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A novel approach to produce Al-alloy foams

X. Fang · Z. Fan

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Abstract The stability of Al foams during processing is crucial to producing uniform Al foams. Once pores form during processing, no matter which conventional methods are used, the pores grow and/or merge into large ones, which could cause Al foams to ''collapse''. Therefore, it has attracted great attention of researchers to enhance the stability of Al foams during processing for improved quality of Al foams. A novel approach to produce Al-alloy foams, ''Rheofoaming'', is presented in this paper. A twin-screw rheomixer fitted with a gas inlet near the end cap is used in this work. The mechanism of this approach is firstly to increase the viscosity of semisolid slurry of Al alloy by adding sub-micron Al_2O_3 particles and then to mix N_2 gas with the semisolid slurry using a twin-screw rheomixer, which can offer high shear rate and intensive turbulence. The gas pores in the semisolid slurry are stretched and broken into smaller ones in the rheomixer. Al foams are very stable during the processing due to small pore sizes and high viscosity of semisolid slurry. The microstructure of rheofoamed Al foams and the process of this new approach have been described in this paper.

Introduction

Due to their high strength, high melting point, low density, good corrosion resistance, high stiffness and high crash energy absorption, metallic foams have a strong application potential in the transportation industry for improving crash safety. Metallic foams absorb energy during a crash, the higher the energy absorbed, the more protection the metallic foams offer. A schematic illustration of compression strain–stress curve of metallic foams is shown in Fig. 1. The energy absorbed per unit volume is defined as the area under the compression stress–strain curve obtained prior to the onset of densification [1]. It can be said that the absorbed energy depends on the strength of the first peak and the length of the plateau of the compression stress–strain curve. Therefore, metallic foams with a high first peak strength and long plateau have good crash energy absorption properties. The compression properties of metallic foams depend on (a) density, (b) homogeneity of the pores [2], (c) defects such as, missing wall, wiggle wall [1] and cracks [3], and (d) size of pores [2]. Homogenising pores and reducing defects can improve the strength of the first peak, because the first collapse will occur in the section with lowest density [4] or defects. The length of plateau increases with decreasing the size of pores, if the density of metallic foams keeps the same [2]. Therefore, homogeneous distribution, and small and uniform size of pores are crucial for achieving excellent compression behaviours of metallic foams.

There are two ways for directly foaming metallic melts: to inject gas into the liquid metal from an external source, or to cause an in-situ gas formation in the liquid by mixing gas-releasing blowing agents to the molten metal [5]. Two basic requirements for producing Al-alloy foams are to increase the viscosity of metallic melt and to introduce gas to the metallic melt. The viscosity of metallic melt is usually increased by adding ceramic particles, such as Al_2O_3 [6–8] or reducing the temperature of the melt to close to the melting point [9]. In order to stabilize gas bubbles in the melt, the viscosity of the melt has to be increased to a critical value [10]. The volume fraction of

X. Fang (✉) · Z. Fan
BCAST, Brunel University, Uxbridge UB8 3PH, UK
e-mail: mtsrxxf@brunel.ac.uk

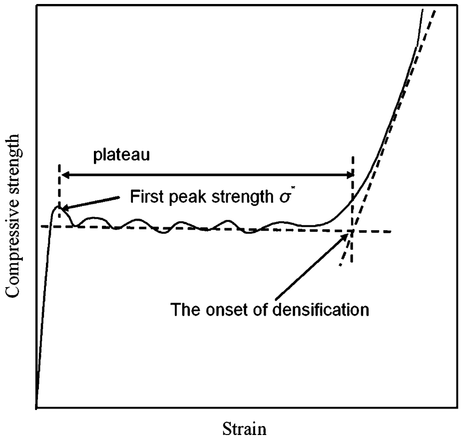

Fig. 1 Schematic illustration of the rheofoaming process

ceramic particles typically ranges from 10% to 20% and the average particle size from 5 μm to 20 μm [11]. Gas bubbles normally are introduced by injecting gas into the melt or using blowing agents. Once the gas bubbles are formed they develop up with the decomposition of the blowing agents and/or merge into big ones. It is almost impossible to control the growth of the gas bubbles in the melt. Therefore, the conventional foam making process suffers from inherent problem of large pore size and even worse, wide scatter in the size distribution of pores. Recently, a twin-screw rheomixer, which was developed at BCAST at Brunel University, can offer very high shear rate and intensive turbulence, hence it has a strong mixing ability to disperse ceramic particles in semisolid slurry matrix. The twin-screw rheomixer can also produce metal melts with a high viscosity and mix gas into the semisolid slurry at the same time. In this paper, a novel approach, 'Rheofoaming', is proposed, using a twin-screw rheomixer to produce homogenous Al-alloy foams with refined pores.

Rheofoaming process

Some gaseous elements can be solubilised in Al melts at a high temperature and decompose into gas bubbles during solidification, but the solubility of gas in Al melts is too low to form Al foams. In order to produce Al foams, a large mount of gas has to be introduced into the Al melt. It is also very important to keep the gas bubbles stable in the melt. The behaviour of gas/Al system is quite similar to immiscible systems, such as Zn–Pb, Ga–Pb and Al–Pb, which have been successfully mixed together using the rheomixer [12–14]. The density difference between Al and gas will cause gas bubbles to escape from the melt under buoyancy forces. The larger the size of a bubble, the higher the buoyancy force is. When two small gas bubbles merge into big one, the velocity of the gas bubble increases. Therefore, reducing the size of gas bubbles can slow down their escaping velocity. The existing approaches, such as injecting gas into the melt or using blowing agents, cannot reduce the size of gas bubbles once they are formed. Apart from reducing the buoyancy force, increasing the viscosity of the melt also slows down the velocity of gas bubbles and thus increases the stability of foams. The turbulence will entrap N_2 into the melt to form gas bubbles during intensive shearing. If the viscosity of the melt is high enough, the entrapped gas bubbles will stay in the melt. If the viscosity is not high enough, stirring has an opposite effect, i.e., degassing rather than increasing the amount of gas bubbles. Therefore, both the high viscosity of the melt and small bubble sizes are crucial to producing homogenous close-cell foams. The twin-screw rheomixer can offer very high shear rate and intensive turbulence in the semisolid temperature range. The viscosity of the melt can be increased not only by lowering the temperature to increase the solid content of Al primary particles, but also by mixing Al_2O_3 particles into the melt. Simultaneously gas bubbles are stretched and broken up into smaller ones under shear in the semisolid slurry. Therefore, homogenous Al/Al_2O_3 foams with uniformly distributed fine pores can be produced using this approach.

Experimental procedures

A twin-screw rheomixer with closely intermeshing, self-wiping and co-rotating twin screws was used for this work (Fig. 2). The details of the rheomixer have been described in Ref. [15]. In brief, the screws have a specially designed profile to achieve high shear rate and high intensity of turbulence. The barrel and screws are made from special materials in order to prevent reaction with molten Al. The accuracy of the barrel temperature is within ±1 °C. In order to introduce N_2 gas to the melt during processing, a gas inlet with a valve was fitted near the end cap of the barrel.

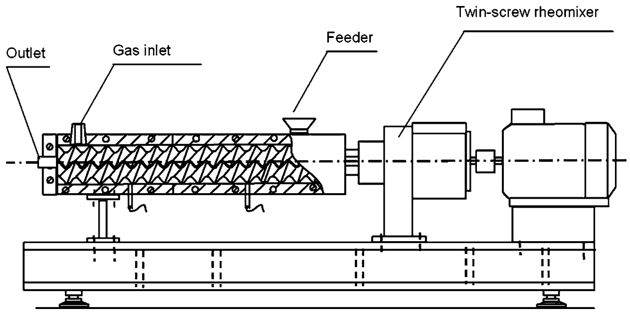

Fig. 2 Schematic illustration of the twin-screw rheomixer

Commercial A380 Al alloy and sub-micron Al_2O_3 particles were used to prepare Al/Al_2O_3 foams in this work. The specifications of the sub-micron Al_2O_3 particles are listed in Table 1. The sub-micron Al_2O_3 particles were baked at 400 °C in a resistance furnace in order to get rid of moisture. A380 alloy was melted in a resistance furnace at 650 °C. The A380 melt was transferred into a crucible, which was kept at a temperature ranging from 570 °C to 575 °C. The A380 melt was sheared using an impeller and cooled down from 650 °C to the temperature of the crucible. Once a semisolid slurry of A380 alloy was formed in the crucible, approximately 5 wt.% of the heated sub-micron Al_2O_3 particles were added to the slurry whilst stirring. After continuously stirring for 120 s, premixed Al_2O_3 particles and A380 semisolid slurry was obtained. The premixed semisolid slurry was immediately fed into the twin-screw rheomixer, which was running at 582 °C and 1,000 rpm, after high-pressure N_2 (1.5–2.0 bar) gas had been flown into the barrel from the gas inlet for about 10 s. The N_2 gas pressure was kept when the melt was travelling from the feeder to the end cap. Once the barrel was fully filled by melt, the N_2 gas was not needed any more and the valve of the gas inlet was switched off. The melt was mixed for 180 s in the rheomixer and then cast into a steel mould.

Samples cut from the cross section of cast foams, were ground and polished down to 1 μm, but not etched for the metallographic examination. The microstructures were examined using a conventional optical microscope and scanning electron microscopy (SEM). The densities of foams were measured using Archimedes' principle.

Results and discussion

Figure 3 shows the microstructure of the premixed slurry prepared using an impeller. The black areas are pores containing Al_2O_3 particles and the bright area is the typical microstructure of the A380 Al alloy, which is nearly free of Al_2O_3 particles. The particles dropped out during sample preparation, so that no Al_2O_3 particles are seen in the metallographic image. The pore size ranges from a few 100 μm to about 3 mm. The density of the premixed Al/Al_2O_3 slurry is 1.87 g/cm^3.

Table 1 Specifications of sub-micron Al_2O_3 particles

Surface area (cm^2/g)	Green density[a] (g/cm^3)	Fired density[b] (g/cm^3)	Particle size distribution		
			d_{10}	d_{50}	d_{90}
7.5	2.1	3.76	1.2	0.5	0.2

[a] Pressed at 27.6 MPa

[b] Fired at 1,500 °C and at rate of 5 °C/min. (soaking time of 2 h)

It is very difficult to mix the sub-micron Al_2O_3 particles into Al melts [16], because Al_2O_3 particles cannot be wetted by Al melts and the sub-micron Al_2O_3 size has a high surface area to volume ratio. Above the liquidus of A380 sub-micron particles cannot be mixed into the melt by stirring. The viscosity of the melt increases exponentially with the volume fraction of Al primary particles. Reducing the mixing temperature can increase the volume fraction of Al primary particles. When the melt temperature drops to a semisolid temperature ranging from 575 °C to 585 °C, the sub-micron Al_2O_3 particles are easily engulfed in to the melt by stirring. The temperatures of 575–585 °C correspond to 10% and 20% volume fractions of Al primary particles for the A380 Al alloy, respectively. Furthermore, the sub-micron Al_2O_3 particles are so small that the as-received sub-micron Al_2O_3 particles are always in a form of agglomeration. The sizes of agglomerations are much larger compared with individual particles, so these agglomerates can be engulfed in the melt under a turbulence of stirring. Initially, the agglomerated Al_2O_3 particles are associated with air bubbles. Consistently, it was easy for them to fall out during the preparation due to their poor interracial attachment to the Al matrix. Under a low shear stress from the impeller, Al_2O_3 particles cannot be deagglomerated and mixed into the melt.

Figure 4 shows the optical microstructure of the Al/Al_2O_3 foam produced using a twin-screw rheomixer. The characteristics of the pores in the Al/Al_2O_3 foam are circular and uniformly distributed. Al_2O_3 particles dispersed uniformly in the Al matrix, although there are some agglomerations, which only contain a few particles (Fig. 5). Figure 6 shows the pore size distribution of the Al/Al_2O_3 foam. The pore sizes range from a few micrometres to about 300 μm and the average pore size is about 80 μm. The peak of the curve is located at 30 μm. More

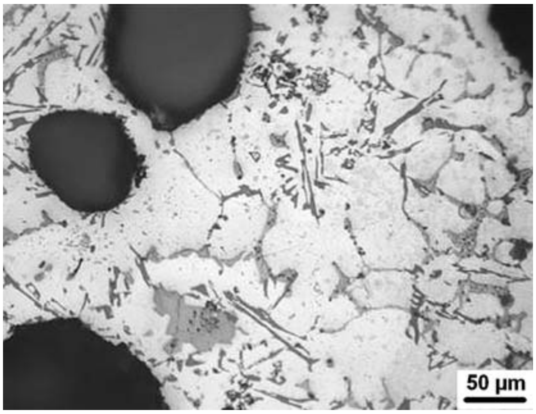

Fig. 3 Optical microstructure of the premixed Al/Al_2O_3 slurry

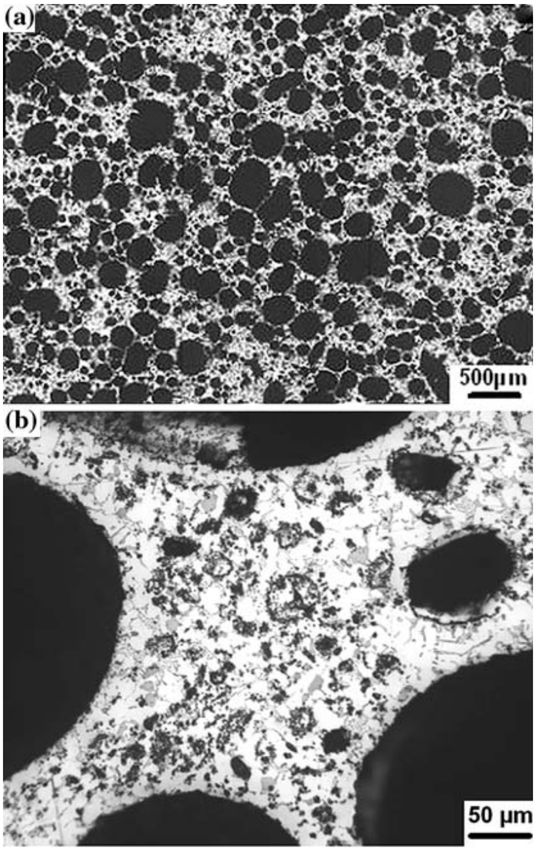

Fig. 4 Optical microstructure of Al/Al$_2$O$_3$ foams produced using the rheomixer, (**a**) low magnification (**b**) high magnification

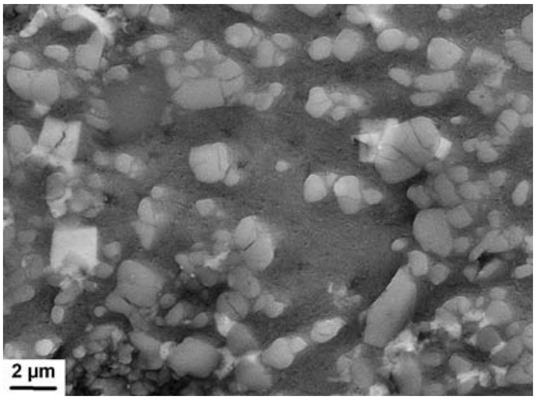

Fig. 5 SEM micrograph shows the sub-micron Al$_2$O$_3$ particles dispersed uniformly in Al alloy matrix

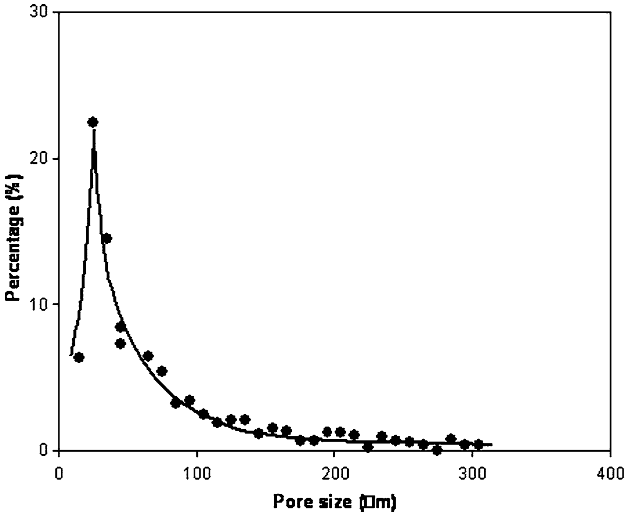

Fig. 6 Pore size distribution of the Al/Al2O3 foam

than 90% pores are smaller than 100 μm. Figure 4b shows that sub-micron Al$_2$O$_3$ particles are uniformly distributed in the A380 matrix. No significant Al$_2$O$_3$ particles are found in the pores during cutting the sample. The density of the Al/Al$_2$O$_3$ foam is 0.8 g/cm^3, corresponding to a porosity of 72%.

The green density of sub-micron Al$_2$O$_3$ particles is 2.1 g/cm^3, while the fired density at 1,500 °C is 3.76 g/cm^3, which is higher than the density (2.8 g/cm^3) of A380 alloy (Table 1). Adding 5 wt.% Al$_2$O$_3$ particles should slightly increase the density of A380 if no gas is brought into the melt. However, the density of the premixed slurry is only 1.87 g/cm^3 (Table 2). Premixing not only engulfs the agglomerated Al$_2$O$_3$ particles into the melt but also brings gas into the melt with Al$_2$O$_3$ particles.

The schematic illustration of rheofoaming process is shown in Fig. 7. There are two main reasons to premix the Al$_2$O$_3$ particles with A380 semisolid slurry. Firstly, the twin-screw rheomixers do not have efficient distributive mixing action, so the premixed slurry of the Al$_2$O$_3$ particles with A380 semisolid slurry has to be achieved before rheofoaming, otherwise, the Al$_2$O$_3$ particles cannot be mixed into the melt. Premixing also brings gas into the melt with Al$_2$O$_3$ particles. Secondly, more N$_2$ gas is mixed into the melt by the twin-screw rheomixer. When the premixed Al/Al$_2$O$_3$ slurry is fed into the rheomixer, the flow rate of the slurry is quite low due to the high viscosity. The screws take the premixed slurry little by little, so the turbulence in the rheomixer can further mix the high-pressure N$_2$ gas into the premixed slurry to increase N$_2$ bubbles, when the slurry was travelling from the feeder to the end cap. Therefore, the porosity of the Al/Al$_2$O$_3$ foam increases from 33% (the premixed slurry) to 72%. Simultaneously the pores in the premixed slurry are sheared and broken into smaller ones under the shear stress. Meanwhile, the shear stress is so high that Al$_2$O$_3$ particles in the pores are squeezed into the A380 semisolid slurry. Although some Al$_2$O$_3$ particles in the foam are still agglomerated, each particle in the agglomeration is well wetted to the A380 alloy matrix (Fig. 5). The rheofoaming process is summarised as following two steps,

Table 2 Experimental conditions and results

Process	Al_2O_3 content (wt.%)	Mixing temperature (°C)	Shear rate (s^{-1})	Shearing time (s)	Pore size (μm)	Density (g/cm^3)	Porosity (%)
Premixing	5	570–575	~10	120	<3,000	1.87	33
Rheofoaming	5	582	1,780	180	80	0.8	72

The density of A380 is 2.8 g/cm^3

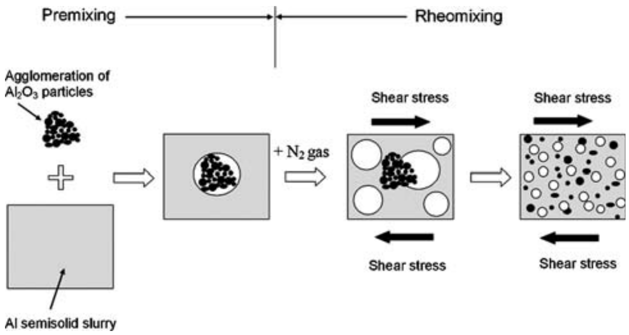

Fig. 7 Schematic illustration of Rheofoaming process

1) Premixing brings ceramic particles and gas into semisolid slurry.
2) Air and N_2 bubbles are sheared and broken into smaller ones.

As we mentioned before, the average size of ceramic particles in conventional Al-alloy foams is 5–20 μm and their volume fraction is 10–20%. Therefore, the ceramic particles in conventional Al-alloy foams can cause a problem for machining due to large particle and high volume fraction [5]. Compared with the conventional Al-alloy foam, only 5 wt.% sub micron Al_2O_3 particles are added in the rheofoamed Al-alloy foams. Thus, the effect of Al_2O_3 on the machinability of the foams produced by rheofoaming should be greatly reduced.

Summaries

The concept of rheofoaming has been proven to be feasible to produce high quality Al/Al_2O_3 foams. The experimental results show that Al/Al_2O_3 foams with small and uniformly distributed pores. With further development, this technique for processing metallic foams can become a potential route for industrial products of high quality metallic foams.

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