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Compressive deformation behavior and strain rate sensitivity of Al-cenosphere hybrid foam with mono-modal, bi-modal and tri-modal cenosphere size distribution

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ABSTRACT

AlSi12Cu1Mg1 aluminium alloy-cenosphere closed cell hybrid foams with different kinds of cenosphere size distribution (mono-modal, bi-modal and tri-modal) are used to see the effect of cenosphere size distribution on their deformation behavior under quasi static compressive loading conditions at different strain rates. The stress strain curves are almost similar type irrespective of the cenosphere size distribution and strain rate. However, the plateau stress and energy absorption increased significantly when one used bi-modal and or tri-modal cenosphere size distribution instead of mono-modal cenosphere size distribution. These plateau stresses and energy absorption also increased marginally with strain rate. The densification strain remained almost invariant with strain rate and cenosphere size distribution. The strain rate sensitivity and strain rate sensitivity parameter is relatively lower in case of bi-modal and tri-modal cenosphere size distribution particularly at higher relative density.

1. Introduction

With the development of new technology and design criteria, requirement of new material with improved properties is required. In today's world safety standards are very high and to achieve those standards there is a continuous force on design and research to improve property of the material. Aluminium foam is a class of light weight material having very low density (0.2 to 0.8 g/cm) [1]. It offers different unique combination of properties like high specific strength and stiffness, sound absorption capability [2], electromagnetic shielding [3], excellent energy absorption [4], thermal insulation [5] and vibration damping [1]. These properties make aluminium foam an important candidate material for use in light weight structure, crash worthiness, vibration and mechanical damping. Closed cell aluminium foam is a material which possesses incomparable properties like energy absorption and impermeability to fluids [6]. It is very effective where there is a requirement of high energy absorption keeping the plateau stress at lower values [7]. Hou et al. [8] investigated the effect of impact velocity, cell thickness and relative density of aluminium foam on energy absorption capacity through compressive deformation. It is reported by these investigators that under dynamic loading aluminium foam exhibits higher plateau stress as compared to that when loaded under quasi-static condition. In recent years, many researcher have studied the effect of strain rate on plateau stresses [9,10] especially under quasi-static condition.

Closed cell aluminium foam is mainly produced through liquid metallurgy route using foaming agent [11–13]. Researchers have used different foaming agents to prepare aluminium foam. Cambranero et al. [14] used calcium carbonate ($CaCo_3$) as foaming agent in Al-Mg-Si alloy foam. They investigated the effect of different characteristics of calcium carbonate powder (i.e. particle size and chemical composition) on micro-architectural and deformation behavior of aluminium foam and they found that the foam made using natural carbonate powder shows better uniaxial compressive properties as compared to that made using synthetic calcium carbonate. Wu et al. [15] used zirconium hydride (ZrH_2) [15] as a foaming agent in an amount of 0.6%–1.4% (mass fraction) and they found that ZrH_2 is mainly suitable for making small cell size with aluminium foams (average diameter 1 mm). TiH_2 [16] and CaH_2 [17] are generally used as a foaming agent. The foam made using foaming agent provides macro-pores (Cell), which is generated due to entrapments of gas bubbles formed due to dissociation of the foaming agents. In other kind of foam, where micro-balloons are introduced in metallic matrix, are called syntactic foams. The aluminium syntactic foam also exhibits very high strength and energy absorption

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capacity under dynamic as well as quasi-static condition [18–22]. Based on this concept researcher have also used the micro-sphere in aluminium foam [23,24] and zinc foam [25] to improve compressive deformation response. These are called as hybrid foam [23]. So in order to reduce the use of foaming agent, reduce macro porosity as well as to increase the plateau stress and energy absorption of aluminium foam, some micro-sphere were incorporated in to melt prior to foaming. Doaud [26] made attempt to make Zn-Al alloy-cenosphere hybrid foam using 15% and 30% vol% of Cenosphere. They observed that the plateau stress of the Zn-Al alloy foam increases when Cenosphere are used for getting hybrid pores. It was noted by the investigator that plateau stress or yield stress of the alloy foam increase by few folds at fixed relative density. Xia et al. [27] investigated the compressive strength of aluminium foam having different content of micro-sphere and also found improved plateau stress and energy absorption over the conventional aluminium foam. Birla et al. [28] studied the effect of micro-sphere particle size on the compression deformation. They also investigated the variation of plateau stress with respect to size of micro-sphere. During the experiment they considered three different particle sizes and found that as the size of cenosphere particle decreases the values of plateau stress and energy absorption get increased. Synthetic, metallic and/or ceramic micro-sphere [27] are costly and adding these micro-spheres in foam increases the cost of aluminium foam. So, in order to increase the compressive strength without increasing the cost of aluminium foam, cenosphere (waste from power plant) was used as a microsphere [27]. Sanders et al. [29] showed the deformation mechanism of syntactic foam with hollow micro-sphere, in comparison to the existing closed cell metallic foam. According to these investigators with an increase of relative density of 10%, foam made using micro-sphere showed 3 times greater modulus and strength than that of conventional foam. Xia et al. [27] analyzed the effect of ceramic micro sphere content on yield strength, mean plateau stress and average densification strain under compression loading analysis of aluminium syntactic foam. They observed that the plateau stress of syntactic foam does not follow any specific trend with cenosphere content. The shells of cenosphere help in increasing the strength of matrix (cell wall). Birla et al. [28] also examined that the plateau stress of aluminium hybrid foam increases with increase in cenosphere up to 30%. They reported that this is due to decrease in macro-porosity and also increase in cenosphere shell. Adding cenosphere in closed cell aluminium foam gives two types of porosity, one is macro-porosity which is caused due to entrapment of gas and other is micro-porosity due to hollow cenosphere particle.

In syntactic foam, some of the researchers have used the mixture of different microsphere size to enhance the property of material [30,31]. Tao et al. [30] uses the bimodal ceramic micro-sphere in aluminium matrix syntactic foam. They considered two range of micro-sphere particle size (i.e. fine particle (75–125 μm) and coarse particle (250–500 μm)). They found that the micro-sphere particle density in syntactic foam with bi-modal size distribution is 10% higher than that in the one with mono-modal size distribution. This led to 8% improvement in the plateau stress and the densification strain.

Therefore, there is a need to develop cenosphere reinforced lightweight high strength Al-cenosphere hybrid foams. Ceramic microsphere reinforced Al-hybrid foam is expected to be more brittle than that of Al-alloy foams or Al-composite foams. This is expected that after deformation the cell wall will be crushed in to finer particles. As strength and energy absorption are reported to be higher, the use of these hybrid foams could be extended for blast resistance panels, antimine boots, multicore integrated armour, crashworthiness components and storage and packaging of explosive. Ones it gets exploded, it will not generate any big heavy secondary debris which would cause further damage to the surrounding. That's why, these materials will be highly useful for crashworthiness, blast resistance and armour application.

To the best of our knowledge, no research has been carried out to investigate the effect of combination of different particle size distribution on the compressive deformation of Aluminium cenosphere foam. Present work deals with the preparation of hybrid foam using mono-modal bi-modal and tri-modal combination of cenosphere particle. Here in bi-modal conditions, combination of two particle size range (i.e. < 100 and > 212 μm) is added to aluminium matrix. Whereas in tri-modal combination, three particle size range (i.e. < 100 μm, 150–212 μm and > 212 μm) were added. Hybrid aluminium foam having bi-modal and tri-modal cenosphere particle size were compared with the one having mono-modal cenosphere particle size range with respect to their plateau stress, densification strain and energy absorption capacity. In addition the strain rate sensitivity and stain rate sensitivity parameter as a function of relative density and particle size distribution in aluminium hybrid foams have also been examined.

2. Experimental

2.1. Raw Materials

The aluminium alloy (AlSi12Cu1Mg1) 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. Cenospheres of three different size ranges (< 100 μm, 150–212 μm and > 212 μm) were 30 vol% are used and they are coded as CP1, CP2 and CP3. The size distribution of these cenospheres is shown in Fig. 1. The chemical composition and X-ray diffraction pattern of these cenospheres are reported elsewhere [32]. According to these reports the cenospheres used in the present studies primarily contain aluminino-silicate phases like mullite and selliminite. In addition to these, minor amounts of ferro-silicate, quartz and carbon presents in these cenosphere.

2.2. Hybrid Aluminium Foams and Microstructures

Closed cell aluminium-cenosphere hybrid foams (CAHF) were made using the stir-casting technique [28]. (i) Firstly the alloy was placed in the crucible and melt at a temperature of 730–750 °C in an electrical resistance furnace. Then, (ii) preheated (900 °C for 2–3 h) cenosphere particle were added manually in the melt through mechanical stirring at a speed 800 rpm. After mixing of cenosphere in the melt, stirring was continued for 4 – 5 min to ensure complete homogeneous mixing of cenospheres particles. After that, (iii) 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 melt temperature was maintained between 660 and 700 °C in order to get varying relative densities in hybrid foams. After completion of foaming agent addition, (iv) the melt is allowed to foam and within 20 to 30 s, the melt get completely foamed. This is ensured when the foaming head stop moving upward in the crucible. Finally, (v) the crucible with liquid foam is taken out of the furnace and force cooled by steam spraying to get HFs. The cross-sectional views of hybrid foam are shown in Fig. 2(a) and (b) respectively. These shows uniform distribution of cell size throughout the cross section in lateral and longitudinal direction. For making CAHF with different kinds of cenosphere size distribution, cenospheres with mono-modal, bi-modal and tri-modal size distributions are used. In case of mono-modal, three types of cenosphere (CP1, CP2 and CP3) are used separately for making CAHF and these CAHF with CP_1, CP_2 and CP_3 cenosphere are referred as HFM1, HFM2, and HFM3 respectively. Similarly, for making CAHFs with bi-modal cenosphere distribution, two types of cenospheres: CP1 and CP3 are used together in equal proportion and these CAHFs are referred as HFBM. Similarly, CAHFs made with Tri-modal cenosphere distribution used mixture of CP1, CP2 and CP3, where each category is used in equal proportion; and these CAHFs are referred as HFTM. In our proceeding sections, these codes will be used for cenospheres and the hybrid foams for further discussion.