Forming of Aluminum Foam Sandwich Panels

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Abstract: In this study, aluminum foam was fabricated using sintering and dissolution process (SDP). Aluminum powder with a particle size (2.88μm) prepared as a raw material was mixed with NaCl with a particle size between (150-800μm) used as a space holder at different ratio (30, 40, 50 and 60 wt. %) and compacted at 200 MPa followed by sintering at 650° C for 2 hrs. The sintered samples were placed into hot water for 10 hrs to dissolve NaCl particles. Uniaxial compression test was carried out to determine the foam structure influence on plastic deformation and the damage in the Al foam. It has been using optical microscope, Energy Dispersive Spectrometry (EDS) and Scanning Electron Microscopic (SEM) to investigate the pores. The properties of Al-foam were improved by extrusion process. The foam porosity is increased from (35%) to (41%). It was found that the extrusion process formed isolated pores with thicker walls than cell walls with interconnected pores to expand the use of foamed aluminum for application. EDS investigated that the ratio of NaCl is decreased after extrusion process for the Al-foam. SEM observed the distance between the pores of Al-foam is decreased after extrusion process.

1. Introduction:
In recent years, there is an increasing interest in aluminum foam due to their advantages, such as relatively high stiffness despite very low density, high specific strength, high corrosion resistance, excellent noise absorption, vibration suppression, excellent properties for impact energy and ease of recycling [1]. Aluminum foam has high potential for various applications, but their use is limited because of its cost and lack of uniformities in properties. But it is expected that the price of foams will decrease in the coming years as the volume of production increases. Recent technological advances in the field of metallic foams have led to the development of a wide range of processing techniques for the open as well as closed cell morphologies [2].

Several methods exist for production of Al foam which can be grouped into five categories according to the form of Al (melt or powder) and the type of the pore foaming agent, namely melt-gas injection, melt-foaming agent, powder-foaming agent, investment casting and melt infiltration [3]. Removable of internal patterns or space holders, leads to open cell structures. Space holder technique is particularly common in powder metallurgy and offer a wide range of structure and properties compared to liquid infiltration technique. Space holder can be removed with different ways, such as by shaking, leaching or by pyrolysis. Several space holder materials are proposed in the literatures such as NaCl particle, carbamide (urea) or carbonate particles [4,5].

Powder metallurgy method is one of the most promising techniques for fabricating metal foams. It was invented in Fraunhofer Institute for Applied Materials Research in Bremen, Germany. This method has a
good control over the cell size, cell shape and with a relatively homogeneous pore structure. The sintering and dissolution process (SDP) is a developed technique by Zhao and Sun (2001) [6] to manufacture low cost open-cell foams using PM route. Zhao, et al., (2004) [7] studied the effect of the compaction and liquid state sintering condition on the structure of Al foam manufactured by sintering-dissolution process. Hussain and Suffin (2011) [8] studied the effect of NaCl space holder content on the morphology and compression properties of aluminum foam. Yavuz A., et al., (2011) [9] investigated the effect of dissolving agent morphology on the production of Al foam by sintering dissolution process (SDP) method. Jamaludin S. B. et al., (2013) [10] studied the characterization of microstructure, porosity and diametric compressive strength of porous aluminum. Suffin N., et al., (2013) [11] studied the effect of different dissolution times on compressive behavior and energy absorption of Al foams fabricated by sintering dissolution process (SDP) using the NaCl as a space holder. Hangai Y., et al., (2013) [12] investigated the compressive properties of the final Al foam produced by sintering dissolution process (SDP) with various dissolution times to obtain a porous Al with various amounts of residual NaCl. By using SDP to synthesize metal foams, the pore size and pore morphology of foams can be controlled by selecting suitable sizes of space holder particles and its volume fraction in the matrix-space holder powder mixture. In addition, the foam porosity can be easily controlled by varying the metal/space holder volume ratio.

This article describes the fabrication open-cell Al foams via sintering dissolution process by using four of Al-NaCl mixture ratios. Foams structure, porosity and density behavior of the foams are also investigated.

2. Experimental Procedure:

The raw materials used in this study are aluminum powder with particle size of ~ 2.88 μm and sodium chloride (NaCl) with particle size of 150-800μm. The particle morphology of NaCl is shown in Figure 1. NaCl particles have semi-equiaxed shape.

![Figure 1. Morphology of NaCl particles by optical microscope.](image)

The Aluminum powder is mixed with different ratios of NaCl powder (30, 40, 50, 60) wt. % as a space holder to create porosity, the mixture is weighted using a 4-digit digital balance and then is mixed in ball milling for one hour with alumina balls in porcelain jar Under 95rpm. The powder mixture is compacted into a steel mold with a diameter (25mm) and height (132.3mm) under a compaction stress (200 MPa) using a hydraulic press that The name of the press was KNUTH, made in Germany, capacity (80 tons).
Figure 2 shows the pressed aluminum samples are sintered into a direct furnace under argon (Ar) atmosphere at 650°C for 2 hours and then is allowed to cool to the room temperature.

![Figure 2. Aluminum specimens after sintering](image1)

The last step is the dissolution process, which consists of placed the samples in hot water with temperature of 95°C for dissolution time (10 hr) ,to remove NaCl particles and create aluminum foam as shown in Figure 3.

![Figure 3. Aluminum foam samples after dissolution process](image2)
The density of foam determined according to the conventional equation as given by (1):

\[ \rho = \frac{m}{V} \quad \ldots \ldots \quad (1) \]

Where:
\( \rho \) = Density \( \text{g/cm}^3 \), \( M \) = mass \( \text{g} \), \( V \) = volume \( \text{cm}^3 \), the volume was determined by the physical dimension of samples.

The sample weight is weighted using a 4-digit digital balance. The samples are then coated with a thin layer of Vaseline jelly, to avoid penetration of water through any pore may be present. It is noted that the weight of Vaseline jelly can be ignored and is not included in the equation (2) for when a large specimen is used and a thin film of jelly is applied. The samples were immersed into a scaled vessel containing water. The volume of displacement will represent the sample volume (Archimedes principle).

The density and porosity of the foams were calculated using (2) and (3) is given by [12]:

Foam density, \( \rho_{\text{foam}} = \frac{w_{\text{air}}}{w_{\text{air}} - w_{\text{liquid}}} \times \rho_{\text{liquid}} \quad \ldots \ldots \quad (2) \)

foam porosity, \( p_f = \left| 1 - \left( \frac{\rho_f}{\rho_{\text{al}}} \right) \right| \times 100\% \quad \ldots \ldots \quad (3) \)

Where, \( \rho_{\text{liquid}} = 1 \text{ g/cm}^3 \), \( \rho_{\text{al}} = \text{aluminum density (2.7 g/cm}^3 \), \( \rho_f = \text{foam density (kg/m}^3 \).

The microstructure of the Al foam samples was examined using the optical microscope, SEM and EDS.

The mechanical properties of foam samples were measured using the Universal Testing Machine (UTM) with capacity 300kN speed 1mm/min at room temperature to determine the compression strength, Yield point and Young’s modulus of foam.

3. Cold Forward Extrusion Procedure:
Cold Forward extrusion die geometry was presented, firstly an extrusion container with internal diameter of 25.1 mm having an outer diameter of 55 mm and a punch of 25 mm are machined. The die inlet geometries for cold forward extrusion are chosen as cosine curved and the length of the die is to 25mm. Schematic representation of the cold forward extrusion dies is given in Figure 4. For cosine profile extrusion had been machined with die having a length of 25 mm. container and the punch a made from 1.2344 DIN hot worked tool steel with hardened to 54HRC. Photographical drawing view of the insert dies and the experimental set-up is shown in Figure 4 respectively.
For the forward extrusion, aluminum foam specimens were made from pressed mixing powder (Al-NaCl) to 25 mm diameter and 50mm in length by using Universal Testing Machine (UTM) model UTS-100 with constant ram speed of 1 mm/min. compression rate is maintained same as that adapted for the experiments. The specimen had oil grooves on both the ends to entrap lubricant during the compression test. The compression load was recorded at every 0.5 mm of punch ravel. The specimen after forward extrusion Figure 5.

![Figure 4](image1.png)  
**Figure 4.** (a) Drawing die compound, (b) die compound with removable die

![Figure 5](image2.png)  
**Figure 5.** Specimens of aluminum foam after forward extrusion.
5. Energy Dispersive Spectrometry & Scanning Electron Microscopic test

The SEM test can supply magnification up to $5 \times 10^5$ times, which is about $2.5 \times 10^2$ times better than the standard microscope. This technology employ electron displacement to produce signals related to the topography of the material and converts these into an image.

The EDS test works by detecting x-rays characteristic of various elements and arranging them in an energy spectrum. EDS software then analyzes to determine and semi-quantify the composition of the material. EDS can be done for samples size as small as a few microns. SEM and EDS line scan analysis were used to analyze the microstructure for the pores of aluminum foam before and after extrusion process.

4. Results and Discussion

4.1 Physical Properties - Porosity and Density

Figure 6 illustrates the effect of NaCl content on porosity and foam density of Al foam. The porosity increases when the NaCl content increased in the Al/NaCl sample and the foam density decrease with increasing NaCl content. During the dissolution process when the NaCl is removed the solid Al turned into a foam. NaCl particle dissolves in a hot water, and the space that created after dissolving process become pores, and that make the sample become lighter. With a higher NaCl content in the sample which is 60 wt. %, some of NaCl particles are in touch with each other and make a continuous three-dimensional network. All the particles in the mesh (network) shape dissolve in the hot water, which results high porosity and low foam density. However, there is a small amount of residual NaCl in the final sample [13].

In contrast, with a smaller NaCl content which is 30 wt. %, some of the NaCl particles are restricted by the Al matrix and that cause the particles unable to dissolve in the hot water, and thus, remain in the foam sample and cause high density and low porosity[13]. Figure 6. shows the porosity increases from (32% to 39%), and the foam density decreases from (1.83 to 1.65 g/cm$^3$), when the NaCl content increases from (30 wt. % to 60 wt.%). Figure 7. after extrusion shows the porosity increases from (35% to 41%), and the foam density decreases from (1.76 to 1.6 g/cm$^3$), when the NaCl content increases from (30 wt. % to 60 wt.%). The results show that the density after extrusion is reduced and the porosity increases from before extrusion.

![Figure 6. The effect of NaCl content on porosity and density.](image-url)
4.2 Mechanical Properties - Compression properties

Figure 8. shows the compressive stress-strain curve of different aluminum foam with different NaCl content. Each curve can be divided into three regions, elastic deformation, long deformation plateau and then densification region [13]. From the curve, yield stress and young’s modulus can be determined as listed in table 1. The pure solid aluminum shows the highest yield strength and Young’s modulus. Young’s modulus which is determined by the slope of the graph in elastic region, the modulus decreased with increasing porosity of the foam. This reduction in Young’s modulus is due to high elastic deformation of foam cells. The modulus of Al-30NaCl foam (0.244GPa) is much higher than that of Al-60NaCl foam (0.053GPa). The pore size of foam also has a significant effect on the elastic modulus. The smaller pore size the higher strength and modulus.

Figure 7. The effect of NaCl content on porosity and density after extrusion.
The foam with 60wt. % NaCl shows the lowest yield stress, Young’s modulus and compressive strength because of the foam with high porosity has larger pore size and thinner cell walls for these reasons the foam has a weak structure [14]. This structure (thin cell walls) could not be sustained to support the load and caused the structure to breakdown, which caused the failure at low stress. At high porosity the existence of the interconnected pores in the foam behave as initial cracks in the structure and easily spread through the structure and that caused the sharp reduction in the stress plateau of this foam type [14].

| Samples          | Pure Al | Al-30NaCl | Al-40NaCl | Al-60NaCl | Al-50NaCl |
|------------------|---------|-----------|-----------|-----------|-----------|
| Yield stress(Mpa)| 853.9   | 489.2     | 324.4     | 170.9     | 106.68    |
| Modulus (GPa)    | 0.426   | 0.244     | 0.162     | 0.085     | 0.053     |
| Compressive strength (MPa) | 1322     | 1048.04   | 810.92    | 427.24    | 266.56    |

4.3 Energy Absorption

Depending on the stress and strain of the plateau region, the energy absorption capability can be determining. Foams have long plateau stage where the cell walls collapse plastic ally to a densified strain at a nearly constant stress. Generally, materials which possess the longest plateau is considered to be the best energy absorption. The energy absorber capability of foam equal to the area under the plateau region which is calculated by the length and height of the flat stress-strain curve or by multiplying the stress value at plateau region and the densified strain value. Mathematically, the change in stress value is more effective than the change in strain value. In other words, it was found that broadest plateau region and highest densified strain give lowest energy absorption, the reason which standing behind this is the lowest value of stress.

From Figure 9 it can be noticed that the energy absorption reduced with decreasing foam density and increasing porosity because the yield stress is decreased and frequently the area under the stress-strain curve decreased. Energy absorption of solid aluminum is the highest (7.205MJ/m$^3$) and when the porosity of foam is (32%) the absorbed energy is (5.242MJ/m$^3$), When the porosity increased the energy absorption decreased as shown in foam with porosity (36%) the energy absorption is (1.272MJ/m$^3$) and for porosity (39%) the energy absorbed by foam is (0.519MJ/m$^3$) because at high ratio of NaCl the cell wall become too thin and thus the structure become weaker so the thinner cell wall dose not sustain loading during compression test.
4.4 Extrusion of Aluminum foam

The length of the die plays strong effect in the value of extrusion load. The load increasing with increase the length of die at constant reduction area and that agreed with [15, 16]. This is belonging to the increasing of friction due to increasing of surface area of active forming area. When adopted cosine profile as design; eliminated the energy dissipated in forming discontinuity [17]. Figure 10, is shown three stages. In stage (A), slightly deformation occurs. The material has not yet filled the die cavity completely. In second stage (B), extrusion load increases as extrusion process proceed with high constant deformation rate. In third stage (C) the steady stead occurs after material filled die cavity completely. This explanation is in conformity with [17]. Extrusion load gradual decreasing due to decreasing friction surface area in container as punch still in progresses.

Figure 10. Effect of die length on extrusion load for reduction area 36% and die length=25mm
4.5 Microstructural Properties - Optical Microscope Before and After extrusion

Figure 11. shows the morphology of foam (pore size and cell walls). It has been shown that when the NaCl content increased larger pore size and higher quantities of pores were achieved. The isolated pores with thick cell wall observed at 30wt.% NaCl content, and the interconnected pores with thinner cell wall at 60wt.% NaCl content. For a high NaCl contents the generation of interconnected pores increased because of the formation of numerous channels between cells. Larger pore size leads to thinner cell walls and that leads to lower density of foam and increased porosity. Foam with 60wt.% NaCl content consisting of higher amount of NaCl particles has the largest pore size and thinnest cell walls, as illustrated in table 2. Consequently, the foam with lowest density was achieved[17].

Table 2. shows the pore size of foams with different NaCl content

| Foam samples | NaCl content |
|--------------|--------------|
|              | Al-30NaCl    | Al-40NaCl    | Al-50NaCl    | Al-60NaCl    |
| pore size(mm)| 0.193        | 0.213        | 0.246        | 0.290        |

![Image](image1.png)

Figure 11. Shows optical micrograph of samples with different NaCl content; (a) Al-30NaCl, (b) Al-40NaCl, (c) Al-50NaCl, (d) Al-60NaCl with magnification 5X.
Figure 12 shows the morphology of foam (pore size and cell walls). It was found that when the extrusion process of the aluminum foam samples, the size and shape of the pores became more regular and became thicker than the cell wall pre-extrusion isolated pores were observed in ratios (30wt.%, 40wt.%, 50wt.%, 60wt. % NaCl) and this indicates that the extrusion process improved the shape of the cell, the isolated pores are thicker walls than cell walls Related pores are interconnected.

**Figure 12.** Shows optical micrograph of samples with different NaCl content after extrusion process; a) Al-30NaCl, b) Al-40NaCl, c) Al-50NaCl, d) Al-60NaCl, e) Al- with magnification 5X.

4.6 EDS Result
EDS test using the high magnification for inspection and the result in the aluminum foam was found to have some elements such as (Cl, Na, Al, C, O and Fe) before the extrusion process, as shown in Figure 13. illustrated the distribution of the elements by increasing the ratio of Cl and decreasing of the other elements. And when re-testing the EDS energy dispersive spectroscopy using the high magnification for inspection of the aluminum foam sample after the extrusion process, it was found that it has such elements as (Al, Cl, O, C, Na and Si) shown in Figure 14. and illustrated the distribution of the elements by increasing the ratio of Al and decreasing of the other elements.
Figure 13a. Morphology of Aluminum foam specimen with 30% NaCl content before Extrusion by SEM

Figure 13b. EDS inspection for pores of Aluminum foam with 30% NaCl content before extrusion
Table 3. shows elements ratio in pores of aluminum foam

| Element | EL [wt.%] | AN [wt.%] | Series   | Unn.C [wt.%] | Norm. C [wt.%] | Atom.C [at.%] | Error [wt.%] | (Sigma) [wt.%] |
|---------|-----------|-----------|----------|--------------|----------------|---------------|--------------|----------------|
| Cl      | 17        | K.series  | 36.17    | 38.04        | 24.88          | 1.30          |
| Na      | 11        | K.series  | 21.29    | 22.39        | 22.58          | 1.52          |
| Al      | 13        | K.series  | 19.49    | 20.49        | 17.61          | 1.03          |
| C       | 6         | K.series  | 14.69    | 15.44        | 29.82          | 4.58          |
| O       | 8         | K.series  | 3.31     | 3.49         | 5.05           | 1.18          |
| Fe      | 26        | K.series  | 0.15     | 0.16         | 0.07           | 0.04          |

Figure 14a. morphology of Aluminum foam specimen with 30%NaCl content after Extrusion by SEM

Figure 14b. EDS inspection for pores of Aluminum foam with 30%NaCl content after extrusion
Table 4. shows elements ratio in pores of aluminum foam

| EL  | AN | Series | Unn.C [wt.%] | Norm. C [wt.%] | Atom.C [at.%] | Error | (Sigma) [wt.%] |
|-----|----|--------|--------------|----------------|--------------|-------|----------------|
| Al  | 13 | K.series | 74.00        | 69.14          | 52.10        | 3.95  |                |
| C   | 6  | K.series | 25.53        | 23.85          | 40.37        | 14.15 |                |
| O   | 8  | K.series | 5.22         | 4.87           | 6.19         | 3.39  |                |
| Cl  | 17 | K.series | 1.87         | 1.74           | 1.00         | 0.26  |                |
| Na  | 11 | K.series | 0.34         | 0.32           | 0.28         | 0.10  |                |
| Si  | 14 | K.series | 0.08         | 0.08           | 0.06         | 0.07  |                |

4.7 SEM Result
Figure 15. illustrated the device for SEM, which examination was used to identify the pore size maximum and minimum pores of Aluminum foam, cell walls and the displacement between the pores before and after extrusion process. Figure 16. illustrated the SEM images of pores of aluminum foam with 1mm, and 50, 100, 200, 300, 500 µm magnification.

The shape of the pores and their walls is clearly observed with the presence of overlapping pores, some of which are closed and connected. The Figure 17. shows after the extrusion process. The shape and wall of the cell are isolated and open pores. It can be concluded through SEM examination that the pressure that was performed through the extrusion process contributed to the increase in the thickness of the walls and the formation of isolated pores after there were overlapping pores. It is related to each other and the Figure 18. shows the size of the pores before the extrusion, the maximum and the minimum. The Figure 19 also shows the size of the pores after the process of extruding the maximum and the minimum. The Figure 20. shows the distance between the pores before the extrusion and the Figure 21. the distance between the pores after the extrusion process. SEM examination for both observed that the distance between the pores decreased after extrusion and became a convergence with the walls of the pores of more thickness.
Figure 16. a, b, c, d, e, f, g and h SEM images pores of aluminum foam with 30% NaCl content before Extrusion at 1mm, 50, 100, 200, 300, 500µm magnification
Figure 17. a, b, c, d, e, f, g, h, i and j SEM images pores of aluminum foam with 30.5 NaCl content after extrusion at 1 mm and 10, 20, 40, 50, 100, 200, 300, 500 μm magnification
Figure 18. a, b, c, d and e SEM images pore size of aluminum foam with 30% NaCl content before extrusion.
Figure 19. a, b, c, d, e, f and g SEM images pore size of aluminum foam with 30% NaCl content before extrusion.

Figure 20. SEM images displacement between the pores of aluminum foam before extrusion.
Figure 21. SEM images displacement between the pores of aluminum foam after extrusion.

5. Conclusions:
1. It is possible to control the value of porosity by controlling the amount of NaCl particles.
2. Increasing the dissolution time leads to slightly rising in the porosity as compared with the increasing in the NaCl content.
3. Optical microscope images that shows the pore size increases with increasing NaCl content and dissolution time which leads to increasing porosity and thus, obtained on a lightweight foam.
4. Improve the properties of Al-foam by extrusion process.
5. By using EDS, it found that the ratio of NaCl is decreased after extrusion process for the Al-foam.
6. By using SEM, it found the distance between the pores of Al-foam is decreased after extrusion process.

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