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Fabrication of localised aluminium foam by a novel polymeric blowing agent

Madhu H.C.*, Satish V. Kailas

Department of Mechanical Engineering, Indian Institute of Science, Bengaluru 560012, India

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ABSTRACT

Closed cell aluminium foams are highly pursued, due to their unique combination of properties. However, the current applicability of the aluminium foams is limited due to issues like high costs, density-gradient and brittleness of the cell walls, which are either related to use of metallic hydride as blowing agent or liquid-state processing. To address these issues, this study presents a first attempt to use polymer as a blowing agent to foam an aluminium alloy. A polymer is Poly (methyl hydro siloxane) was dispersed into an Al2024 sheet of 6 mm by Friction Stir Processing, in a localised region. This processed sample was pyrolysed at temperatures between solidus and liquidus (500–640 °C) of the alloy and at various durations (5–60 min) to foam the localised precursor. The density of resulting foams was measured by the Archemidies method and the resulting pore structures were characterised by Scanning Electron Microscopy (SEM) and micro X-ray Computed Tomography (CT). The results show that by as pyrolysis temperature increases relative density reaches a minimum of 0.65 at 560 °C. Beyond 590 °C, relative density increased from the optimum due to escape of foaming gasses. With increasing pyrolysis temperature, the pore size increased from few microns to several hundred microns. Further, quasi-static compression test was done on as processed, solutionized and aged foams. Due to increased strain hardening in aged samples energy absorbed during compression increased by 80% in the plateau region. Hence, polymeric a blowing agent can be used to synthesize heat-treatable foams with controllable absorption energy.

1. Introduction

Closed cell metallic foams due to their unique structure have a wide range of applications that include energy absorption, damping, sound attenuation, and thermal management [1, 2]. Of the various metallic foams produced, aluminium foams have attracted much of the attention due to low density, and good energy absorption capability [3]. Although, aluminium foams are can be synthesized by many methods, a simpler and hence more widely used method to synthesize foam is by using a blowing agent [4]. The blowing agent upon heating decomposes and release gas, which will foam the material. The blowing agents can be dispersed into the metal, in molten-state to foam the metal, directly [5] or they can be dispersed in the solid-state [6] and then heated to a temperature above melting point to foam the metal. Foaming in a molten-state is a fast process, which is completed within few minutes [7]. Hence, it is difficult to control the resulting pore structure. Further, as the entire metal is melted, a localised area within a larger part cannot be foamed by this method. A locally foamed metal sheet could be used either for vibration damping or to improve control over the crumple zone of an automotive structure. Furthermore, when foams are synthesized in the molten state, the viscosity of the matrix is low, which leads to porosity gradient due to buoyancy effects [8, 9]. To mitigate this, viscosity enhancers such as calcium are added to the melt [10, 11], which forms compounds that are brittle and deteriorate cell wall ductility.

The blowing agents that have been used to foam the metal are either metallic hydrides [12] or inorganic compounds like carbonates [13, 14]. Of these, Titanium hydride (TiH_2) has been more widely used as a blowing agent [15]. However, upon decomposition of TiH_2, Ti reacts with aluminium to form Al_3Ti, which is a brittle intermetallic that deteriorates mechanical properties of the foam [16, 17]. The failure mode of the cell walls in many such types of foam is brittle [18, 19]. Further, as TiH_2 is a fire and explosion hazard they need to be handled with care [20]. Further, the addition of the viscosity enhancers and the metallic hydrides change the sensitive chemistry of the matrix used. Hence, foaming a high strength precipitate hardenable alloy, without considerable deterioration of properties is a challenge.

As mentioned earlier, the blowing agent can be dispersed either in liquid or solid-state. Dispersing the blowing agent in the solid-state to obtain a precursor and then heat-treating to obtain a foam has several

* Corresponding author.
E-mail addresses: hcmadhu@gmail.com (M. H.C.), satvk@iisc.ac.in (S.V. Kailas).

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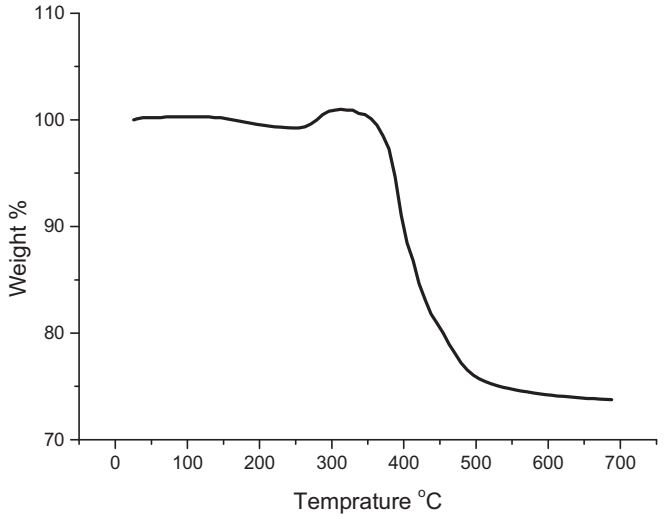

Fig. 1. Shows thermogravimetric curve of PMHS.

advantages, like formation of near-net-shaped parts, safer process etc. These precursors can be synthesized by either powder metallurgy route [11] or the accumulative-roll-bonding route [6, 21]. The powder metallurgy route consists of mixing aluminium powder with blowing agent and compacting to obtain the precursor. This process is both time-consuming and as well as expensive due to the metallic powders. In case of accumulative-roll-bonding, the blowing agent is placed between two bulk aluminium sheets and bonded together. The bonded sheets are cut and re-bonded together. The process is repeated until a foamable precursor is obtained. Although the starting materials are relatively inexpensive, to obtain even dispersion of blowing agent requires time-consuming pre-processing. To overcome these issues recently Yoshihiko Hangai and Takao Utsunomiya [22] dispersed the TiH_2 by Friction Stir Processing (FSP) to synthesize the precursor. This precursor was further heat-treated to obtain aluminium foam.

FSP is a high strain-rate microstructure refinement tool, where a rotating tool, with a shoulder, is plunged into the workpiece and traversed. Friction between the tool and the workpiece leads to heating of the workpiece and aids in plastic deformation of the material. The combination of frictional heating and severe plastic deformation leads to grain refinement [23]. Due to severe plastic deformation during FSP, it is an excellent tool to homogenize nanocomposites [24]. Further, secondary particles can be dispersed evenly into a matrix within a short duration. Hence, FSP has been used to disperse a variety of secondary particles such as ceramics [25, 26], metallic [27], graphitic [28] and polymeric particles [29, 30] to synthesize composites.

In the current study, to overcome issues a novel process was developed to synthesize localised metallic foam using a polymer as blowing agent. For this, a polymer is evenly dispersed into aluminium matrix using FSP. The region dispersed with a polymer or the nugget the region, which foams when pyrolysed. The pyrolysis was carried out in the semisolid region of the alloy to have better control over the resulting density and pore structure. This also ensures that nugget is foamed without affecting the adjoining base metal. The precursor was also pyrolysed for various durations at a particular temperature to understand the effect of pyrolysis duration on relative density and pore structure. Furthermore, the heat-treatability of the foam was verified by uniaxial compression tests carried out on the solutionized aged foams and was compared with as-processed foam.

Table 2
Processing parameters selected for FSP.

Processing parameters	
Tool rotation speed	800 RPM
Tool travers speed	8 mm/min
Tool tilt angle	2°
Plunge depth	5.2 mm

2. Experimental

Silicon based polymer, Poly (methyl hydro siloxane) (PMHS) with a chemical formula $(CH_3)_3SiO\ [(CH_3)HSiO]_nSi(CH_3)$ was used as blowing agent. As received polymer was in liquid form and the number-average molecular weight of the polymer was between 1700–3200 g mol^{-1} (source: Sigma-Aldrich). As solid powders can be easily dispersed by FSP, the liquid polymer was crosslinked to obtain a solid. The polymer was crosslinked by adding catalyst 1,4-Diazabicyclo[2.2.2] octane (source: Sigma-Aldrich). The cross-linking was carried out at room temperature for 8 h [31]. At the end of 8 h, a crosslinked polymer was obtained. The crosslinked solid polymer was ground to a fine powder using mortar and pestle. Further, to verify the decomposition range of the synthesized polymer, Thermogravimetric Analysis (TGA) was done from 30 °C to 700 °C at 10°/min heating rate. The TGA curve shows (Fig. 1) that the decomposition of the polymer starts around 350 °C and ends around 550 °C.

Aluminium alloy Al2024, with a density of 2.72 g/cm^3, was used as the matrix material for this study. The nominal composition of the alloy is given in Table 1. Six millimetre Al2024 plates measuring 200 mm length and 70 mm width were milled to obtain a groove of 3 mm width and 4 mm depth. The groove was filled with the crosslinked and ground polymer. The filled groove was closed by a 2 mm thick strip and sealed by the pin-less tool of 25 mm diameter. On this assembly, FSP was done by a tapered tool with diameter varying from 10 mm to 8 mm having a 25 mm shoulder, 5 mm long threaded pin. The three passes of FSP were done to disperse the polymer particles within the matrix. The plate was cooled to room temperature between the passes. The parameters of FSP are as given in Table 2. The schematic of the process is shown in Fig. 2. To confirm even dispersion of the polymer after FSP, samples were cut by wire Electric Discharge Machine (EDM) in a direction perpendicular to tool traverse direction. The machined samples were mechanically ground on SiC papers of 400–3000 grit and then polished on velvet cloth using Alumina particles (1 μm). These polished samples were etched with Keller's reagent and were observed under a stereo microscope.

This evenly distributed composite was pyrolysed at various temperatures and durations in a pre-heated furnace. After the pyrolysis, the samples were air-cooled. The foamed region was machined from the pyrolysed samples to measure the density. The density was measured by Archimedes principle using a weighing machine with a resolution of 1 mg. Further, these foamed samples were sliced along the cross-section and prepared for microstructural analysis similar to precursor samples. The microstructural analyses of the samples were done on TESCAN VEGA3 SEM. To quantify the distribution of the pore size and shape with increasing temperature, SEM images were taken from five zones of the nugget i.e. bottom left, bottom right, centre, top left and top right. These images were analysed using ImageJ (image analysis software) to calculate the pore diameter and the aspect ratio. The structure of the metal foam was imaged by X-ray micro Computed Tomography (CT)

Table 1
Nominal composition of Al2024.

Element	Al	Cu	Mg	Mn	Fe	Si	Zn	Cr	Ti
Wt%	90.7–94.7	3.8–4.9	1.2–1.8	0.3–0.9	Max 0.5	Max 0.5	Max 0.25	Max 0.1	Max 0.15