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Back pressure equal channel angular consolidation—Application in producing aluminium matrix composites with fine flyash particles

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Abstract

Back pressure equal channel angular consolidation (BP-ECAC) is an innovative process to synthesise bulk materials from particles. It enables particles from nano to micro scales to be consolidated into fully dense materials at much lower temperatures and under much simpler conditions. It is particularly useful in consolidating particles with non-equilibrium microstructures and in producing metal matrix composites (MMCs). As an example, BP-ECAC was used in this investigation to produce aluminium matrix composites with flyash particles. Compared to the conventional powder metallurgy (PM) and ingot metallurgy, BP-ECAC is more efficient and capable of incorporating very fine particles at higher volume fractions with more uniform particle distribution. In particular, it can be used to produce master composite billets for subsequent melting and casting.

Keywords: Aluminium matrix composites; Flyash; Powder metallurgy; Particles; Equal channel angular consolidation

1. Introduction

Consolidating particles into bulk materials for various applications has evolved from an ancient art to modern science and engineering over the history of human civilisation. Although melting and casting of metals had overtaken clay shaping and firing as the most important manufacturing technology for a long time, fabrication using particles has many advantages over using melt or bulk solid. First of all, materials that are difficult to melt or form have to be shaped using particles, as in the case of ceramics to which clay belongs. Solidification is often accompanied by severe segregation of alloying elements, causing undesirable consequences such as brittleness and lowered strength. More importantly, many non-equilibrium phases such as nano and amorphous structures can be most economically produced in the form of particles; these non-equilibrium structures are critical to the enhancement of many materials properties such as strength and stiffness. It is increasingly desirable to form a new material using a variety of phases which cannot be as easily produced using solidification and heat treatment alone, e.g. metal matrix composites (MMCs).

The conventional powder metallurgy (PM) relies on sintering at elevated temperatures to achieve consolidation. Bonding between particles is achieved through diffusion which requires both high temperature and long time. This not only makes the process expensive but also tends to destroy any non-equilibrium structures existing in particles. Without any assistance from pressure or liquid, full density is also hard to obtain. It is thus desirable to develop a consolidation process at much lower temperatures and for much shorter times.

One of the most promising methods makes use of severe plastic deformation (SPD) to achieve consolidation. Both high-pressure torsion (HPT) [1–4] and equal channel angular (ECA) deformation [5–7] have been used. The particles can be consolidated at much lower temperatures (even room temperature). However, the thickness of material produced by HPT is very limited and shear is not uniform from the centre to the edge. With ECA deformation, much larger samples and uniform shearing across the volume can be achieved. However, full density may not be reached without multiple passes [6].

Recently, it has been demonstrated that application of a back pressure during ECA deformation is effective to produce fully dense materials from consolidating Al, Ti and nanometre sized Al particles [8–10]. The so-called back pressure equal channel angular consolidation (BP-ECAC) process was carried out at temperatures much lower than those used in sintering, with no need to can and degas the particles. Full bonding was achieved

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between particles instantaneously as they passed through the shearing zone. Nanometre sized grains were achieved from consolidating nano particles.

One obvious application of BP-ECAC is to synthesise MMCs. Particulate reinforced MMCs may be solidification processed by stirring ceramic particles into metal melt [11]. However, it is difficult or impossible to incorporate very fine particles (typically ceramic particles have to be >∼5–10 μm) and the volume fraction is limited to around 20–30%. The process and the compositions of the alloy and the particles have to be tightly controlled to avoid excessive reaction between particles and the melt. The manufacturing is often expensive. Alternatively, MMCs can be produced by powder metallurgy [12] in which the ceramic and metal particles are mixed before sintering although the presence of ceramic particles makes the consolidation process even more difficult and secondary process is often necessary to eliminate pores.

In the present investigation, BP-ECAC was used to synthesise Al based composites containing flyash particles, ULTALITE^{TM}.[1] Flyash is a by-product of coal power stations. Much of the flyash is presently treated as a waste product for uses such as land fill although a small quantity is utilised as fillers in concrete and other materials. In an earlier project [13], flyash particles were successfully incorporated into aluminium alloys through solidification processing and their uses in automotive applications such as brake components were demonstrated [14]. It is shown here that BP-ECAC is capable of producing ULTALITE^{TM} with more uniform particle distributions, using finer particles or as master billets of high volume fractions for diluting and casting.

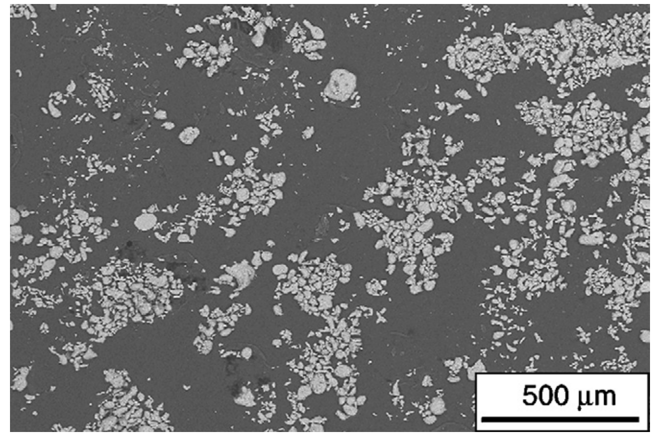

Fig. 1. The appearance of the as-received pure Al particles.

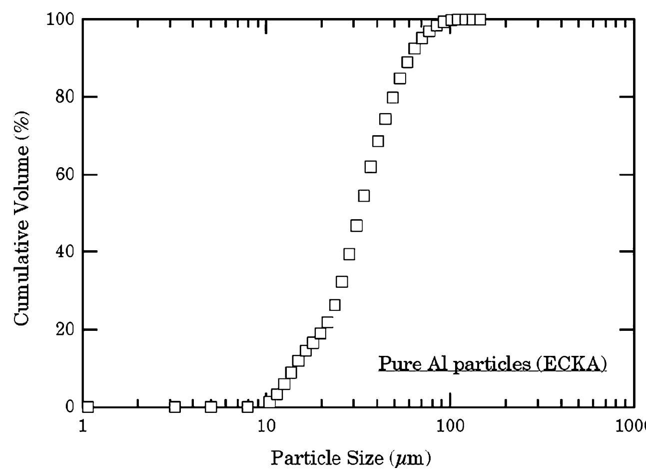

Fig. 2. Size distribution of the as-received Al particles.

2. Experimental materials and procedures

For BP-ECAC, the raw materials used were pure Al powder and flyash particles. The pure Al powder was supplied by ECKA Granules Australia. The particles were produced by atomisation with the following specified composition: Al > 99.7 wt.%, Si < 0.10 wt.%, and Fe < 0.20 wt.%. The particles were analysed using inductively-coupled plasma atomic emission spectroscopy which revealed the following composition: Al–0.02 wt.%Si–0.11 wt.%Fe, conforming to the specification. Analysis using a LECO RO-416DR instrument showed oxygen content of 0.38 wt.%, presumably associated with the oxide layer on the surface. The particles had irregular shapes as shown in Fig. 1. The size distribution of the particles is shown in Fig. 2, with a 50 percentile size of ∼30 μm and a maximum size of ∼100 μm.

Two types of flyash particles with different size distributions were supplied by Cement Australia. They are referred to as coarse (Swanbank by product name) and fine (Tarong) flyash particles, respectively, in the following text. These particles are mostly spherical in shape, as shown in Fig. 3 for the fine flyash. The size distributions of the two types of flyash are displayed in Fig. 4. The 50 percentile particle sizes are 18 and 8 μm for the coarse and fine types of flyash, respectively. In particular, the fine flyash contained a significant amount of particles of <∼2 μm in size (∼10 vol%) with a maximum size of <40 μm.

Two loadings of flyash were made, 20 and 50 vol%, corresponding to the standard and concentrated ones, respectively. The flyash particles were mixed with Al ones in the designated proportions using a mechanical stirrer at 1000 rpm for 20 min at room temperature.

The set-up of BP-ECAC is shown in Fig. 5 with a 90° die. A constant back pressure was applied through the back plunger in the exit channel. The composite mixture was wrapped in Al foil and packed in the entrance channel with graphite lubrication. The die was heated to and kept at the processing temperature (between 400 and 600 °C) which was controlled to ±1 °C. The pressing speed used was between 0.2 and 20 mm/min and the constant back pressure between 50 and 200 MPa. One pass was sufficient to produce the required billets although multiple passes might be applied.

For melting and casting, billets with concentrated flyash particles, i.e. 50 vol%, were diluted to ∼10 vol% in A356 (nominally Al–7Si–0.3Mg) at 610–630 °C with extra Mg addition to compensate for loss during melting. The melt was mechanically stirred to prevent segregation before casting into com-

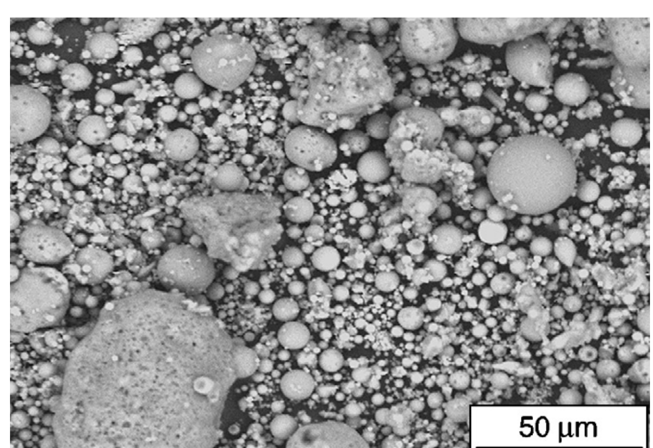

Fig. 3. The appearance of the fine flyash particles.

[1] Trade name by Cyco Tech, Melbourne, Victoria, Australia.