

PRODUCTION OF ALUMINIUM FOAM AND THE EFFECT OF CALCIUM CARBONATE AS A FOAMING AGENT

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(Received February 22, 2011 Accepted April 2, 2011)

Metallic foams are gaining ground as important new engineering materials. Aluminium foams were produced with different densities using different percentages of calcium carbonate as a foaming agent. The mechanical properties of the foamed material were tested using uniaxial-compression test. Plateau stress σ_{pl} , densification strain ϵ_d and energy absorption capacity U , were calculated. The obtained results show that the collapse strength and the absorbed energy of foams increase with increasing the density.

1. INTRODUCTION

Metallic foams are a new, as yet imperfectly characterized, class of materials with low densities and novel physical, mechanical, thermal, electrical and acoustic properties. They offer potential for lightweight structures, for energy absorption, and for thermal management. The present most commercially available metal foams are based on aluminum or nickel. Methods exist for foaming magnesium, lead, zinc, copper, bronze, titanium, steel and even gold [1]. The properties of metallic foam and other cellular metal structures depend upon the properties of the metal, the relative density and cell topology (e.g. open or closed cell, cell size, etc.) [1]. In order to improve the cellular structure of the materials and also to make the production technologies more reliable and reproducible, foam stability of liquid metals, i.e. avoidance of rupture and drainage, has to be understood and controlled [2]. Many distinct process-routes have been developed to make metal foams [1, 2]. Metallic foams can be produced by melt foaming process [3–5]. In this fabrication technique, some viscosity increasing agents such as SiC, SiO₂, MgO and Al₂O₃ particles are added to the metallic melt in order to make the melt get an appropriate viscosity. It was suggested that the viscosity increasing agent not only stabilized the cell wall but also affected the mechanical properties of the foams [5–11]. TiH₂ is the most popular foaming agent [1-5], but the relatively new trend in metallic foam production used the Calcium carbonate as a foaming agent [8-14]. The carbonate decomposes within the molten metal and forms CaO solids and the reactive gas CO₂. Under conditions of aggressive agitation, the gas bubbles formed within the molten metal are ruptured and fragmented, exposing more of the reactive gas to the molten metal. This gas reacts with the molten aluminum forming CO gas and in-situ formed Al₂O₃. The CO and CO₂ gas bubbles, as well as Al₂O₃, CaO and other metallic oxide phases, stabilize the liquid metal suspension by modifying the viscosity and surface energy of the molten metal [13, 14]. In this work the Al-foam is produced using calcium carbonate (CaCO₃) as a foaming agent and the effect of CaCO₃ wt.% addition on mechanical properties of aluminium foam is studied.

2. EXPERIMENTAL WORK

2.1 Materials Used

The following materials are used:

- Metal: commercial pure aluminum (99.86%Al) supplied from the Aluminium Company of Egypt.
- Foaming agent: Calcium carbonate powder was used as a foaming agent, supplied by (El Gomhouria Co.), the purity of powder is (99%) with size cut less than 38 μm . In order to determine reasonable foaming temperature of Aluminium melt, the decomposition temperature of CaCO_3 blowing agent has to be measured. So, CaCO_3 blowing agent was studied with Thermogravimetric Analysis with heating rate of 20 $^\circ\text{C}/\text{min}$. the decomposition is beginning from about 650 $^\circ\text{C}$ to about 780 $^\circ\text{C}$ as shown in Fig.1 so that the temperature of melt in foaming process was taken about 725 $^\circ\text{C}$. at higher temperature (higher than 780 $^\circ\text{C}$) the calcium carbonate will decompose very quickly without good distribution in the melt.

Thermal Analysis Result

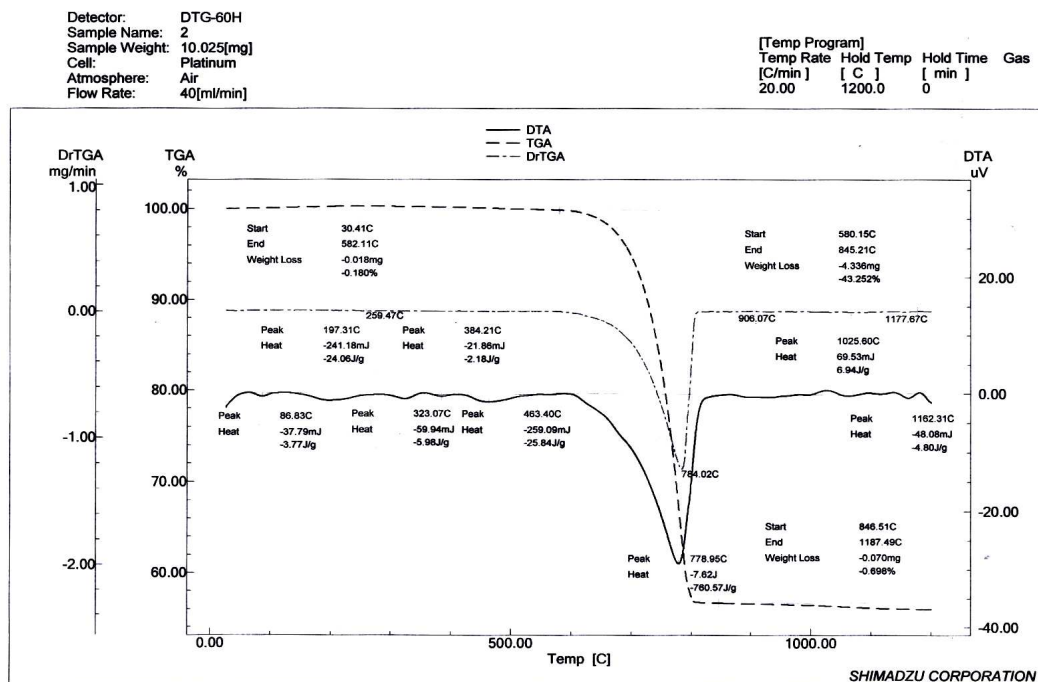


Figure 1: Thermal analysis of CaCO_3

- Alumina: Highly pure alumina powder from the aluminum company of Egypt for increasing the viscosity of molten aluminium, and it has the following particle size distribution as shown in Table 1.

Table 1: Particle size distribution of al Al₂O₃

size, μm	wt%	size, μm	wt%
-200+160	0.86	-71+63	9.32
-160+125	2.05	-63+53	8.57
-125+100	7.03	-53+45	8.26
-100+90	17.93	-45+38	3.11
-90+71	40.43	-38+0	2.44

2.2 Equipments

Cylindrical steel mold with dimensions of 8.5cm inner diameter , 22.9 cm height and 2 mm thickness was used for the melting and foaming process. Muffle furnace for melting process, and another tailored muffle furnace with 10.5 cm cylindrical chamber with a temperature controlling unit were used for the foaming process. For mixing a steel mixer with high speed motor was used. Optical microscope with image analysis program (MetallurgyPlus- image analysis system Nascent Technology Inc.) for microscopically inspection. The mechanical properties characterizations were done by universal testing machine (model fritz heckert EU20).

2.3 Experimental Procedure

A flow diagram of the foaming process is shown in Fig.2. About 500 gm of the aluminum was melted, the temperature of a cylindrical steel mould coated with anti-sticking material (commercial calcium carbonate) was adjusted in a resistance furnace and the molten metal poured into the mould. The temperature of molten metal was about 725 °C and Al₂O₃ powder was added, the mix was then stirred with stainless steel mixer to keep the efficient uniform distribution of alumina particles in the molten aluminum at 1500 rpm for about 1min. Then, the mixer speed is adapted at 2000 rpm and the foaming agent (CaCO₃) is added and mixed for about 30 sec. All the mixing process was carried out in the furnace at 725 °C. This temperature led to thermal decomposition of the foaming agent as shown in Fig.1. The mould is then taken out and let in air to cool.

2.4 Investigations and Measurements

- Measurement of density:

The volume of sample is calculated from its dimensions. The sample was weighed and the density was calculated by dividing sample weight over its volume.

- Pore size

A scanned image of the produced Al-foam specimen is shown in Fig.3. it will be used for pore characterization.

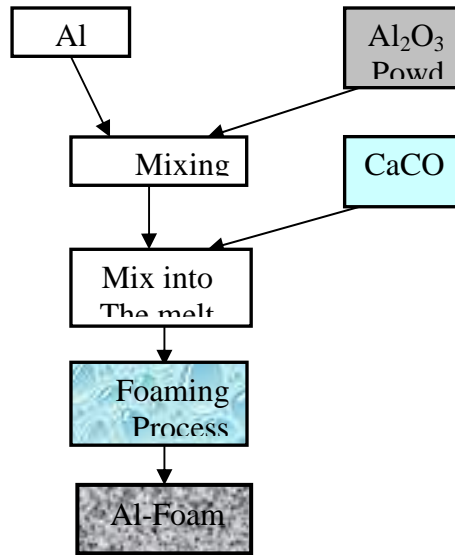


Figure 2: A flow diagram of the foaming process

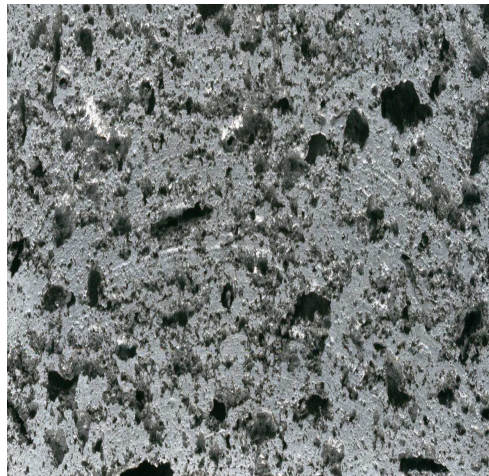


Figure 3: Scanned image showing pore distribution of the produced foam specimen

A well-conditioned, flawless surface appearance can be observed. In order to measure the porosity fraction, porosity size (maximum and minimum diameter) of the specimen, an image analysis on a cross section of the foaming direction was conducted with an image analyzer (metallurgyplus software). Since the shapes of pores were not perfect circles, equivalent diameter is used for the pore size. An equivalent diameter is the diameter of a circle having the same area as the pore, which was calculated automatically by image analyzer.

- Compression test

Due to the potential applications of metallic foams in the field of crash and energy absorption, compressive test of metallic foams has gained a great importance that

enables to characterize their mechanical properties [15]. Twenty five compression test specimens were machined with the size of 85 mm diameter and 35 mm height, the surface skin that is inevitably generated in the process of the production of Al foam was retained. In the preparation of the specimen, the minimum dimension of the specimen should be at least 7 times the pore size to avoid porosity size effect [16]. The compression tests were carried out on aluminum foams at a constant loading rate of 2.5 KN/sec

3. RESULTS AND DISCUSSION

3.1 Microstructural Characterization

All foam samples show heterogeneities and imperfections in their structure. A representative SEM image of the foam is shown in Fig.4. In addition to heterogeneities, morphological defects such as fractured or collapsed cell walls, irregular cell shape and cell wall buckling are prominent in the cell structures. Pores with fractured cell walls form large, non-equiaxed cells with their neighbors. Moreover, these elongated cells often contain buckle in the cell walls thus providing less mechanical support upon loading. This behavior was observed by others [17].

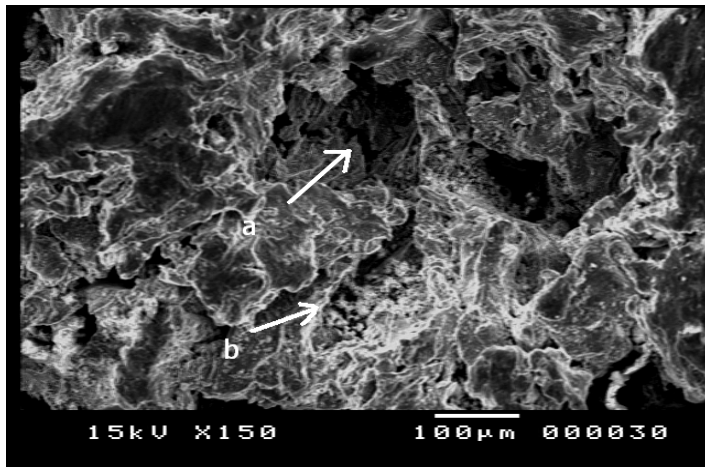


Figure 4: SEM image of Al-foam produced using CaCO₃ as a foaming agent (a- fracture and b- irregular cell shape)

Pore size was determined for the specimens using optical microscopy and image analysis and the results are as shown in Table2.

Table 2: Pore size of Al-foam specimen

Maximum diameter ,mm	Minimum diameter ,mm	Average diameter ,mm	Porosity %
3.822	0.043	0.86	44.84

This average diameter is taken in consideration in preparation of samples for compression test as illustrated earlier. The average cell size is inversely related both to the average cell wall thickness and to the density and can be influenced by adjusting the impeller speed and other parameters [3, 18]

3.2 Effect of Foaming Agent on Foam Density

As shown in Fig.5 the relative density ρ/ρ_s (ρ density of Al-foam, ρ_s density of solid aluminium) decreases with the increase of CaCO₃ wt%, although it seems essentially constant after 2%.

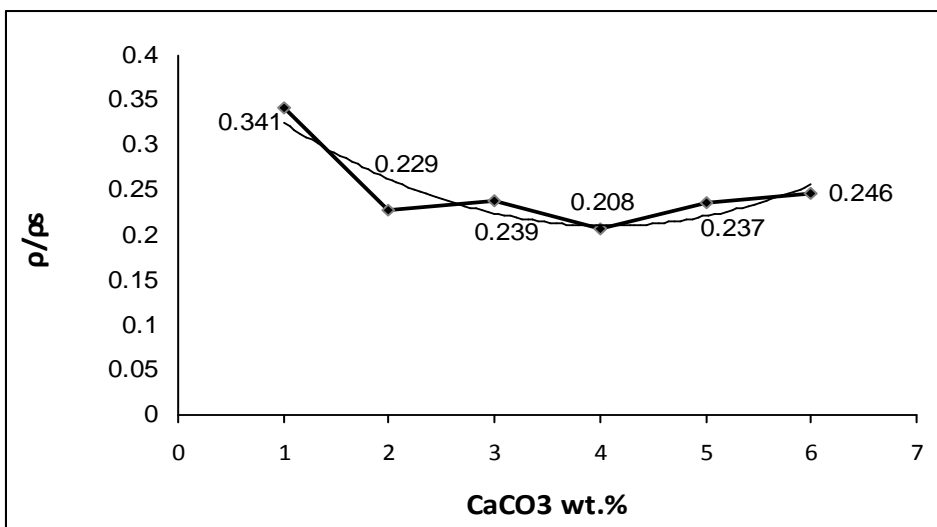


Figure 5: Effect of CaCO₃ addition on foam density

3.3 Compressive Behavior of Aluminum Foam

Figure 6 shows the nominal compressive stress–strain curves of Al-foams with different CaCO₃ wt.%. The stress–strain curves were obtained by dividing the applied load by the cross-sectional area of sample to obtain the stress, and dividing the measured displacement by the length of the specimen to obtain the strain. The stress strain curves can be divided into three stages: (1) an elastic region, where the compressive stress increases with increasing strain almost linearly and the overall elastic deflection of the cell walls takes place (2) a plastic region, where the stress slowly increases with increasing deformation and the initiation and propagation of fracture bands or bucking of the cell walls occurs and (3) a densification region, where the stress rises steeply at high strains and the sufficient collapse of cell walls and packing of broken fragments prevails[17]

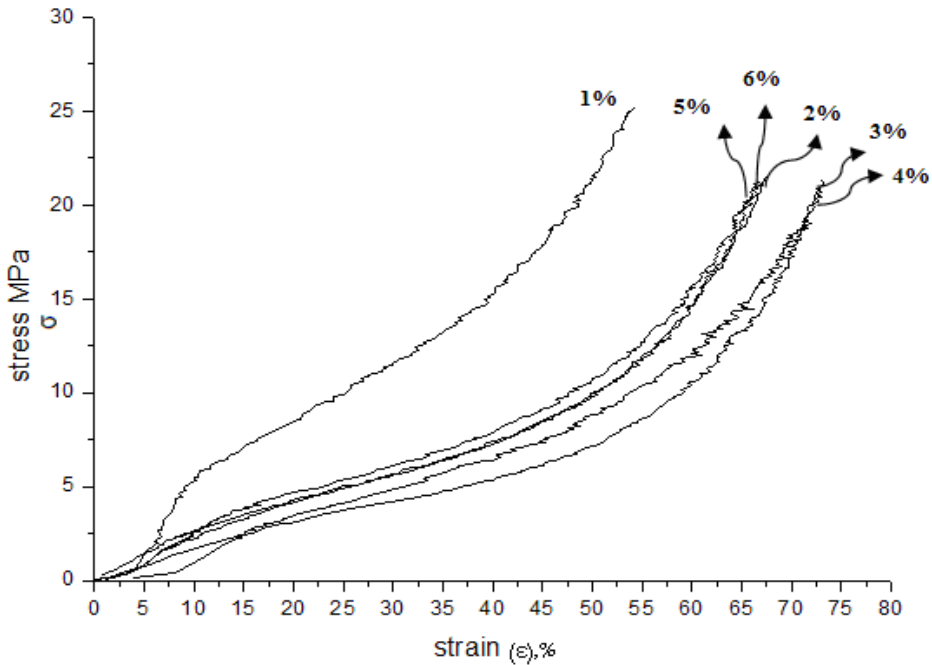


Figure 6: Compressive stress–strain curves of Al-foams with different CaCO₃ wt.% addition.

3.4 Energy Absorption Characteristic

One of the important technological properties to estimate the application of metallic foams is energy absorption capacity. Metallic foams can dissipate energy by the yielding, buckling, fracture of the cell structure, the friction between the cell wall fragments, and sticky flow of the gas trapped in the foams [19]. From compressive stress–strain curve ($\sigma - \epsilon$) the compressive properties (plateau stress σ_{pl} , densification strain ϵ_d and energy absorption capacity) of the aluminum foam are determined. The plateau stress σ_{pl} , is taken as the average stress between 5% and 30% strain during compression [20-22]. The energy absorption per unit volume, U , is the area under the stress–strain curve up to the onset of densification as shown in Fig.7. The densification strain ϵ_d is determined where the slope of the stress–strain curve increases steeply (at the nominal compressive stress equals twice the plateau value) [20-22].

The energy absorption of aluminum foam is related to the area under the compressive stress–strain ($\sigma - \epsilon$) curve:

$$U = \int_0^{\epsilon_d} \sigma d\epsilon$$

Where U is the energy absorbed per unit initial volume up to the densification strains ϵ_d [21]. Figures 8(a-c) shows the variation of plateau stress σ_{pl} , densification strain ϵ_d and energy absorption capacity U with respect to relative density, respectively.

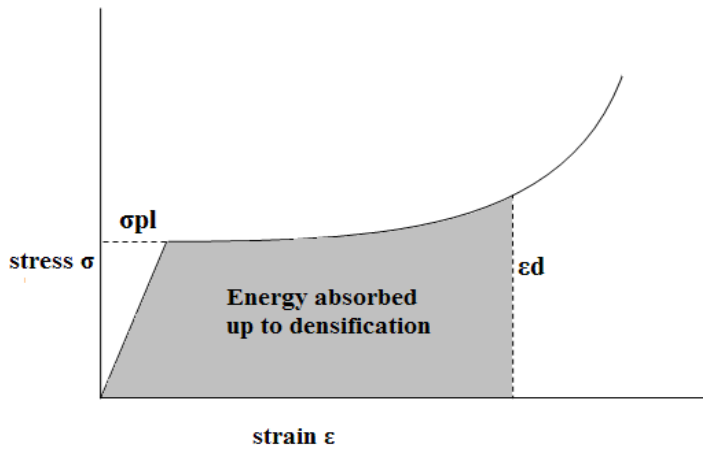


Figure 7: Compressive curve for a metal foam – schematic showing properties

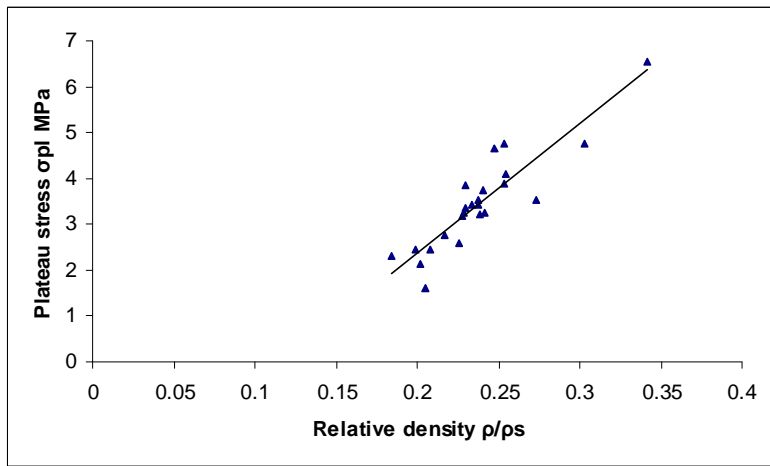


Figure 8-a: Plateau stress σ_{pl} variation with respect to relative density

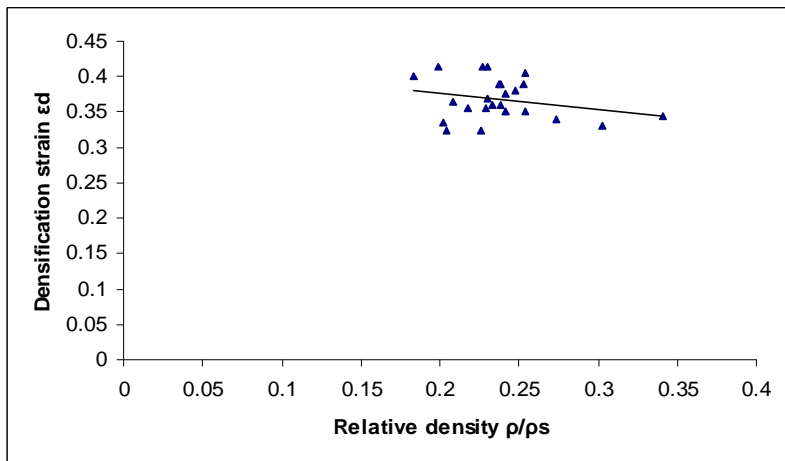


Figure 8-b: Densification strain ϵ_d variation with respect to relative density

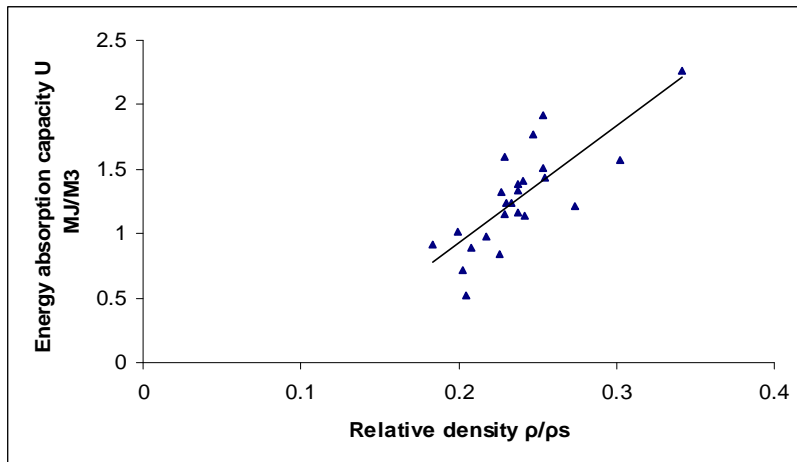


Figure 8-c: Energy absorption capacity U variation with respect to relative density

With increase in relative density plateau stress and energy absorption capacity will increase, but densification strain will decrease.

The energy absorption capacity of metallic foams is mainly due to cells yielding, buckling, fracture, and the friction between cell walls when they contact each other. The foams with higher relative density have higher yield and fracture strength than those with lower density. And they can also provide more friction source during the collapse course because of higher volume fraction of matrix metal in the foams. Therefore, the foams with higher relative density can dissipate more energy than those with lower density during compression. These factors are mainly responsible for the higher energy absorption capacity of higher density foams.[23]

4. CONCLUSIONS

Deformation and energy absorption characteristics of Al-foam produced with calcium carbonate as a foaming agent were investigated through uniaxial compression testing. The foam samples were produced with different densities. The following can be concluded:

- 1- Calcium carbonate can be an efficient foaming agent for producing closed-cell Al-foams with acceptable mechanical properties
- 2- The lowest density was obtained at about 4% addition of CaCO_3 .
- 3- Energy absorption and plateau stress increase with relative density increase.

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أنتاج الالومنيوم الرغوى وتأثير استخدام كربونات الكالسيوم كعامل ترغية

يعتبر الالومنيوم الرغوى من المواد الهندسية الجديدة المهمة لما لها من تطبيقات كثيرة فى المنشآت خفيفة الوزن وأمتصاص الصدمات وغيرها من التطبيقات الكثيرة. وقد تم أنتاج الالومنيوم الرغوى بكثافات مختلفة باستخدام نسب مختلفة من كربونات الكالسيوم كعامل ترغية . وقد تم تعيين بعض الخواص الميكانيكية عن طريق إجراء أختبار الضغط لعدد من العينات ووجد أنه مع زيادة الكثافة تزيد كلا من القدرة على أمتصاص الطاقة (U) و الاجهاد اللازم للإنهيار (σ_{pl}).