Materials Science & Engineering A 685 (2017) 213–226

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Effect of cenosphere content on the compressive deformation behaviour of aluminum-cenosphere hybrid foam

Shyam Birla[a,b], D.P. Mondal[a,b,*], S. Das[a,b], Deepak Kumar Kashyap[b], Venkat A.N. Ch[b]

[a] Academy of Scientific and Innovative Research (AcSIR), India
[b] CSIR-Advanced Materials and Processes Research Institute, Bhopal 462026, India

ARTICLE INFO

Keywords:
Cenosphere volume fraction
Hybrid foam (HF)
Compressive deformation
Aluminium alloy LM13

ABSTRACT

Al-cenosphere closed cell hybrid foams (HFs) of varying relative densities were made by melt foaming method through stir casting technique. In order to investigate the effect of cenosphere content on the compressive deformation behaviour of HFs, varying amounts of cenospheres (18, 25, 30 and 35 vol%) was used as thickening agent and CaH_2 (0.6 wt% of alloy) was used as foaming agent. Two types of pores come in this hybrid foam: (i) micropores due to the hollow cenosphere and (ii) macropores due to the entrapment of gas generated. The results showed that the cenospheres particles were uniformly distributed in the cell wall. It was noted that the addition of cenospheres improved the yield strength, the plateau stress, and the energy absorption capacity of HFs, up to a 30 vol% of cenosphere. Further increase in cenosphere content leads to reduction in the plateau stress and the energy absorption capacity of HFs. It is interestingly noted that the densification strain is almost invariant to the cenosphere volume fraction. Attempts are also made to empirically correlate the deformation response with the cenosphere volume fraction and relative density.

1. Introduction

Aluminium foams are a class of materials which are made up of aluminium and largely of gas filled pores. The aluminium alloys generally exhibits better specific strength and stiffness as compared to steel and cast iron. Therefore, attention has been paid to use different kind of aluminium alloys for making closed cell aluminium foam [1,2]. These foams are widely used for their light weight and shock absorbing capacity [1,3]. Most of the space in these foams is empty (typically 75–90%). The foams are of two types: open and closed cell foams [2], depending on whether the pores form an interconnected network (open cell) or they are sealed with cell wall. These foams show higher strength and energy absorption capacity under dynamic condition also and hence could be used in automobile vehicles for crash protection and energy absorption [4,5]. With increasing number of vehicles on the road due to the increasing demand, lighter and energy efficient automobile body is rising day by day. Al-foams also have good crash-worthiness due to their high energy absorption capabilities at significantly low plateau stress and can prove to be good alternative materials in the future automobile and aerospace industry [6]. Some attentions have been paid on the manufacturing and characterisation of aluminium alloy foams which exhibit excellent mechanical and physical properties [3,7–10]. Closed cell aluminium foam is fabricated mainly through liquid metallurgy routes by stir casting technique using foaming agent [3,11] or foaming of melt through simultaneous gas purging and stirring [1].

The plateau stress and energy absorption of the foam are proportional to the strength and energy absorption of the alloy with which the foam is made off [2]. It is reported that, both the plateau stress as well as energy absorption follow power law relationship with relative density of foam [12,13]. As the Al-Si alloy are cast alloy and solidifies through wide temperature range, these alloys are mostly used for foaming [3,14,15]. A few literatures are available on making of Al-LM13 alloy foam using liquid metallurgy route [3,10,16]. With the coming of advanced preparation methods, a variety of Al-foams are being made. Limited literatures are available on hybrid Al-foams, where micro-spheres are used as thickening as well as stabilizing agent [3,12,17–19]. Xia et al. [17] studied compressive properties of closed cell Al-foams with different content of ceramic microspheres and examined an improvement in the energy absorption, yield strength, mean plateau stress, densification strain and energy absorption efficiency over conventional foams. It is reported that microsphere content to be limited in order to get optimum strength and energy absorption capacity. The foam was manufactured with different volume fraction (0, 2.5, 5, 12.5 and 20) of ceramic microspheres and reported that in case of 2.5 vol% of ceramic microspheres highest average yield strength

* Corresponding author at: CSIR-Advanced Materials and Processes Research Institute, Bhopal 462026, India.
E-mail address: mondaldp@yahoo.com (D.P. Mondal).

http://dx.doi.org/10.1016/j.msea.2016.12.131
Received 14 October 2016; Received in revised form 30 December 2016; Accepted 31 December 2016
Available online 02 January 2017
0921-5093/

(8.02 MPa) and energy absorption capacity could be achieved. An attempt was made by Rohatgi et al. [18] to prepare A356/Fly ash cenosphere syntactic foam by gas pressure infiltration technique. It was reported that the flow stress as well as plateau stress increased with decrease in cenosphere volume fraction. The compressive response of the matrix alloy is compared with syntactic foams containing different volume fractions of cenospheres. They further reported that the compressive strength of the aluminium syntactic foams increased with the increasing the cenosphere particles size. However, this is curious here the cenosphere shell thickness may be increasing with increase in cenosphere size. Mondal et al. [12] produced aluminium cenosphere syntactic foam having a density of 1.5–1.9 g/cc through stir casting technique where 30–50 vol% of cenosphere was used as a space holder to create microporosity as well as strengthening of the matrix. They had used cenosphere of average size of 75 μm. They found that the plateau stress of syntactic foam decreases with increasing the cenosphere volume fraction and porosity fraction following a power law relationship. But, the densification strain increases linearly with cenosphere volume fraction. Daoud et al. [19] prepared Zn12Al based composite foams containing hybrid pores through stir casting technique following direct foaming of the composite melt using $CaCO_3$ as a foaming agent and cenospheres as a thickening agent as well as micropores forming element. They have used 15 and 30 vol% cenosphere, having average diameter and shell wall thickness of 160 and 10 μm respectively. It was observed that the yield, the plateau and the plastic collapse stress of Al-hybrid foams does not follow any specific trend of variation with cenosphere volume fraction. At higher strain rate, hybrid foam exhibited improved strength and energy absorption, while at lower strain rate the conventional foam exhibits better strength. At lower strain rate the hybrid foam with lower cenosphere content provides higher strength and energy absorption. Here, with increasing volume fraction of cenosphere, the ceramics shell content increases. This might be changing the deformation response. But why its trend is changing with strain rate not discussed clearly. Zhang et al. [20] produced closed cell Al foams through liquid metallurgy route by using melt foaming method with addition of different volume fraction of multi-walled carbon nanotubes. It was reported that the addition of different content of multi-walled carbon nanotube significantly improves the yield strength; the mean plateau stress, the densification strain and the energy absorption capacity of pure aluminium foams. The foam was manufactured with different volume fraction (0%, 0.2%, 0.5%, 0.8% and 1.0%) of multi-walled carbon nanotube. It is reported that multi-walled carbon nanotube content to be limited in order to get optimum strength and energy absorption. In case of 0.5 vol% multi-walled carbon nanotubes, the compressive strength of foam was observed to be 3.25 MPa for relative density of 0.15. The reduction in plateau stress and energy absorption above 0.5 vol% of CNT is due to increased tendency of clustering of carbon nanotubes. The present investigators have also made attempt to make hybrid LM13–cenosphere foam [3] using $CaCo_3$ as foaming agent. They observed that the hybrid foams exhibits improved plateau stress and energy absorption comparable to that of Al-composite closed cell foam. However, the effect of cenosphere concentration on the deformation behaviour of LM13-cenosphere hybrid foam has not been examined so for. In the present study LM13-cenosphere hybrid foams has been made using varying amount of cenosphere through stir casting technique. The microarchitecture and compressive deformation response of the synthesised LM13-cenosphere hybrid foams were studied as a function of relative density and cenosphere concentration.

2. Experimental

2.1. Synthesis of hybrid foam

Aluminium alloy (LM13)-cenosphere hybrid foams of varying relative densities were made through stir casting technique. The alloy

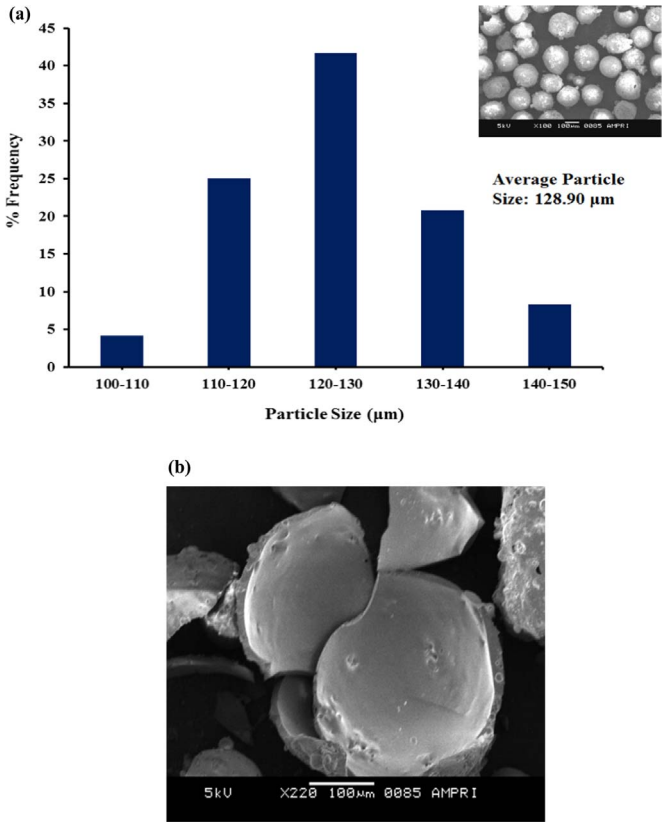

Fig. 1. (a) The average size distribution and micrograph of +100 μm (average size 128.90 μm) cenospheres (b) Micrograph of crushed cenosphere.

nominally contains Cu: 0.7 wt%, Mg: 1.0 wt%, Si: 11.8 wt%, Fe: 1.0 wt %, Mn: 0.5 wt%, Ni: 1.5 wt%, Zn: 0.5 wt%, Pb: 0.05 wt%, Ti: 0.06 wt%, Al: balance. Firstly the alloy was placed in the crucible and melt at a temperature of 720–750 °C in an electrical resistance furnace. Then, preheated (1000 °C for 3 h) cenospheres (average size: 129 ± 9.03 μm) in different weight fractions (0.04, 0.05, 0.06 and 0.07) were added manually in the melt through mechanical stirring at a speed 800 rpm. The size distribution of cenospheres and its micrographs are shown in Fig. 1(a). It is evident from this figure that the cenosphere surfaces are relatively smoother and these are nearly spherical in shape. The average shell thickness of cenosphere was noted to be 6.5 ± 1.2 μm, from the micrograph of crush cenosphere as shown in Fig. 1(b). The density of these cenospheres and crushed cenospheres was measured through the Archimedes principle using the specific gravity bottle technique [21] and is noted to be 0.6g/cc and 2.6g/cc respectively. Thus, it is expected that the cenosphere volume fraction in the cell wall of hybrid foam would be around 18, 25, 30 and 35 vol% for 4, 5, 6 and 7 wt% cenosphere respectively. The chemistry of cenospheres is shown in Table 1. The cenosphere shell primarily consists of alumina-silicate phases like mullite. In addition, it contains quartz, graphite, iron oxides and silicates, calcium oxides etc. in minor quantity as reported in detail elsewhere [12]. After mixing of cenosphere in the melt, stirring was continued for 2–3 min to ensure complete homogeneous mixing of cenospheres particles. After that, dry and preheated CaH_2 powder (0.6 wt%) of average size: 18 ± 2 μm, was added manually in the melt again through mechanical stirring. While adding CaH_2 powder, the

Table 1
Chemical composition of cenosphere (in wt%) [12].

SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Carbon
58.5	29.3	6.1	0.7	5.4