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## A NOVEL SINTERING-DISSOLUTION PROCESS FOR MANUFACTURING Al FOAMS

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### Introduction

Al foams have found increasing applications in a wide range of structural and functional products, due to their exceptional mechanical, thermal, acoustic, electrical and chemical properties [1–3]. Al foam structures have densities only fractions of that of a solid structure and therefore have high specific strength and stiffness. They also have excellent properties for impact energy, vibration and sound absorption. Examples of their applications include lightweight panels for building and transport against buckling and impact, non-flammable ceiling and wall panels for thermal and sound insulation. Open cell foams can also be used as heat exchangers, filters and catalyst carriers. The applications of Al foams on a large scale are likely to be in the automotive industry with an aim to improve the vehicle crashworthiness and thus passenger safety.

There currently exist a wide range of manufacturing methods [1–3], which can generally be grouped into five categories according to the forms of the precursory Al and the types of the pore-forming agents, namely melt-gas injection, melt-foaming agent, powder-foaming agent, investment casting and melt infiltration. However, the Al foams produced by these methods are either too expensive due to the high production costs or too poor in quality due to poor controllability in pore structure and porosity. As a consequence, the commercial applications of Al foam components are still limited. With a rapidly increasing demand for high quality Al foams, there has been a growing need for developing cost effective manufacture technologies.

This paper describes a new sintering-dissolution process (SDP) for manufacturing net-shape, open-cell Al foams, characterises the porosity, microstructure and compressive properties of the foams produced under a range of SDP conditions, and discusses the capabilities of SDP.

### Experimental Procedure

SDP consists of the mixing, compacting, sintering and dissolution stages as shown schematically in Fig. 1. The raw materials are Al and NaCl powders. The particle sizes of the Al powder are not critical but generally required to be smaller than 1 mm. The particle sizes of the NaCl powder depend on the intended pore sizes of the final foam. The Al powder is first mixed thoroughly with the NaCl powder at a pre-specified volume or weight ratio. The resultant Al/NaCl powder mixture is compacted into a net-shape preform under an appropriate pressure. The preform is then sintered at a temperature either

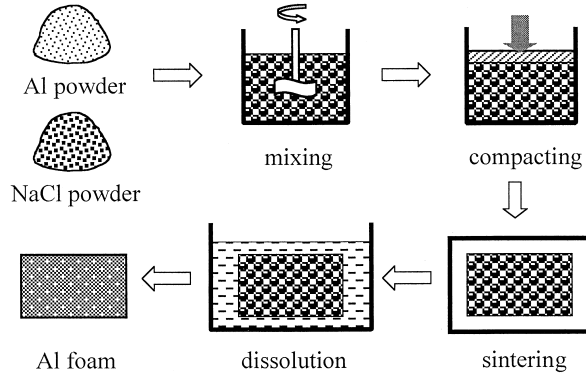


Figure 1. Schematic of the sintering-dissolution process for manufacturing Al foams.

above or below the melting point of Al (660°C) but far below that of NaCl (801°C). After the Al in the preform forms a well-bonded networked structure, the preform is cooled to room temperature. The imbedded NaCl particles are finally dissolved in water, leaving behind an open cell Al foam with the same chemical composition as that of the original Al powder.

In manufacturing the Al foam specimens, a commercial purity gas atomised Al powder with particle sizes below 450 μm and a commercial purity NaCl powder with nodular particles and particle sizes of 300-1000 μm were used. The two powders were mixed thoroughly at different weight ratios with the Al weight fractions in the range 0.20–0.75. The mixtures were compacted into preforms in steel moulds using a hydraulic press with a pressure typically of 200 MPa. The preforms, together with the moulds, were sintered in an electric furnace at 680°C for 180 min and were then allowed to cool to the room temperature. The sintered specimens were removed from the moulds and placed into a warm, running water stream for 45 min to dissolve the NaCl particles embedded in the Al matrices.

For each specimen, the weights of the initial Al powder, the NaCl powder, a sample cut from the sintered Al/NaCl preform, and the resultant Al foam were measured using a balance to an accuracy of 0.01g. The size of the foam was also measured to determine its volume and hence its density. The fraction of the residual NaCl in the Al foam with respect to the total NaCl in the initial Al/NaCl preform, φ, was determined by:

$$\phi = \frac{W_f - W_p f_{Al}}{W_p (1 - f_{Al})} \tag{1}$$

where  $W_f$  and  $W_p$  are the weights of the Al foam and the corresponding pre-dissolution Al/NaCl preform respectively, and  $f_{Al}$  is the Al weight fraction in the initial Al/NaCl powder mixture. In order to give a direct indication of the porosity of the Al foam, the foam was characterised by relative density, which is the ratio of the density of the foam to that of the bulk Al. Theoretically, the relative density is equivalent to the volume fraction of Al in the initial Al/NaCl preform, if the preform is 100% dense and all the NaCl particles in the preform are completely dissolved away in the dissolution stage. The theoretical relative density of the resultant foam, ρ, was therefore calculated from the Al weight fraction in the preform by:

$$\rho = \frac{f_{Al} \rho_{NaCl}}{f_{Al} \rho_{NaCl} + (1 - f_{Al}) \rho_{Al}} \tag{2}$$

where  $\rho_{Al} = 2.70 \text{ kg/m}^3$  and  $\rho_{NaCl} = 2.17 \text{ kg/m}^3$  are the Al and NaCl densities respectively.

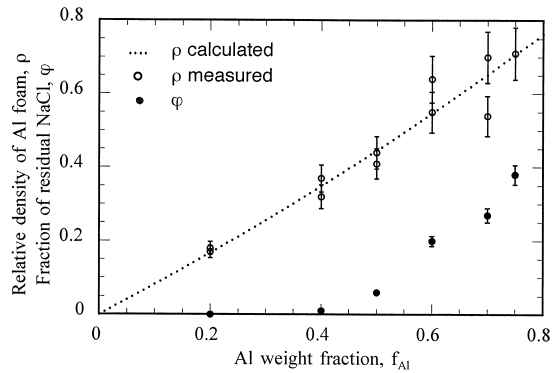


Figure 2. Relationship between relative foam density, fraction of residual NaCl and Al weight fraction.

The microstructure of the foam specimens was examined by a Hitachi S-2460N scanning electron microscope (SEM). The compression tests of the specimens were conducted on an Instron4505 materials testing system at a crosshead speed of 1 mm/min. The specimens for the compression tests were 20 mm in diameter and 20 mm in height.

### Results and Discussion

It was demonstrated in the experiments that net-shape Al foam components can be produced in SDP by either liquid or solid state sintering. In liquid state sintering, the sintering temperature was higher than the melting point of Al. The Al particles in the Al/NaCl preform all melted and became a continuous liquid pool filling up the spaces between the solid NaCl particles. Because of the poor wetting and the difference in density between liquid Al and solid NaCl, the molten Al tended to separate with the NaCl particles. Without physical confinement, the molten Al would ooze out from the preform under gravitational and capillary forces. A mould must be used during sintering to maintain the preform geometry. Solid state sintering was conducted without using a mould, because the sintering temperature was lower than the melting point of Al. However, it required a strict control over the processing conditions, such as the physical and chemical characteristics of the Al powder and the sintering environment. Further work is needed to evaluate and compare the benefits of the liquid and solid state sintering approaches.

Fig. 2 shows the variations of the theoretical and measured relative densities of the Al foam,  $\rho$ , and the fraction of the residual NaCl in the Al foam,  $\varphi$ , with the Al weight fraction in the initial Al/NaCl powder preform,  $f_{Al}$ . The theoretical relative density was calculated by equation (2), assuming that the initial Al/NaCl preform was 100% dense and all the NaCl particles in the subsequently sintered preform was completely dissolved away. In practice, however, there was always some air trapped in the Al/NaCl preform during compaction, leading to a lower relative density than the theoretical value. In most cases, the NaCl particles in the sintered preform could not be dissolved completely. Some NaCl particles remained in the resultant foam, leading to a higher relative density than the theoretical value. As a consequence, there was often a considerable difference between the calculated and measured relative densities.

The amount of trapped air in an Al/NaCl preform is determined by the particle morphology and size of the Al and NaCl powders as well as the compacting pressure. Under the current compacting conditions, the effect of trapped air is not significant. The effect of the residual NaCl in the foam on

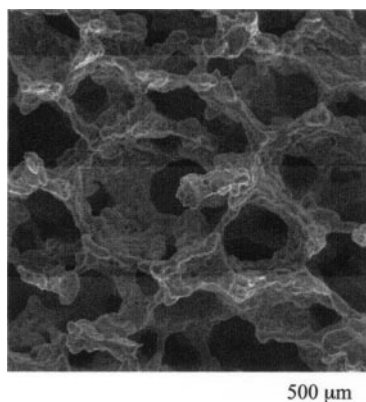


Figure 3. SEM micrograph of a typical Al foam manufactured by SDP.

the relative density of the foam, however, cannot be neglected. A sintered Al/NaCl preform can be seen as a composite of Al matrix with embedded NaCl particles. With a high volume fraction of NaCl in the preform, most NaCl particles are in contact with each other and form a continuous three-dimensional network. Because all the NaCl particles in the network can be dissolved away by water, there is only small amount of residual NaCl in the resultant foam. In contrast, with a low volume fraction of NaCl in the preform some NaCl particles are enclosed completely by the Al matrix. These isolated NaCl particles cannot be dissolved away and remain in the foam. Increasing Al weight fraction in the Al/NaCl preform decreases the NaCl volume fraction and therefore increases the amount of residual NaCl in the final Al foam. Fig. 2 shows that residual NaCl in the foam was very small when the Al weight fraction in the preform was below 0.4. When the Al weight fraction was increased to 0.5, 0.6, 0.7 and 0.75, the fraction of the residual NaCl in the foam with respect to the total NaCl in the initial preform increased to 0.06, 0.20, 0.27 and 0.38, respectively. The relative density of the foam with a high Al weight fraction in the initial preform was therefore expected to be higher than the theoretical value. The measured relative densities of the foams at Al weight fractions  $>0.6$ , however, were not always higher than the calculated ones and showed greater variations between individual measurements. This might be because the Al distributions in the Al/NaCl preforms were not uniform and consequently the local Al weight fractions of the samples were somewhat different from those of the whole specimens from which the samples were cut.

SDP is most suitable for manufacturing Al foams with relative densities between 0.15 and 0.5. Within this range, the residual NaCl in the foam is less than 10% of the total NaCl in the initial preform. The relative foam density can be controlled with reasonable accuracy by mixing Al and NaCl powders at a pre-specified weight ratio based on equation (2). It is difficult to obtain a relative foam density below 0.15 by SDP, because the Al particles in the Al/NaCl preform with a low Al weight fraction are largely in isolated patches rather than a continuous network. At a relative density greater than 0.5, the Al foam contains more than 10% of the initial NaCl. The residual NaCl may result in undesirable corrosion of the Al matrix, degrading the mechanical and chemical properties of the foam.

Fig. 3 shows the SEM micrograph of a typical Al foam with an Al weight fraction in the initial Al/NaCl preform of 0.2. The foam has a homogeneous structure with open pores and pore sizes in the range 300-1000  $\mu\text{m}$ , which represent the particle characteristics of the original NaCl powder. It is demonstrated that the morphology and sizes of the pores in the foam can be easily controlled by selecting an appropriate NaCl powder. It is also possible to obtain a purposely tailored distribution of

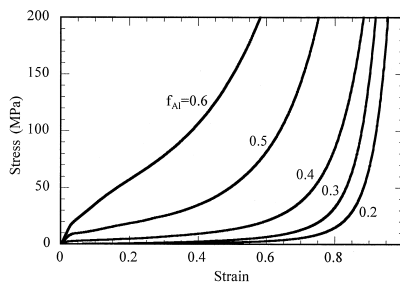


Figure 4. Compressive stress-strain curves of Al foams with different Al weight fractions.

pore size or relative density in the foam by using NaCl powders with different particle size ranges or by varying the local Al weight fraction in the Al/NaCl preform.

Fig. 4 shows the compressive stress-strain curves of the Al foams with Al weight fractions in the initial Al/NaCl preforms of 0.2, 0.3, 0.4, 0.5, and 0.6 respectively, which correspond to theoretical relative foam densities of 0.17, 0.26, 0.35, 0.45 and 0.55 respectively. The curves are generally characterised by an initial elastic response, followed by a deformation “plateau” with a positive slope and finally a transition to densification. The stress at the macroscopic yield point and the subsequent plateau stress at a certain strain increase with increasing relative foam density. One of the characteristics of the foams manufactured by SDP is a very smooth plateau region in the stress-strain curve, as a result of the homogeneously distributed pores having a narrow size range.

The microstructural and mechanical characteristics of the Al foams manufactured by SDP are largely affected by the sintering temperature and time for a certain NaCl powder and a fixed Al/NaCl volume ratio. Sintering temperatures lower than 640°C resulted in poor or no bonding between the Al particles, leading to foam disintegration during dissolution or subsequent handling. Temperatures higher than 700°C, however, increased the flowability of the molten Al, which resulted in partial separation of the Al/NaCl mixture and hence a non-uniform distribution of local relative density. Similarly, sintering times shorter than 120 min were not sufficient to ensure good bonding. On the other hand, sintering times longer than 360 min may lead to significant oxidation of the Al matrix or undesirable redistribution of the molten Al within the preform. The preliminary experimental results suggested that the optimum sintering temperature and time are likely to be in the ranges 640–700°C and 120–360 min respectively.

### Summary

A novel process, SDP, has been developed for manufacturing Al foams. In SDP, Al and NaCl powders are first mixed at a specified ratio and compacted into a preform. The preform is then sintered below the melting point of NaCl. An Al foam is obtained after the NaCl particles embedded in the sintered preform are dissolved away by water. SDP is capable of producing low-cost, net-shape Al foams with controlled pore morphology, size, distribution and porosity. SDP is a very promising technology for manufacturing Al foams with relative densities in the range 0.15–0.5 and has great potential for industrial applications.

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