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CHARACTERIZATION OF ALUMINIUM FOAM PRODUCED FROM ALUMINIUM SCRAP BY USING $CaCO_3$ AS FOAMING AGENT

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ABSTRACT

In this paper, the characterization of aluminum foam produced from aluminum scrap by using $CaCO_3$ as foaming agent was investigated. The results showed that the density of aluminum foam lies in the range of 0.40 to 0.60 g/cm^3 and relative density ranged from 0.14 to 0.25 with high porosity between 78% and 85%. The microstructure examination of aluminum foam was done using XRD, SEM, and EDX. The obtained results indicate that, the aluminum holes were distributed uniformly in the matrix. The electrical resistance of aluminum foam was determined and compared with electrical resistance of dense aluminum. The results showed that the electrical resistance of aluminum foam is greater than the electrical resistance of dense aluminum. But, the thermal conductivity of aluminum foam is lower than thermal conductivity of dense aluminum. Energy absorption of aluminum foam was obtained by both impact and compression tests and it was observed that the energy absorption obtained from impact test is close to the energy absorption obtained from compression test. The produced aluminum foams can be used for high impact energy absorption applications.

Keywords: Aluminum foam - Energy absorption - Electrical resistivity - Thermal conductivity

1. Introduction

Metal foams can be defined as metallic materials with a cellular structure, which have an attractive combination of mechanical and physical properties [1and 2]. Their light weight, high specific stiffness, high strength to weight ratios, greatly increased energy absorbing capabilities and noise control make them ideal candidates for use in several manufactures like the automotive, aerospace, ships, railway, biomedical and building industry. They used also in filters, silencers, and flame arresters and for water purification [3, 4, 5, 6, 7 and 8]. There are two main methods for making metal foams: The direct foaming methods start from a molten metal consisting of uniformly dispersed non-metallic particles which generates gas is injected to create foam. Alternatively, (TiH_2) or (ZrH_2) can be added to the melt which then decomposes leading to the same effect but the new trend is using a calcium carbonate or dolomite as a foaming agent. Indirect foaming methods start from a solid precursor which

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consists of an aluminum matrix containing uniformly dispersed blowing agent particles, mostly titanium hydride. This precursor expands in the melt forms a foam [9 and 10]. Aluminum foams have become more important in the past years due to the strong indigence of the transport industry for reduce operating costs, higher payloads, improved environmental agreement as well as increased passenger safety [4]. The application in automobile industries is one of the importance application of aluminum foam, because it has excellent crash energy absorption and it can convert crash energy into deformation energy and absorb the maximum energy [11]. However, the thermal conductivities of closed-cell foams are lower than those of the fully dense parent metal, offering a degree of fire protection in, for instance, an automobile bulkhead between engine and passenger compartment. More important, open cell metal foams can be used to increase heat transfer in applications such as heat exchangers for airborne equipment, compact heat sinks for power electronics, heat shields, air-cooled condenser towers and regenerators [12 and 13]. Moreover, the electrical conductivity of metal foam is less than that of the metal from which it made for the obvious reason that the cell interiors, if gas-filled, are non-conducting. The large attainable surface area of open cell metal foams makes them attractive as electrodes for batteries. Even though Ni - foams are extensively used in this application. In the field of sound absorption, the aluminum foam makes an incident sound wave is neither reflected nor transmitted; its energy is absorbed in the material [12, 14 and 15]. The damping capacity of aluminum foam coupled with mechanical strength and stiffness at low weight makes an attractive combination, so it used in car floors and barriers. . These applications are examples of structures the primary function of which is to carry loads, but if this is combined with vibration damping and sound absorption the product quality is enhanced [12 and 16].

The possibility of producing of aluminum foam from aluminum scrap by using calcium carbonate as foaming agent was published elsewhere [2]and this paper aims to characterize the produced foam; macrostructure, microstructure, mechanical and physical properties.

2. Experimental work

2.1. Preparation of aluminum foam from aluminum scrap

Aluminum foam was prepared from aluminum scrap by melting aluminum scrap in a vertical furnace at temperature up to 800^{o}C. After melting, the layer of oxides on the surface of the molten metal was removed using graphite rod. A 3% wt. of Al_2O_3 powder was added to molten aluminum as thickening agent and blended by stainless steel mixer with stirring speed 1200 rpm to about 30 second to adjust the viscosity of the melt. Then, a 5% of $CaCO_3$ powder used as foaming agent was added and mixed by stainless steel mixer with the same stirring speed 1200 rpm to about 45 second. After mixing process, the mixing process has been stopped and hold in the furnace for about 3-6 minutes to complete the foaming process, and then the aluminum foam was cooled in the air [2].

2.2. Thermal analysis (TA)

Thermal analysis (TA) was performed by simultaneous DTA-TGA apparatus in a cell of platinum, and at nitrogen atmosphere with a flow rate of 40 ml/min. Samples were analyzed with a temperature rate of 10^{o}C/min. The aluminum foam specimens were prepared to the macrostructure and microstructure examination using a wire-cutting machine. The density of sample was determined by a volumetric method (from the weight and the geometry) according to the equation[13]:

$$\rho = m/v \quad (1)$$

Relative density can be computed as for the equation [17]:

$$\rho^* = \rho_\phi/\rho_\sigma \quad (2)$$

The porosity is known as the percentage of void spaces present in the solid [18].

Porosity of metal foam can be computed using the following equation [19]:

$$\text{Porosity } \% = (1- \rho^*) \times 100 \quad (3)$$

The prepared specimens were analyzed using (XRD); (SEM) and (EDX).

The electrical resistivity of aluminum foam sheet (15×10 mm) can be measured by using a two-point probe technique with DC resistivity Agiellent 16339 apparatus. The electrical resistivity can be computed from the equation:

$$P = \theta\Lambda/A \quad (4)$$

Where: R is the resistance, Ω; A is a cross-sectional area, m^2; L is the length, m. the electrical conductivity is the reciprocal of the electrical resistivity (Θ) with (units, Ω.m) which can be computed from the equation:

$$\theta = P\, A/\, \Lambda \quad (5)$$

Thermal conductivity carried out at temperatures 300 K, 400 K on a cylindrical sample with a diameter 25.4 mm and height 2mm by using heat conduction apparatus, P. A. Hillton. It can be calculated from Fourier's equation:

$$Q = -\, KA(dt/dx) \quad (6)$$

Where: Q is the quantity of heat per time; K is the thermal conductivity; *A* is the cross sectional area; dt/dx is the temperature gradient. The compression test were done by Zoton universal testing machine at constant loading rate of 2.64 N/mm^2 and carried out on cylindrical specimen with 33.8 mm diameter and 45 mm height. Impact test was carried out by Charpy impact test, the apparatus consists of a pendulum of known mass (m) and length that is dropped from a known height (h_1) to impact a specimen of aluminum foam with standard size (10mm×10mm×55mm). The energy absorption by impact test (U) can be calculated from the equation:

$$U= mg\, (h_1-h_2) \quad (7)$$

Where: m is the pendulum mass; g is gravitational acceleration, m/s^2; h_1 is the height of pendulum before falling; h_2 is the height of pendulum after falling.

3. Results and discussions

3.1. Microstructure

The photograph of the cross section of the specimen foamed from the aluminum scrap at optimum conditions (5% $CaCO_3$, 3% Al_2O_3, 45 sec as stirring time and 800^oC) after wire cutting is shown in Figure (1).

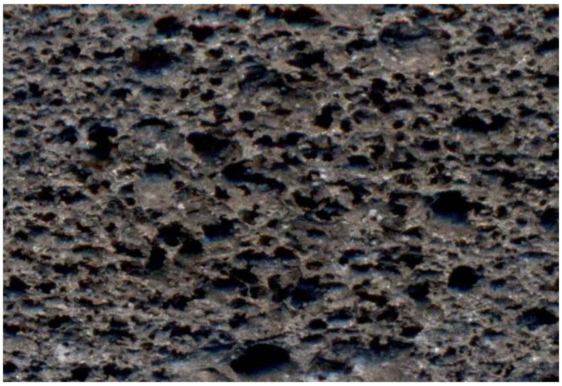

Fig. 1. As-cutting photograph of produced aluminum foam (X1).

Figure 1 shows that, a uniform distribution of porosity overall the cross sectional areas of aluminum foam and the foams have cells of nearly honeycomb shape, closed symmetrical [2].

Figure (2): shows the XRD pattern of the produced aluminum foam, from the pattern it can be noticed that, many phases were formed during the aluminum foam preparation; Al and some oxides such as Al_2O_3 and CaO, these phases were formed from the decomposition of calcium carbonate and according to the reaction:

$$CaCO_{3\,(s)} \longrightarrow CaO_{\,(s)} + CO_{2\,(g)} \tag{8}$$

Differential thermal analysis (DTA) and thermogravimetric (TGA) were carried out for $CaCO_3$. Figure (3) shows (DTA) and (TGA) for $CaCO_3$. From the Figure, it is shown that, the DTA of pure $CaCO_3$ range from 720 to 830^oC with endothermic peaks appear at 772^oC this temperature represents the degree of decomposition of $CaCO_3$, according to equation (8), thus, for fabricating aluminum foam by using calcium carbonate ($CaCO_3$) as foaming agent, it is preferred to use temperatures range from 750 to 850^oC.

TGA was applied for studying decomposition reactions; the mass of the tested sample was measured with the increasing temperature.

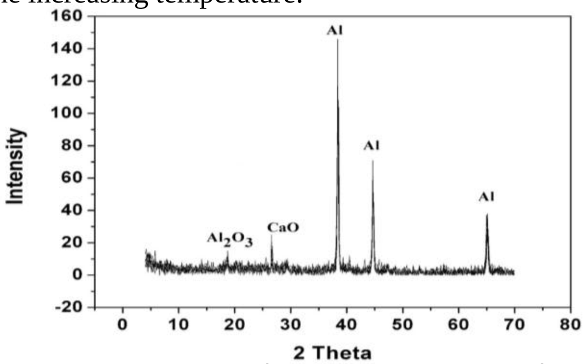

Fig. 2. XRD pattern of the produced aluminum foam

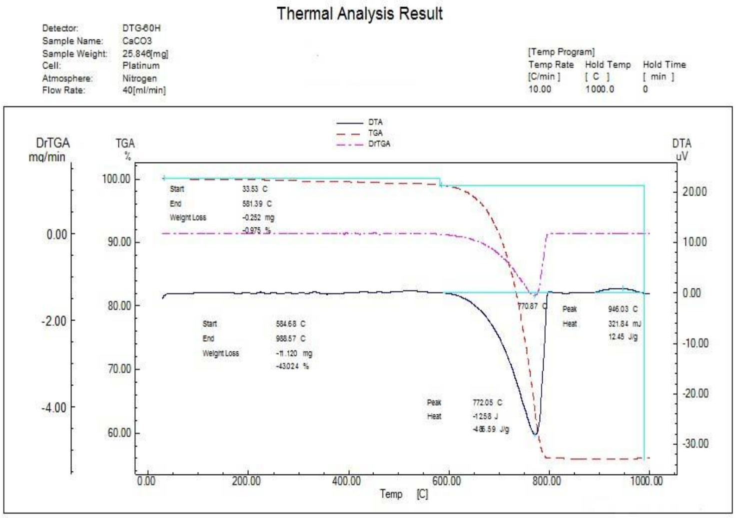

Fig. 3. Thermal analysis of $CaCO_3$

From Figure (3), it can be noticed that, the weight is decreased from 25.52 to 14.40 mg at temperature ranged from 720 to 800^oC. The loss about 11.12 mg according to the decomposition of $CaCO_3$ to (CaO) and (CO_2) according to Equation (8), this loss is a carbon dioxide (CO_2) released from the decomposition of calcium carbonate, from theoretical calculations; we can calculate the amount of CO_2 gas.

$$CaCO_{3\,(s)} \longrightarrow CaO_{\,(s)} + CO_{2\,(g)}$$

According the previous reaction, the volume of evolved CO_2 gas is 20583.24 cm^3. All CO_2 evolved as gas bubbles causes foaming in molten Al and react with some of molten Al to form Al_2O_3 according to the following reaction

$$2Al + 3CO_2 \longrightarrow Al_2O_3 + 3CO \quad (9)$$

Figure (4) Shows microstructures of cell walls of produced aluminum foam, the walls of these cells are surrounded by various mixed thin oxides film such as oxides of Ca, Al, Mg and Si oxides. These oxides were confirmed from EDX analysis in the table (1) and Figure (5), and it can be formed by the following reactions:

- Ca and Al oxides formed from Equations (10), (11) and

- CO_2 reduced by Mg and Si, which exists in aluminum scrap to form MgO(s) and SiO_2 according to the equations:

$$Mg_{\,(l)} + CO_{2\,(g)} \longrightarrow MgO_{\,(s)} + CO_{\,(g)} \quad (10)$$

$$Si_{\,(l)} + 2CO_2 \longrightarrow SiO_{2\,(s)} + 2CO_{\,(g)} \quad (11)$$

These oxides are working to strengthen and stabilize the walls of the cells of the foam at foaming stage. It is possible for the CO produced to be further reduced in reactions forming Al_4C_3 or SiC according to Equation. (12, 13) and (14) [20].

$$8\,Al_{(l)} + 3\,CO_{2\,(g)} \longrightarrow 2\,Al_2O_{3(s)} + Al_4C_{3\,(s)} \quad (12)$$

$$6\,Al_{(l)} + 3\,CO_{\,(g)} \longrightarrow Al_2O_{3(s)} + Al_4C_{3\,(s)} \quad (13)$$

$$4\,Al_{(l)} + 3\,Si_{(alloy)} + 3\,CO_{2\,(g)} \longrightarrow 2\,Al_2O_{3\,(s)} + 3\,SiC_{(s)} \quad (14)$$

Table. 1.
EDX analysis of produced aluminum foam

Element	O	Mg	Al	Si	Ca
Wt.%	8.53	0.68	85.75	2.64	2.40
At%	13.70	0.72	81.63	2.42	1.54

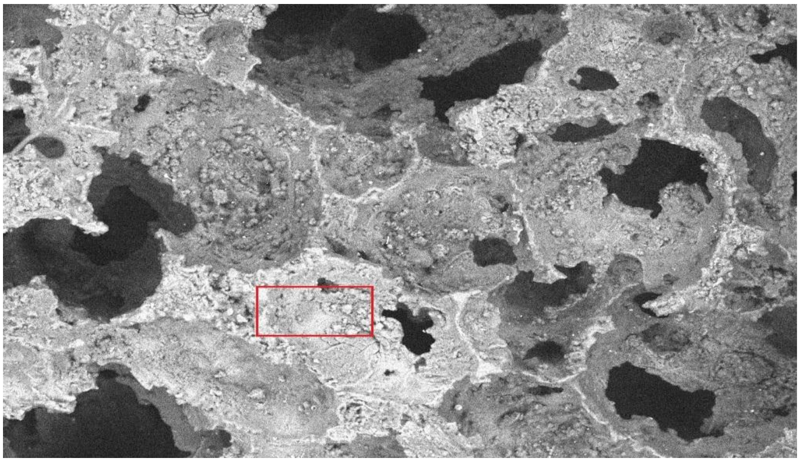

Fig.4. SEM images of cell walls of produced aluminum after wire cutting (X250).

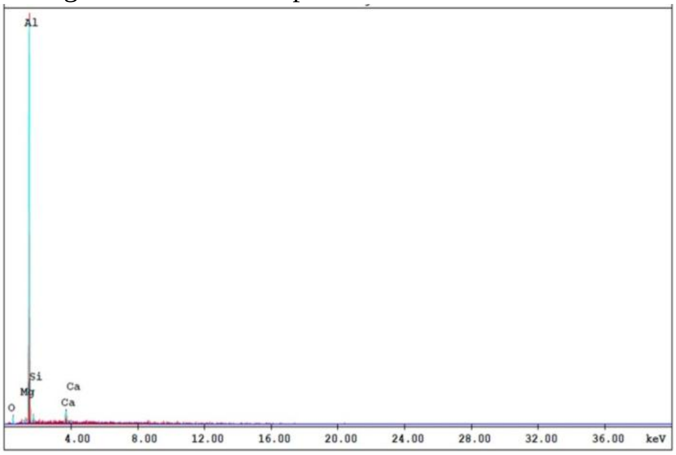

Fig. 5. EDX analysis of produced aluminum foam.

3.2. Aluminum foam can be characterized by mechanical and physical properties

3.2.1. Physical properties

3.2.1.1. Density

The densities were calculated from its dimensions according to Equation (1) and it was found that, the density ranged from 0.40 to 0.60 g/cm^3.

3.2.1.2. Relative density

Relative densities of produced aluminum foam can be calculated from the Equation (2) it was found that, it is ranged from 0.14 to 0.25.

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3.2.1.3. Porosity

Porosity of produced aluminum foam can be calculated from the Equation (3) and it was ranged from 78% to 85%. The pores size ranged from o.5-2 mm

3.2.1.4. Electrical resistivity

The electrical resistivity (Θ) of fabricated aluminum foam was calculated from Equation (5), it can be noticed that the electrical resistivity of the –fabricated aluminum foam with density ranging from 0.4-0.6 g/cm^3 at room temperature ($\Theta = 3.63\times10^{-5}$ Ω.m) is higher than the electrical resistivity of dense aluminum at room temperature ($\Theta = 2.82\times10^{-8}$ Ω.m) [21] due to the spaces between pores of aluminum foam, which works to prevent the passage of electric current through parts of the sample. The comparison between the electrical resistivity of the produced aluminum foam which has a relative density ranging from 0.14-0.25 ($\Theta = 3.63\times10^{-5}$ Ω.m) and the published data of electrical resistivity of aluminum foam which has the same relative density (Θ=90-3000 $\times10^{-8}$ Ω.m) it can be noticed that, the results of electrical resistivity of the fabricated aluminum foam is closed with that published in open literatures, which shows that, the product can be used in electrical insulation applications.

3.2.1.5. Thermal conductivity

The result of thermal conductivity of the fabricated aluminum foam was calculated using Equation (6). The results indicated that the thermal conductivity of aluminum foam with density ranging from 0.4 to 0.6 g/cm^3 at room temperature is K =1.10 W/m.K, while the thermal conductivity of dense aluminum at room temperature is K =237 W/m.K [22 and 23], Therefore the thermal conductivity of fabricated aluminum foam is less than thermal conductivity of dense aluminum, this is due to the voids within the bulk of aluminum foam, which works to prevent the heat transfer through parts of the specimens. According to Ashby reference [12], it can be noticed that, the thermal conductivity of aluminum foam which has a relative density 0.02 to 0.2 ranging from 0.3 to 10 W/m.K. The Ashby results were closed, and this proves that, the fabricated foam can be used in thermal insulation applications.

3.2.2. Mechanical properties

3.2.2.1. Compression test

Figure (6) shows the stress–strain curve of aluminum foam using compression test for a sample with 5 % $CaCO_3$ and 3% Al_2O_3, 45 sec stirring time at 800°C. From the figure it can be shown that, the stress–strain curve of aluminum foam can be divided into three stages:-

1- Linear elastic deformation stage (up to 7.5% of strain): the relation between stress and strain being a straight line and the slope of the line (elastic modulus) E = 10 MPa, this is due to the elastic bending of cell wall as in the case of dense metals.

2- Plastic collapse deformation stage (up to 56% of strain), this stage can be divided into initial collapse stage and successive collapse stage. During this stage, owing to the inhomogeneous density of closed-cell aluminum foam, the plastic deformation takes place asynchronously when the material is loaded by external force, as a result the destruction firstly appears at the weakest field, wall of cell buckling, fracturing and yielding, so the cells of this layer are compacted, and the force on this layer release temporarily, therefore stress reduces suddenly during initial collapse stage. As the strain increases, the proximate cells of the compacted layer contact each other, and the destruction takes place in new layers and the process above repeats, which is the successive collapse stage [28].

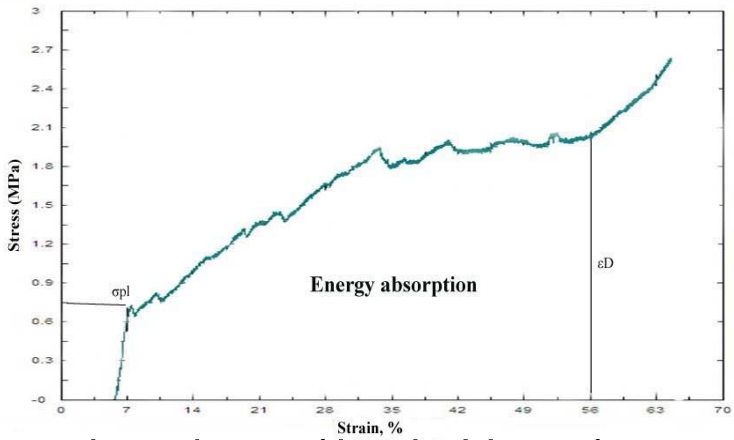

Fig. 6. The estimated energy absorption of the produced aluminum foam using compression test.

3- Densification deformation stage, at this stage, rapidly increasing stress and little increase of strain were happened and the slope of the line become large, that caused by the collapse of the cells and begin to touch each other and the material attains bulk-like properties.

3.2.2.2. Calculation of energy absorption

Applications in energy absorption systems offer a great potential for the use of aluminum foams [24]. In this part, the energy absorption can be obtained by impact and compression tests.

3.2.2.1. 1. Energy absorption by compression test

Toughness or energy absorption (U) by compression test is defined as the energy necessary to deform a given specimen to a specific strain [25] and it can evaluated by the area under the compressive stress–strain (σ - ε) curve:

$$U = \int_0^{\varepsilon D} \sigma \, d\varepsilon \qquad (15)$$

Where U is the energy absorbed per unit initial volumes up to the densification strain ε_D [25, 26 and 27]. The plastic strength, σ, was known as the first peak stress before the onset of load drop due to plastic instability [27].

Figure (6) shows the energy absorption of fabricated aluminum foam, and we can see that, fabricated aluminum foam has high energy absorption up to 56% strain with high plateau stress. Increasing in plateau stress associated increasing in energy absorption capacity and the value of energy absorption of produced aluminum foam is 0.7 MJ/m^3.

3.2.2.1.2. Energy absorption by impact test

Energy absorption by impact test has been obtained from Equation (7) and we can deduce that, the value of energy absorption of produced aluminum foam by impact test is 0.73 MJ/m^3.

From the results of impact and compression tests, we can conclude that, the energy absorption is the same at both tests, from the above results, it can be indicated that the energy absorption capacity of the fabricated foam is high and it can be used in the field of automotive applications in which needs high impact energy absorption.

3.3.3. Foam property charts

Foam property charts are charts, which give an overview of the properties of metal foams, allow scaling relations to be deduced and enable selection through the use of material indices, these charts were constructed using the CES (1999) software and database.

3.3.3.1. Projection of thermal conductivity of produced aluminum foam on Ashby charts

Projection of thermal conductivity of produced aluminum foam on Ashby charts showed in Figure (7) and it is clear that, thermal conductivity of fabricated aluminum foam are comparable with different foams in thermal conductivity against density chart.

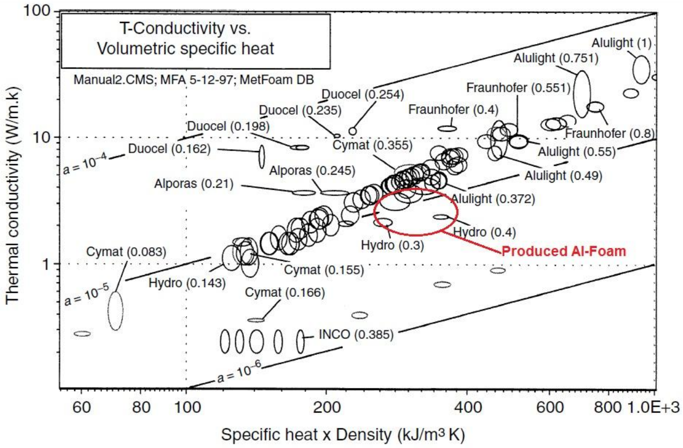

Fig. 7. The relationship between the thermal conductivity, λ, plotted against volumetric specific heat $C_p\,\rho$ for currently available metal foams.

3.3.3.2. Projection of properties of produced aluminum foam on Ashby charts

The projection of the fabricated aluminum foam shown in Figures (8) and (9) and it is clear that, the properties of the fabricated aluminum foam are comparable with different foams in the Young's modulus against density chart, as well as the compressive strength vs. density chart.

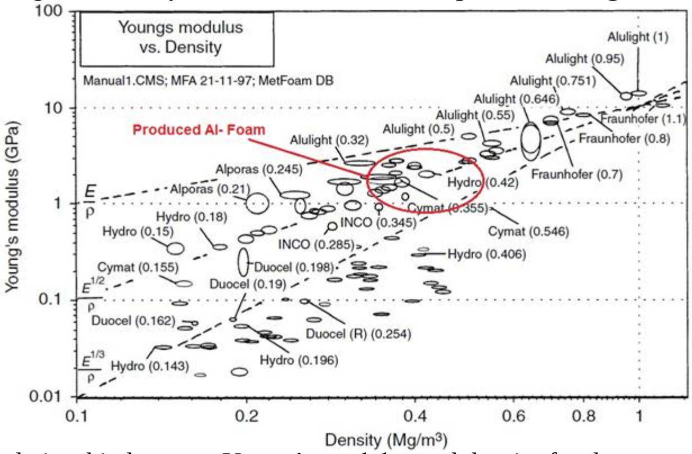

Fig. 8. The relationship between Young's modulus and density for the presented metal foams.

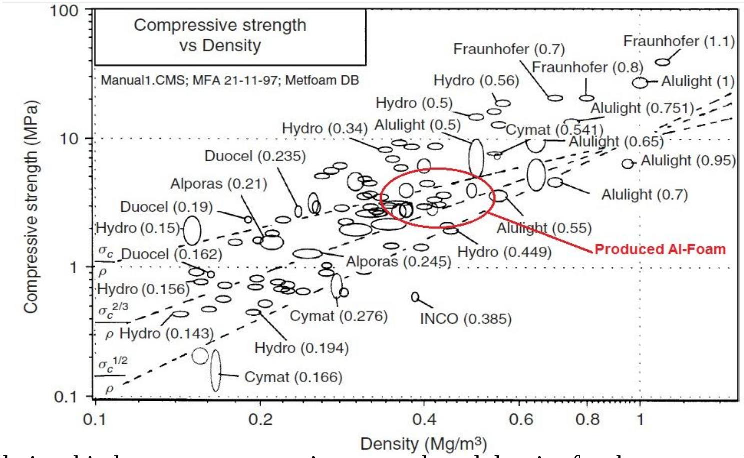

Fig. 9. The relationship between compressive strength and density for the presented metal foams.

4. Conclusions

From the above results concerning the fabricated Aluminum foam using aluminum scrap was tested at temperature from 800 to 850°C. The $CaCO_3$/ Al scrap wt. ratio was 5%, Al_2O_3/ Al scrap wt. ratio was 3% and stirring time was 45 second at stirring speed 1200 rpm. It can be concluded that:

1. The density of foamed aluminum ranging from 0.40 to 0.60 g/cm^3, with relative density ranged from 0.14 to 0.25 and porosity ranged from 78% to 85%.
2. Electrical resistivity of produced aluminum foam is greater than the electrical resistivity of dense aluminum and it is confirmed with that published in literature.
3. Thermal conductivity of produced aluminum foam is less than thermal conductivity of dense aluminum, and this is confirmed with the data obtained from open publications.
4. Energy absorption U of produced aluminum foam was obtained by impact and compression tests is almost the same at both tests. Therefore it can be applied at high energy absorption applications.

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توصيف الالومنيوم الرغوي المنتج من خردة الالومنيوم باستخدام كربونات الكالسيوم كعامل ترغية.

الملخص العربي

في هذه المقالة تم توصيف الالومنيوم الرغوي المنتج من خردة الالومنيوم باستخدام كربونات الكالسيوم كعامل ترغية.

- تم إنتاج الالومنيوم الرغوي المنتج بكثافات تتراوح من 0.4 إلي 0.6 جم / سم^3 والكثافة النسبية تتراوح ما بين 0.14 – 0.25 مع نسبة مسامية عالية تتراوح ما بين 78% - 85% .
- تم اختبار البنية المجهرية للألومنيوم الرغوي باستخدام اجهزة (XRD – SEM – EDX)، والنتائج التي تم الحصول عليها اوضحت ان الفجوات موزعة بانتظام في مادة الاساس.
- واوضحت النتائج كذلك ان المقاومة الكهربية للألومنيوم الرغوي اعلي من المقاومة الكهربية لفلز الالومنيوم ويؤكد ذلك ما هو منشور في ابحاث في ذلك الامر.
- لكن التوصيلية الحرارية للألومنيوم الرغوي أقل من التوصيلية الحرارية لفلز الالومنيوم ويكون في نطاق ما تم نشره سابقا.
- وتم كذلك اختبار امتصاص الطاقة لعينات من الالومنيوم الرغوي في حالتي اختبار الصدم واختبار الضغط واوضحت النتائج ان الطاقة الممتصة في حالة اختبار الصدم قريبة من قيمة الطاقة الممتصة في حالة اختبار الضغط مما يؤدي ذلك الي امكانية استخدام الالومنيوم الرغوي في تطبيقات الطاقة الممتصة العالية.