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Microstructural and mechanical properties of Al–SiO_2 nanocomposite foams produced by an ultrasonic technique

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ABSTRACT

In this study, nanocomposite foams reinforced with different weight percentages of silicon dioxide nanoparticles (0.25, 0.5, 0.75 and 1.0 wt%) were fabricated using the ultrasonic and stir casting techniques. For this purpose heat treated TiH_2 was used as foaming agent. Microstructural studies were done by optical microscope and scanning electron microscope. Hardness evaluation of precursor nanocomposites showed that the hardness was significantly increased by the addition of SiO_2 nanoparticles and Al–0.75 wt% SiO_2 nanocomposite makes the highest hardness. Evaluation of compressive behavior of Al–SiO_2 nanocomposite foams showed that the plateau stress increases more than 3 times as the foam relative density increases from 0.09 to 0.16. Energy absorption of Al–SiO_2 nanocomposite foams has been found to be dependent on both relative density and structural properties.

1. Introduction

In the recent years, there has been a significant increase in research on metallic foams, especially those made of aluminum and its alloys, due to the progress made in processing methodologies that yield high quality foams at a low cost [1–3].

Different methods have been developed to produce aluminum foams such as foaming by gas injection, solid–gas eutectic solidification, direct foaming and the powder compact melting technique. Among these, the direct foaming technique using foaming agent is useful for commercial applications due to its easy availability of production equipment and its low cost compared to other techniques [4,5].

Kadoi [6] showed that the decomposition of TiH_2 starts at around 420 °C, but in aluminum foam fabrication by the melt route technique, the samples are heated between 600 °C and 700 °C. Thus, the temperature difference between the TiH_2 decomposition and foam fabrication strongly influences the yield and the foaming phenomenon. He showed that with increasing temperature and time of the TiH_2 heat treatment as a foaming agent in air, decomposition temperature elevates.

One of the most interesting points for using ceramic nanoparticles as reinforcing phase is using them for strengthening the metal matrix without changing its flexibility. The generally used ceramic particles in foaming processes are in microscale; therefore, the usage of high amounts of them in Al foam makes it so brittle [7,8].

Dispersion of nanoparticles by using an ultrasound process based on melt route has been recently introduced [9]. It is believed that high intensity ultrasonic waves generate strong cavitation and acoustic streaming effects. Acoustic cavitation involves formation, growth, pulsation, and collapsing of the micro-bubbles in melt under cyclic high intensity ultrasonic waves (thousands of microbubbles will be formed, expanding during the negative pressure cycle and collapsing during the positive pressure cycle (Fig. 1)) [10–12]. By the end of one cavitation cycle, the micro-bubbles implosive collapse will produce transient micro "hot spots" that can reach very high pressures of about 1000 atm and heating and cooling rates above 10^{10} K/s. Transient cavitations can produce an implosive impact strong enough to break up the clustered fine particles and disperse them more uniformly in liquids. It is envisioned that strong ultrasonic nonlinear effects might efficiently disperse nanoparticles into alloy melts and also enhance their wettability. This is why making high performance lightweight metal matrix nanocomposites (MMNCs) using ultrasonic waves is so common [13,14].

As a general rule, the compressive stress–strain curves of closed cell Al foams show three regions: the linear elastic, the plateau and

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the densification. Pure aluminum foams exhibit plastic behavior but aluminum alloy foams often exhibit a brittle feature, therefore showing different curve shapes in compressive deformation. The strengths of foamed aluminum alloys are not sufficient for some commercial uses. Several methods have been used to improve the strength characteristics. Among these methods, aluminum composites reinforced with ceramic particles are mainly characterized by higher modulus and strength as compared to the unreinforced matrix materials. One of the common features of energy absorption materials is that there is a discernible plateau in their compressive stress–strain curves. Foamed aluminum has this feature; it means that they can absorb energy by deformation but keep the stress almost constant [15–17].

Based on the literature survey done by the authors, there is no evidence of using sonicator to produce nanocomposite foams. For this purpose in the current research, it will be tried to produce Al nanocomposite foams reinforced with different content of SiO_2 nanoparticles using the ultrasonic technique. Microstructure and compressive characteristics of foamed Al–SiO_2 nanocomposites, and hardness of nanocomposites have been investigated.

2. Experimental details

Chemical composition of aluminum alloy which was used as the matrix is presented in Table 1. To select a suitable reinforcement, important factors such as density, wettability and chemical reactivity at high temperatures should be considered [18]. Silicon dioxide powder with particles size from 40 to 80 nm was selected as reinforcement material because of its good wettability with aluminum alloys. TiH_2 powder was used as foaming agent with purity more than 98% and was heat treated at 450 °C for 3 h to improve gas releasing behavior [6,19].

Aluminum foams were fabricated with 0.25, 0.5, 0.75 and 1.0 wt% silicon dioxide nanoparticles. For this purpose, first Al alloy was melted in a furnace at 700 °C and then 1 wt% Mg was added to the molten Al to enhance wettability of nanoparticles. Silicon dioxide powder was added to the molten aluminum at 680 ± 10 °C and stirred at 700 rpm for 20 min. After this step, ultrasonic probe (BANRY, China) has been immerged into the melt and flustered it at 20 kHz frequency for 10–15 min for an improvement in wettability and distribution of nanoparticles in the molten alloy. Just after that TiH_2 powder was added to the molten aluminum nanocomposite and stirred immediately for 1–2 min at 700 rpm. In the next stage, the mixture was kept for 2–3 min at 660 °C for further decomposition of foaming agent. Finally, the expanded molten metal was brought out from furnace rapidly, casted in the die and cooled in the ambient atmosphere. It is worth noting that in order to ensure the stability of the particles a pull out test was carried out by inserting a steel wire loop into the nanocomposite melts. The continuity of melt in the loop implies the optimal viscosity for the foaming process.

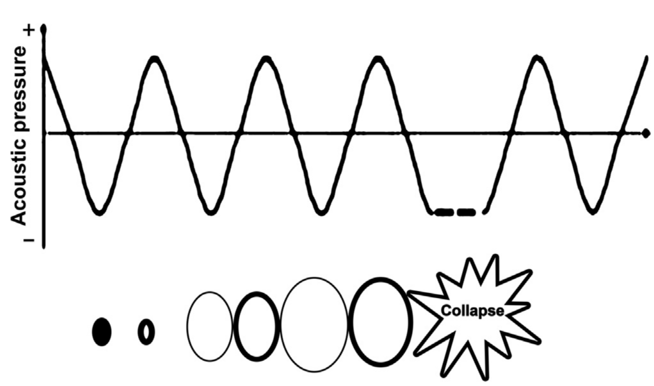

Fig. 1. Effect of ultrasonic wave on bubble size changes and their collapse [11].

Table 1
Chemical composition of Al alloy.

Element	Si	Zn	Fe	Cu	Mg	Pb	Mn	Ni	Ti	Al
wt%	8.62	1.46	1.16	0.83	0.23	0.15	0.14	0.09	0.03	Remaining

Nanocomposite foams were evaluated using the standard techniques of metallographic preparation and observation with LEO 1450VP (35 kV) scanning electron microscope to view distribution of silicon dioxide nanoparticles.

The relative density of foams (ρ/ρ_s) is defined here as the ratio of the apparent density of the foams (ρ) to the fully dense composites (ρ_s).

Hardness measurements were carried out on the base metal and nanocomposite samples (foaming precursors) by using the Vickers hardness test and the applied load was 30 kg.

Uniaxial compression tests were performed with a universal testing machine (ZWICK Z250) and the strain rate was kept $3\times10^{-3}\,s^{-1}$. The plateau stress and densification strain were calculated by average stress in the range of 20–30% strain as indicated in JIS H 7902 and in strain accordance with 1.3 times of the plateau stress as DIN 50134 standards, respectively. Energy absorption was calculated using the given expression [20,21]:

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

3. Results and discussion

3.1. Structural investigation

As the reader knows the transmitting of load from one cell wall to the other will be done via a strong interface. For this reason the cell wall thickness must not be thin. In order to avoid thinning the wall thickness addition nanoparticles is very common. Indeed they play as a stabilizer and their presence causes to form some kind of dynamic stabilization, i.e. drainage effects are postponed. They also capture between neighboring bubbles and represent obstacles which delay or completely stop cell wall thinning [22]. Fig. 2(a) and (b) show the microstructure of Al alloy and Al–0.5 wt% SiO_2 nanocomposite under stir casting and ultrasonic processing, respectively.

As it can be seen in Fig. 2, nanocomposite processing causes changes in metal matrix microstructure. Liu and Ji [23,24] showed that different kinds of intermetallic compounds can form, if Al–Si alloys containing Fe re-melt near to Fe-rich intermetallic phase formation temperature. Also, Shabestari [25] showed that the formation temperature of intermetallic compounds will increase by rising the amount of Fe in Al alloy (Fig. 3).

It is known that the nature and distribution of precipitate in matrix material have a large effect on the foam properties [26]. Nano-sized SiO_2 ceramic particles can effectively modify intermetallic phases in aluminum alloys because they act as nucleation sites for intermetallic compounds. The modification process of intermetallic compounds can be done by changing the initial coarse needle phases to star like and polyhedral like phases. These new forms of intermetallic compounds containing Fe don't reduce the mechanical properties of aluminum alloys. In addition they act as a hard phase with high thermal stability that prevent loss of strength and hardness of Al alloys at high temperatures [27].