MICROSTRUCTURE AND COMPRESSIVE PROPERTIES OF ALUMINUM FOAM FABRICATED USING SINTERING DISSOLUTION PROCESS

by

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for the Degree of
Master of Science

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DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled "Microstructure and Compressive Properties of Aluminum Foam Fabricated Using Sintering Dissolution Process". I also declare that it has not been previously submitted for the award of any degree or diploma or other similar title of this of any other examining body or University.

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LIST OF ABBREVIATIONS

Al	Aluminum
CIP	cold isostatic pressing
CPU	central processing unit
ºC/ min	degree Celcius/minutes
e.g	for example
et al	and others
g/cm^3	grams/cubic centimeters
GPa	gegaPascal
kN	kiloNewton
Mg	Magnesium
mm/min	millimeter/ minute
MPa	megaPascal
NaCl	Sodium Chloride
OM	optical microscope
P	pressure
SAF	stabilized aluminum foam
SDP	sintering dissolution process
SEM	scanning electron microscope
Si	Silicon
Sn	Tin
T	temperature
V	volume
W	energy absorption capability

W_a	weight of the dry sample
W_b	weight of the sample in the water
W_c	weight of the wet sample
XRD	X-ray diffraction

LIST OF SYMBOLS

%	percent
wt%	weight percent
ºC	degree celcius
n	integer
λ	wavelength of incident wave
d	spacing between the planes in the atomic lattice
θ	angle between the incident ray and the scattering planes
ρ	density
σ	stress
ε	strain
μ	micron

MIKROSTRUKTUR DAN CIRI-CIRI MAMPATAN BUSA ALUMINUM DIFABRIKASI MENGGUNAKAN PROSES PENSINTERAN PELARUTAN

ABSTRAK

Proses pensinteran pelarutan (SDP) merupakan proses yang dapat menghasilkan busa aluminum sebagai bahan penyerap dengan kualiti yang baik. Tujuan kajian ini adalah untuk mengkaji kesan pelbagai parameter terhadap morfologi dan ciri mampatan busa aluminum difabrikasi menggunakan kaedah SDP. Dalam kajian ini, Sodium chloride (NaCl) digunakan sebagai agen pembusaan. Busa aluminum difabrikasi menggunakan kaedah (SDP) yang melibatkan proses pencampuran (1jam), pemadatan (200 MPa), pensinteran (570 ºC) dan pelarutan (90 ºC). Bahagian pertama dalam kajian ini ialah mengkaji kesan perbezaan kandungan agen pembusaan dalam busa aluminum terhadap ketumpatan, morfologi, sifat mampatan dan tenaga penyerapan. Hasil kajian menunjukkan agen pembusaan menyumbang kepada keliangan tinggi dan tenaga penyerapan di mana menghalang struktur busa daripada runtuh semasa pembebanan mampatan. Sebaliknya, kandungan agen pembusaan yang terlalu tinggi menyumbang baki partikel NaCl dalam busa aluminum, menghasilkan busa yang berkeliangan tinggi dengan sifat mampatan dan tenaga penyerapan yang rendah. Didapati peningkatan masa pelarutan meningkatkan tenaga penyerapan, disebabkan pelarutan keseluruhan partikel NaCl.

MICROSTRUCTURE AND COMPRESSIVE PROPERTIES OF ALUMINUM FOAM FABRICATED USING SINTERING DISSOLUTION PROCESS

ABSTRACT

Sintering dissolution process (SDP) is a technique which enables fabrication of aluminum foam as a suitable absorber material with good quality. The aim of this research is to study the effect of various parameters towards morphology and compression properties of aluminum foam fabricated using SDP method. In this research, sodium chloride (NaCl) powders were used as space holder. Aluminum foams were fabricated using SDP method which involves milling (1 hour), compaction (200 MPa), sintering (570 ºC) and dissolution process (90 ºC). The first part of this research is to investigate the effect of different space holder content in aluminum foam on density, morphology, compression properties and energy absorption. The result shows that the space holder contributes to higher porosity and energy absorption which prevented the foam structure from collapsed during compression loading. In contrast, too high space holder content leading to high tendency of residual NaCl particles in aluminum foam which resulted in porous foam with lower compression properties and energy absorption. It was found that increasing dissolution time improved energy absorption due to complete dissolution of NaCl particles.

CHAPTER 1

INTRODUCTION

1.1 Introduction

In recent years, many industries are interested in materials that offer functional properties such as high strength-to-weight ratio, good impact energy, high thermal conductivity and high permeability especially for automotive, aerospace, railway, building and chemical application. Compared to bulk materials, cellular materials provide impressive properties which make it interesting for wider application. The current understanding and optimization on cellular material especially metallic foam has open more attention from researcher to investigate the potential of cellular material for suitable application. Metallic foam, particularly aluminum foam, exhibits unique properties such as high specific strength, stiffness, excellent impact energy and sound absorption properties. Due to these reasons, aluminum foams have been considered as outstanding material as it perform successfully as energy absorber, lightweight structural for building and transport against buckling and impact, non-flammable ceiling and sound insulation (Zhao and Sun, 2001).

Several methods exist for manufacturing aluminum foam which is melt-gas injection, melt-foaming agent, powder metallurgy, investment casting and melt infiltration (Michailidis and Stergioudi, 2011). Powder metallurgy have been considered as a suitable method for aluminum foam fabrication that attracts many researchers to fabricate aluminum foam using powder metallurgy. This is because, this method flexible that leads to desire designed foams at cost effective (Michailidis and Stergioudi, 2011; Bafti and Habibolahzadeh, 2010; Jiang *et al.*, 2005). Zhao and Sun (2001) have introduced a new development in powder metallurgy process for aluminum foam fabrication which is called sintering dissolution process (SDP) that involves milling, compaction, sintering and dissolution process. SDP is a process that used space holder which will leave behind open cell aluminum foam after the preform go through dissolution process. For example, Surace *et al.* (2009) used sodium chloride (NaCl) particles as space holder with the range of amount 30-70 wt%. They found out that aluminum fraction is the most important parameter affecting relative density and compressive stress. Meanwhile, Jiang *et al.* (2005) fabricated open cell aluminum foams using carbamide to produce samples with porosities between 50% and 80%. They found that pores shape was obtained depending on the shape and size distribution of space holder. Michailidis and Stegioudi (2011) also demonstrated that the SDP method using crystalline raw cane sugar which they concluded that this method can be used for manufacturing open cell metal foams with porosities in range of 40-70%. Thus, it is noted that, despite the fact that SDP method is an attractive method which can control pore shape and porosity, it also can achieve a good compression properties of aluminum foam.

Properties of aluminum foam are largely influenced by morphology of the foam structure and pores distribution. More improvement on the fabrication process has been done by researchers in order to improve compressive properties of aluminum foam. Since compressive properties are important criteria of aluminum foam to be used as energy absorber. For example, Jiang *et al.* (2005) who studied on the effect of tailored porous morphology found that spherical-shaped pores showed higher compressive strength compared with strip-shaped pores. They also stated that higher sintering temperature resulted in better binding among the aluminum particles which leads to a higher compressive strength. Besides that, Baiti and Habibolahzadeh (2010) found that compression behavior of the foam improves as sintering time or temperature increases. They also found that the addition of 1 wt% Mg and 1 wt% Sn powders lead to liquid phase sintering and results in a dense aluminum matrix with higher mechanical properties.

1.2 Problem statement

One of the most difficult tasks in the fabrication of metallic foam using SDP method is to obtain a good pore distribution in foam structure. Distribution of pore is important since the properties of foam material are depending on their structure. During milling process, it is required to produce homogenous distribution of metallic powder and space holders. When milling process takes place, mixture powders with different compositions of space holder have different densities of mixture powder, which cause different distribution in the final mixture. The result of this condition is that the difference in packing of the particle powders during powder compaction step.

Another problem faced during aluminum foam fabrication process using SDP is inhomogeneity of pore shape as there is a strong relationship between morphology and mechanical properties. Generally, pores shape is reflected by the shape of the space holder. Many researchers investigated the effect of pore shape and rounded space holder seems to be interest as it to avoid stress forming between the space holder and metallic powder. Morphology of the pore structure also is influenced by the amount of space holder. The amount of space holder will affect the morphology of foam structure when interconnected pores are formed which make the pore size become larger. In order to obtain tailored distribution morphology of foam structure, an appropriate selection of space holder must be made in order to control the shape of pores.

In fabrication of aluminum foam using SDP method, space holder is an important part to be considered. Several space holder materials are proposed by researchers such as NaCl particles, carbamide or carbonated particles (Michailidis and Stergioudi, 2011). Given its low cost, NaCl particles have been chosen as space holder. This can reduce the cost of aluminum foam fabrication due to SDP method is expensive because of using pure metallic powder. On the other hand, using space holder method may cause residue of space holder in foam structure due to incomplete dissolution of space holder. In this research, NaCl particles were chosen as space holder because of its solubility in water, which gives more effective dissolution process. However, during dissolution process, there might be residue of NaCl particles left in aluminum foam which cause by higher amount of NaCl particle. Given its brittleness, the presence of NaCl particles in foam structure may infer the performance of the foams. NaCl powder is also chemical inertness in contact with aluminum powder. Besides that, NaCl powder has high melting point (801 ºC) which is important during sintering stage. This is because, space holder can hold the pores structure during the sintering process. So that it will produce strong bonding pore structure for further process. Meanwhile, if melting point is lower as has as carbamide (133 ºC) the dissolution process was held first before sintering process. So it will produce slumping material which has weak bonding structure for further sintering process.

Jiang *et al.* (2005) claimed that aluminum foam made by SDP may have lower mechanical properties compared to other techniques such as infiltration or casting methods. This is because using powder metallurgy can be formed friction during powder pressing or during dissolution time which may damage or cracked the foam. Therefore, it is important to achieve a strong bonding between the powders without damaged the sample for further process.

Referring to the problems statement mentioned above it can be summarized that morphology and porosity of aluminum foam depends on amount of space holder. The higher amount of space holder will leads to better energy absorption. However, inhomogeneity problem that occurs may influence shape, cell wall and distribution of pores. Besides that, the appropriate selection of dissolution time is important to avoid space holder residue and crack in aluminum foam. Due to these problems, different amount of space holder also was investigated to study the effect on morphology and properties of aluminum foam. Increasing the dissolution time was chosen as a means to solve the problem because of intending to completely dissolve all the NaCl particles.

1.3 Research objectives

In order to investigate the performance of aluminum foam using SDP method there are several objectives that need to be achieved which are:

1. To fabricate aluminum foam using NaCl particles as space holder.
2. To investigate microstructure-properties correlation of aluminum foam.
3. To study the effect of dissolution time on foam morphology and properties of aluminum foam including porosity, compression strength and energy absorption.
4. To study the mechanisms and failure characteristic of aluminum foam during compression loading.

1.4 Scope of work

1. Space holder that has been chosen in this research is Sodium Chloride (NaCl) particles.
2. The amounts of space holder used are 20, 40, 60 and 80% of NaCl particles.
3. The dissolution times investigated are 1, 2 and 3 hour.
4. This research focused on morphology, compression and energy absorption of aluminum foam.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Foams are cellular material containing pores. Typically, foams can consist 20-95% of pores which made these materials have low density (Ishizaki *et al.*, 1998). Foams have densities only fractions of a solid structure and therefore have high specific strength and stiffness. Foams also provide excellent properties for impact energy, vibration and sound absorption. For these reasons, considerable attention has been devoted recently to the fabrication of foams, which offer the prospect of wider application. Porous metals, ceramic and polymer are commonly used for industrial application in chemistry, mechanical engineering, biotechnology and electronic. The aim of this research is to improve the performance of porous metal, which is aluminum foam, so that they can be used in industry or in certain application.

2.2 Metallic foam

As a new class of structural material, metal foams have good potential in automotive, railway, aerospace and chemical applications where weight reduction, chemical pollutant minimization and improvement in comfort and safety are needed (Nieh *et al.*, 2000). In view of potential applications, metal foams have an extended stress plateau in the compressive stress-strain curve which is effectively for absorbing energy. Currently, there has been increasing interest in using aluminum and steel as metallic foams. In this research aluminum was selected as main material in fabricate foam.

2.2.1 Aluminum foam

Aluminum foams have received a considerable amount of attention because of their advantages such as relatively high stiffness in spite of very low density, excellent noise absorption and vibration suppression, and recycling with ease (Jeon *et al.*, 2009). As with environmental economics, care must be taken to ensure a complete view of the costs and benefits involved. For example, aluminum is more easily recycled than plastic and being one of the most recycled materials in the world. Because of the economic advantages, it is cheaper to recycle aluminum than to mine bauxite ore and manipulate it through the production process to form new aluminum. With remarkable properties of aluminum to resist corrosion compared to other metals, there has been an increasing demand for developing cost effective manufacturing technology. Considering this tendency, aluminum provides environmental and economic benefits to communities and industries across the country. Besides that, aluminum foams have superior performance in terms of energy absorption with respect to polymeric foams, even considering the greater weight per unit volume. For example, aluminum foams have five times larger range of allowable temperature than polymer which is in the limit around 100ºC (Peroni *et al.*, 2008).

2.2.2 Steel foam

Steel is an alloy that consists mostly of iron and has carbon (alloying element) content between 0.2% and 2.1% by weight, depending on the grade. The alloying element which added in the steel is to controls properties of the steel such as the hardness, ductility, and tensile strength. Steel with increased carbon content can be made harder and stronger than iron, but such steel is also less ductile than iron. Besides usage of aluminum, steel also has been used widely in the construction of roads, railways, other infrastructure and buildings. However, the heavy weight condition of the steel limited its application. Concerning this matter, steel foam have been fabricated which resulting in densities less than half that of steel. Park and Nutt (2000) claimed that the steel foams behave much like aluminum foam under compressive loading which both foams show almost identical response in stress-strain compressive curve. Although the densities the steel (3.5 g/cm^3) and aluminum (0.54 g/cm^3) foams are different, the similarity of the two curves is surprising given the vastly different pore structure.

2.2.3 Titanium foam

Titanium is as strong as steel, but 45% lighter. Titanium foams can be used in structural applications such as sandwich core for aerospace vehicles, and at elevated temperatures up to 400 ºC as heat exchanger or catalyst substrate. Considering titanium's unique properties, there are many researchers interested in fabricating titanium foam. For example Esen and Bor (2007) who was fabricating titanium foam using magnesium spacer particles. The impressive property of titanium is biocompatibility which is non-toxic and not rejected by the body. Because it is biocompatible titanium is used in a gamut of medical applications including surgical implements and implants, such as hip balls and joint replacement. However titanium is 60% heavier than aluminum. Thus, researchers make an improvement by produced titanium foam which is lightweight. For example, Singh *et al.* (2009) producing Titanium foams via the space-holder method. They claimed that suitable porosity of titanium foam is important to closely match the permeability values possessed by healthy bone, hence is the most suitable for bone implant applications.

2.3 Application of metallic foam

Metallic foams are a class of materials with very low densities and novel mechanical, thermal, electrical, and acoustic properties. In comparison to conventional solids and polymer foams, metal foams are light weight, recyclable, and non-toxic. Particularly, metal foams offer high specific stiffness, high strength, enhanced energy absorption, sound and vibration dampening, and tolerance to high temperatures. Furthermore, by altering the size and shape of the cells in metal foams, mechanical properties of the foam can be engineered to meet the demands of a wide range of applications. Figure 2.1 shows some potential applications of the metal foams as function of open, partially open and closed pores. The question from which metals or alloys a given type of cellular structure can be manufactured is also important. Structural, load bearing parts have to be light because otherwise they would be made from conventional massive metals or alloys. Therefore, aluminum, magnesium or titanium foams or porous metals are preferred for such applications

(Banhart, 2001). The following section discussed the application of metallic foam in wider technology.

Higher demand for safety of automobiles in accordance with low fuel consumption required weight reduction. This reduction, however, should not take place at the expense of the size of the passenger compartment. One therefore tries to introduce new compact engines or reduce other structures to maintain passenger comfort. This creates new problems with heat dissipation in the engine compartment, because all aggregates are very closely spaced, or with crash safety owing to the reduced length of the crash zones. Metal foams offer a possible solution for some of these problems which summarize the three application fields for metal foams in Figure 2.2.

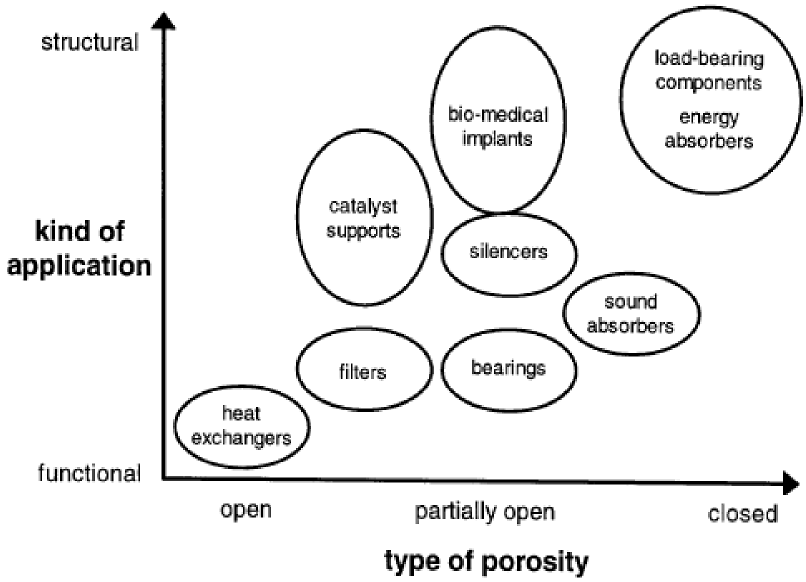

Figure 2.1: Applications of cellular metals grouped according to types of foam (Banhart, 2001).

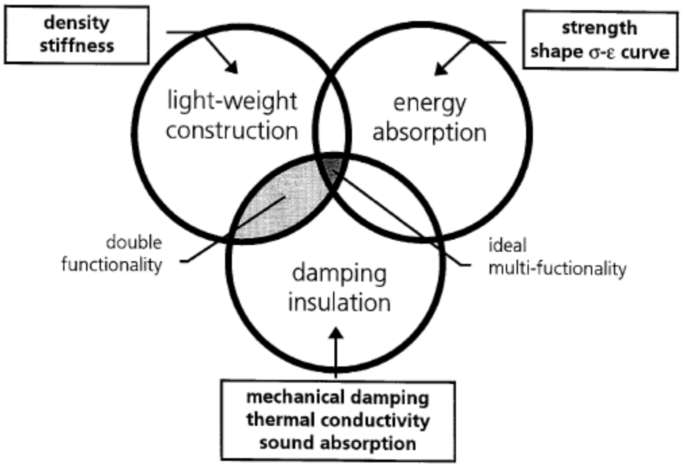

Figure 2.2: Main automotive application fields of structural metal foams (Banhart, 2001).

2.3.1 Lightweight construction

In lightweight construction, metallic foam combined their two properties which are density and stiffness to provide a good structure. This proved that application of foam have been shown to be significantly lighter, while offering notably increased structural rigidity compared with solid metal components. Al foams can be used to optimize the weight-specific bending stiffness of engineering components. The bending stiffness of flat Al foam panels of a given weight, width and length, e.g., is approximately proportional to their thickness, and therefore inversely related to density (Akseli, 2005). Examples of lightweight construction in automotive industry are foam panel for door and floor coatings. In aerospace applications, the replacement of expensive honeycomb structures by foamed aluminum sheets or metal foam sandwich panels could lead to higher performance at reduced costs.

2.3.2 Energy absorber

Aluminum foams display on attractive property in automotive application that is their energy absorption. It has low rebound in dynamic crash situations which has been determined to less than 3% in one study compared with 15% for a polyurethane foams (Banhart, 2001). Homogeneous aluminum foams or syntactic cellular metals show quite good absorption properties since they exhibit a long plateau range in stress-strain compression curve. Examples of applications where foam-filled structures are crushed axially include crash boxes for head-on impacts or under ride protectors for lorries, whereas crashing in the bending mode is involved in A-pillar or B-pillar reinforcements or in other side impact protections. Cymat Technologies has commercialized Stabilized Aluminum Foam (SAF), a revolutionary material with numerous automotive applications. Many potential applications for SAF take advantage of the material's energy absorption capability. One of the promising applications of Cymat Technologies is crash box. As shown in Figure 2.3, crash box is placed between the impact beam and the front rail of the car to absorb medium speed collision energy, thereby reducing repair costs.

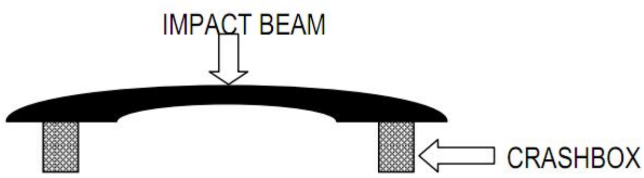

Figure 2.3: Crash box in automotive application (www.cymat.com, 2009).

The benefits of SAF-filled crash boxes include it can absorb more energy than an empty section of similar mass. From Figure 2.4 illustrates the dual actions of SAF in the crash boxes. It can be seen that the crash box foam not only absorb energy, but it also behaves differently which is more folding cause of the impact. This is due to the crash box which has been filled with SAF absorb the energy and prevent the crash box became flat or shallow after the impact. This phenomenon shows that crash box foam absorb more energy than when it is empty (www.cymat.com, 2009).

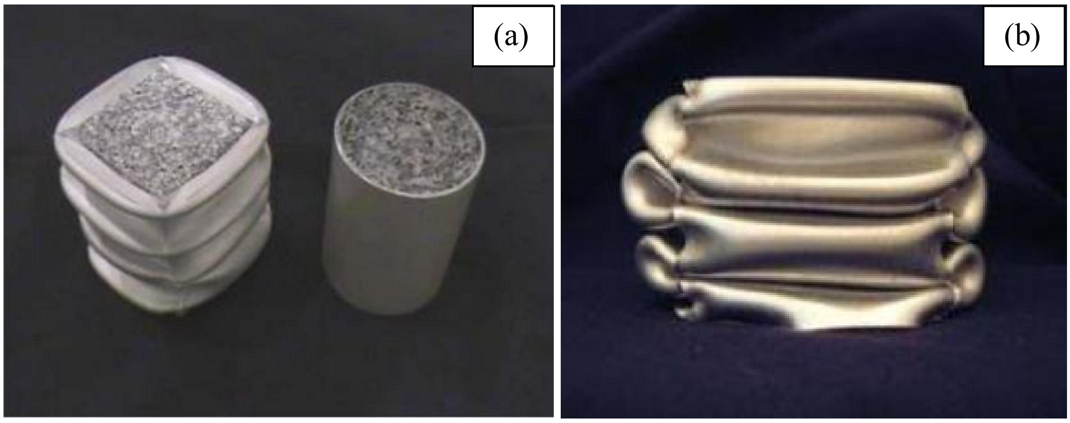

Figure 2.4: Stabilized Aluminum Foam (SAF) a) crash boxes filled with aluminum foam, b) folding behavior of SAF crash box (www.cymat.com, 2009).

2.3.3 Sound Absorber

Besides lightweight construction and energy absorber, sound absorption and insulation is also important part in the automotive industry. Polymer foams are often used for noise control. However, as sound absorber, polymer foam does not heat resistant and self-supporting. Combinations of polymer foams and aluminum foils might be a solution but are often not desirable. Aluminum foams at the current state-of-the-art technology do not exhibit excellent sound absorption properties due to their predominantly closed porosity but are at least heat resistant and self-supporting. Provided that one could sufficiently improve the sound absorption properties, an excellent material for such heat resistant sound absorbers could be obtained. ‘‘Alporas’’ foams are being used as sound absorbers along motorways and other busy roads in Japan to reduce traffic noise and in the Shinkansen railway tunnel to attenuate sonic shock waves. For this purpose, foamed sheets are rolled after foaming and slicing (Banhart, 2001).

2.3.4 Heat Exchangers and Cooling Machines

Porous materials have large surface area, so they have been used conventionally used in heat exchangers and heat sinks. The heat exchanger functions when a fluid is circulated through the open-cell foam which was in contact with some power electronic device that required cooling or heating (Akseli, 2005). In microelectronic devices, compact heat sinks are used for cooling off with a high power dissipation density such as computer chips or power electronics. Metal foams can perform better if they are selected in a way that thermal conductivity is kept as high as possible with their flow resistance maintained as low as possible. Another application field for open cellular materials is transpiration cooling. The high surface area, low flow resistivity and good thermal conductivity of some of the materials used make them promising candidates for such purposes (Banhart, 2001). For example, Metafoam produced product by increasing heat dissipation by more than 65% and maintaining current production processes intact, enables faster, thinner, and lighter products. Metafoam’s heatpipes perform better than high-end commercially available CPU cold plates because the metallic foam's microstructure yields very high surface area which drastically increases contact surface with coolant. The copper foam is cut, shaped and inserted in a copper tube as shown in Figure 2.5. The heatpipes enhances heat pipe capillary force with its unique metal foam wick (www.metafoam.com, 2005).

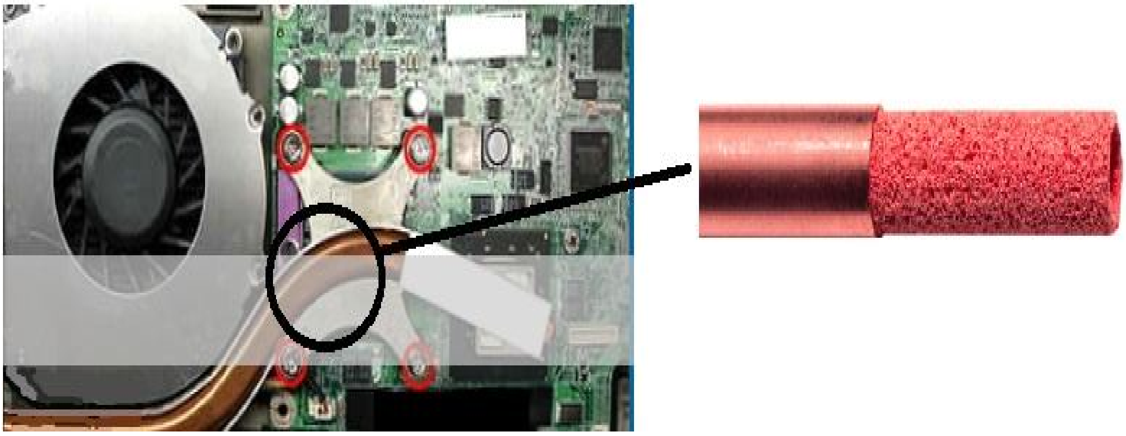

Figure 2.5: Metafoam's heatpipes of copper foam in CPU devices (www.metafoam.com, 2005).

2.3.5 Decorative materials

Besides have been used for indoor sound absorption purposes in entrance halls of public buildings, foam panels are also used because of the interesting visual appearance of the metal foam. It makes a statement as a dramatic new cladding for a feature wall or for cladding the entire exterior of a building (Figure 2.6 (a)). Its metallic luster combined with a variety of finishes, each of which offers a distinctive surface that cannot be exactly reproduced, can add a signature touch to any work of architecture. The foam panel also has fantastic acoustic features. The finishes may be used for creating designer ceilings (Figure 2.6 (b)) (www.inventables.com, 2010).

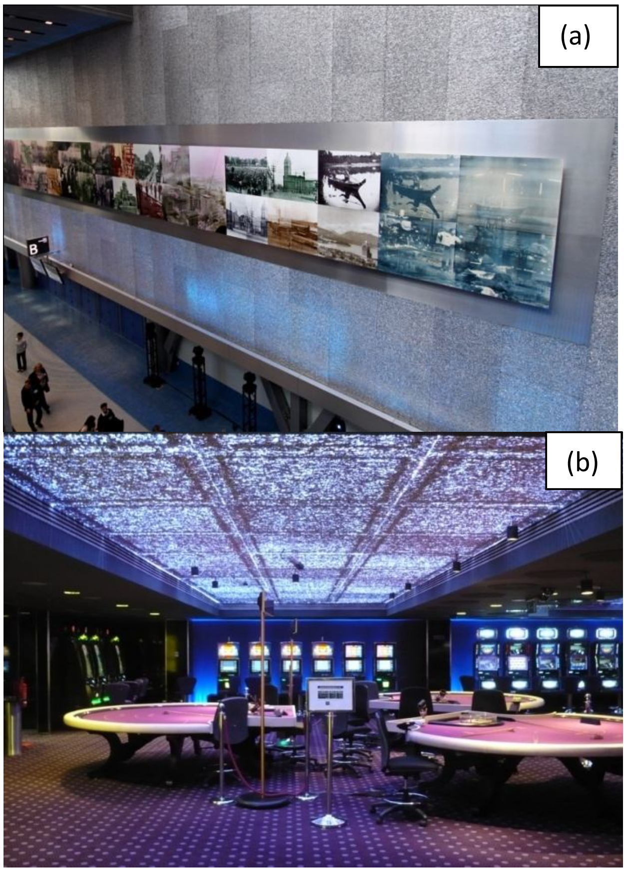

Figure 2.6: Foam panel application as decorative materials; (a) cladding wall, (b) finished ceilings (www.inventables.com, 2010).

2.4 Fabrication methods for aluminum foam

Several methods have been developed for production of metallic foams. Generally, there are four categories of most commonly manufacturing methods in metal foam production, such as melt-gas injection, melt foaming agent, powder compact foaming and investment casting and melt infiltration.

2.4.1 Melt gas injection

Direct injection of gases to molten metal is the simplest method in manufacturing metal foam. The production process is shown in Figure 2.7. Silicon carbide, aluminum oxide or magnesium oxide particles are dispersed within the molten metal to enhance the viscosity of the melt (Banhart, 2000). It is necessary to increase the viscosity of the metal so that it would simply bubble through the molten. Gas is then added under the surface of the molten using a rotating impeller designed to produce small bubbles. The foam which forms on the surface is drawn off, rolled slightly to form flat sheets and cooled. The molten is solidified before the gas bubbles can escape (Curran, 2001). This process can produce parts in large quantities at low cost. However, these parts have relatively large and irregular pores (Manonukul, 2010).

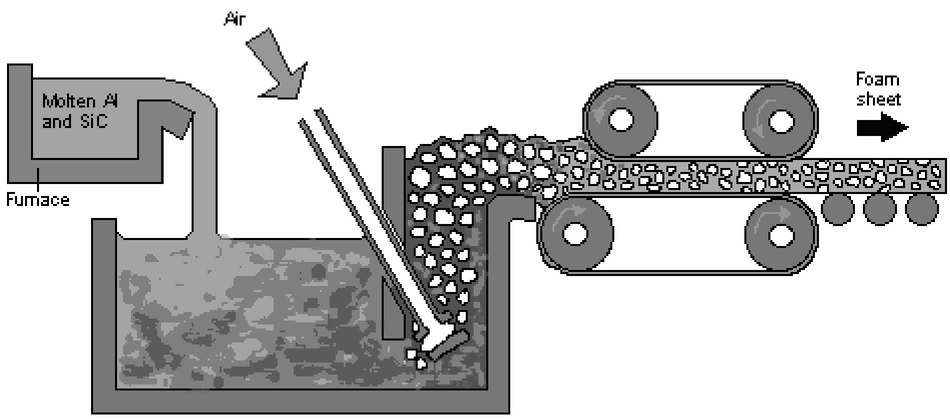

Figure 2.7: The production process of melt gas injection (Curran, 2001)

2.4.2 Melt foaming agent

Instead of injecting gas into melt metal, this method involves on addition of a blowing agent which decomposes under the influence of heat and releases gas which then propels the foaming process. This process is described schematically in Figure 2.8. In the first step, about 1.5 wt% calcium metal is added to an aluminum melt at 680°C. The molten is stirred for several minutes until the viscosity has reached the desired value. Then titanium hydride (TiH_2) is added which serves as a blowing agent by releasing hydrogen gas in the hot viscous liquid (Banhart, 2000). TiH_2 is well suited to this process as it is stable at room temperature, but readily decomposes at temperatures similar to the melting point of aluminum to give off large volumes of hydrogen gas. The process is easily scaled up, but remains expensive and relatively hazardous, due to the use of calcium and the need to handle escaped hydrogen gas (Curran, 2001).

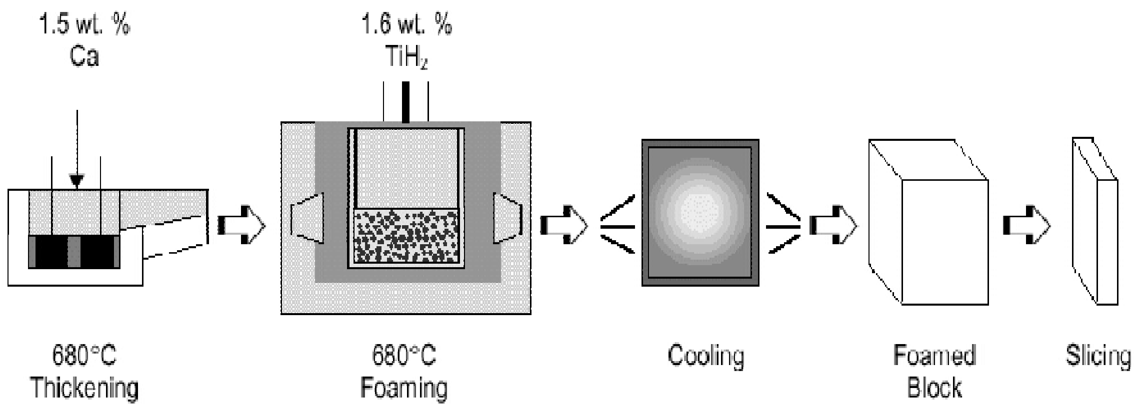

Figure 2.8: The production process of melt foaming agent (Banhart, 2000)

2.4.3 Powder metallurgy

Besides using melting method, metal foams also can be produced by using powder metallurgy method. One of powder metallurgy methods is powder-foaming agent method. The production process begins with mixing metal powder and foaming agent and then compacted into a net-shape preform. In principle, the compaction can be done by any technique that ensures that the foaming agent is embedded into the metal matrix without any notable residual open porosity. The foaming agent, which is homogeneously distributed within the dense metallic matrix, decomposes. The released gas forces the melting precursor material to expand, thus forming its highly porous structure (Banhart, 2000). Another powder metallurgy method is sintering dissolution process (SDP) which introduced by Zhao and Sun, 2001. This method included mixing, compaction, sintering and dissolution process. Different with powder-foaming agent method, SDP method using space holder which produced pores structure after dissolution process.

2.4.4 Investment casting/ Infiltration

A mould is filled with the mould material typically sodium chloride, NaCl, due to its low cost as shown in Figure 2.9. It is then sintered in air and cooled. Molten aluminum is simply poured onto the block to infiltrate the channels. The NaCl preform is held under vacuum while a block of aluminum on the preform is melted and high pressure of an inert gas is applied during subsequent infiltration step. After solidification, the entire structure is then removed from the mould, cooled, and machined to the desired dimensions prior to removal of the NaCl. The

NaCl is subsequently leached by submersion in distilled water to give open-cell foam. This use of pressure during the infiltration step enables foams with cells as small as 50μm to be produced.

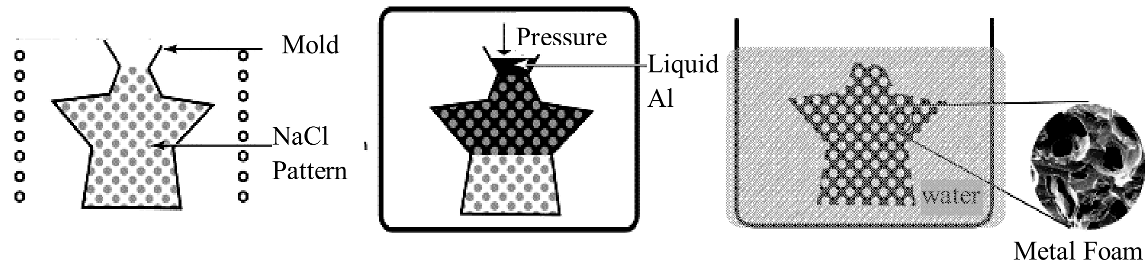

Figure 2.9: The production process of infiltration (March and Mortensen. 2001)

2.5 Sintering Dissolution Process

Sintering dissolution process (SDP) is one of the powder metallurgy routes that can be used in manufacturing metal foam. SDP method was developed by Zhao and Sun on 2001. This method was introduced with the aim to investigate the capabilities of SDP and to study the properties of the foams produced under a range of SDP. A numbers of papers are available in literature concerning SDP as fabricating method (Bafti and Habibolahzadeh, 2010; Bin *et al.*, 2007; Jiang *et al.*, 2005; Michailidis *et al.*, 2011; Surace *et al.*, 2009). Since then, this method appears interesting either in research area or industry.

2.5.1 Steps of Sintering Dissolution Process

SDP method consists of mixing, compaction, sintering and dissolution process. The schematic of SDP method is shown in Figure 2.10. The aluminum powder is mixed thoroughly with space holder. The NaCl particles are used as space holder due to it is easily dissolved in water and cheap. The mixture is compressed and then sintered in furnace with argon atmosphere. The NaCl particle in the preform is removed in hot water to leave behind porous metal foam.

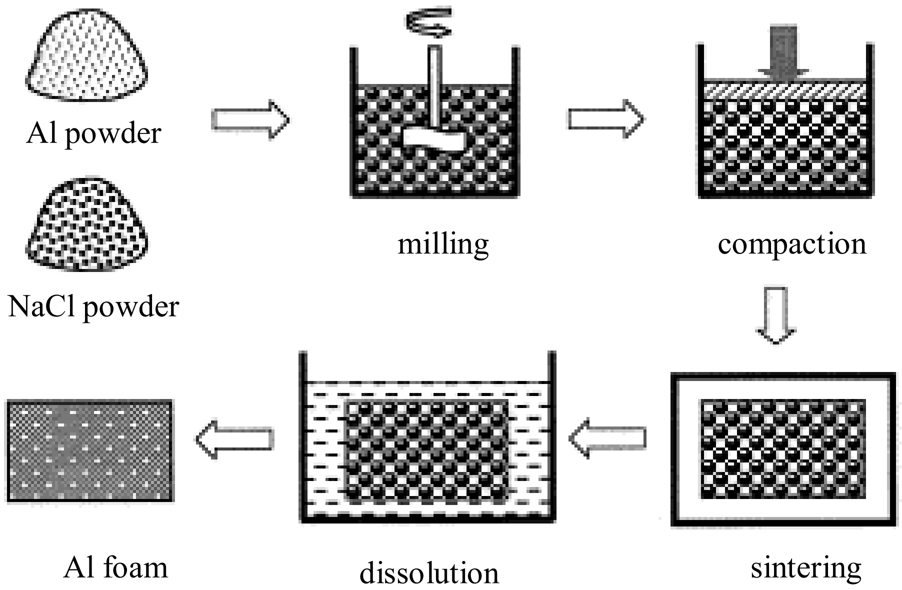

Figure 2.10: Schematic of the sintering-dissolution process for manufacturing Al foams (Zhao and Sun, 2001).

2.5.1.1 Milling Process

Tailored distributions of space holder and aluminum foam during milling process are required to obtain good quality of foams. Due to low cost, chemical inertness in contact with aluminum, relatively high melting point and easily dissolved in water, sodium chloride (NaCl) is often used as space holder (Gaillard *et al.*, 2004). Besides NaCl particles, carbamide powders also have attracted researcher's interests to use this powder as foaming agent. For example, Jiang *et al.* (2005) research have used a novel method for making open cell aluminum foams by SDP. In their study, carbamide was selected as space holder because it has high roundness and smooth surface. To avoid segregation of dissimilar powder and particles, a small amount of binder (2% in weight) was added during the milling process. The commonly used binders are ethanol and methanol.

In fabrication of aluminum foam using space holder method, pore size and shape are predominantly controlled by the foaming agent. An appropriate selection of space holder influences the finish product behavior (Gaillard *et al.*, 2004). Many researchers investigated the effect of controlling the size of foaming agent on the properties of foam. Bin *et al.* (2007), in their research have studied the effect of pore size and relative density on mechanical properties of aluminum foam by preparing five different sizes of space holder (0.20-0.45, 0.45-0.66, 0.66-0.90, 0.90-1.60. and 1.60-2.00 mm). They concluded that the properties of foams increased with the increasing pore size. They claimed that foam with lower density exhibit a longer and flatter plateau.

Density and porosity of porous material leads to enhanced specific properties. Generally, foams have a porosity of 20%-90% (Ishizaki *et al.*, 1998). SDP is the most suitable process for fabricating Al foam with relative densities between 15% and 50% (Zhao and Sun, 2001). Based on their research, foam with relative density below 15% is not practical to be produced because the aluminum particles are largely in isolated patches rather than a continuous network. Meanwhile, foams with relative density greater than 50% may results in residual NaCl particles in the foam structures. In Jiang *et al*. (2005) research, they produced foams with porosities between 50% and 80%. They reported that space holder can be removed entirely after dissolution process when the porosity was above 65% which caused interconnected pores. However, when porosity was greater than 80% the sample collapsed during dissolution process. They described that porosity and relative density of foam were depended on foaming agent. In this research, aluminum foams were fabricated using 20, 40, 60, and 80% of space holder which theoretically results 15%-50% of relative densities.

2.5.1.2 Compaction Process

Compaction of aluminum and NaCl particles mixture powder is carried out to obtained green body into required shape and easy handling for further process. Green body has a low strength and can damage easily. Green body for porous materials requires low green density and homogenous packing of particles. Thus, the powder must be fed properly into the die cavity. In order to achieve homogenous packing of particles, fluidity of powder is the most influential factor in packing the powder into the die. A powder with low fluidity cannot be distributed uniformly. Thus, to obtain