Enhancement of mechanical properties of porous aluminum by silica sand particles

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Abstract. Porous aluminum was fabricated using space holder process. The spherical carbamide powder and silica sand were used as space holder and reinforcement materials, respectively. Aluminum powders were mixed with five different silica sand contents and were then mixed with 10 wt.% carbamide powder. The mixed powders were cold compression at 400 MPa and sintered at 550 °C for 5 hours. Microstructure of specimen was characterized by scanning electron microscope. Hardness and compressive strength were also investigated in this study. It was found that microstructure and mechanical properties of porous aluminum strongly depended on silica sand contents. From SEM observation, it is clearly seen that addition of silica sand led to increasing pore in the porous aluminum. Mechanical properties of porous aluminum can be enhanced by silica sand particle reinforced.

1. Introduction
During last two decades, porous aluminum has become an attractive topic in materials science research and also in the industry, especially in the automotive industry [1]. These are owing to their unique mechanical and physical properties such as high strength to weight ratio, light weight, high energy absorption and sound absorption [2]. Although, it has the excellent mechanical properties as mentioned earlier its strength is not appropriate for some engineering applications. Therefore, it is necessary to improve its mechanical property for fulfilling the demands. One promising method for improvement of porous aluminum strength is reinforced with particles. Several elements have been successfully used for enhancing of dense aluminum mechanical property i.e. copper, magnesium, silicon, scandium, alumina, silica sand and so on[3-9]. It is well known that the competition in an industry is relatively high, especially in terms of the product price. Thus, to sustain their business, all the companies need to reduce the manufacturing cost. From this point of view, silica sand has become a promising reinforcement material because it is extremely cheap compared with the other reinforcement particles. On the other hand, many researchers have found that the hardness of dense aluminum increased more than one time when silica sand was added [8-9]. However, it should be noted here that it has rarely been used in porous aluminum which has relatively less grain boundary. Recently, porous aluminum can be produced by various processes such as melt gas injection, melts with blowing agents, casting around space holder material, powder compact process. It has found that those processes have limitation on the controlling the pore shape and distribution [10]. Therefore, space holder method has become a promising method because the morphology of pore can be controlled more precisely [11-13]. This fabrication method involves four steps, e.g. mixing based material with space holder particles, compaction, remove space holder particles and sintering. Carbamide powder is one of the most widely used space holder materials because it is cheap and easy to purchase. Therefore, carbamide powder is selected as space holder material in this study.
In the present work aimed to improve mechanical properties of porous aluminum by reinforced with silica sand particles. Microstructure and mechanical properties of porous aluminum will be systematically studied.

2. Experimental procedure

High purity aluminum powder with a purity of 99.9 % and mean particle size of 44 µm supplied by Supbon Co., Ltd. was used as a starting material. The aluminum powder used in this study has an irregular shape as shown in Figure 1 (a). Silica sand powder from Trad province, Thailand was used as a reinforcement material. The received silica sand was firstly cleaned by water to remove impurity, dried, mechanical grounded for refining the particle size and then sieved with a 300 µm sieve, respectively. Spherical carbamide powder with an average particle size of 2.4 mm was used as space holder material. Morphologies of silica sand and carbamide powders were shown in Figure 1 (b) and (c), respectively.

In order to produce porous aluminum, the aluminum powder was firstly mixed with 5, 10, 15 and 20 wt.% silica sand powder by mixing machine at a constant mixing speed of 100 rpm for 4 hrs. Then the mixed silica sand/aluminum composite powders were continuously mixed with 10 wt.% carbamide powder by mixing machine under the same mixing speed for one more hour. In this study, the high purity aluminum powder was also mixed with 10 wt.% carbamide powder under the same mixing conditions for comparison. After that, all mixed powders were compacted in a cylinder die with a constant pressure of 400 MPa at room temperature. Subsequently, green compacted specimens were removed space holder materials by placed in ultrasonic water bath at 80 °C for 1.5 hrs. Afterward, the green porous were sintered at 550 °C for 5 hrs with a heating rate of 10 °C/min. After sintered, the specimens were furnace cooled to room temperature. The microstructure of porous aluminum was characterized by LEO 1450 VP scanning electron microscopy. Specimens for microstructure analysis were prepared by mechanical polishing using 600, 800, 1200 and 2000 grit SiC papers, followed by ached in a solution of 6 vol.% nitric acid (HNO₃), 12 vol.% hydrochloric acid (HCl), 1 vol.% hydrofluoric acid (HF) and 81 vol.% distilled water for 15 seconds. Density and porosity of porous aluminum were calculated using the classical equation 1 and 2, respectively.

\[
\rho_s = \frac{W_d}{W_w - W_z} \times \rho_{\text{water}} \tag{1}
\]
\[ \text{Porosity} = (1 - \frac{\rho_s}{\rho_T}) \times 100 \]  
\[ \rho_T = \rho_{Al} V_{Al} + \rho_{sand} V_{sand} \]  

Where Wd is dry weight of specimen, Ww is weight of suspended specimen in the water, Ws is weight of saturated specimen, \( \rho_s, \rho_{Al} \) and \( \rho_{sand} \) are density of specimen, aluminum and silica sand (density of aluminum and silica sand are 2.7 and 2.65 g/cm\(^3\), respectively), \( V_{Al} \) and \( V_{sand} \) are volume fraction of aluminum and silica sand, respectively.

Hardness test was measured using microhardness tester model Innova test Europe BV equipped with 10 mm Brinell indenter at 100 kgf of a load. Hardness test was conducted randomly at five different points per one specimen. The average hardness value was computed from three values exclude the minimum and maximum values. The compressive test was carried out by a 10 kN load universal testing machine with a cross head speed of 1 mm/min. The specimens used for the compression test were prepared according to ASTM E9-89a that is 13 mm in diameter and 25 mm in height.

3. Results and discussion

3.1. Density and porosity

Density and porosity of porous aluminum plotted as a function of silica sand content is shown in Figure 2. It can be seen from this figure that the density gradually decreased with increasing amount of silica sand. This is attributed to silica sand has lower density than aluminum. Therefore, it causes a decreasing in porous aluminum density when increases silica sand powder content. It was also found that porosity of porous aluminum increased with increasing silica sand content. Similar observations have been found in silica sand/aluminum composite fabricated by powder metallurgy route [7-9]. This may cause by silica sand is incredibly harder than aluminum. Thus, silica sand probably not plastically deform like aluminum during the compaction process. Moreover, it is also had a different thermal expansion and shrinkage with aluminum. So, that may cause pore between aluminum and silica sand interface.

![Figure 2. Density and porosity of porous aluminum versus amount of silica sand.](image)

3.2. Microstructure evolution

Microstructure of porous aluminum at various silica sand contents are shown in Figure 3. It can be seen clearly from Figure 3 that the specimens consisted of rounded pores with an average pore size of 2.4 mm, which is same as the initial characteristic of the carbamide particles. This is attributed to the decomposition of carbamide particles during the space holder removal process caused the pores in specimen. Thus, the morphology of pores was similar with space holder materials. These results
indicated that the shape and size of pores in porous metallic materials fabricated by this method can be controlled by morphology of space holder materials.

![SEM micrograph of porous aluminum-silica sand (a) 5 %wt. and (b) 10 %wt. silica sand](image)

Figure 3. SEM micrograph of porous aluminum-silica sand (a) 5 %wt. and (b) 10 %wt. silica sand (8x).

In order to investigate the influence of silica sand powder on microstructure evolution in porous aluminum, the microstructure observation was performed with a higher magnification at the cell wall regions. SEM micrographs of cell wall porous aluminum at different silica sand content ranging from 0 wt.% to 20 wt.% are shown in Figure 4 (a) – (e), respectively. Porous aluminum without silica sand has high density (Figure 4 (a)). Microstructure of porous aluminum with addition of 5 wt.% in Figure 4 (b)) showed that the specimen consisted of uniformly second phase distribution. Second phase particles had well bonded with aluminum matrix. With increasing silica sand to 10 wt.%, voices between silica sand and aluminum bonding surface was observed (Figure 4 (c)). Amount of voices at the interface second phase particle regions increased with an increasing silica sand content (Figure 4(d) and (e)). These results obviously indicated that increasing amount of silica sand is lead to increase amount of pore in aluminum. This results is well consisted with the porosity measurement results (Figure 2).

![SEM micrographs of porous aluminum at various silica sand contents: (a) 0 wt.% (b) 5 wt.% (c) 10 wt. % (d) 15 wt. % and (e) 20 wt. % silica sand](image)

Figure 4. SEM micrographs of porous aluminum at various silica sand contents: (a) 0 wt.% (b) 5 wt.% (c) 10 wt. % (d) 15 wt. % and (e) 20 wt. % silica sand (50x).

3.3. Hardness

The hardness of the porous aluminum is plotted as a function of silica sand content in Figure 5. The hardness of porous aluminum enhanced from 15.12 HB to 17.35 HB when added 5 wt. % silica sand. Hardness continuously increased with increasing amount of silica sand up to 15 wt.%. Future increasing silica sand particles, the hardness decreased to 20 HB. It can be seen from this results that
the hardness of porous aluminum is strongly depended on the silica sand content. Hardness of porous aluminum enhanced 75% when added 15 wt.% of silica sand.

**Figure 5.** Hardness of porous aluminum versus amount of silica sand.

### 3.4. Compressive test

The compressive stress-strain of porous aluminum at five different silica sand contents is shown in Figure 6. The compressive stress-strain curve of porous aluminum exhibited three different stages that is linear elastic deformation, plateau deformation and densification deformation stage, which is usually observed in the porous metallic materials \[11,12,14\]. Compressive strength of porous aluminum showed the similar trend with hardness test results. That is the strength increase with increasing silica sand content up to 15 wt.% and then slightly decreased with future increasing of silica sand particle. The increasing of strength in porous aluminum when silica sand was added is caused from the present of second phases inhibited dislocation motion and harden material. These results indicated that the mechanical property of porous aluminum can be enhanced by addition of silica sand particles.

**Figure 6.** Compressive stress-strain curves of porous aluminum at different amount of silica sand.

### 4. Conclusions

Porous aluminum was synthesized by space holder method by using spherical carbamide powder as space holder material. Silica sand particles were purposely added to enhance mechanical properties of porous aluminum. The influence of silica sand content on microstructure evolution and mechanical properties of porous aluminum were investigated. The main results obtained from this study are summarized as follows:
1. The density of porous aluminum decreased and porosity increased with increasing of silica sand content.
2. The debonding of silica sand particle with aluminum matrix was observed when added silica sand above 5 wt.%
3. Hardness and strength of specimens were increased with increased amount of silica sand up to 15 wt.% silica sand and then decreased with future increasing of volume of silica sand. Mechanical properties of porous aluminum enhanced 75 % when added 15 wt.% silica sand particles.

5. References
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