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Original Research Paper

Physical and mechanical properties of porous copper nanocomposite produced by powder metallurgy

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ABSTRACT

In this study porous copper nanocomposite reinforced with Al_2O_3 nanoparticles was successfully produced with adjustable mechanical properties and homogeneous pore morphology using powder metallurgy process. For this purpose, lost carbonate sintering (LCS) method with K_2CO_3 as a filler material was used to fabricate composite foam. The process consisted of mixing of metal powder and adjustable nano particles along with filler material, pressing and sintering. Under this condition the filler material was disappeared during sintering and a homogenous porous structure was formed. Experiments were conducted with 2 wt.% of nano alumina and different weight fractions (15, 20, 30, 40, and 50) of K_2CO_3. Type and morphology of pores were investigated using scanning electron microscopy (SEM). Differential thermal analysis (DTA) and thermo gravimetric analysis (TGA) were also carried out to determine thermal behavior of potassium carbonate. EDS and XRD methods were used to analyze phase transformation during manufacturing process. Mechanical properties of the produced samples were investigated by uniaxial compression test. Compressive behavior of nanocomposite copper foams showed that they present more enhanced mechanical behavior in comparison with regular copper foams. The results showed that plateau stress of nanocomposite foam increased more than 2 times in compared with regular copper foam in same porosity percentage. The examination of uniaxial compression tests showed that the plateau stress and energy absorption of nanocomposite foams were in the range of 18–111 MPa and 6.82–29.97 MJ/m^3, respectively.

1. Introduction

Porous metals or metallic foams are engineering materials with a unique combination of physical and mechanical properties. They have been developed during recent years in various fields of industry and are expected as novel engineering materials due to their superior properties [1–3]. The properties include high specific strength, heat conductivity, electrical conductivity, compressive ductility, and excellent acoustic properties [4,5]. Successful experience of usages of open cell metallic foams in filtering applications as well as mass and heat transfer has been considered recently [6,7]. In addition to Al, as the most widely used metal foam, other porous metals like Cu, Ni, and Ti are also used [8].

A relatively new class of cellular metal has been developed recently in which the metal matrix is reinforced by incorporating hollow reinforcements [9]. The metal matrix syntactic foams (MMSFs) offer opportunities to further modify the energy absorbing properties of the materials. The modification is accomplished not only by selection of matrix, heat treatment, and volume fraction and size of voids, but also by selection of reinforcement specifications. The increased strength of cell walls of composite foams results in a more complex deformation behavior. The behavior is characterized by multiple failure and densification which results in improved energy absorption in compared with ordinary metal foams. Typically, compression behavior of foams consists of initial peak stress marking the onset of plastic deformation, plateau stress after the peak, densification strain, and total energy absorption [10]. The ability of a metal foam for using in many applications is dependent on their ability to withstand cyclic compression [11,12]. Plastic deformation under cyclic loading occurs within deformation bands, which begins to form preferentially in large cells in the sample, until the densification strain has been reached [13].

Numerous methods have been developed to produce porous copper, such as directional solidification, vapor deposition and powder metallurgy [14,15]. Among the methods, powder metallurgy

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(PM) technique is a promising and cost-effective route for producing foams with controlled pore shape, pore size, and porosity content [16].

Many of the recent studies focus exclusively on producing methods of metal foams, while the adjusted mechanical behavior is significant for producing structural components [15,17]. Therefore, the main objective of this article is to improve mechanical properties of metal foams for energy absorption systems in order to develop the range of applications of copper foams. For this reason, in this study a stronger material foam with increased properties was produced by reinforcing copper matrix with nano Al_2O_3 particles using powder metallurgy technique.

2. Experimental procedure

99.9% pure copper powder was used in this investigation as matrix material. Nano alumina particles were used as reinforcement in the copper matrix to produce nanocomposite foam. Selection of a suitable reinforcement was done according to the critical factors including chemical reactivity at elevated temperatures and density [18]. Particle size distribution and also EDS pattern of copper powder were determined by means of scanning electron microscopy (SEM) LEO 1450VP (35 kV). In this regard after sample preparation, many microstructures were obtained from different regions of the samples. To produce metal foam, commercial potassium carbonate (K_2CO_3) consisted of granular particles with particle size below 500 μm was used as foaming agent. To determine the decomposition behavior of potassium carbonate, DTA analysis was carried out from ambient temperature up to 1100 °C under argon atmosphere.

Cu and Al_2O_3 powders in micro and nano particle size, respectively were mechanically milled separately for 4 h in a high energy planetary ball mill with stainless steel balls under controlled atmosphere in order to produce a metal matrix for the foams. The ball-to-powder weight ratios (BPR) were 10:1 and the rotation speed was 250 rpm. The nano alumina content was selected as 2 wt.%. In continue, the nanocomposite powder was blended with different content of K_2CO_3 as foaming agent. The weight percent of K_2CO_3 was varied from 15% to 50%.

In the next step, well mixed mixture of powders was uniaxially pressed under 250 MPa compaction pressure in a hydraulic press. Then, according to DTA results of K_2CO_3, the sintering and foaming treatment were performed at 850 °C and 1000 °C, respectively at a rate of 10 °C/min under non-oxidation atmosphere. For comparison purpose, a compacted copper sample, as non-composite matrix, was sintered at the same condition. The entire preparation process of samples is shown schematically in Fig. 1. The specifications of foam samples produced in this study were also listed in Table 1.

The fabricated composite foams were characterized by X-ray diffraction (XRD) to investigate the phases produced through milling or manufacturing process.

Table 1
Foam samples characterization.

Sample	Al_2O_3 nanoparticles (wt.%)	Foaming agent (wt.%)
1	–	–
2	–	50
3	0.5	–
4	1	–
5	2	–
6	3	–
7	2	50
8	2	40
9	2	30
10	2	20
11	2	15

The apparent density of nanocomposite foams (ρ_f) was obtained by measurement of weight and volume of each specimen and also using Archimedes method. The density of fully dens composites (ρ_s) was calculated theoretically. Relative density and porosity content of each specimen were obtained using Eqs. (1) and (2), as follow:

$$\text{Relative density} = (\rho_f/\rho_s) \quad (1)$$

$$\text{Porosity } (\%) = [1 - (\rho_f/\rho_s)] \times 100 \quad (2)$$

Compression test was performed on all foam samples using a Universal ZWICK (Z250) testing machine with strain rate of $3 \times 10^{-3}\ s^{-1}$. Anti-friction agent was applied as lubricant during compression test. Compression test of all foam samples were investigated in accordance with Japanese Industrial Standards JIS-H-7902 [19]. The evaluation of densification strain was performed according to DIN 50134 standard in which average stress in the range of 20–30% strain was calculated. Then plateau stress was evaluated at 1.3 times of this average stress. By calculating strain at plateau stress, densification strain was evaluated.

Energy absorption of the samples was determined using calculation of the area under the curves up to their own densification strain according to JIS H 7902 and the following expression.

$$\text{Energy absorption} = \int_0^{\varepsilon D} \sigma\, d\varepsilon\ (\text{MJ/m}^3) \quad (3)$$

3. Results and discussion

3.1. Pore morphology and structure

Particle size distribution of copper powder and also EDS pattern of the powder, determined by means of SEM, are shown in Fig. 2. The results of microstructure analysis showed that particle size of alumina is below 100 nm indicating they are in nano scale (Fig. 3). As it is proved, the strengthening effect is quite significant when the reinforcement particle size is less than 100 nm [18]. Potassium carbonate, as foaming agent, is the most appropriate material for producing copper foams as patented by Zhao et al.

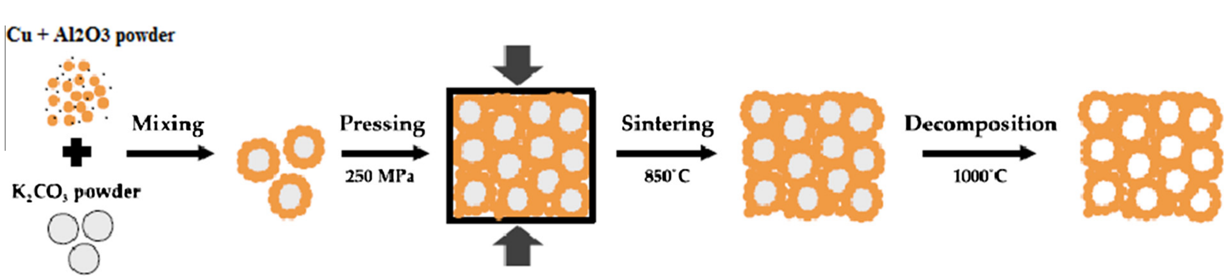

Fig. 1. Schematic illustration of powder metallurgy technique used in this study.