Electrical Conductivity of Aluminium-Sicp foam by Stir-Casting Technique Using Dual Foaming Agent

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ABSTRACT

Aluminium Composite foams is produced by melting Aluminium alloy (LM6) containing foaming agent(s) and vigorous stirring. TiH_2 is a common agent for this. As TiH_2 decomposes into Ti and gaseous H_2 when heated above about 465°C, large volumes of hydrogen gas are rapidly produced, creating bubbles that lead to a closed cell foam. A novel Strategy to enhance the electrical conductivity of Al-MMC foams is discussed here, and it is demonstrated that titanium hydride (TiH_2) in the form of 10-15 µm diameter particles can be pre-treated by selective oxidation to produce more uniform foams having better electrical conductivity. It is found that the electrical properties of the foams and the uniformity of cell size distribution is improved when the foam is blown with an optimized mixture of $CaCO_3$ and pre-treated TiH_2.

In order to define the relationship of electrical conductivity with relative density of this material, correlations which uniquely defines the electrical behaviour of this modified Al-MMC foam has been developed.

Keywords: Al-Si MMC foam, Electrical conductivity of cellular materials, Dual foaming agent.

1. INTRODUCTION

Metal foam is a type of cellular solids, having a combination of properties such as high stiffness with very low density and a capability to absorb impact energy. These unique combinations of properties indicate various potential applications such as packaging materials for protection sensitive devices, machinery enclosures, automobiles, and as sound absorbing material under difficult situations. Beside this, the electrical conductivity of this type of material is highly attributed to the pores in the structure. The study of electrical conductivity of metallic foams is necessary as very few research works has been carried out to give a proper electrical characterization of cellular materials.

The main aim of the present investigation is to determine the electrical conductivity of the closed cell Aluminium Metal Matrix Composite (Al-MMC) foams developed in the laboratory. The outcomes of the experimental investigation are compared with the established theoretical models developed by different researchers [5-9] so that it can be further referred for different industrial applications.

Electrical conductivity is the property of a metal that indicates its ability to conduct electricity. Electrical conductivity λ_c ($\Omega^{-1} \cdot m^{-1}$) is the reciprocal of the resistivity ρ ($\Omega \cdot m$). Let R be the resistance in Ohms (Ω) and V is voltage drop in volts. Then, by Ohm's law, resistance is the voltage (V) divided by current (I) in amperes (A). Ohm's law may also be written in the form

$$j = \lambda_c E_p, \text{ or } E_p = \rho j \qquad (1)$$

In equation (1), j is the current density (current per unit area, I/A) and E_p = V/L is electric field or electrical potential gradient, V is the voltage drop measured across a length L of material, λ is the electrical conductivity and ρ is the resistivity. The resistance R = V/I is related to resistivity ρ via

$$R = \rho\, L/A.$$

Therefore,

$$\rho = \frac{VA}{IL} \qquad (2)$$

The electrical conductivity can be calculated from the measure of the resistivity of the material, and is equal to the reciprocal of the resistivity. Thus electrical conductivity can be represented as,

$$\lambda_c = \frac{1}{\rho}$$

The mechanical and physical properties of the developed material showed significant dependence on its porosity or relative density. The electrical conductivity of the material is also expected to be dependent on its relative density. Investigations in connection with the measure of electrical conductivity of various aluminium foams have been carried out by different researchers, namely Kovacik and Simancik [5], Feng et al. [6], Kim et al. (2005) [7], and Cuevas et al. [8]. The dependence of the electrical conductivity of various aluminium foams on its relative density has also been reported by them. It is therefore of interest to corroborate such findings for the developed aluminium foam.

2. SYNTHESIS OF AL-SiCp FOAM

The material under investigation is closed cell aluminium foam, manufactured through liquid metallurgy route in the **Foundry Laboratory of Jadavpur University, Kolkata,** using aluminium alloy (LM6: consisting of 0.1% Cu, 0.1% Mg, 0.13% Si, 0.6% Fe, 0.5% Mn, and trace amount of Zn, Pb, Sn and rest Al). The aluminium alloy used is of density (**ρ_s**), 2.7gm/cm3, having electrical conductivity (**λ_s**) as 31 X 10^{-6} $(\Omega.m)^{-1}$. The ingot is melt in a tilting resistance furnace. The formation of foam requires a high liquid-metal viscosity which is achieved by the addition of Silicon Carbide (SiCp) particulate to the melt. The amount of Aluminium is 1 kg. 5% SiC (pre-heated) are added to the melt, which also increases the mechanical strength of the foamed component. For homogeneous mixture of SiC in Al matrix, continuous stirring is required. The achieved high viscosity allows liquid Aluminium to be stable at a temperature of TiH_2-decomposition (465°C) which is much lower than the freezing temperature of liquid Aluminium.

The homogeneous Al-SiC mixture is then poured into a pre heated mold (which is fitted with a stirring arrangement) after removal of slag as much possible. 2.5% blowing agent (Titanium Hydride) is added to the mold. TiH_2 begins to decompose into Ti and gaseous H_2 when heated above about 465°C. By adding titanium hydride particles to the aluminum melt, large volumes of hydrogen gas are rapidly produced, creating bubbles that leads to a closed cell foam structure. It is needed to stir the mold with constant speed for good foaming.

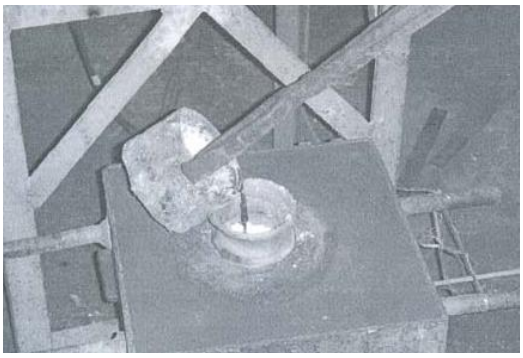


Figure 1: Pouring of Al-SiC melt into mold.

As TiH_2 is a very costly material, so, manufacturing of Al-SiCp foam by this method is not so cost effective. The solution to this problem is Calcium Carbonate (which is very cheap in cost). So, instead of adding 2.5% TiH_2, a dual foaming agent (2% $CaCO_3$ and 0.5% – 1.0% TiH_2) is added separately and this produces same result with minimum cost. Addition of Ca in Al matrix slightly changes the mechanical properties but it is nearly identical.

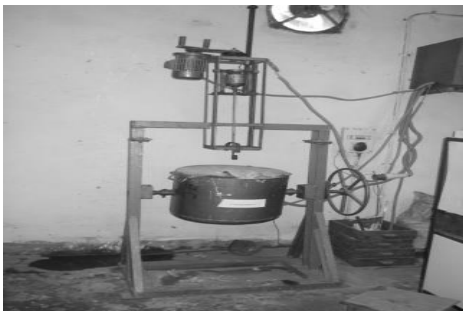


Figure 2: Tilting resistance furnace used for production of Al-SiC foam.

The properties of metal foams depend on many morphological features, such as pore size distribution, cell wall curvature, defects, etc.[3]. Although the exact interrelationship between properties and structure is not yet sufficiently known, one usually assumes that a uniform distribution of convex pores free of defects is highly desirable. The task for the experimentalist is to produce such structures. A short look at existing foams shows that there is still much potential for development since these often tend to be irregular [4].

Thus, the foam fabricated by this method are usually non-uniform which leads to inferior mechanical electrical and properties. The reason for this can be non-adoption of TiH_2 to the melting range of the alloy to be foamed. This is avoided by pre treatment of titanium hydride (TiH_2) in the form of 10-15 µm diameter particles by selective oxidation.

The pre treatment of TiH_2 was first introduced by B. Matijasevic-Lux and J. Banhart for manufacturing of Aluminium foam through powder metallurgy [10]. The same method is followed here for stir-cast route also.

TiH_2 powder supplied by LOBA chemical, India (purity 98.9%) was used in this study. The powder was supplied in the ''untreated'' state. Pre-treatments of the TiH_2 powder were carried out isothermally at various temperatures (450, 480, 510 °C) and times (30, 60, 120 and 180 min) under air in a chamber furnace. For heating, the ceramic crucible (with required amount of TiH_2) is placed into a volume chamber muffle furnace and is left there for the time specified. After pre-treatment all powders were gently homogenized by tumbling in a container.

Hydrogen starts to be released from TiH_2 at about 405 – 470 °C with some variations between powders of different origin. However, most of TiH_2 powder starts decomposing at 465°C.

As heating is carried out under air, an oxide layer grows which is roughly 100 nm thick [10] after 180 min at 480°C and contains an outer shell of TiO_2 and an inner shell of Ti_3O.[10]. Pre-treatment under air also reduces the amount of hydrogen and shifts the temperature of decomposition by 160°C. Using pre-treated TiH_2 for foaming Al alloys delays foaming and leads to a more uniform distribution of rounder pores, which enhances the electrical conductivity of the material. The best parameters found are close to 60 min at 480°C. It is noted that at higher pre-treating temperature (510°C), the amount of available hydrogen is not sufficient to produce uniform foam.

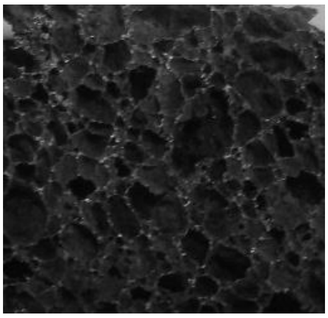


Figure 3. Surface of closed cell Al-SiCp foam

3. DESIGN AND FABRICATION OF THE EXPERIMENTAL SETUP

The electrical conductivity of the aluminium foam samples is calculated from the resistivity of the sample under closely controlled laboratory conditions. The electrical resistivity of the foams is measured using a set up based on modified design of four-probe resistivity measurement apparatus. It is found that the conventional four-probe resistivity measurement method cannot be used in this case. Because in conventional four-probe method, four equi-spaced probes placed in a line are to be kept in contact with the specimen surface, which is almost impossible in case of aluminium foam because of its cellular structure. Also trial measurement of conductivity of the developed aluminium foam revealed that the conductivity of the material varied from point to point across the surface. Therefore it is necessary to design and fabricate a setup for measurement of average resistivity of the material across the entire surface. The schematic diagram of the setup is shown in Figure 4. The setup consists of two right angled copper plates for holding the specimen and for passing current through the specimen. One copper plate is fixed in the wooden base while the other had a sliding arrangement for fixing the specimen tightly. A voltmeter is connected to the two terminals (copper plates) and DC is passed through the terminal. The amount of current passed is measured using an ammeter. The actual setup is shown in Figure 5.

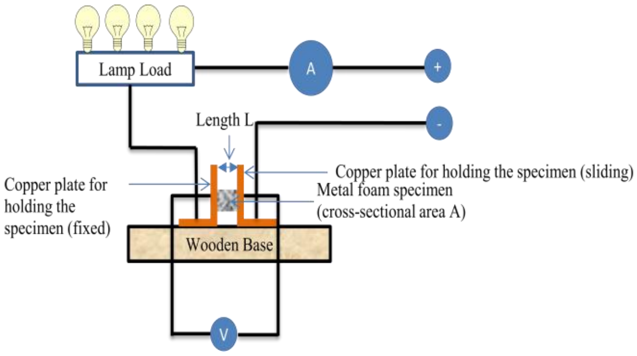


Figure 4: Schematic diagram of the setup for measurement of resistivity

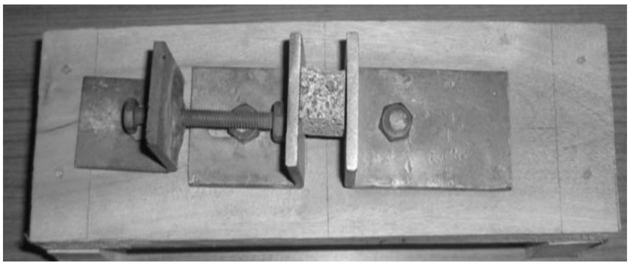


Figure 5: The setup for measurement of resistivity

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

Specimens of different relative densities are prepared for measuring resistivity of aluminium foam. Each specimen is cut by wire cut EDM of dimensions 20x20x30 mm. The developed setup is used for measurement of electrical resistivity. The specimens are fixed between the copper plates and current is made to pass. The voltages are made to vary by varying the load in the circuit using different lamp load. The resistivity of the material is calculated using equation (1). The electrical conductivity is calculated using equation (2).

The measured value of the electrical conductivity is plotted against relative density of the specimen, as tabulated in Table 1. The experimental results indicated a clear dependency of the electrical conductivity of the material with its relative density. The electrical conductivity increases with increase in relative density. As the relative density of aluminium foam increases, the cross-section available for conduction increases. Thus the tortuosity of the current path decreases and the conductivity is increased. The electrical conductivity of the aluminium alloy used for synthesis of the aluminium foam is measured to be 31 X 10^{-6} $(\Omega.m)^{-1}$.

Untreated TiH2		TiH2 at 450C 60 mins		TiH2 at 480C 60 mins		TiH2 at 510C 60 mins	
Relative Density	Electrical ConductivityX 10E-6 (ohm.m)-1.	Relative Density	Electrical Conductivity X 10E-6 (ohm.m)-1.	Relative Density	Electrical Conductivity X 10E-6 (ohm.m)-1.	Relative Density	Electrical Conductivity X 10E-6 (ohm.m)-1.
0.1545	2.308119	0.1162	1.801158	0.1015	1.625041	0.1272	1.801167
0.1648	2.4352123	0.119	1.608318	0.1176	1.962056	0.1225	1.709774
0.1711	2.6555702	0.143	2.076246	0.1265	2.154089	0.147	2.199174
0.1765	2.8970906	0.1624	2.476547	0.132	2.274691	0.153	2.323599
0.1976	3.4754451	0.1832	2.929733	0.15	2.679073	0.179	2.886017
0.1988	3.5169845	0.19	3.080976	0.158	2.863313	0.188	3.088158
0.2037	3.6604566	0.2047	3.418342	0.187	3.552589	0.2005	3.370025
0.2148	3.983438	0.21	3.541583	0.198	3.822251	0.205	3.480022
0.2222	4.0428923	0.2125	3.60073	0.2015	3.908992	0.211	3.621399
0.2296	4.167289	0.22	3.778585	0.215	4.247261	0.22	3.836233

Table 1: Electrical conductivity of aluminium foam produced by using different techniques.

5. RELATIONSHIP BETWEEN ELECTRICAL CONDUCTIVITY AND RELATIVE DENSITY

Relationship between electrical conductivity and relative density for metallic foam materials has been proposed by various researchers. All of them proposed a relationship between the normalized electrical conductivity, $\lambda_{co}/\lambda_{cs}$, defined as the quotient between the electrical conductivity of the foam (λ_{co}) and the electrical conductivity of the bulk material of which the foam is constituted (λ_{cs}), and the relative density or the porosity of the foam. Some of these proposed relationships are described next.

Kim et al. (2005) [7] proposed that the normalised electrical conductivity of aluminium closed-cell foams produced with the help of a foaming agent follows a power law relationship with the relative density.

$$\frac{\lambda_{co}}{\lambda_{cs}} = (RD)^{\frac{3}{2}} \qquad (3)$$

The equation (3) is in agreement with the general relation by Ashby et al. [9]:

$$\frac{\lambda_{co}}{\lambda_{cs}} = \alpha(RD) + (1-\alpha)(RD)^{\frac{3}{2}} \qquad (4)$$

For closed-cell foams the value of α is very small, and assuming $\alpha \rightarrow 0$, Eq (4) becomes Eq. (3).

Ashby et al. [2] later proposed another relationship considering the effects of the nodes.

$$\frac{\lambda_{co}}{\lambda_{cs}} = \frac{1}{3}(RD) + \frac{2}{3}(RD)^{\frac{3}{2}} \qquad (5)$$

Feng et al. [6] proposed a relationship specific to closed cell aluminium foam produced by powder metallurgy route.

$$\frac{\lambda_{co}}{\lambda_{cs}} = \frac{2K(RD)}{2K+\{1-(RD)\}} \quad (6)$$

In equation (6), K is a constant determined by the cell structure, when the shape of the cell is spherical and K = 0.343.

Cuevas et al. [8] studied various relationship and presented a more general relationship.

$$\frac{\lambda_{co}}{\lambda_{cs}} = [1-(1-RD)^s]^t \quad (7)$$

The values of the indexes t and s, various depending on the type of aluminium foam. The values of t and s for closed cell aluminium foam are 1.429 and 0.834 respectively.

All the relationships discussed above are purely based on experimental results and have no theoretical basis. As such these relationships are also expected to have implicitly taken in to consideration the cell variation, imperfections and defects.

The relationships of normalised electrical conductivity with relative density presented through equation (3) to (7) are plotted in Figure 6(a). The experimentally obtained results using the normalised electrical conductivity of the Al-SiC foam made by 'untreated' TiH_2 (Eq. 8) is also plotted in the same figure, for comparison. The results are usually in agreement with proposed equations, but these are quite different from each other. The experimental results are found closer to the relationship defined by equation (3) and (5).

Similarly, Results obtained from Al-SiC foam made by TiH_2 pre-treated at various temperatures, shown in Table 1, are also plotted in fig. 6(b)

Given the diversity of equations and the great variety of reported data by different authors, it would be very interesting to have a specific equation which gives a description of the behaviour of this type of closed cell aluminium foam. Therefore an empirical equation is used to fit the experimental data in order to describe the relationship of normalised electrical conductivity with relative density specific to the aluminium foam developed in different techniques. power law equations adequately fit the experimental data.

For Untreated TiH_2:

$$\frac{\lambda_{co}}{\lambda_{cs}} = (RD)^{1.4} \quad (8)$$

If TiH_2 is pre-treated at 450ºC for 60 minutes:

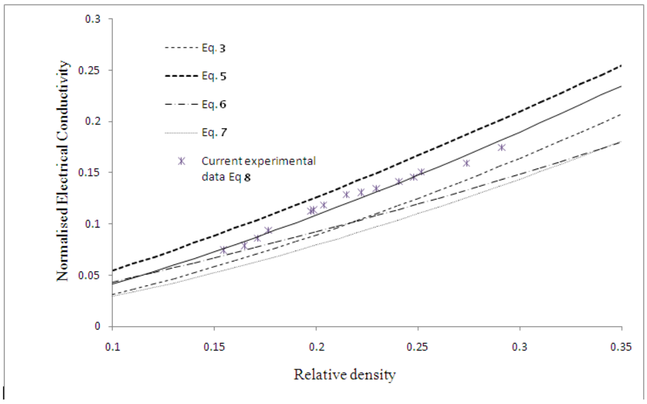
$$\frac{\lambda_{co}}{\lambda_{cs}} = (RD)^{1.39} \quad (9)$$

If TiH_2 is pre-treated at 480ºC for 60 minutes:

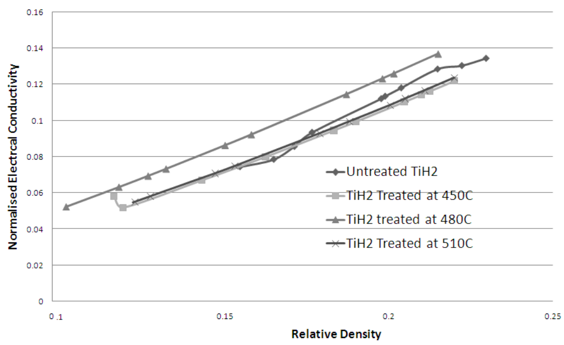
$$\frac{\lambda_{co}}{\lambda_{cs}} = 0.98\,(RD)^{1.28} \quad (10)$$

If TiH_2 is pre-treated at 510ºC for 60 minutes:

$$\frac{\lambda_{co}}{\lambda_{cs}} = (RD)^{1.38} \quad (11)$$



(a)



(b)

Figure 6: (a) Normalised electrical conductivity of aluminium foam of different relative density

(b) Normalised electrical conductivity w r t pre heat temperatue of TiH_2

6. CONCLUSIONS

The electrical conductivities of aluminium alloy foams made by different pre-treatment temperature of foaming agent, and with different relative densities are investigated. It is shown that the relative density has a significant effect on the electrical conductivity of this material. The measured values of electrical conductivity are compared with several normalised electrical conductivity and relative density relationships proposed by various researchers. There is a good congruence between the experimental values and the relationships proposed by various researchers. A proposed power law function can be successfully applied (equation 8-11) to describe the dependence of electrical conductivity of closed cell aluminium alloy foams on the relative density.

It is also shown that, if the primary foaming agent, TiH_2, is pre treated at different temperature, the electrical conductivity changes abruptly. But if TiH_2 is pre treated at 480ºC for 60 minutes, before using it as a foaming agent, the best result can be obtained. The reason may lie in the homogeneity of pores in the produced foam.

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