RESEARCH ARTICLE

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Manufacture of Functional Open-cell Al Foams with Recycled Al Scraps using NaCl Ball Space Holder

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Interconnected open-cell Al foams, with various fractions of recycled Al alloy scrap, have been produced using a sintering and dissolution process (SDP). The foams are suitable for various functional applications, such as heat exchangers, bone-replacement implants, interconnects, catalyst supports, and sound insulators. Firstly, the NaCl paste was pelletised, by hand, to make spherical balls of approximately 5 mm diameter. The Al alloy scrap was obtained from turning operation in lathe machine. Porous structure was obtained after dissolution of the NaCl balls. The microstructure of Al foams was examined using SEM and EDX. The results show that pores were uniformly distributed along Al matrix and interconnected with surrounding pores. The compressive strength of the foams with small scrap content of 20 wt.% is increased. However, when scrap content is higher, the strength is decreased, as a result of incomplete thermal bonding between Al powder and scrap particle, and excessive oxide content in foam microstructure.

Introduction

Metal foams have attracted many industries, owing to their outstanding properties; such as large energy absorption, high specific strength and stiffness, light weight, large surface area and high damping property [**1**]. The structure of foams can be classified into closed- and open-cell porous structure, which is important to application selection. The closed-cell foam is suitable for structural application at which high strength and energy absorption are required. Open-cell foams are used in functional applications for which a requirement of high strength materials is not demanded, such as heat exchangers, bone-replacement implants, interconnects, catalyst supports, and sound insulators. There are many processing methods to produce metal foams. The sintering and dissolution process (SDP) approach is a powder metallurgical technique that is widely used for manufacture of open-cell metal foams [**2,3**]. This method has advantages of pore morphology control, for cell shape, cell size and cell distribution, by which mechanical property of foam can be tailored. In the SDP process, NaCl particle is typically used as space holder material. The drawbacks of SDP are a long dissolution time for complete elimination of NaCl and possible corrosion of base metal from residual NaCl in foam structure. In addition, the use of angular NaCl particle, particularly for small pore of < 1 mm, results in lower mechanical property, when is compared with spherical NaCl [**4**]. There are many ways to produce NaCl with spherical shape [**4-8**]. Among these, the process to pelletise spherical NaCl balls by hand is the simplest, flexible and economical method [**7**].

Although metal foam clearly presents many outstanding properties and benefits, the utilisation of metal foam is not widespread as expected, very much due to its high relative cost. The cost of metal foam can be several times higher than conventional metals. One method of cost reduction is by using recycling metal waste from manufacturing industry. Many researchers have tried to produce metal foams from scrap or use scrap as additional material [**9-12**]. The scraps, mostly aluminium, are derived from the machining of semi-finished metal products. However, there is no prior report of employment of these recycled Al scrap in production of open-cell foams with spherical NaCl.

Therefore, the present research aims to produce open-cell Al foams by replacing a conventional Al with recycled Al alloy scrap on the SDP process, with the use of spherical NaCl space holder. The effect of scrap addition at various contents on microstructure and mechanical property of the foams was examined.

Experimental

The as-received pure atomised Al powder, with a purity of 99.95% and a mean particle size of 106 μm, was supplied from Ecka Granules. The Al alloy scrap was obtained from a milling factory in Thailand. The dirt and grease of scrap were removed using acetone. The scrap was ground using a ball milling machine, for 120 min, followed by cleaning and drying in air. The powder mixture was made by weighing and mixing Al powder with 0, 20, 50 and 100 wt.% ground scraps. Salt balls, of approximately 5 mm, were made from mixing ground NaCl powder with tapioca starch, polyethylene glycol (PEG) and water. The thick paste of mixture was pelletised to make spherical balls. The green balls were then sintered at 750°C for 60 min, in air, to increase their strength.

To prepare for a compact sample, the mixture of Al powder and ground scraps was mixed with NaCl balls in a volumetric ratio of 50%. Initially, the salt balls were placed in a 22 mm diameter tool steel die, lubricated with magnesium stearate suspended in acetone. The powder mixture was then poured into the die, followed by small manual shaking. The uniaxial compaction was performed at a compaction pressure of 600 MPa. Compacts were placed in a tube furnace heated up to 700°C, and held for 180 min, in N_2 atmosphere. Dissolution of NaCl balls was implemented in hot water for at least 60 min.

The density of samples was determined by measuring dry mass and cylindrical dimensions. The X-ray fluorescence (XRF) was employed to determine the chemical compounds of scraps. Foam samples were sectioned for microstructural investigation, using a high precision cutting machine. A standard metallography of Al alloys was carried out for grinding, polishing and etching of samples. Microstructural examination of foam structure was conducted using both optical and JEOL JSM 6400 scanning electron microscope (SEM), equipped with energy dispersive X-ray spectroscopy (EDX). Compressive mechanical testing was performed on the samples using an AG-100 kNXplus Shimadzu universal mechanical testing machine at a crosshead speed of 1 mm/min. Each test was stopped at approximately 80% compressive strain or when the samples were largely fractured.

Results and discussion

Fig. 1 presents as-received metal scraps and the scraps after grinding. The scraps were ground into a randomised shape with particulate sizes of 0.5 - 1.5 mm. No agglomeration of the scraps was observed. The chemical composition of scraps is shown in **Table. 1**. The major alloying elements of the scraps compose of Si, Fe, Mg, Na and Ca, which is similar to the alloy content of ADC12 alloy. It should be noted that the Si content is slightly higher than the eutectic composition in the Al-Si binary phase diagram.

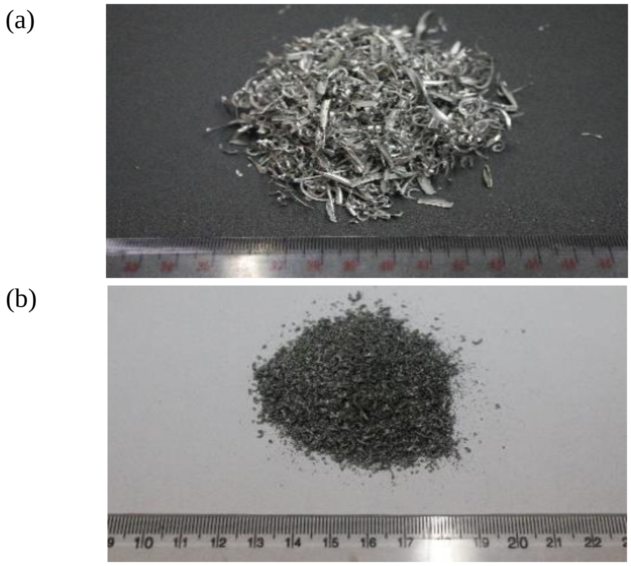


Fig. 1. (a) As-received scraps. (b) Ground scraps.

Table 1. Chemical composition of scraps.

Chemical composition (wt.%)							
Al	Si	Fe	Mg	Na	Ca	Cl	K
Bal	13.3	1.05	0.471	0.428	0.402	0.195	0.17

The macrostructure and surface morphology of salt balls are presented in **Fig. 2**. It can be seen that the salt balls were loose and not attached to each other. No cluster of the balls was also observed. The salt balls mostly have spherical shape. The distortion of the shape was resulted from pelletisation by hand and sintering effect. The neck formation and bonding between ground NaCl powders were clearly seen in **Fig. 2b**, as a result of diffusion through sintering process. The NaCl ball then has higher strength and can resist higher compaction pressure than the green ball.

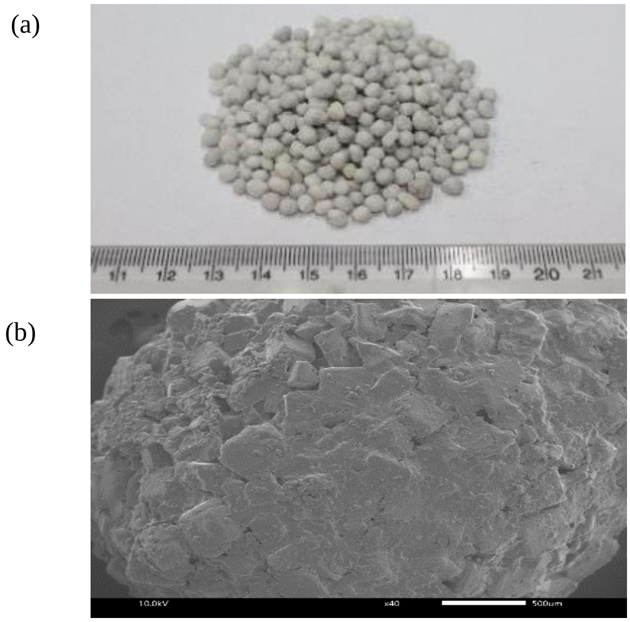
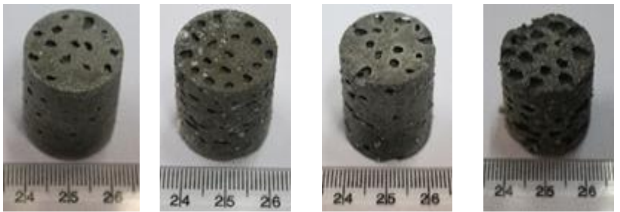


Fig. 2. Sintered NaCl balls showing (a) macrostructure (b) surface morphology.



0 wt.%	20 wt.%	50 wt.%	100 wt.%
ρ^* = 57%	ρ^* = 55%	ρ^* = 50%	ρ^* = 49%

Fig. 3. Al foam samples with (a) 0 wt.% (b) 20 wt.% (c) 50 wt.% (d) 100 wt.% scraps.

Fig. 3 exhibits open-cell Al foam samples with different scrap contents. The relative density of the foams is between 49 and 57%. It should be noted that the limit for the highest porosity produced using the SDP method is approximately 70%, depending upon the shape and size of space holders. In all cases, the foam samples have interconnected porosity from dissolved salt balls. A slight damage of the foams was found in the samples with 50 and 100 wt.% scraps. The examination inside the foam samples revealed that there was a small trace of NaCl entrapped in porous microstructure and the pore shape was not spherical, in the direction perpendicular to the compaction force, but rather slight flattened with a circular profile. This effect is stronger when higher compaction pressure is applied. Several cracks were observed in the samples, particularly for samples with higher scrap content. This is likely due to incomplete bonding between scrap and Al powder and among scrap itself. The scrap contains high oxide content which obstructs thermal bonding of Al.

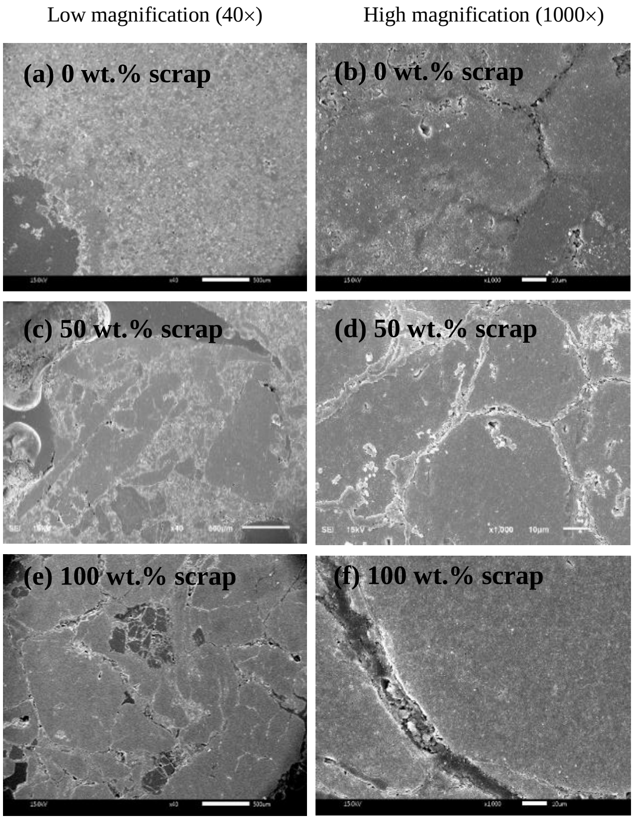


Fig. 4. SEM micrographs showing Al foam samples with (a) (b) 0 wt.% (c) (d) 50 wt.% (e) (f) 100 wt.% scraps.

The microstructures of open-cell Al foam samples with various scrap contents are presented in **Fig. 4**. The Al foam shows a clean Al matrix with little oxide. A clear change in foam microstructure is observed when the scraps were added. The Al foam samples with scrap exhibit a large number of oxide, appearing as white particles, on the matrix surface. The oxide tended to form a cluster, mainly distributed along grain boundary. In the foam samples with scrap, the EDX analysis showed a high content of Si and O, and a small content of Cl. The presence of Cl is as a result of incomplete dissolution of salt balls. The microstructure of Al foam samples with scrap exhibited several cracks along grain boundary, which are interfacial space between particles, indicating incomplete thermal bonding among Al particles and fine scraps.

Fig. 5 shows the compressive mechanical behavior of Al foams with various scrap contents. The compressive plot of Al foam without scrap is of typical of that in open-cell metallic foam, exhibiting three different regions which can be identified as linear elastic deformation, plastic plateau region and densification. However, in all cases of Al foams with scrap addition, the plateau region tends to be fluctuated and the stress was reduced after the yield point, indicating brittle mechanical behaviour of the foams. The Al foams with scraps have higher yield strength than the foam without scrap. The highest yield strength of 15.7 MPa was found in the Al foam added with 20 wt.% scrap. It is known that the compressive strength is strongly dependent on intrinsic properties of foam material, foam density type of cellular structure, pore morphology and pore connectivity. An enhanced compressive strength in Al foams with scraps is mainly due to the presence of eutectic Si hard phase. Moreover, the addition of scraps in foams resulted in more volumetric fraction of alloy content, yielding to an increase in foam density, of equivalent foam volume.

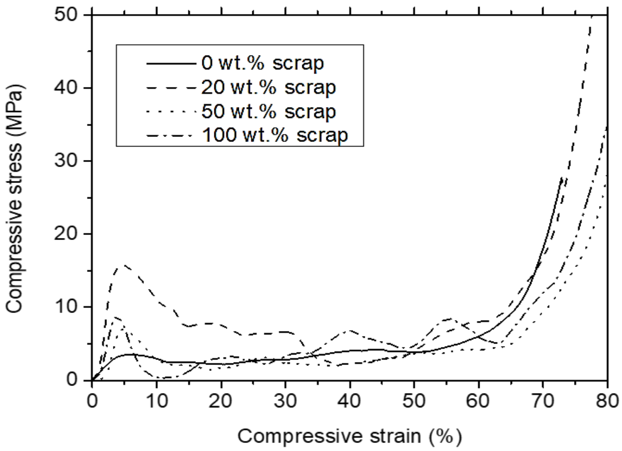


Fig. 5. Compressive behaviour of Al foams with 0, 20, 50 and 100 wt.% scrap contents.

Nevertheless, the benefit of scrap addition can be reduced as a result of the presence of defects in foam microstructure. This can be seen for the foams with 50 and 100 wt.% scraps which have a significant decrease in compressive strength after the yield point. The defects, as cracks at particle interface, were formed by incomplete thermal bonding during sintering process, due to a high content of oxide in the scrap. Typically, the surface of scrap is covered with a high oxide content, due to their relatively large surface area to volume ratio. Additionally, the oxide content also increased after the grinding of scrap, as the new oxide film can be formed. With high oxide content, the ground scrap became more difficult for complete sintering, resulting in the formation of crack between Al powder and scrap particle.

The present research work has demonstrated that open-cell Al foams can be produced using Al alloy scraps through a replication method with NaCl ball space holder.

An improvement in mechanical property can be largely obtained from the alloy property in scrap. However, complete sintering, with proper sintering temperature, holding time and atmosphere, as well as addition of oxide reducing agent are essential to successful production of these foams with increasing mechanical property.

Conclusion

Manufacture of open-cell Al foams with recycling Al alloy scraps has been successfully conducted with salt ball space holder. The pore is slight flattened with a circular profile, due to high compaction pressure, and replicated to the morphology of salt ball, which is interconnected to other salt balls. Compared with the Al foam without scrap, the foams with scrap have higher compressive yield strength as a result of the presence of eutectic Si hard phase in the scrap. However, the benefit of scrap addition is reduced when there is incomplete thermal bonding between Al powder and scrap particle, and excessive oxide content in foam microstructure, leading to decreasing mechanical property.

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Author's contributions

Conceived the plan: S.A.; Performed the expeirments: S.A., K.N., K.J.; Data analysis: S.A., K.N., K.J.; Wrote the paper: S.A. Authors have no competing financial interests.

Keywords

Aluminium alloy, NaCl, recycle, porous metal.

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