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COMPARISON OF MECHANICAL AND ELECTRICAL PROPERTIES OF FOAMS FABRICATED BY THE METHODS OF SINTER FOLLOWED COLD PRESS AND HOT PRESS

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ABSTRACT

Spherical carbamide and salt (NaCl) has been employed to produce aluminum foams by space holder technique via powder metallurgy route in Cold Press - sintering and Hot Press as individual parameters. The effect of different processing parameters such as applied space holder volume, sintering temperature and time, on compression, bending and electrical properties of the resultant foams has been evaluated. Aluminum foam samples with 65, 70 and 75vol. % porosity were successfully produced. The results indicate that the appropriate compressive properties of foams are achieved under 400MPa compacting pressure, sintering temperature and time of 630°C and 2 hours, respectively. Morphological variations were monitored by scanning electron microscopy. Mechanical properties were measured by compressive tests.

Keyword: foams, sinter process, cold pressing, hot pressing.

INTRODUCTION

Aluminum foams have recently attracted considerable attention in both academia and industry because of their exceptional mechanical, thermal, acoustic, electrical properties for structural applications, such as energy absorption, the most important considerations are porosity, specific strength, ductility in compression and cost. The overwhelming majority of metal foams in the market are therefore Al foams manufactured by liquid or semi-liquid foaming technologies. [1-4].

Several methods exist for the production of Al-foams which can be grouped into five categories according to the form of the Al (melt or powder) and the type of the pore-forming agent, namely melt-gas injection, melt-foaming agent, powder-foaming agent, investment casting and melt infiltration. The gas expansion methods (by addition of a foaming agent that decomposes at a suitable temperature), usually leads to close cell structures [5-10]. For open-cell structures, removable internal patterns or space holders are necessary. Space holder techniques are particularly common in powder metallurgy and offer a wider range of structure and properties compared to liquid infiltration techniques. Space holders can be removed in a number of ways, e.g. by shaking, leaching or by pyrolysis. Several space-holder materials are proposed in literature such as NaCl particle, carbamide (urea) or carbonate particles [11-15].

Production of foam by SDP technique is confined, as NaCl particles are generally irregular and also it takes a long time to dissolve in hot water and sintering stage [16]. The space holder technique using carbamide or ammonium bicarbonate has also succeeded in the studies to produce metallic foams [17-18]. The advantage of this method, compared to SDP, is less time-consuming during dissolution stage, ease in complete elimination of the spacer from the foam, and less contamination and no corrosion of the base metal, as is expected in SDP method by NaCl spacer [19]. In this article, production of aluminum foam by spherical carbamide spacer has been experienced and compares property of foam produced via hot press method. Influence of different processing parameters on mechanical properties of the resulted foam has been studied.

EXPERIMENTAL

Aluminum MERCK art. No.1056 and sodium chloride (NaCl) (99.0%, 100-200μm) were used as raw materials. Sodium Chloride and Al were ball-milled in a stainless steel jars for 15 h with ball to powder weight ratio of 20:1. Ball-milling was performed in a planetary ball-mill with jar speed of 270 rpm. The powders were then mixed in different ratios to obtain various densities (65%, 70% and 75%). Mixtures were charged into a hot-press mold (high speed steel) with dimensions of 5mm×20mm×10mm. A special novel method was applied as following: the hot-pressing was performed at different temperature of 300, 400 and 500°C under the pressure of 400 MPa in argon atmosphere. Salt (NaCl) was removed from hot-pressed samples by soaking the samples in boiling water for 2 h.

The weight of aluminum/carbamide mixture was constant and equal to 40g, in all experiments. The mixing of the powders was performed in a rotary mixer for 2 h. Ethanol (2vol. %) was sprayed on carbamide nodules before mixing stage, to obtain a sticky surface for adhesion of aluminum particles. This promoted uniform distribution of aluminum powder over carbamide nodules. The mixture was uniaxially compacted in a steel die to produce compacts of 30 mm diameter. A series of compacting experiments were carried out by changing the compacting pressure from 200 to 400MPa. In order to determine the suitable compacting pressure and its influence on the green density of the compact, three specimens; Al-65wt. % carbamide, pure aluminum, and pure carbamide was produced under 400 MPa compacting pressures. Porosity percentage of the foam was changed from 65% to 75vol. %, to evaluate the flexibility of the method. Mean particle size of the carbamide granulates in

these experiments was 2mm and. Height of the compacts was considered as a criterion for foamability of the green compacts, since weight of the mixtures and diameter of the compacts were fixed at 40 g and 30 mm, respectively.

Carbamide content of the compacts was dissolved by immersing the samples in a genteelly stirring water bath at 25°C. Then the samples have been washed by ethanol and dried in an oven at 40°C for 2 h. Weight of the immersed sample was assessed every 15min to determine Dissolving trend of the carbamide. Specimens were removed from the water bath at regular intervals, and weighed after drying in an oven at 40°C for 2 h to determine the amount of leached carbamide. The practice was repeated until the weight of the samples became fairly stable. The dissolving time of carbamide was measured for three types of samples containing 65, 70 or 75wt% carbamide. Porosity of the resulted foam, Pf, after dissolving stage, was calculated as follow:

$$\text{Porosity} = (1 - (\rho f / \rho s)) \times 100$$

where, ρf and ρs are densities of the green foam and bulk aluminum (2.7 g/cm^3 for pure aluminum), respectively. The density of the aluminum foams, ρf was calculated by measuring the weight and the volume of each compact; the volume was determined from physical dimensions. [20-22]. Microstructures of the aluminum foams were examined by Philips XL30 scanning electron microscope (SEM) operating at 25 kV. The compressive tests of the specimens were conducted on an Extras Materials Testing System (version 4.08) at a crosshead speed of 1 mm/min. The dimensions of the specimens for the compressive tests were 20mm in length, 10mm in width and 5mm in thickness. Effect of the heating (hot-pressing) on the raw materials was examined by X-ray diffraction using a Philips (30 and 25mA) a diffractometer with CuK_ radiation (λ = 1.5405 Å).

The compacts were dried in an electrical oven at 60°C for 6 h to ensure fully removal of their moisture before sintering stage. Sintering stage of the samples was carried out in a muffle electrical furnace at 630°C at 1h.

Electrical conductivity of the foams was measured using a two-probe resistivity measurement apparatus. The probes were glued to specimen by silver paste. For each current measurement across the specimen, the voltage drop between the probes was also measured and the electrical conductivity was calculated using the following equation where "*I*" is electrical current across the specimen, *L* is distance between two probes, *A* is cross-section area of the specimen and *V* is voltage drop between the probes.

$$\sigma = \frac{i.l}{\Delta V.A}$$

RESULT AND DISCUSSIONS

Uni-axial compressive tests were performed on the aluminum foams with different microstructures at the same strain rate. It should be noted that the compressive loads were applied along directions perpendicular to the pressing directions. The engineering stress-strain curves of the hot pressed aluminum foams with 65%, 70%, 75% interior porosity sintered at 873K are shown in Figure-3. Stress-strain behavior of aluminum foams prepared by above mentioned method is similar to that of other metal foams (23, 24). This behavior can be characterized by introducing three distinct regions: stress rises linearly with strain at low stresses (elastic deformation), followed by a long deformation plateau during which the cell walls buckle and collapse, and then a densification regime where the cell walls come in contact one with another, causing an abrupt rise in the flow stress. All samples show similar curve as Figure-3. In this figure, the first section corresponds to the elastic deformation of Al foam. In this section stress has a linear relation with strain. The slope of this section is known as elastic module. At the end of this section, plastic deformation begins. The intersection of the 1st and 2nd sections is well known as yield point. The 2nd section is collapse plateau. Here, the plastic deformation and the fracture of cell wall are progressed simultaneously. So, the stress generated in the 2nd section is not increased after reaching the yielding point. The slope of this section corresponds to collapse rate. All samples have a fixed slop at this section, meaning that, there is equilibrium between collapsing and work hardening of Al foam. The final section is densification. The foamed aluminum deforms as a solid material. Due to the brittle behavior of Al foams, they all fractured at the end of experiment. The surface area under stress-strain curve corresponds to the toughness.

In a given porosity, all mechanical properties increase with increasing temperature, except for collapsing rate. This is due to the more densification at higher temperatures. Applying load and temperature during hot-press leads to higher diffusion and more interfaces between the Al particles. On the other hand, at higher temperatures, by increasing interface between particles and strength of pores wall, collapse rate decreases. Increasing porosity at constant temperature leads to undesired mechanical properties.

The advantages of this method will be more clarified when it is compared with the results of other researches. Maximum yield point obtained in other researches is 5-20MPa (25, 26) while minimum yield point of 19.4MPa was obtained in our work. In fact, the dense layer formed on the surface of the foam is responsible for improvement of yield point. It implies that a great deal of the load has been exerted to this layer and it acts as bulk full density Al due to its very low porosity. As seen, with increasing the porosity, the connections between Al particles tend to be as weak as possible and final strength of the foam will decrease consequently.

It shows that the porosities have very strong connection (thick wall) with approximately dense walls. The interface between Al particles is shown in Figure-2(a). As seen, large radius necking will cause strong connection of particles. Figure-2(b) illustrates that salt particles act as micro-molds and Al particles take the shape of these

molds. This implies that salt particles transfer the applied load to surrounded Al particles and lead to the flattening and welding. This theory will be confirmed by reminding the high temperature (873K) and pressure of the compaction. Strong connection between Al particles and higher strength are direct results of this phenomenon.

It indicates that hot pressed method requires less processing time compared to conventional solid-state sintering, and also it results in a dense microstructure without any significant micro porosity. Micro-porosities in a sintered sample could act as initial cracks in the matrix and they should be kept as low as possible if a high strength porous metal is desired. Compressive stress-strain curves (Figures 3 and 5) demonstrate that the hot pressed foam of the compacts improves the mechanical properties of the foams, as a result of elimination of micro-porosities (Figures 4e and 2b). In addition, the liquid-phase sintering process leads to the typical compression curve of metallic foams with three distinct zones of elastic deformation, plateau stress, and a progressive densification regime where the cell walls come in contact together, causing an abrupt rise in the flow stress. Compressive strength of the solid-state sintered foam is substantially inferior (Figure-5) and it does not show a regular compression behavior of foam metals. This behavior relates to presence of micro-porosities in this sample (Figure-5), which act as initial cracks in foam and easily propagate throughout the framework. Semi-plateau stress in the solid-state sintered foam declines sharply to 0.5 MPa at the second reign; corresponding to the behavior of brittle foams, while behavior of the liquid-state sintered foam demonstrates a ductile regime under compressive stress with at least 5 MPa plateau stress in its second region.

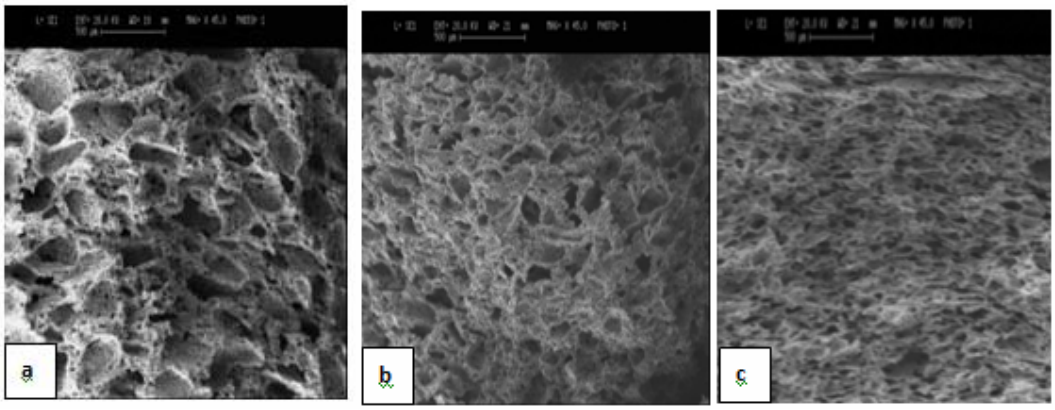

Figure-1. SEM microstructure of aluminum foams fabricated with NaCl as space older with different porosity. (a) 75%, (b) 70%, and (c) 65%.

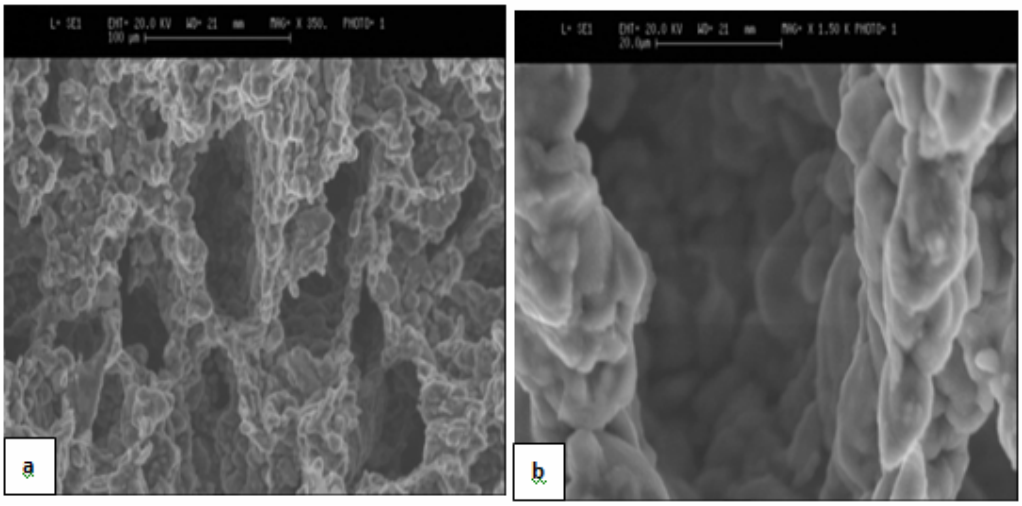

Figure-2. SEM microstructure of aluminum foams with 65% porosity.

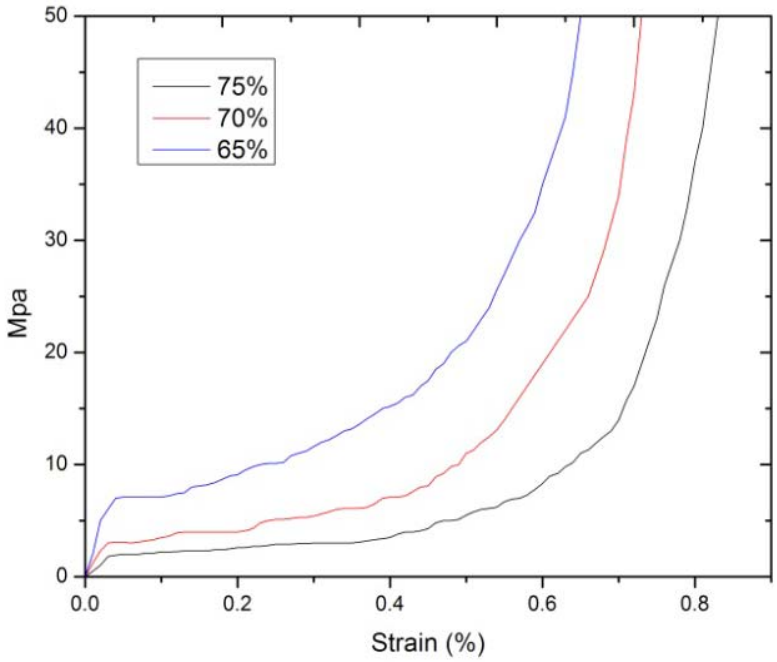

Figure-3. Compressive stress-strain behavior of aluminum foams fabricated by hot press method and different porosity conditions.

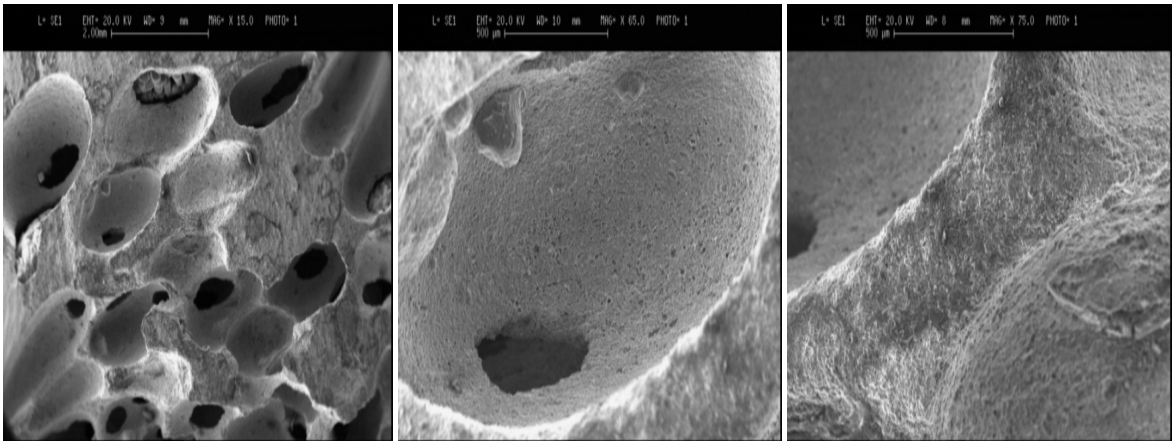

Figure-4. Microporosity (not designed porosity) in foam fabricated via carbamid as space holder.

It indicates that hot pressed method requires less processing time compared to conventional solid-state sintering, and also it results in a dense microstructure without any significant microporosity. Micro-porosities in a sintered sample could act as initial cracks in the matrix and they should be kept as low as possible if a high strength porous metal is desired. Compressive stress-strain curves (Figures 3 and 5) demonstrate that the hot pressed foam of the compacts improves the mechanical properties of the foams, as a result of elimination of micro-porosities (Figures 4e and 2b). In addition, the liquid-phase sintering process leads to the typical compression curve of metallic foams with three distinct zones of elastic deformation, plateau stress, and a progressive densification regime where the cell walls come in contact together, causing an abrupt rise in the flow stress. Compressive strength of the solid-state sintered foam is substantially inferior (Figure-5) and it does not show a regular compression behavior of foam metals. This behavior relates to presence of micro-porosities in this sample (Figure-5), which act as initial cracks in foam and easily propagate throughout the framework. Semi-plateau stress in the solid-state sintered foam declines sharply to 0.5 MPa at the second reign; corresponding to the behavior of brittle foams, while behavior of the liquid-state sintered foam demonstrates a ductile regime under compressive stress with at least 5 MPa plateau stress in its second region.

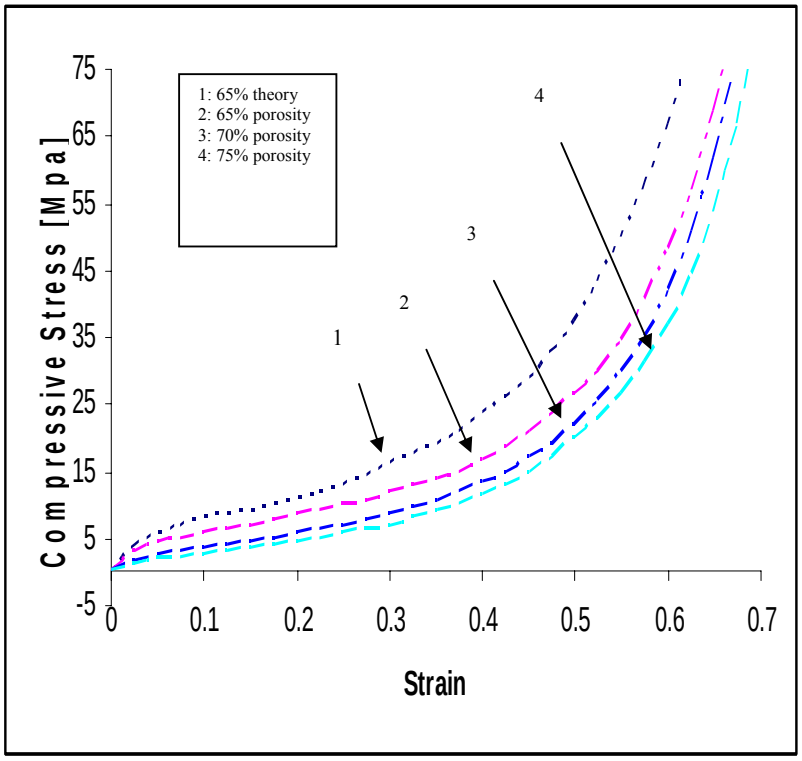

Figure-5. Stress-strain curve of the compressive test for the 65%, 70%, 75% in compare to 65% theory porosity value and hot pressing condition.

For more characterization, the electrical conductivity of the samples was measured by two-probe method. Five measurements were performed on each sample to improve accuracy. The averages of the measurements are presented in Table-2.

For a given porosity, higher temperature leads to higher electrical conductivity. On the other hand, at a constant temperature, an increment in porosity decreases electrical conductivity. This can be summarized as a rule: the higher density, the higher electrical conductivity (as confirmed mechanical properties). With increasing the density, the electrical conductivity of foam approaches to that of the pure bulk Al. as we can seen Measurements show that Electrical conductivity in hot pressed foam is more than foam with carbamid as space holder.

Table-2. Comparison of electrical property between foam fabricated with NaCl space holder and carbamide in different porosity conditions.

Space holder	**porosity**	% **65**	% **70**	% **75**
Carbamide	Electrical conductivity	4310	3670	2260
NaCl	Electrical conductivity	8170	6840	4720

CONCLUSIONS

Results show that the compressive strength and the electrical conductivity increase with rising temperature and decreasing porosity and hot pressing method due to best result as cold press-sintered foams. In general, the maximum hot pressing temperature of 873K and minimum interior porosity of 60% are the best production condition. SEM images show a very good connection between Al particles with high necking radius. Hot molding of the Al particle in the space between salt particles (in effect of hot pressing), is the probable mechanism of the porosity formation.

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