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Particle shape effects in flotation. Part 1: Microscale experimental observations ☆

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ABSTRACT

There has long been speculation as to whether some particle shapes are more 'floatable' than others, which might be due to differences in the induction period required to achieve attachment between the particles and the air bubbles in the pulp. To resolve this, we used the *Milli-Timer* apparatus to directly observe the process of particle–bubble interaction and attachment by means of a magnified, high-speed video recording, thus providing a direct measure of the induction period for attachment.

To assess the influence of particle shape on induction time we used two varieties of methylated borosilicate glass particles — spheres and angular 'frit' — in a range of tightly-sized fractions. Other factors that could affect the induction time, such as the polar angle of sliding commencement, and approach velocity, are accounted for using multiple nonlinear regression.

Our results illustrate the importance of particle shape on induction period, with angular particles exhibiting induction periods that were an order of magnitude lower than those of spheres. Furthermore, the induction period was seen to decrease with increasing particle velocity, or kinetic energy on approach, but increased as the trajectory approached the limit of just grazing the bubble. These results indicate that attention should be paid to the shape of particles obtained from the grinding operation, besides particle size.

1. Introduction

Flotation is a key unit operation employed in mineral processing and a range of other industries. Successful flotation hinges on the attachment of (certain) particles to bubbles. In real industrial systems the particles fed into a flotation cell will exhibit a variety of shapes, varying from approximately spherical (*e.g.* zircon, slags) (see Wotruba et al., 1991), to cuboidal (*e.g.* galena) (Dippenaar, 1982), to platy (*e.g.* talc, chlorite) or acicular (*e.g.* tremolite) (Kursun and Ulusoy, 2006). How important is this shape in determining attachment?

Anecdotally it is expected that particle shape can have a significant effect on 'floatability': the common view is that angular particles are easier to float than rounder particles. However, such overall tendencies leave it unclear as to which flotation subprocesses are most affected by particle shape. For example, in the pulp we could consider collision rate, attachment efficiency, stability against detachment, and entrainment, besides a number of froth characteristics. Traditionally the efforts to model the interaction of particles and bubbles have typically assumed that both objects are perfect spheres (see Nguyen and Schulze, 2004). Some exceptions are studies on the final moments prior to breaching of the liquid gap, in which bubble deformation is modelled (Chan et al., 2011), and studies that examine the equilibrium configuration of a non-spherical particle after attachment has occurred in the pulp (Huh and Mason, 1974; Schulze, 1984: 199ff) (*cf.* Coghill and Anderson, 1923: 44ff) or the froth (Dippenaar, 1982; Morris et al., 2011). Hence, modelling is not yet at a stage to fully explain the relative importance of particle shape or roughness.

1.1. Measurement of particle shape and roughness

In flotation the particles of interest are typically sized at around 10–150 μm (Shergold, 1984: 231). If the deviations occur on a scale comparable to the particle size, then we shall refer to this as a

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difference in shape. If the deviations occur on a scale much smaller than the particle size, then we shall refer to this as a difference in surface roughness. An equivalent distinction is between "structure" and "texture" (Ahmed, 2010).

An important element of working with real particles is to characterise their shape and surface roughness. Unfortunately, there is no single unambiguous parameter to fully characterise either of these properties, which has hindered research into this important area (Holt, 1981; Yekeler et al., 2004; Kursun and Ulusoy, 2006; Ahmed, 2010). The topic of roughness is scarcely more tractable: the topography of a solid surface can exhibit different characteristics on different lengthscales, such as 'rough' or 'smooth' asperities. Attempts to deal with these problems through use of fractal dimensions (*e.g.* Filippov et al., 1999; Ahmed, 2010) are subject to question, in general, as the features of a given particle are unlikely to conform to a true fractal rule over a broad enough range of lengthscales to be physically useful — unlike the features of aggregates (Verrelli, 2008).

1.2. Influences on particle shape, and roughness

Different views exist on the dominant reason why particles have the shapes that they do, which can be summarised as the effect of the inherent material character, and the effect of the processing (Holt, 1981). For example, malleable materials such as some metals can deform plastically (*e.g.* Ofori-Sarpong and Amankwah, 2011), while brittle materials such as quartz will fracture (*e.g.* Holt, 1981). Laminated materials preferentially fail along certain orientations, while amorphous materials do not; on the other hand, the easy slip plane in the layered material may yield a smoother failure surface. The tendency to fail along grain boundaries or through grains also varies between materials, depending *inter alia* upon the structural homogeneity (Gaudin, 1926).

In the industrial context, working with a given material, the type of grinding takes on increased importance. A number of studies have been reported in the literature in which the effects of different grinding processes on a given sample are reported. A typical result is that more angular particles are produced from rod mills (attributed to impact processes), compared to rounder particles obtained from ball mills (attributed to abrasion and chipping) (Yekeler et al., 2004), although this depends on the details of operation (Gaudin, 1926). Yet at the same time the particles ground in a rod mill have been reported to be smoother than particles from a ball mill (Yekeler et al., 2004).[3] Autogenous milling produced intermediate results in each parameter in the work of Yekeler et al. (2004), while Forssberg and Zhai (1985) reported that autogenously ground ore particles were less elongated than those from either ball or rod milling.

Hiçyılmaz et al. (2006) characterised pyrite particles of a given size fraction obtained from dry autogenous grinding as being rougher (by BET surface area) and more acute (by aerodynamic resistance) than those obtained from dry ball milling. This differed from their earlier results for barite (Hiçyılmaz et al., 2005), in which dry ball milling produced rougher and more acute particles than dry autogenous milling, for a given size fraction. This emphasises the effect of the feed material on the outcome (Hiçyılmaz et al., 2006). For the barite samples the smaller size fractions were reported to be rougher and more acute in shape (Hiçyılmaz et al., 2005), while the opposite trend was reported for the pyrite samples (Hiçyılmaz et al., 2006).

Dry and wet milling were carefully studied by Feng and Aldrich (2000), who found that the dry-ground particles had relatively rough surfaces containing microstructural defects, whereas the wet-ground particles had smoother, cleaner surfaces.

It should be clear that comparison between studies on different materials is fraught with difficulty; yet even when the material is identical, the situation may not be straightforward. Besides the type of material and type of machine, the resulting particle shapes depend *inter alia* on: size of feed material; speed of operation of equipment; geometry of equipment; product particle size, and particle size distribution (Gaudin, 1926; Holt, 1981).

1.3. Effect on flotation

1.3.1. Shape

One of the key resistances to attachment is the hydrodynamic resistance arising as liquid drains out of the gap between a bubble and an approaching particle. Aspherical particles could experience a lower resistance (depending upon their shape and orientation), and hence require less time for the intervening gap to thin sufficiently to be breached, and attachment occur.

There have been few systematic studies on the effect of particle shape or roughness upon flotation performance.

One of the earliest notable studies on this topic was carried out by Anfruns and Kitchener (1977). They concluded that angular particle shapes have much higher attachment efficiencies than spheres, which they attributed to easier rupture of the "wetting film". In that work the angular particles were composed of quartz (Brazilian rock crystal), while the 'ballotini' spheres were of lead glass. Despite care taken to ensure the same size (31 μm equivalent Stokes diameter), similar density, and similar surface properties, an effect of the difference in materials cannot be entirely ruled out (*cf.* Verrelli et al., 2012). In distilled water, Anfruns & Kitchener found collection efficiencies about four times greater for angular quartz than for spherical glass particles. According to their experimental description, the collision rates would be the same in each case, entrained particles were eliminated, and detachment was implied to be negligible; hence, the differences should be due to variation in the ease of attachment.

Studies on talc have suggested that rounder (but rougher) particles produced by ball milling are less easily recovered in a microflotation cell (Yekeler et al., 2004) and in column flotation (Kursun and Ulusoy, 2006), compared to more elongated (but smoother) particles produced by rod milling. These experiments used a relatively broad class of particle sizes (40–250 μm). Despite the "similar" particle size distributions from each mill (Yekeler et al., 2004), narrower fractions would avoid the potential issue associated with dependence of shape upon particle size. Even within a given narrow size fraction, the predominant shape may depend upon whether it comes from the lower end of a coarse grind, or the upper end of a fine grind.

Wotruba et al. (1991) reported that prismatic zircon particles of a given size floated better than those with more spherical or ellipsoidal shapes in a 1.5 L cell. (Confirmed independently by Gül (2006).) The particles all had essentially the same composition by XRF. The prismatic particles tended to have smoother faces and sharper edges than the other types of particle in the flotation feed. However, even after roughening the faces and rounding down the sharp edges, the prismatic particles remained more floatable. Wotruba et al. proceeded to characterise the ease of detachment of the original particles from a bubble, and found that the energy necessary for detachment was significantly greater for prismatic particles attached parallel to their long axes ('flat-attached') than for either rounded particles or 'end-attached' prismatic particles. This can be related to the length of the three-phase contact line (TPCL) formed. Wotruba et al. accepted that rounded particles may also be

[3] The rod-milled particles were also claimed to be more hydrophobic than the ball-milled product (Yekeler et al., 2004). However, that conclusion rests on comparing extrapolations of surface tension that are subject to uncertainties larger than their differences, besides being founded on Zisman's theory, which is itself subject to criticism (Siboni et al., 2004).