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Research paper

Fabrication of Functionally Graded Open-cell Aluminium Foam Using Graded NaCl in Infiltration Casting

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Abstract

Functionally graded material (FGM) is a material that has varying composition, porosity and microstructure. Such material is created to achieve a specified function. As for this research, an Aluminium based FGM was fabricated using infiltration-casting method whereby graded NaCl act as the filter and space holder material. The NaCl grain is graded into 2, 3 and 4mm in size. The results showed that the porosity of the Functionally Graded Open Cell Aluminium Foam (FGOCAF) fabricated using infiltration process is highly dependent on the sizes of NaCl grains used. By increasing the size of NaCl grain in infiltration casting method, significantly increase the porosity of the FGOCAF. It can be concluded that the NaCl grain plays an important role to define the functionality-graded structure of the final product whereby the product will show layers of porosity inside it.

Keywords: *Aluminium Foam; Functionally Graded; Infiltration Casting; Porous; NaCl*

1. Introduction

Nowadays, researchers perceive the significance of imaginative materials to use for monetary and ecological reasons [1]. Functionally Graded Materials (FGMs) are materials that contain a spatial degree in structure or potential arrangement for a particular application [2]. The term “Functionally Graded Materials” has existed since the mid- 1980s, the concept has been utilized in engineering for a relatively long time [2]. FGM occur in nature such as bones, teeth and plants as it shows that the materials have a specific service requirement [3]. One of the most important characteristics of FGM is the ability to inhibit crack propagation. This property makes it beneficial in penetration resistant materials used for armour plates and bullet-proof vests [3]. It is also widely applied on aeroplanes, medical, energy and also optoelectronics [3]. FGM is not only occurs naturally but also it can be produced to fit specific application.

Metal foam such as aluminium foam (Al Foam) is a material that inhibits porous structure in it [4]. Metal foam is a type of cellular material that is widely used in constructions, heat exchanger, energy absorption, sound absorption and also filtration [4]. As a cellular material, porosity, pore size, pore structure and density of the foam are among the main factors that control the properties of the metal foam [5]. Metal foam can be divided into 2 types that is open-cell type and closed-cell type [5]. Closed-cell type of metal foam characteristics is the cell that incorporates a pore that has no interconnection with the surrounding neighbour cell while open-cell type shows otherwise. In achieving such pore structure, the casting method used is called batch casting process [6]. Fig. 1 shows the process of batch casting to produce closed cell aluminium foam. The example of a closed-cell aluminium foam product is Alporas. The addition of calcium, Ca inside the molten aluminium will act as the thickening agent whereby, when the TiH_2 is added and thermally decomposed inside the melts, hydrogen gas will be released and the thicken aluminium melts will stabilize the bubble formation. Thus, when it is cooled down, the bubble will stay inside the solidified aluminium.

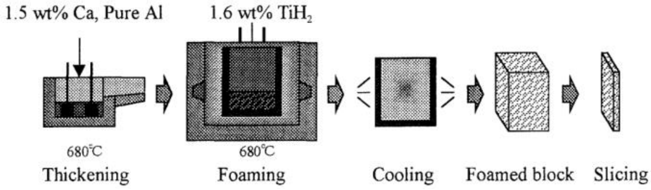

Fig. 1: Batch casting process for Alporas [6]

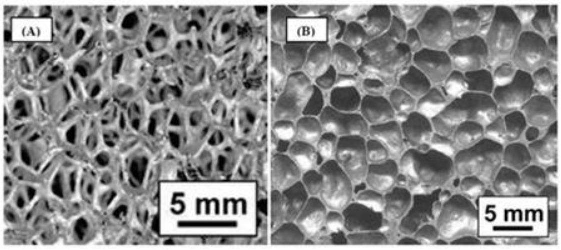

Fig. 2: (A) Open-cell (ERG Duocel) and (B) Closed-cell (ALPORAS)[5].

Fig. 2 shows the differences of structure between open-cell and closed-cell. An open-cell aluminium foam however has the exact opposite structure of its pore whereby the pore cell can be seen interconnected with each other which indicate larger surface area of empty spaces inside it. It may achieve up to 74% of porosity percentage, however it is really brittle when it achieves higher porosity percentage [9,11].

Aluminium foam is a metal foam product that is widely industrialised nowadays. The ability to withstand the corrosion, abundant in nature and also recyclable is among the reason the product is much familiar than other metal foam produced in the industry [5]. This research is more focused on the open-cell aluminium foam

(OCAF). One of the main methods to produce OCAF is infiltration casting which uses a soluble precursor such as NaCl to create the pore structure [7]. Fig. 3 shows the infiltration casting method flow [8].

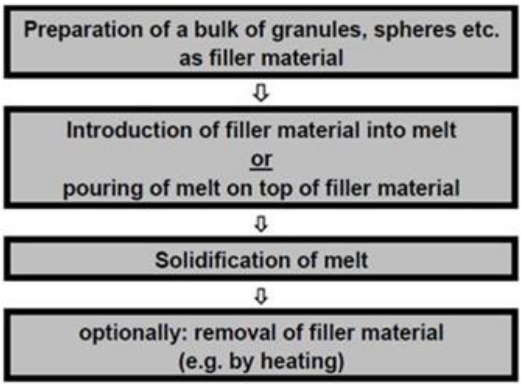

Fig. 3: Infiltration casting method flow [8].

The bulk granules, sphere and etc act as the filler material. The filler material will be introduced into melts. The first rule of choosing the filler material for infiltration casting is to make sure that the filler material has higher thermal stability than the melts. In other words, the filler material should not melt together with the melts when casting. After the solidification of melts, filler material must be able to be removed from the solidified melts without ruining the feature that have been left by the filler as the result of infiltration casting. In selecting the correct filler material it is really important in infiltration casting as it is affecting the cost and also the time to obtain the final product of the casting method itself.
There is also a method of producing "Functionally Graded Open Cell Aluminium Foam" (FGOCAF) by using a powder metallurgy route. The method is called sintering and dissolution process where the filler is removed by dissolving the filler to create porous structure [10]. However, the pore size produced is in micro scale due to the size of the filler.

OCAF with a non-functionally graded structure is produced to meet suitable application as it is really crucial when it comes to cost saving. In order to improve the ability and cost saving to the optimum level, OCAF must be explored in term of the structure. Thus, the idea of fabricating FGOCAF is worthwhile to be fabricated and observed.

2. Sample Preparation

The solid aluminium ingot is prepared by cutting precisely to the volume and shape of the cylindrical mould. Sodium chloride, NaCl is chosen as the filler material for the fabrication of the FGOCAF. It is the most suitable filler material as to comply with the infiltration casting method. NaCl have higher thermal stability than the aluminium ingot that act as melts. Moreover, NaCl can be removed from the solidified aluminium by dissolving it in water as NaCl can dissolve in water. In order to achieve the functionally graded structure, the NaCl in this fabrication process were sieved into 3 difference grain sizes respected to its grain diameters that is 2 mm, 3 mm, and 4 mm. The NaCl used in the fabrication is a basic common salt (cooking salt). The sieving process was done by using a mechanical sieve shaker. The mould used in the fabrication process in cylindrical in shape and having open end on both of its side. This is to ensure the removal of the casting product could be done easily. Fig. 4 shows the flow of FGOCAF mould setup. The infiltration casting method is first started by preparing a mould. The mould is cylindrical in shape with an inner diameter of 28 mm, outer diameter of 35.5 mm and 100 mm in length. In order to ease the removal of the casting product from the mould, the inside wall of the cylindrical mould is coated with a thin layer of ceramic compound. The ceramic compound used to coat the inside surface area of the mould should withstand higher temperature than the Al inside the mould. The ceramic compound used to coat the inside of the mould for the casting process is Boron Nitride. The Boron Nitride used in layering the inner wall of the mould is in a powder form. It is mix with a suitable amount of Ethanol till the mix becomes a runny paste before it can be applied inside the mould using a paint brush. After the inside of the mould have been coated with Boron Nitride, the mould is then put straight on its side, flat on the mould base vertically.

In order to create the functionally graded structure, the NaCl grain that has been graded is used. For this fabrication, functionally graded structure is achieved by layering 2 layers of NaCl grains with different size on top of each other. Courser size of NaCl is put on top of finer NaCl. If done otherwise, the finer NaCl will infiltrate into the gap that is left between the course NaCl grains. 50 % of the mould height will be filled with 2 layers of different size of NaCl grains with each layer having the same volume. 40% left of the volume is filled with solid aluminium ingot on top of the NaCl grain. The top cover of the mould is mounted on top of the mould and secured by tighten the nut and bolt. The two openings of the mould which is argon gas inlet and vacuum pump outlet is closed using a valve to prevent pressure lost. Leaking of the mould will give major effect to the product as the melted Al have to travel all the way down through the NaCl. If the leak occurs on the top cover, Al will only flows down assisted by gravity and may not reach the bottom. If the leaks occur on the base, melted Al most probably flows out from the mould. Fig. 5 shows the enclosed and tighten mould.

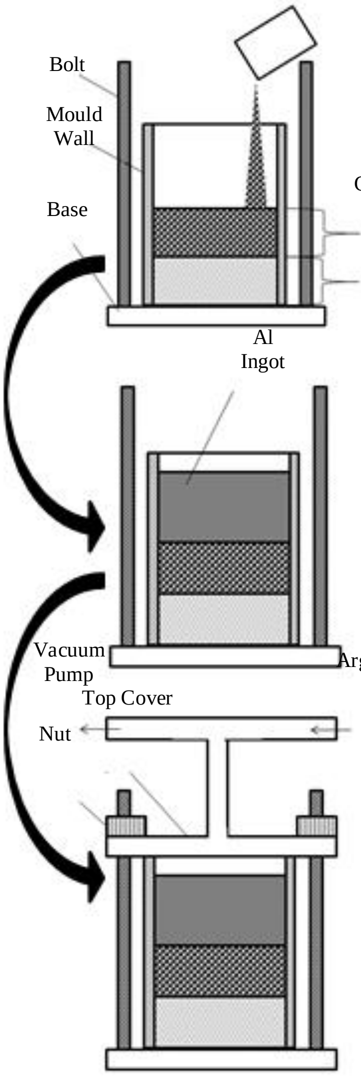

Fig. 4: FGOCAF Mould Setup Flow

Fig. 5: Closed and tightened mould.

The furnace used for the casting is a top loading furnace type. The top cover of the furnace have to be custom made to allow the top part of the mould which has a long shaft to be able to protrude out from the furnace without loss of heat to the surrounding and can be handled easily when there is a need to check the mould for random leakage during the casting process. Fig. 6(a), 6(b) and 6(c) shows the top loading furnace, top cover design and mould top cover.

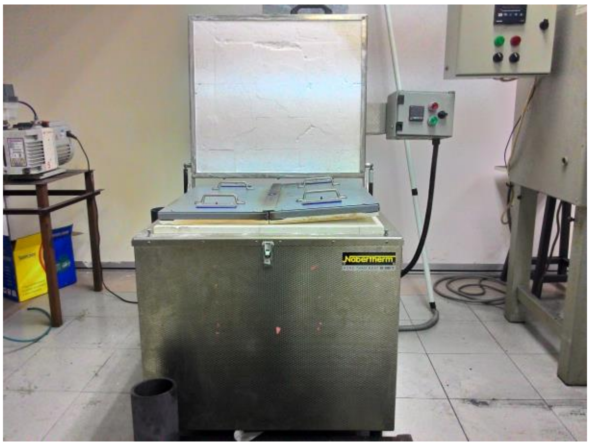

Fig. 6(a): Top loading furnace

The top loading furnace is heated up to 710°C together with the mould inside it. The mould is placed inside the furnace for a period of 3 hours whereby the aluminium ingot will melt and it would be in liquid state. The furnace together with the mould needs 2 hour to achieve 710°C and was let to soak for 1 hour. Fig. 7 shows the graph of the temperature vs time to show the chronology of the casting process.

Fig. 6(b):Design of furnace top cover.

Fig. 6(c): Design of the mould top cover.

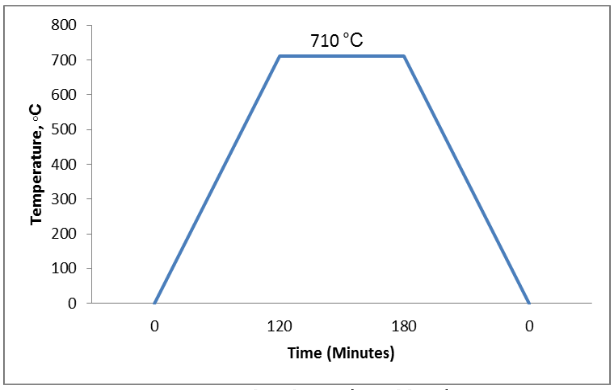

Fig. 7:Heating and soaking of mould in furnace.

After 1 hour of soaking the mould at 710°C, the molten aluminium is forced down the mould. In order to force the molten aluminium down the mould, the state of the art mould setup would have 2 openings which is argon gas outlet and vacuum pump outlet that is controlled by a valve. The mould is vacuumed for 5 minutes and then purging process is done to force molten aluminium down the mould using inert argon gas with a flow rate of 10 l/min for 5 minutes. After vacuuming and gas purging was done, the mould was pulled out from the furnace and let to cool at room temperature.

The sample was extracted from the mould and it was placed in a water bath inside an ultrasonic cleaner for about 3 hours for 3 cycles. This process is known as water leaching. This was done to eliminate NaCl grains inside the samples by dissolving the NaCl in water. Fig. 8 shows the surface of the sample before undergoing water leaching. It can be seen that NaCl grains are still intact with the aluminium. The sample was then cut into 30mm thick. The sample was then observed, measured and weighed for determining their density and porosity percentage. Afterwards, the sample undergoes X-ray imaging to observe the porous structure.

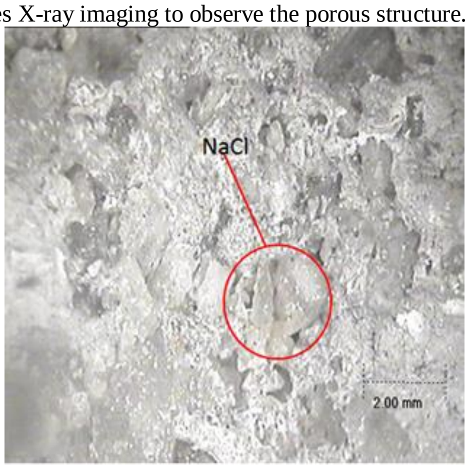

Fig. 8: Surface of FGOCAF before leaching.

3. Results & Discussion

There are 3 variations produced from the fabrication of the FGOCAF. Fig. 9 shows the variation of the samples produced. The 3 variations of the samples were different from one another according to the layering of NaCl grain arrangement inside the mould. The difference of pore size and also the layering can be seen on the surface of the samples. Table 1 shows the 3 variations of FGOCAF samples made from the fabrication.

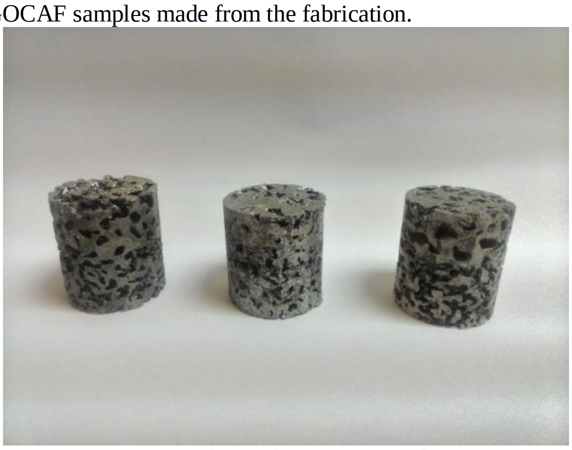

Fig. 9: Fabricated FGOCAF Samples

Table 1: Variation of FGOCAF Samples

FGOCAF Samples	Layer 1 NaCl Size (mm)	Layer 2 NaCl Size (mm)
A	2	3
B	3	4
C	2	4

3.1. Porosity & Density

Each of the samples fabricated are having 3 copies of them with the same layering of NaCl grains. It is then weigh and calculated to obtain the density and porosity percentage. Table 2 shows the average porosity and average density of FGOCAF sample. It shows that sample B has the lowest density 0.82 g/cm3 while sample C has the highest density 0.99 g/cm3. This directly shows that the larger the NaCl grains used in the fabrication, the density will decrease and the porosity will increase. It is also observed that the structure is in brittle state whereby, there are chips of aluminium shard and dust that always coming out from inside of the samples. Thus, it may decrease in its density and increase it percentage of porosity slowly over time if it is regularly moved and subjected to vibration.

Table 2: Average porosity and average density of FGOCAF.

FGOCAF Samples	Average Porosity %	Average Density g/cm^3
A	64.81	0.95
B	69.62	0.82
C	63.33	0.99

3.2. Cross-sectional Pore Structure

Fig. 10 shows the X-ray image of the cross section of the samples. It is seen that sample A and sample B are showing less distinctive pore size between two different pore size layers created by NaCl grain. The interconnection between larger and the smaller pore can slightly be seen through the X-ray image. For sample C, the differences between the pore is noticeable due to 2mm difference between NaCl grains that is layered inside the mold. It is most likely that if the grain size of NaCl used between layers is close in sizes, it may result in greater connectivity between the two layers of different pore size. The connectivity between the larger and the smaller pore size is important in real world application whereby it can be subjected to be used as filter and heat exchanger. Liquid must be able to penetrate all the way through the pore in any direction to serve the purpose of the application. Through the x-ray image also, it can be seen that the shape of the pore is irregular due to the shape of the NaCl grain. Due to the irregularity of the NaCl grain, it is hard to control the range of density of the samples. The larger the sizes of NaCl grain, the larger the range of density and porosity percentage between each samples with the same layering.

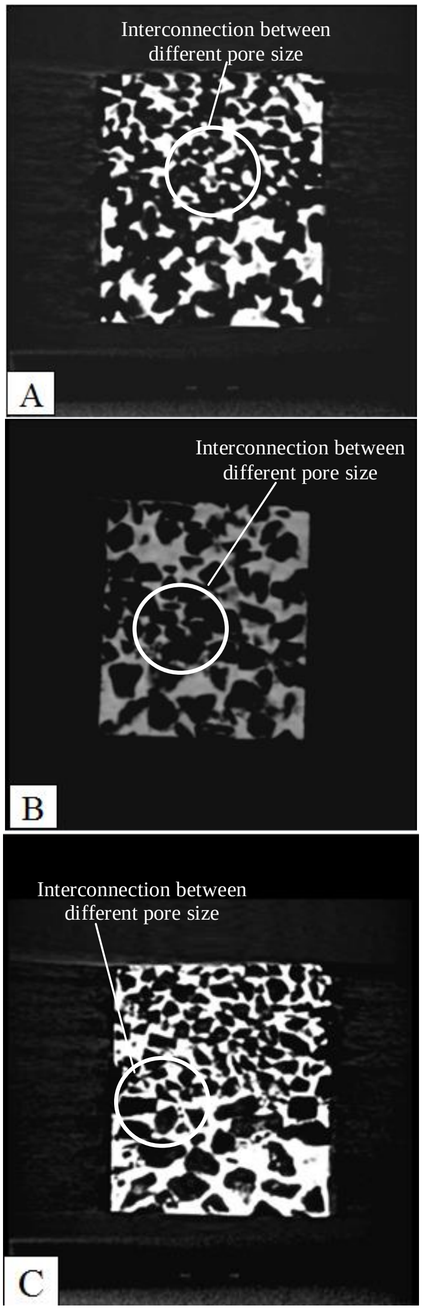

Fig. 10: X-ray cross sectional view of FGOCAF.

4. Conclusion

From the fabrication process, it shows that, the porosity of Functionally Graded Open Cell Aluminium Foam FGOCAF produced by infiltration process is very dependent on the sizes of NaCl grains used. By increasing the size of NaCl grain in infiltration casting method, it will give a significant increase in the porosity of FGOCAF. Through fabrication of FGOCAF, it is found that, it is hard to control the porosity of the pore because of the irregularity of the NaCl grain shape. It may be helpful if the grain of NaCl can be in a regular shape such as spherical in shape. This may help to maintain and control the porosity and density of open cell aluminium foam fabricated using infiltration method. Aluminium foams are suitable for sound absorption application in the real world whereby there are a few industry that have been manufacturing and selling it in bulk quantities.

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