and dislocations around the reinforcement particles. These factors impede the free flow of conduction electrons and, thus, decrease the electrical conductivity. As the size of the reinforcement particles decreases the effective surface area increases, leading to introduction of more geometrically necessary dislocations and residual stresses. Therefore, a decrease in the conductivity is observed for the composites with small sized reinforcements. It is observed that the volume fraction of porosity increases with increase in the reinforcement volume fraction. It has also been observed that the porosity increases with increase in the effective surface area of the reinforcement particulates. This necessitates the need to consider porosity in combination with SiC content. The sum of SiC and porosity volume fractions leads to combining both the effects and, therefore, we see a linear relationship. This does not happen when electrical conductivity plotted with SiC content, as the variation of porosity with the SiC content was not considered. It was observed that a little difference between the calculated values and the measured values exist for higher values of the porosity and SiC content, however, this difference decreased when the effect of the plastic zone was considered. Therefore, it can be concluded that the conductivity is dependent upon the porosity, SiC content and residual stresses around SiC particulate. The reinforcement and porosity content have additive effect on the electrical conductivity as both of them give deteriorating effects on the conductivity.

References

1. S. Y. CHANG, C. F. CHEN, S. J. LIN and T. Z. KATTAMIS, *Acta Mater.* **51** (2003) 6191.
2. M. VOGELSANG, R. J. ARSENAULT and R. M. FISHER, *Metall. Trans.* A **17A** (1986) 379.
3. C. T. KIM, J. K. LEE and M. R. PLICHTA, *ibid.* A **21A** (1990) 673.
4. R. J. ARSENAULT and N. SHI, *Mater. Sci. Engng.* A **81** (1986) 175.
5. L. WEBER, J. DORN and A. MORTENSEN, *Acta. Mater.* **51** (2003) 3199.
6. A. SCHNEIDER, V. UHLENWINKEL, T. WRIEDT, H. HARIG and K. BAUCKHAGE, in the Proceedings of the 5th International Conference on Spray Forming, Bremen, June 2003, edited by K. Bauckhage, V. Uhlenwinkel and U. Fritsching (Universität Bremen) p. 219.
7. A. L. GEIGER and J. A. WALKER, *J. Metals* **43**(8) (1991) 8.
8. M. GUPTA, G. KARUNASIRI and M. O. LAI, *Mater. Sci. Engng.* A **219** (1996) 133.
9. J. KOVACIK, *Scripta Mater.* **39**(2) (1998) 153.
10. P. S. LIU and K. M. LIANG, *Mater. Sci. Tech.* **16** (2000) 341.
11. Y. FENG, H. ZHENG, Z. ZHU and F. ZU, *Mater. Chem. Phys.* **78** (2002) 196.
12. O. F. BOISTOV, L. I. CHERNYSHEV and V. V. SKOROKHOD, *Powder Metall. Metal Ceram.* **42**(1–2) (2003) 88.

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