A NONDESTRUCTIVE ELECTRICAL METHOD FOR EVALUATING MECHANICAL PROPERTIES OF AL-FOAM

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Abstract: Al alloy foams of composition Al-3wt.%Si-2%Cu-2%Mg was produced using powder metallurgical method. Mechanical properties of foams having different density were measured using uni-axial compression test and the measured properties such as elastic modulus and strength were compared with those of other existing commercial foams. The newly produced (Al-3%Si-2%Cu-2%Mg alloy) foams showed comparable strength and elastic modulus with other existing commercial foams. Electrical conductivity of the foams was measured. Mathematical relations were established between electrical conductivity and compressive properties of Al-foams with an aim to propose a nondestructive method for evaluation of mechanical properties of foams based on electrical conductivity. Curves obtained from derived relations fit very well with the experimental result.

Keywords: Aluminum foam, Powder metallurgy, Electrical conductivity

Introduction: Metal foam is one of the latest invention in the field of engineering materials, however due to its various attractive properties such as super light weight, good impact absorption, high strength, high stiffness and outstanding damping capability, it has emerged as one of the most appropriate solution for many structural and functional use in such diverse fields as automotive, transport, ships and military applications. Industrial production of foamed metals is now established for application like sandwich structures [1], panels [2], crash absorbers [3], heat exchangers [4] and so on. Since industrial exploitation of a new material is always determined by the possibility to reproduce its mechanical and physical properties, these days many of the researchers in the field of metal foam are working with an aim to propose quality control methods for the development of reliable foam products and in this attempt, many of them are considering various nondestructive testing and inspecting techniques for both during production and post production evaluation of mechanical properties.

H.P. Degischer and A. Kottar [5] studied the applicability of various nondestructive testing methods for characterizing Al-foams. Their work showed that eddy current and conventional ultrasonic testing are not fruitful for characterizing Al-foams, however the x-ray computed tomography (CT) can reveal the heterogeneity of mass distribution and enables a detailed structural analysis of the foam. D. Connelis et al. [6] performed study on closed cell foams using desktop x-ray micro-tomography, while F. Grote and A. Schievenbusch [7] used micro tomography for nondestructive imaging of open cell (AlNg1SiCu) foam where they studied the porosity, average cell size, distribution in cell size and arrangement of cells using both the conventionally scanned and tomographic cross-sections.

In this paper we have proposed a nondestructive method based on measuring the electrical conductivity for evaluating mechanical properties of Al-foams. The Al-Si-Cu-Mg alloy foams were produced using powder metallurgical method. Compressive mechanical properties of foams were experimentally measured. Mathematical relationship has been established between electrical conductivity and mechanical properties bridging the existing relationship of these properties with foam density. The derived equations have been modified so that the applicability of these equations can be extended to real foams. Mechanical properties of the foams obtained from experiment were plotted against electrical conductivity along with the plot of proposed equations. It was found that the proposed equations fit very well with the experimental result.

Experiment: The aluminium alloy powder of particle size 150 to 900 μm were produced by melting the elements in required proportion (Al-3wt.%Si-2%Cu-2%Mg) and using centrifugal atomization. 99% (weight) of Al-alloy powder and 1% TiH_2 were mixed in a rotating V-mixer with a velocity of 300 rpm for 30 minutes. The mixture was then consolidated by cold compaction at a pressure of 4 MPa and hot extruded into a square bar of cross section 120 x 5 mm at a temperature 430^{O}C with an extrusion ratio of 20 : 1 in a uni-axial extrusion machine.

Foaming of the extruded rods was performed by keeping them inside a closed mould and heating them in a pre-heated furnace. The pre-set furnace temperature was 700^{O}C and the foaming time was 15 minute. The foam density was controlled by varying the amount of precursor material in the mould. Foaming process was terminated by simply removing the moulds from the furnace. Skin was removed from these foams and specimens were cut to the appropriate dimension (35 x 35 x 40 mm for both compression test and conductivity measurement) using a band saw with a guide to ensure that the cuts were made accurately and straight. Such a dimension was chosen so that the edge length of compression test specimens in all cases be at least seven times the cell size. This is required to avoid edge effects which may reduce the measured values of Young's modulus and compressive strength [8].

Compression Test: The uni-axial compression test was performed on the specimens using an MTS 830 machine. Fig. 1 shows a compression test specimen. The load and displacement was monitored by a computer equipped with a data acquisition system. All stress and strain used here are nominal stress and nominal strain deduced from the recorded load-displacement data. Stress was taken as the ratio of load to the initial loading area while strain was taken as the ratio of displacement increment to the initial height of the specimen. In this work, load was applied at a constant displacement speed of 0.02 mm/s and the specimens were compressed between parallel steel platens to ensure perfect axial loading. Compression was stopped when 85 % strain was reached.

Electrical Conductivity: Electrical conductivity of the foams was measured by using two-probe resistivity measurement method. The circuit diagram of the apparatus used in this method is shown in Fig. 2. In this method, a constant current is supplied across the two ends of a parallelepipe-shaped specimen located between the i-i terminals and the potential difference is measured using the two measuring probes at x and x′ as shown in Fig 2. The electrical conductivity is then computed using the equations:

$$\rho = (R_S A_C / L)(V_P / V_S)$$

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

Where ρ = electrical resistivity, R_S = resistance of standard resistor, A_C = cross sectional area of the specimen, L = length of specimen i.e. the distance between two measuring probes, V_s is the potential difference across the standard resistor while V_p is the potential difference across the probes and λ is the electrical conductivity of the specimen.

Four-probe resistivity measurement method can also be used in this case. However in four-probe method four

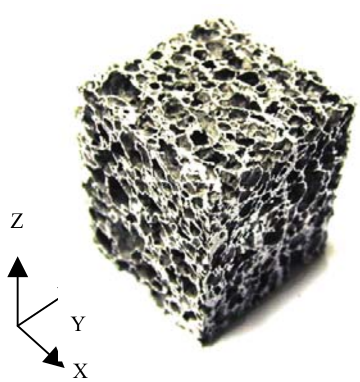


Fig. 1 Compression test specimen of Al-Si-Cu-Mg alloy foam, $\rho^*/\rho_s = 0.23$

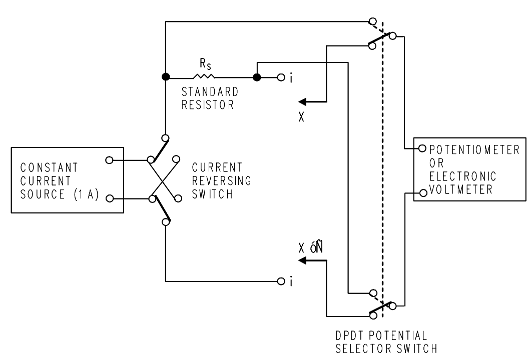


Fig. 2 Circuit diagram of the apparatus used in two-probe resistivity measurement method

equi-spaced probes placed in a line are to be kept in contact with the specimen surface, which is not always possible in case of Al-foam because of its cellular structure. So we used the two probe resistivity measurement method instead of the four-probe method.

In the experiment a constant current supplier and the voltage measurement system accommodated by the probe station and Burster 2304 resistomat were utilized for the measurement. The distance between the two probes was 40 mm and the supplied current was 1 Amp. The polarity of input current was altered forward and backward during the measurement to reduce the thermoelectric effect and average of these readings was taken as conductivity of the specimen.

Result and Discussion: Fig. 3 shows the ideal stress-strain curve of Al-foams while Fig. 4 shows the experimental stress-strain curves of Al-Si-Cu-Mg alloy foams up to 80 % strain. All the curves display an initial nearly linear region where partially reversible cell wall bending occurs, followed by a plastic plateau stress at which successive bands of cells collapse, buckle, yield and fracture. Beyond the deformation plateau, densification takes place and the stress rises sharply as complete compaction commences. The curves are smooth in the elastic deformation range however throughout the plastic range they exhibit stress oscillations. These stress oscillations are typically associated with brittle failure of cell walls [9].

For most of the foams, the stress after reaching an initial peak drops significantly. This drop being the difference of upper and lower yield stress is an effect of the collapse of one (weakest) pore layer [10] i.e. the band of pores corresponding to the lowest local density or highest cluster defects. The unloading portions of the curves in Fig. 4 are omitted for the sake of clarity. The unloading curves showed a much higher slope (i.e. elastic modulus) than the initial loading curves. This indicates that local yielding occurs almost immediately on loading [11-13].

The elastic modulus and plastic plateau stress of Al-Si-Cu-Mg alloy foams normalized by those of the precursor material (E_s=73 GPa and σ_{ys}=151 MPa) are compared with the normalized elastic modulus and plateau stress of various existing commercial foams in Figs. 5 and 6. Curves of Alporas, ERG, Alcan, Mepura and Fraunhofer foams in Figs. 5 and 6 were regenerated from a previous paper of Andrews, Sanders and Gibson [8]. Figs. 5 and 6 show that the newly produced Al-3wt.%Si-2%Cu-2%Mg alloy foam possesses comparable elastic modulus and plateau stress with other existing commercial foams indicating that Al-Si-Cu-Mg alloy foam has high potential for industrial application.

Electrical versus mechanical properties: Figs. 3 and 4 reveal a three stage compressive behavior namely an initial elastic regime, a plastic plateau regime and a densification regime in the stress strain curve.

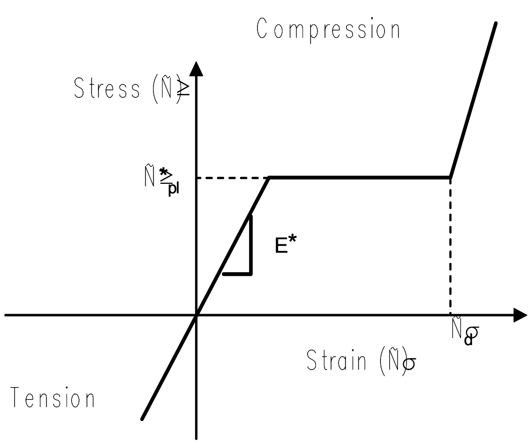


Fig. 3 Ideal stress-strain curve of Al-alloy foam

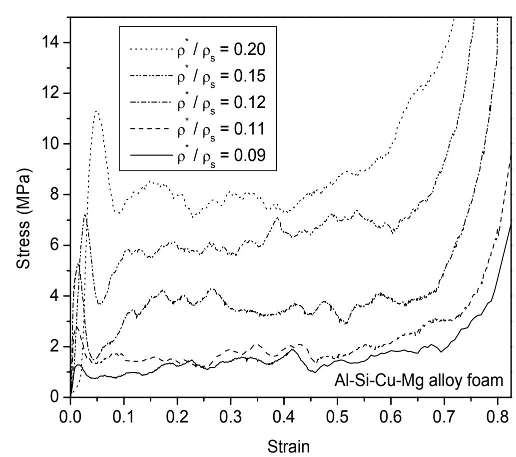
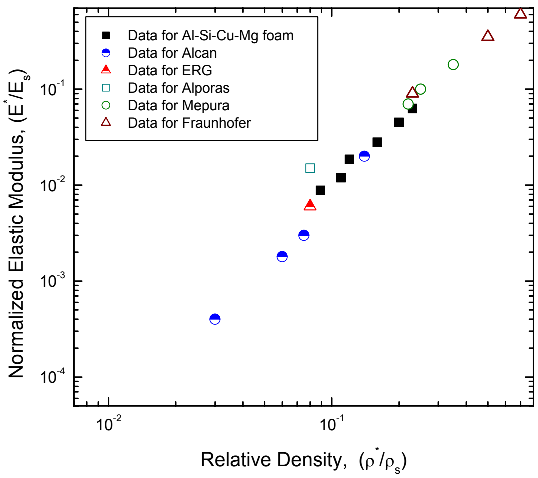


Fig. 4 Stress-strain curve of Al-Si-Cu-Mg alloy foams up to a strain 80 %



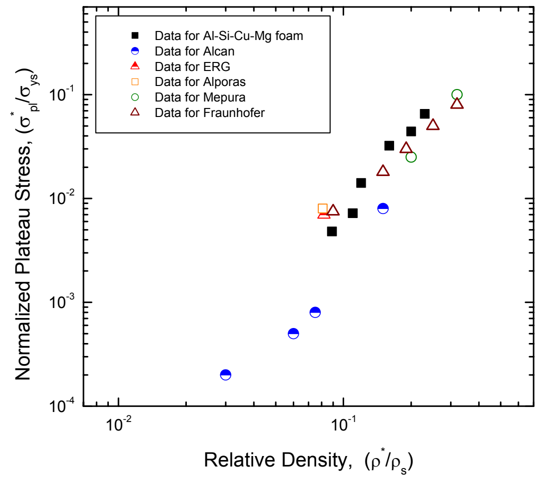
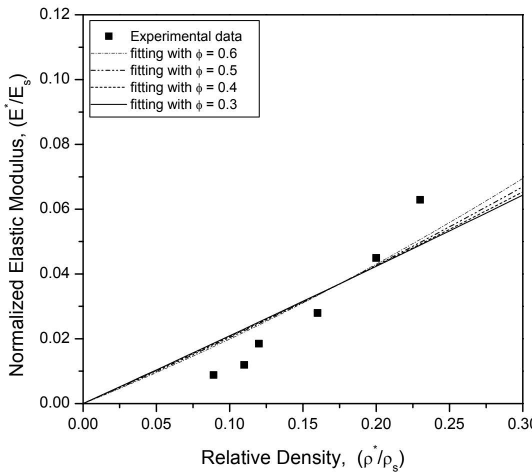


Fig. 5 Normalized elastic modulus (E^*/E_s) versus relative density (ρ^*/ρ_s) graph of Al-foams [from ref. 8]

Fig. 6 Normalized plateau stress ($\sigma_{pl}^*/\sigma_{ys}$) versus Relative density (ρ^*/ρ_s) graph of Al-foams [from ref. 8]



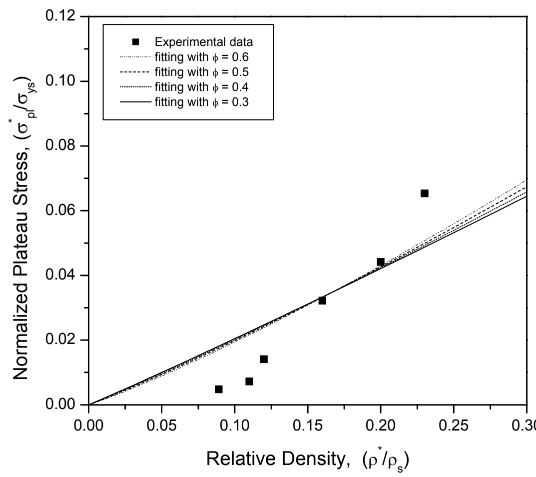


Fig. 7 Normalized elastic modulus (E^*/E_s) versus relative density (ρ^*/ρ_s) graph of Al-Si-Cu-Mg alloy foams

Fig. 8 Normalized plateau stress ($\sigma_{pl}^*/\sigma_{ys}$) versus relative density (ρ^*/ρ_s) graph of Al-Si-Cu- Mg alloy foams

Ashby et al. [14] and A. E. Simon et al. [15] told that the deformation of metal foam is governed by two mechanisms: (1) Bending of cell wall which has a quadratic dependency on the relative density and (2) Stretching of cell faces which is linearly dependent on relative density. Thus for compressive elastic modulus, plateau stress and densification strain Ashby et al. established a set of scaling laws [16, 14] as:

$$\frac{E^*}{E_s} = C_1\phi^2\left(\frac{\rho^*}{\rho_s}\right)^2 + C_1(1-\phi)\left(\frac{\rho^*}{\rho_s}\right) \qquad (1)$$

$$\frac{\sigma_{pl}^*}{\sigma_{ys}} = C_2\phi^{3/2}\left(\frac{\rho^*}{\rho_s}\right)^{3/2} + C_2(1-\phi)\left(\frac{\rho^*}{\rho_s}\right) \qquad (2)$$

$$\varepsilon_d = C_3\left[1 - 1.4\left(\frac{\rho^*}{\rho_s}\right) + 0.4\left(\frac{\rho^*}{\rho_s}\right)^3\right] \quad (3)$$

Where E_s, σ_{ys} and ρ_s are the elastic modulus, yield strength and mass density of solid cell wall of the foam material, ϕ is the volume fraction of solid contained in the cell edges while E^*, σ_{pl}^* and ρ^* are the elastic modulus, plateau stress and mass density of foam. Eqns.1-3 are expected to work well only for low density foams i.e. when value of ρ^*/ρ_s is less than 0.2 [17, 8]. However, in reality these equations (Eqns.1-3) over predict foam properties even when value of ρ^*/ρ_s is less than 0.2. We fitted Eqns.1 and 2 for ϕ = 0.3 to 0.6 using the experimental results from Fig. 4, and obtained the results as shown in Figs. 7 and 8. The value of ρ_s for Al-Si-Cu-Mg alloy was 2.79 gm/cm^3. It is evident from Figs. 7 and 8 that Eqns. 1 and 2 do not fit well with our experimental data for any value of ϕ. The probable reason is that the scaling laws (Eqns.1 and 2) are only ideal representations. In real foams there are cell wall curvatures, corrugations and defects due to which foams (specially closed cell foams) are likely to show a lower elastic modulus and strength than predicted by Eqns.1 and 2. Therefore to extend the applicability of these equations to real foams a third term should be added so that effects of curvature, corrugation and defects can be accounted. For simplicity, we assumed this third term to be $f(\rho^*/\rho_s)$ for Eqn. (1) and $g(\rho^*/\rho_s)$ for Eqn. (2) such that:

$$f\left(\frac{\rho^*}{\rho_s}\right) = a\left(\frac{\rho^*}{\rho_s}\right)\left(b - \frac{\rho^*}{\rho_s}\right) \quad (4)$$

$$g\left(\frac{\rho^*}{\rho_s}\right) = c\left(\frac{\rho^*}{\rho_s}\right)\left(d - \sqrt{\frac{\rho^*}{\rho_s}}\right) \quad (5)$$

Where a, b, c and d are constants. Besides, the relative density in Eqns. 1 to 3 is just average value which can not account the local heterogeneity of foam structure. Hence, in contrast to the relative density, if the scaling laws are expressed in terms of some other parameter which is dependent on the relative density of foam as well as the local in-homogeneity and defects, then it can be expected that properties of foams will be better represented.

Electrical conductivity is one such parameter which depends not only on the relative density but also on the defects in foam such as corrugations, broken cell walls and micro cracks. It can be easily understood that as the relative density of Al-foam increases, the cross section available for conduction increases. Thus the tortousity of the current path decreases and the conductivity is increased. Ashby et al. showed that the relationship between electrical conductivity and relative density of Al-alloy foam is given by:

$$\frac{\lambda}{\lambda_s} = \alpha\left(\frac{\rho^*}{\rho_s}\right) + (1-\alpha)\left(\frac{\rho^*}{\rho_s}\right)^{3/2}$$

Where λ= electrical conductivity of foam and λ_s= conductivity of solid material from which foam is made (in case of Al-Si-Cu-Mg alloy, $\lambda_s = 23.5\times10^6\ (\Omega m)^{-1}$). For closed cell foams the value of α is negligible. Then the equation becomes:

$$\frac{\lambda}{\lambda_s} = \left(\frac{\rho^*}{\rho_s}\right)^{3/2} \quad (6)$$

Yi Feng et al. [18] also showed that the relationship between electrical conductivity and relative density of Al-alloy foams is given by Eqn. 6. The electrical conductivity versus relative density graph of Al-Si-Cu-Mg alloy foams shown in Fig. 9 is also consistent with the above equation. Thus incorporating the relations from Eqns. 4,

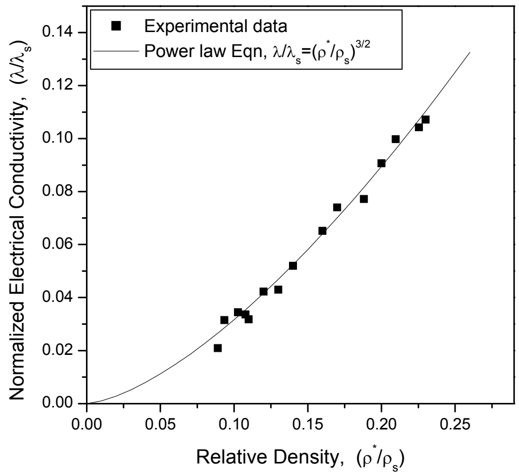


Fig. 9 Electrical conductivity versus relative density curve of Al-Si-Cu-Mg alloy foams.

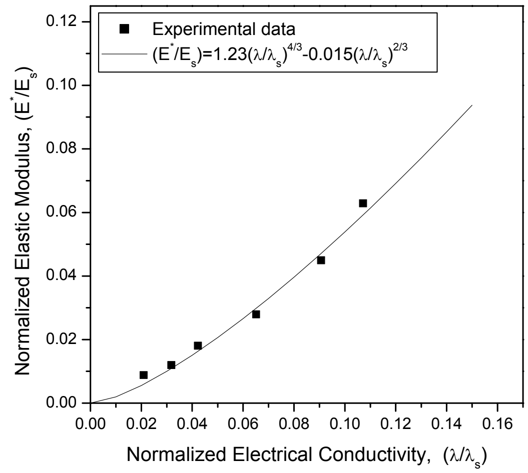


Fig. 10 Normalized elastic modulus versus normalized electrical conductivity curve

5 and 6 into Eqns.1, 2 and 3, the compressive properties can be rewritten in terms of λ/λ_s as:

$$\frac{E^*}{E_s} = \left(C_1\phi^2 - a\right)\left(\frac{\lambda}{\lambda_s}\right)^{4/3} + \left(C_1(1-\phi) + ab\right)\left(\frac{\lambda}{\lambda_s}\right)^{2/3}$$

$$\frac{\sigma_{pl}^*}{\sigma_{ys}} = \left(C_2\phi^{3/2} - c\right)\left(\frac{\lambda}{\lambda_s}\right) + \left(C_2(1-\phi) + cd\right)\left(\frac{\lambda}{\lambda_s}\right)^{2/3}$$

or

$$\frac{E^*}{E_s} = A\left(\frac{\lambda}{\lambda_s}\right)^{4/3} + B\left(\frac{\lambda}{\lambda_s}\right)^{2/3} \tag{7}$$

$$\frac{\sigma_{pl}^*}{\sigma_{ys}} = C\left(\frac{\lambda}{\lambda_s}\right) + D\left(\frac{\lambda}{\lambda_s}\right)^{2/3} \tag{8}$$

$$\varepsilon_d = C_3\left[1 - 1.4\left(\frac{\lambda}{\lambda_s}\right)^{2/3} + 0.4\left(\frac{\lambda}{\lambda_s}\right)^2\right] \tag{9}$$

Where A, B, C and D are fitting constants. Thus mechanical properties of Al-foam can be more easily obtained measuring the electrical conductivity and using Eqns 7, 8 and 9. The least square curve fitting of experimental data for Al-Si-Cu-Mg alloy foams by Eqns. 7 to 9 resulted in A=1.23, B=-0.015, C=1.27, D=-0.33 and C_3=0.9.

Substituting these values into equations 7, 8 and 9 we obtain the normalized elastic modulus, plastic plateau stress and densification strain curves as shown in Figs. 10, 11 and 12. During experiment the elastic modulus was measured from unloading curves at 1 % strain and plateau stress was taken as the average stress in the range 10 % to 50 % strain. The densification strain was taken as the strain at the point of intersection between the horizontal plateau stress line and the backward extended densification line.

Figs. 10, 11 and 12 reveal an excellent agreement between experimental results and the values predicted by Eqns.7 to 9 indicating a high potential for applicability of electrical conductivity in evaluating the mechanical properties of Al-foam. Thus the proposed nondestructive method for evaluating mechanical properties of Al-foams using electrical conductivity seems to be very promising and effective.

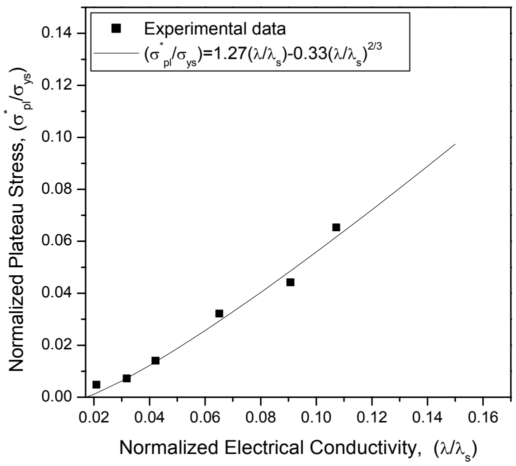


Fig. 11 Normalized plastic plateau stress versus normalized electrical conductivity curve

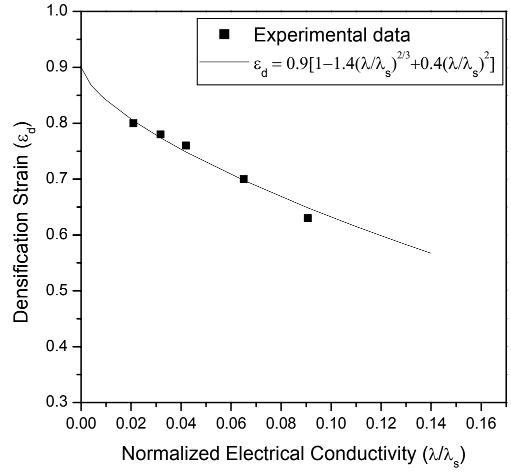


Fig. 12 Densification strain versus normalized electrical conductivity curve

Conclusions: Compressive mechanical properties of Al-3wt.%Si-2%Cu-2%Mg foams produced by powder metallurgical method have been studied along with their electrical conductivity in the range of relative density 0.09 to 0.25. The newly produced Al-3wt.%Si-2%Cu-2%Mg alloy foams showed comparable elastic modulus and plateau stress with other existing commercial foams indicating that Al-Si-Cu-Mg alloy foams have a high potential for engineering applications. The experimentally measured electrical conductivity and the relative density followed the power law equation given by Gibson and Ashby. A nondestructive method based on electrical conductivity measurement has been proposed for evaluating mechanical properties of foams. The proposed method has been proved to be very effective in case of Al-Si-Cu-Mg alloy foams and is expected to work well for other Al-foams too.

Acknowledgement: This research was supported by the Korea Science and Engineering Foundation (KOSEF) by grant No. R01-2002-000-00093-0(2002) from its basic research program.

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