MECHANICAL PROPERTIES AND ENERGY ABSORPTION OF CERAMIC PARTICULATE AND RESIN-IMPREGNATION REINFORCED ALUMINIUM FOAMS

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ABSTRACT

The mechanical properties of aluminium foams can be improved by matrix reinforcement and resin-impregnation methods. In the present study, aluminium foams were reinforced by both ceramic particulate reinforcing of the aluminium matrix and resin-impregnating pores. The mechanical properties and the energy absorption of the reinforced aluminium foams were investigated by dynamic and quasi-static compression. Results indicated that the ceramic particle additions of CBN, SiC and B4C in aluminium foams increase the peak stress, elastic modulus and energy absorption of the aluminium foams, under both conditions of dynamic and quasi-static compression. Moreover, the aluminium foams with and without ceramic particle additions exhibited obvious strain rate sensitivity during dynamic compression. Furthermore, the resin-impregnation improves the mechanical properties and energy absorption of aluminium foams significantly. However, aluminium foams with resin-impregnation showed negligible strain rate sensitivity under dynamic compression. It is reported that both the ceramic particle addition and resin-impregnation can be effective techniques to improve the mechanical and the energy absorption properties of aluminium foams.

1. INTRODUCTION

Aluminium foams possess a unique combination of physical, mechanical, thermal, electrical and acoustic properties. In particular, they are lightweight and show excellent energy absorption. This makes them attractive in applications where crashworthiness and weight are critical, e.g. automotive industry and construction materials [1-3]. Many efforts for the improvement in quality of metal foams have been made over the past 10 years. However some deficiencies such as non-uniformities and imperfect mechanical properties in aluminium foams should be improved [4,5]. The mechanical properties of aluminium foams can be improved by matrix reinforcement e.g. adding fine ceramic particles or alloying elements in the base powder in the powder metallurgical route [5,6].

Esmaeelzadeh et al [6] reported the foaming behaviour and compression properties of AlSi–SiC containing various amounts of SiC particle with different particle sizes. Addition of SiC particles changed the properties of precursor material and the cell structure and furthermore the compressive behaviour of metal foams. The smaller SiC particles improve foamability and the foam stability. Foams with SiC particles show more brittle behaviour during loading compared to AlSi7 foams. Weigand [7] indicated that the combination of base material and ceramic particle can affect the foaming behaviour. The addition of SiC particles to P/M aluminium foams increases linear expansion and compressive strength whilst drainage and cell coarsening rate reduce [5]. It is believed that the mechanical properties of aluminium foams can be influenced by the particle size and volume fraction [8,9] and the addition of fine ceramic particles would be benefit to improve it.

On the other hand, there was little attention paid to the contribution of the gas phase in the pore to overall properties of the foam [10]. The mechanical properties of the foam would be significantly enhanced if the gas phase is substituted by a stiffer or higher damping phase. From this consideration, an epoxy resin was used to fill open cell aluminium foam in the present study. It is expected that the impregnation can provide the new composite with improved mechanical behaviour and energy absorption capacity.

In the present work, three types of fine ceramics, cubic boron nitride (CBN), silicon carbide (SiC) and boron carbide (B4C) were chosen as additions to enhance the performance of Al foams. Various amounts of ceramic particle were blended with aluminium powder to produce aluminium foams in powder metallurgical route. For the impregnated aluminium foams, aluminium foams were prepared by the infiltrating cast with salt (NaCl) preform and then impregnated with an ‘infusion grade’ epoxy resin. The effects of the ceramic particles addition and resin impregnation on the deformation behaviour and mechanical properties of the foam composites under dynamic and quasi-static compressive loading were investigated.

2. EXPERIMENTAL

In the present work, aluminium foams reinforced by various ceramic additions with different porosities were produced by a powder metallurgical process, i.e. the so-called space-holding sintering method [11,12]. The characteristics and morphology of the starting materials are summarized in Table 1 and Figure 1. The method consists of the following four steps: mixing, compacting, sintering and leaching. Firstly the starting materials, i.e.
aluminium powder and ceramic particles were thoroughly mixed together using a ball milling system. Space-holding particles (NaCl) then were added. After the ingredients mixed together homogeneously, the mixture were then poured into a mould and compacted into green compacts with sizes of 20 mm×50 mm×15 mm at a pressure of 200 MPa for 30 min. The green compacts were subsequently sintered into composites at a temperature near the melting point (660°C) of aluminium under an argon gas atmosphere. The sintering process consists of 2 h preheating to reach the temperature of 660°C, 4 h holding at 660°C and cooling down to the room temperature. Thereafter, the composites were placed into a hot running water bath to leach out the embedded space-holding particles (NaCl), leaving behind an aluminium foam with a porous structure.

Table 1. Characteristics of starting powder materials

<table>
<thead>
<tr>
<th>Name</th>
<th>Purity (%)</th>
<th>Size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>99.7</td>
<td>45</td>
</tr>
<tr>
<td>B₄C</td>
<td>98.0</td>
<td>5</td>
</tr>
<tr>
<td>CBN</td>
<td>97.0</td>
<td>5-10</td>
</tr>
<tr>
<td>SiC</td>
<td>98.5</td>
<td>5</td>
</tr>
<tr>
<td>NaCl</td>
<td>99.9</td>
<td>500-800</td>
</tr>
</tbody>
</table>

Figure 1. Morphology of starting powders

For the preparation of the resin impregnated aluminium foam samples, aluminium foams with various porosities and large cell size were prepared by the infiltrating cast with salt (NaCl) preform first. Subsequently, these foams were infiltrated with an ‘infusion grade’ epoxy resin, L285 and matching amine hardener H287.

Quasi-static compressive tests were conducted using a MTS 100 kN material testing system with control software at a strain rate of 1×10⁻³ s⁻¹. Compressive samples with sizes of 10 mm×10 mm×20 mm were cut from large sample plates. The load – displacement relationships were recorded. The peak stress was measured as the stress reached at the onset of the plastic collapse on the stress-strain curve. The energy absorption was calculated from the integrated area under the quasi-static stress-strain curves up to 50 % strain [13,14].

Stress-strain behaviour at a dynamic strain rate was characterized using the Split Hopkinson Pressure Bar method (SHPB). In the present study, the stress-strain rate sensitivity of the aluminium foam samples was evaluated using the SHPB testing at a strain rate range from 0.2×10³ s⁻¹ to 1.9×10³ s⁻¹. Compressive samples with sizes of Ø12 mm×6 mm were cut from large sample plates. At least three specimens for each sample were tested in the same test condition to guarantee the reliability of results.

3. RESULTS AND DISCUSSIONS

3.1 Effects of Ceramic Particle Additions on the Mechanical Properties

Aluminium foams with fine ceramic particle additions of B₄C, CBN and SiC were produced by a powder metallurgical process to investigate the effect of ceramic addition on the mechanical properties of foams. Aluminium foams with various ceramic addition ratios of 10 % and 15 % (based on the weight of aluminium powder, hereafter mass %) with 70% porosity and cell

Figure 2. Quasi-static stress- strain curves of the aluminium foams with the ceramic additions
size of 500-800 µm were fabricated in the present investigation. Both quasi-static and dynamic compressive tests were conducted to evaluate the mechanical properties and the strain rate sensitivity of aluminium foams.

The quasi-static stress-strain curves of the investigated aluminium foams are shown in Figure 2. It can be seen that the plateau stress of the aluminium composite foams increased with the increased ceramic additions. The stress-strain curves of the ceramic particle reinforced composite foams also showed more fluctuation in the plateau region compared to pure aluminium foam. The stress-strain curves showed the most fluctuating with B₄C addition and the smoothest effect with CBN addition.

Table 2 summarise the characteristics, peak stress, elastic modulus and energy absorption of the aluminium foams reinforced with and without the ceramic particle reinforcement. The peak stress, elastic modulus and the energy adsorption of the aluminium foams reinforced with ceramic particle additions increased significantly with the increasing of ceramic particle additions. In particular, the aluminium foam (porosity 70 %) with 15 % CBN particle addition showed the best energy absorption of 19.4 MJ/m³, compared to that without ceramic reinforcement of 10.9 MJ/m³. SiC particle additions showed a moderate reinforcement effect on the energy absorption of 15.2 MJ/m³; whilst the B₄C particle additions showed a minor reinforcement effect on the energy absorption of 11.9 MJ/m³.

Table 2. Characteristics of Al foams reinforced with ceramic additions

<table>
<thead>
<tr>
<th>Ceramic addition</th>
<th>C (wt.%)</th>
<th>P (%)</th>
<th>σ_max (MPa)</th>
<th>E (GPa)</th>
<th>W (MJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>0</td>
<td>70</td>
<td>5.9</td>
<td>5.9</td>
<td>10.9</td>
</tr>
<tr>
<td>B₄C</td>
<td>10</td>
<td>70</td>
<td>8.5</td>
<td>8.0</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>70</td>
<td>9.2</td>
<td>9.7</td>
<td>11.9</td>
</tr>
<tr>
<td>CBN</td>
<td>10</td>
<td>70</td>
<td>7.8</td>
<td>7.8</td>
<td>14.3</td>
</tr>
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<td>70</td>
<td>8.4</td>
<td>8.4</td>
<td>19.4</td>
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<td>SiC</td>
<td>10</td>
<td>70</td>
<td>7.0</td>
<td>8.1</td>
<td>13.0</td>
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<tr>
<td></td>
<td>15</td>
<td>70</td>
<td>8.5</td>
<td>9.1</td>
<td>15.2</td>
</tr>
</tbody>
</table>

* C: Ceramic additions based on Al powder weight; P: Porosity; σ_max: Peak stress; E: Elastic Modulus; W: Energy absorption

The dynamic stress-strain behaviour of the aluminium foams with three kinds of ceramic particle additions were evaluated using the SHPB testing at a strain rate range from 0.2×10³ s⁻¹ to 2.0×10³ s⁻¹. Figure 3 shows the stress – strain curves at a dynamic strain rate from 0.5×10³ s⁻¹ to 1.8×10³ s⁻¹ for the aluminium foam samples. It can be seen that for the aluminium foam samples with and without the ceramic particle additions of SiC, B₄C and CBN, the plateau stress increased with increasing of strain rate as shown in Figure 3(a), (b), (c) and (d) respectively. It can be concluded that the aluminium foams with and without ceramic particle additions showed obvious strain rate sensitivity.

3.2 Effects of Resin Impregnation on the Mechanical Properties

The quasi-static stress - strain curves of the aluminium foams with porosities of 60 % and 70 % and with and without resin-impregnations are shown in Figure 4. The cell size of aluminium foams ranges from 1.0-2.5 mm. It
can be seen that all the aluminium foam samples with and without resin-impregnation showed the typical deformation behaviour for metal foams, i.e. the three deformation regions of the initial elastic region, followed by a plateau region and finally the densification region. In particular, the stress-strain curves of the aluminium foam samples with resin-impregnation exhibited a more stable plateau deformation region and an increased plateau stress for the aluminium foams with porosities of 60% and 70%. It can also be seen that the aluminium foams with resin-impregnation experienced higher energy absorption during compression due to the higher plateau stress. Table 3 lists the mechanical properties and energy absorption of the aluminium foams with and without resin-impregnation. It can be seen that the peak stress of the resin-impregnated aluminium foam samples was nearly 10 times of that of the foam sample without resin impregnation.

**Figure 4.** Stress – strain curves of aluminium foams with and without resin-impregnation

**Table 3.** Mechanical properties and energy absorption of aluminium foams with and without resin-impregnation

<table>
<thead>
<tr>
<th>Al foam</th>
<th>P (%)</th>
<th>$\sigma_{\text{max}}$ (MPa)</th>
<th>E (GPa)</th>
<th>W (MJ/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No impregnation</td>
<td>60</td>
<td>6.9</td>
<td>2.0</td>
<td>25.6</td>
</tr>
<tr>
<td>Resin impregnation</td>
<td>70</td>
<td>72.8</td>
<td>18.6</td>
<td>159.3</td>
</tr>
</tbody>
</table>

* P: Porosity; $\sigma_{\text{max}}$: Peak stress; E: Elastic Modulus; W: Energy absorption

For resin impregnated aluminium foams, the elastic modulus increased nearly 9 times compared to the aluminium foams without resin impregnation. The energy absorptions of the aluminium foams without resin impregnation were 25.6 MJ/m$^3$ and 22.6 MJ/m$^3$ with porosities of 60% and 70%, respectively. For resin impregnated aluminium foams, the energy absorption for the samples with porosities of 60% and 70% were 159.3 MJ/m$^3$ and 150.2 MJ/m$^3$ respectively. These values are nearly 6.5 times that of foam sample without resin impregnation. The resin impregnation enhanced the energy absorption significantly. From Table 3, it can be...
concluded that the resin impregnating is an effective way to improve the energy absorption capability and mechanical properties of aluminium foam materials.

The stress-strain rate sensitivity of the aluminium foams with resin impregnation were evaluated using the SHPB testing in a strain rate range from $0.5 \times 10^3 \text{ s}^{-1}$ to $1.9 \times 10^3 \text{ s}^{-1}$. Figure 5 shows the stress - strain curves for the aluminium foam samples tested at a dynamic strain rate from $0.5 \times 10^3 \text{ s}^{-1}$ to $1.9 \times 10^3 \text{ s}^{-1}$. For the aluminium foam samples without the resin impregnation, it can be seen that the stress increased obviously with the increasing of the strain rate as shown in Figure 5 (a) and (b). For the foam samples with a porosity of 60%, the samples were tested at two strain rates, $0.45 \times 10^3 \text{ s}^{-1}$ and $1.54 \times 10^3 \text{ s}^{-1}$. The foam sample exhibited a higher stress at the strain rate of $1.54 \times 10^3 \text{ s}^{-1}$ that that at the strain rate of $0.45 \times 10^3 \text{ s}^{-1}$. For the sample with a porosity of 70%, the samples were tested at the strain rates of $1.46 \times 10^3 \text{ s}^{-1}$ and $1.80 \times 10^3 \text{ s}^{-1}$. The stress - strain curves exhibited the same tendency of an increasing stress with the strain rate. It can be concluded that the aluminium foams without resin impregnation exhibited obvious strain rate sensitivity.

On the other hand, the resin-impregnated aluminium foam samples showed different deformation behaviour under dynamic compressive testing. The strain rate showed no obvious influence on the stress - strain curves for the resin-impregnated aluminium foam samples, as shown in Figure 5(c) and (d). The resin-impregnated foam samples showed very similar dynamic deformation porosities of 60% and 70%, as shown in Figure 5(c) and (d), respectively. The stress - strain curve for the sample with a porosity of 60% under the strain rate of $0.8 \times 10^3 \text{ s}^{-1}$ almost overlapped that of the sample tested at the strain rate of $1.9 \times 10^3 \text{ s}^{-1}$; similarly, the stress - strain curve for the sample with a porosity of 70% under the strain rate of $1.6 \times 10^3 \text{ s}^{-1}$ overlapped that of the sample tested at the strain rate of $1.9 \times 10^3 \text{ s}^{-1}$. Therefore, it can be concluded that the resin-impregnated aluminium foam samples showed insignificant strain rate sensitivity.

4. CONCLUSIONS

Ceramic particle additions such as B4C, CBN and SiC on aluminium foams can be of benefit to increase the peak stress and elastic modulus of aluminium foams, and furthermore to improve their energy absorption. In particular, among the three kinds of ceramic particle additions, the CBN additions to the aluminium foams showed the most significant effect on the energy absorption properties of the foam; SiC additions showed a moderate effect; whilst the B4C showed a minor energy absorption enhancement. The aluminium foams with and without ceramic particle additions showed obvious strain rate sensitivity.

The resin impregnated aluminium foams exhibited much higher stress and elastic modulus, therefore, much higher energy absorption during compression compared to pure aluminium foams. However, the resin-impregnated aluminium foams showed insignificant strain rate sensitivity.

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References