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COMPRESSIVE MECHANICAL PROPERTIES OF CLOSED CELL Al-Si-Cu-Mg ALLOY FOAMS

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ABSTRACT

Closed cell Al-Si-Cu-Mg alloy foams of two different compositions were produced using the powder metallurgy method. Uni-axial compression test was performed on foams with different composition and different density. The electrical conductivity of the foams was also measured. Compressive stress-strain curve of the foams were compared with those of existing commercial foams. Both of alloy 544 (Al-5%Si-4%Cu-4%Mg alloy) and alloy 322 (Al-3%Si-2%Cu-2%Mg alloy) foams showed comparable strength and elastic modulus with the existing commercial foams. It is already well established that mechanical properties of Al-foam depends on its relative density while the power law equation for electrical conductivity of metal foam given by Ashby suggests that electrical conductivity of aluminium foam is a function of its relative density. Since the mechanical properties of Al-foam and its electrical conductivity both are function of relative density, so they can be expressed as a function of each other. In this paper mathematical relations have been derived to establish direct link between electrical conductivity and compressive properties of Al-Si-Cu-Mg alloy foams.

Keywords: Aluminum foam, Powder metallurgy, Plateau stress, Electrical conductivity.

1. INTRODUCTION

Metal foam shows a combination of advantages of a metal such as strength, toughness and conductivity, and the structural advantages of a foam such as ultra light weight with stiffness and adjustable cell structure. Due to the combination of these attractive properties, metal foam is emerging as one of the most appropriate solution for structural and functional design of engineering materials in such diverse fields as automotive, railway, ship and aerospace industries.

Designing of metal foam for these applications demands complete characterization of its mechanical properties. During the last two decades extensive experimental and theoretical work has been performed on the mechanical properties specially on the compressive mechanical properties of Al-foam. E. Andrews, W. Sanders and L. J. Gibson studied compressive and tensile modulus and strength of several present generation commercial Al-foams and compared them with models of cellular solids [1]. T. G. Nieh, K. Higashi and J. Wadsworth studied the compressive properties of open cell 6101 ERG Al-foam based on the cell morphology [2]. D. Ruan et al. studied compressive behavior of Cymat closed cell foams at low and medium strain rates [3]. A. E. Markaki and T. W. Clyne investigated the compressive and tensile properties of Al-5Ca, Al-12Si-0.6Mg and Al-1Mg-0.6Si alloy foams based on the cell wall microstructure [4]. Yi Feng et al. investigated the compressive properties of T6 aged 201 Al-alloy foams depending on aging heat treatment [5], while E. Koza et al. studied the compressive strength of Al-Si10 foam considering the effect of density, structural homogeneity and sample size [6]. Most of these work revealed a three stage compressive behavior namely an initial elastic regime, a plateau regime and a densification regime in the stress strain curve of Al-foams. The compressive elastic modulus, plateau stress and densification strain as given in literature [7,8] are:

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

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

$$\varepsilon_d = 1-\frac{1}{4}\left(\frac{\rho^*}{\rho_s}\right) \quad (3)$$

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.

Equations 1-3 indicate that the most important parameter controlling mechanical properties of Al-foam is its relative density. But a major problem in metallic foam production is ensuring homogeneous density of the foam. Although the overall density of foam can be easily controlled during the production, the elimination of local inhomogeneity is almost impossible because of the non uniform heating rate and temperature distribution in the foam volume, pore shape anisotropy and structural defects [6]. For this reason, to estimate the mechanical properties of produced Al-foam, monitoring of local density is essential. However, in case of continuous production process or during the production of complicated shape components, measurement of local density involves technical difficulties. Therefore, some non destructive techniques are needed to estimate the mechanical properties of Al-foam.

Measurement of electrical conductivity can be a suitable alternate technique in this case. 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.

Power law relation given by Ashby and findings of Yi Feng et al. [9] are also consistent with this concept. Yi Feng et al. showed that the relationship between electrical conductivity and relative density of Al-alloy foam is in agreement with the percolation theory and can be expressed using power law equation given by

$$\frac{\lambda}{\lambda_s} = \left(\frac{\rho^*}{\rho_s}\right)^{3/2} \quad (4)$$

Incorporating this relation into equations 1-3 the compressive properties can be rewritten as:

$$\frac{E^*}{E_s} = C_1\phi^2\left(\frac{\lambda}{\lambda_s}\right)^{4/3} + C_1(1-\phi)\left(\frac{\lambda}{\lambda_s}\right)^{2/3} \quad (5)$$

$$\frac{\sigma_{pl}^*}{\sigma_{ys}} = C_2\phi^{3/2}\left(\frac{\lambda}{\lambda_s}\right) + C_2(1-\phi)\left(\frac{\lambda}{\lambda_s}\right)^{2/3} \quad (6)$$

$$\varepsilon_d = 1 - \frac{1}{4}\cdot\left(\frac{\lambda}{\lambda_s}\right)^{2/3} \quad (7)$$

Thus mechanical properties of Al-foam can be more easily obtained measuring the electrical conductivity and using equations 5-7.

In this paper Al-alloy foams of different compositions and different densities were produced using powder metallurgy method. Electrical conductivity of the foams was measured using two-probe resistivity method, and mechanical properties were evaluated from electrical conductivity of alloy 322 foams. Compressive mechanical properties of alloy 544 and 322 foams were measured using the uni-axial compression test and the compressive behaviors were investigated. Properties obtained from experiment were compared with those of existing commercial foams.

2. EXPERIMENT

2.1 Material and Specimen

The aluminium alloy powder of particle size 150 to 900 µm were produced by melting the elements with two different compositions as shown in table1 and using centrifugal atomization.

99% (weight) Al-Si-Cu-Mg alloy powder and 1% TiH_2 were mixed in a rotating V-mixer with a velocity of 300 rpm for 30 minutes. The mixtures were then consolidated by cold compaction at a pressure of 4 MPa and hot extruded into a square bar of cross section 12 x 12 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 removing the samples from the furnace.

Skin was removed from these foams and specimens were cut to the appropriate dimension (35 x 35 x 40 mm) 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

Table 1: Composition of 322 and 544 alloy powders

Composition (wt.%)	Si (%)	Cu (%)	Mg (%)	Al (%)
Alloy 544	5	4	4	87
Alloy 322	3	2	2	93

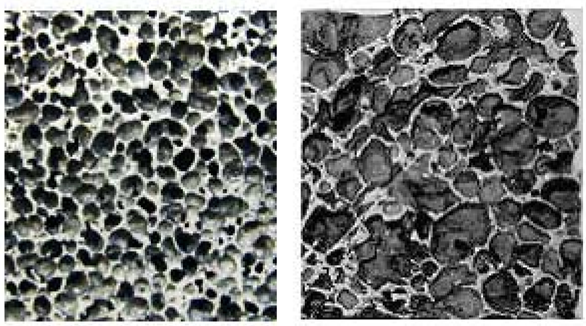

Fig 1. Cellular structure of produced alloy 322 foam (a) $\rho/\rho_s = 0.30$, (b) $\rho/\rho_s = 0.09$.

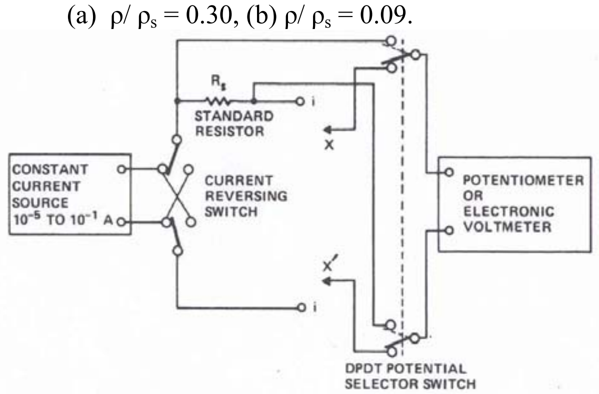

Fig 2. Schematic diagram of the apparatus used in two-probe resistivity measurement method.

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 [1]. Fig.1 shows the cellular structure of two different density alloy 322 foams.

2.2 Electrical Conductivity

Electrical conductivity of the foams was measured by using two-probe resistivity measurement method. A schematic 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 near the center of a surface using the two measuring probes at x and $x^{/}$ as shown in Fig 2. The electrical conductivity is then computed using the equations

$$\rho = (R_S wd/D)(V_P/V_S) \quad (8)$$

$$\lambda = \frac{1}{\rho} \quad (9)$$

Where ρ = electrical resistivity, R_S = resistance of standard resistor, D = distance between the two probes, w and d are the width and thickness of specimen, 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 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 preferred the two probe resistivity measurement method to 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 20 mm and the supplied current was 1 Amp. Total number of specimen for measurement of electrical conductivity was 30. For each of the specimens, conductivity was measured at 20 to 30 different locations and an average of these readings was taken as conductivity of the specimen. The polarity of input current was altered forward and backward during the measurement to reduce the thermoelectric effect.

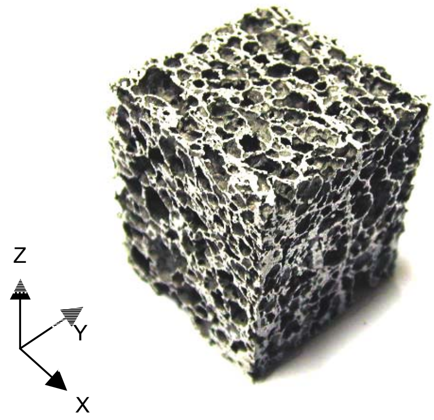

Fig 3. Compression test specimen of alloy 322 foam, $\rho/\rho_s = 0.23$.

2.3 Compression Test

The uni-axial compression test was performed on the specimens using an MTS 830 machine. Fig 3 shows a compression test specimen. The load and displacement was monitored by a computer equipped with a data acquisition system.

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.

3. RESULT AND DISCUSSION

The electrical conductivity versus relative density graphs of alloy 322 and 544 foams are shown in Fig 4. The Figure shows that the power law equation 4 well describes the conductivity of Al-Si-Cu-Mg alloy foams. Using the least square non linear curve fitting on experimental data we obtained the value of exponent, n = 1.49 which is very close to the value 1.50 given by Gibson and Ashby. The electrical conductivity of alloy 322 and 544 precursors before foaming were almost equal, hence the same power law equation is used for both of alloy 322 and 544 foams in Fig 4. Experimental data showed some scatter which is due to the typical morphological defects including broken cell walls, missing cells, inclusions, cell wall curvature and corrugations [9].

Fig 4 reveals that the experimental results in case of very low density foams are much lower than those predicted by the power law equation. This is because the low density foams being highly porous contain a large number of missing cells and broken cell walls which reduce their electrical conductivity.

The stress-strain curves of 544 and 322 alloy foams up to 80 % strain are shown in Figs 5 and 6 respectively. All the curves display an initial nearly linear region where partially reversible cell wall bending occurs,

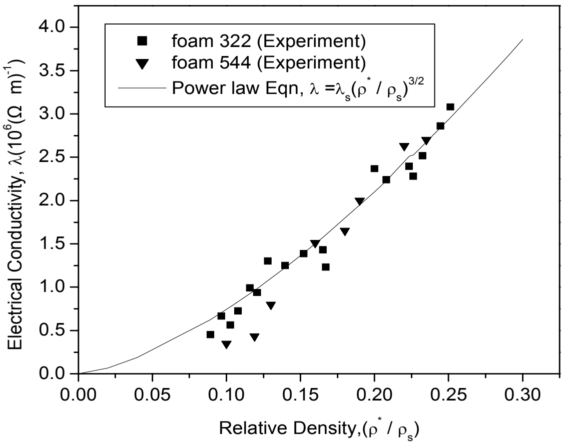

Fig 4. Electrical conductivity versus relative density curve of 544 and 322 alloy foams.

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. In case of alloy 322 foam, more experimental data were available than those shown in Fig 6. However some of the experimental curves are omitted for the sake of clarity of graph and for keeping the scale within same range as in Fig 5.

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 [4] and disintegration of some cells of the specimen near its peripheral region.

For most of the foams, the stress after reaching an initial peak drops significantly. This drop being the difference of upper and lower yield strength is an effect of the collapse of one (weakest) pore layer [6] i.e. the band of pores corresponding to the lowest local density or highest cluster defects.

The unloading portion of the curves in Figs 5 and 6 are omitted for the sake of clarity. The unloading curves show a much higher slope (i.e. elastic modulus) than the initial loading curves. This indicates that local yielding occurs almost immediately on loading [10-12].

The plateau stress of alloy 544 foams is not a perfect plateau i.e. the stress gradually increases with strain throughout the plateau region but the alloy 322 foams maintain an almost constant stress throughout the plateau region.

Comparison among alloy 322 and 544 foams of similar density showed that the initial yielding in alloy 322 foam starts at much higher stress and the average plateau strength of alloy 322 foams are also much higher than those of alloy 544 foams. Therefore the energy absorption capability of alloy 322 foams is much higher than that of alloy 544 foams.

Observation of deformation behavior revealed that the first noticeable deformation in the weakest band formed an inclined localized deformation band indicating that the failure mechanism in the weakest band was basically shear failure but as the deformation propagated to subsequent weaker regions, a cooperative collapse occurred giving rise to both inclined and horizontal deformation bands simultaneously.

The stress-strain curves of alloy 322 and 544 foams are compared with those of various existing commercial foams in Fig 7. Curves of Alporas (ρ=0.343 g/cm^3), ERG (ρ=0.216 g/cm^3), Alcan (ρ=0.38 g/cm^3), Alulight (ρ=0.365 g/cm^3) and Fraunhofer (ρ=0.375~0.750g/cm^3) foams were regenerated from a previous paper of Andrews, Sanders and Gibson [1]. The figure shows that the stress-strain curve of a 544 alloy foam of density 0.472 g/cm^3 is comparable with that of Fraunhofer foam of average density, 0.562 g/cm^3 while a 322 alloy foam of density 0.293 g/cm^3 is almost similar to an ERG foam of density 0.216 g/cm^3.

Figs 8 and 9 show the normalized elastic modulus and plastic plateau strength of alloy 322 foams calculated from measured electrical conductivity and obtained directly from experiments.

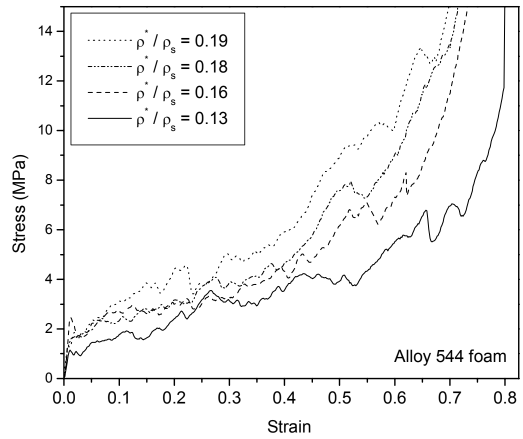

Fig 5. Stress-Strain curve of alloy 544 foam up to a strain 80 %.

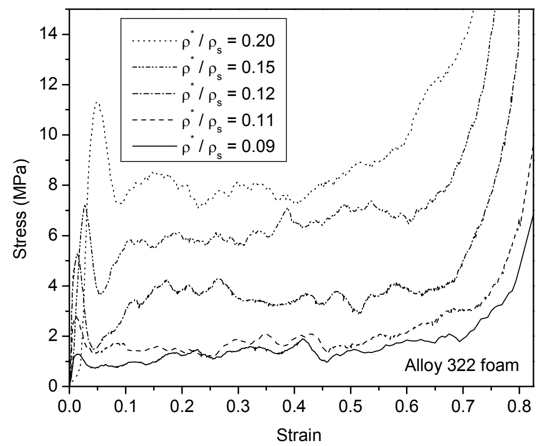

Fig 6. Stress-Strain curve of alloy 322 foam up to a strain 80 %.

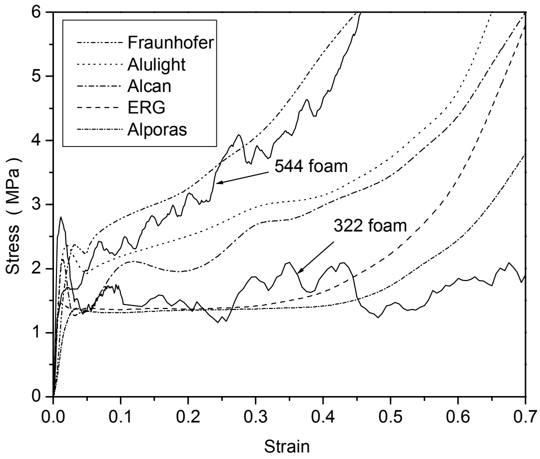

Fig 7. Comparison of stress-strain curve of alloy 544 (ρ=0.472g/cm^3) and 322 (ρ=0.293g/cm^3) foam with that of existing commercial foams.

The elastic modulus was measured from unloading curves at 0.2 % strain and plateau stress was taken as the average stress in the range 10 % to 50 % strain. The least square curve fitting of experimental data by equations 1 and 2 resulted in C_1=0.41 and C_2=0.39 with ϕ =0.95. Inserting these constants into equations 5 and 6 leads to the form:

$$\frac{E^*}{E_S} = 0.37\left(\frac{\lambda}{\lambda_s}\right)^{4/3} + 0.02\left(\frac{\lambda}{\lambda_s}\right)^{2/3} \quad (10)$$

$$\frac{\sigma_{pl}^*}{\sigma_{ys}} = 0.38\left(\frac{\lambda}{\lambda_s}\right) + 0.03\left(\frac{\lambda}{\lambda_s}\right)^{2/3} \quad (11)$$

The plots of equations 10 and 11 along with the experimental results are shown in Figs 8 and 9. Both figures reveal an excellent agreement between experimental and computed values indicating a high

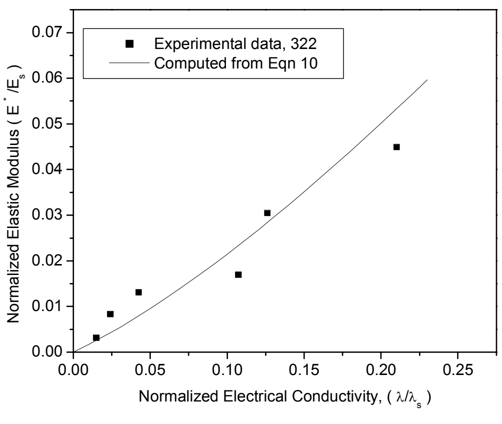

Fig 8. Normalized elastic modulus versus normalized electrical conductivity curve in case of alloy 322 foam.

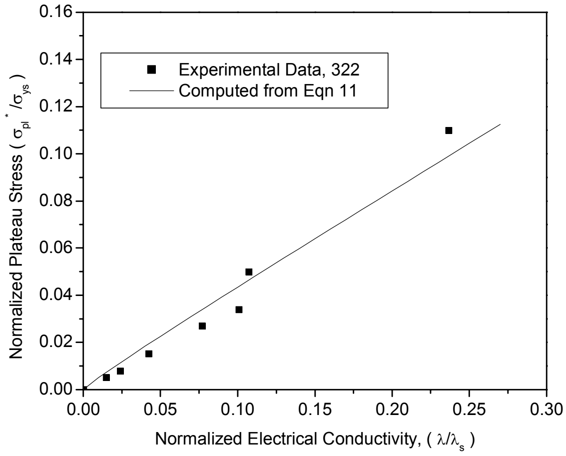

Fig 9. Normalized plastic plateau stress versus normalized electrical conductivity curve in case of alloy 322 foams.

potential for applicability of electrical conductivity in evaluating the mechanical properties of Al- foam.

4. CONCLUSIONS

Compressive mechanical properties of alloy 322 and alloy 544 foams have been studied along with their electrical conductivity in the range of relative density 0.09 to 3.00.

Both foams showed the traditional features of Al-foam like initial elastic deformation, followed by a plastic plateau region and the final strain densification. In case of similar density alloy 322 and 544 foams, the initial yielding in alloy 322 foams started at much higher stress. Alloy 322 foams maintained almost constant stress throughout the plastic plateau region, however the stress of alloy 544 foams was gradually increasing in the plateau region. The average plateau strength of alloy 322 foams was also much higher than that of alloy 544 foams of same density. Therefore the energy absorption capability of alloy 322 foams is much higher than that of alloy 544 foams.

The first noticeable localized collapse (in the weakest band) was due to shear failure, however in case of the collapse in subsequent weaker regions both normal and shear failures occurred simultaneously.

The experimentally measured electrical conductivity and the relative density followed the power law equation given by Gibson and Ashby and the experimentally obtained elastic modulus and plastic plateau strength were found to be in good agreement with those evaluated by using equations 10 and 11. Thus the electrical conductivity of foam can be used to compute its mechanical properties.

5. ACKNOWLEDGEMENT

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