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The link between froth surface grade and flotation feed grade

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ABSTRACT

In froth flotation, particles that are recovered to the concentrate comprise those attached to bubbles and unattached particles, which include entrained material and particles that have become detached from bubbles in the froth phase, but that are carried into the concentrate. The grade of the particles remaining attached to bubbles at the froth surface is of interest as it offers information on the selective nature of the froth phase and has been shown to indicate the maximum mineral grade that can be obtained for a given feed. In this paper, the grade of particles attached to bubbles at the froth surface is shown as a function of cell feed grade down a bank of cells, and is linked to variation in mineral liberation and flotation kinetics.

The grade of attached particles at the froth surface is measured by touch sampling; touching an individual bubble with a microscope slide and collecting the solids. Data from two surveys carried out over the first four cells of the rougher bank at the same copper concentrator have been analysed. It has been shown previously that the surface grade measured in this way does not vary with operating conditions such as air rate, and here it is shown that when plotted as a function of cell feed grade, the attached particle grade exhibits a clear trend that can be modelled empirically by the equation $x = 1 - \exp\left(-aG_{vf}^{b}\right)$, where x is the inferred liberation, taken as the attached particle grade at a given feed grade as a fraction of the maximum grade obtainable for the feed to the bank, and G_{vf} is the cell feed grade. The shape of the curve, determined by the fitted parameters a and b, is dependent on the mineralogy and liberation characteristics of the feed. This relationship suggests that the variation in flotation kinetics for particles of different liberation in a flotation feed can be linked to attached particle grade.

1. Introduction

In froth flotation, recovery of particles is generally characterised as being by ‘true flotation’, i.e. particles that attach to bubbles in the pulp phase and are subsequently recovered to the concentrate, or by non-selective entrainment, carried into the concentrate unattached to bubbles in the Plateau borders (Warren, 1985). Recovery by true flotation is described using a first order rate constant to account for the collection of particles in the pulp phase and a froth recovery term, which accounts for particles arriving at the pulp–froth interface attached to bubbles, and which are subsequently recovered to the concentrate. Froth recovery does not distinguish between particles remaining attached through the froth phase and those becoming detached during coalescence events, but which are recovered unattached. During coalescence in the froth phase, particles may become detached, whether through loss of bubble surface or the vigorous nature of the event itself, particularly near the pulp–froth interface (Ata, 2012). The rejection of unattached particles from the froth is strongly dependent on physical properties of the particles, such as size and density, and the physical properties of the froth, such as viscosity in the Plateau borders (the channels between bubbles) (Neethling, 2008).

Whether or not the froth phase is selective in the rejection of particles of lower grade has been the subject of several studies at both laboratory and industrial scale (Ata, 2009; Gourram-Badri et al., 1997; Rahman et al., 2013; Seaman et al., 2004; Yianatos et al., 1988, 2014). At laboratory scale, Ata (2009) studied the detachment of particles during the coalescence of two bubbles with one or both bubbles coated with silica particles of different size and with varying concentrations of surfactant. Experiments showed that increasing surfactant concentration resulted in a decrease in the detachment of particles during coalescence, and while the surfactant adsorbed both at the surface of the particles and at the air–water interface, it was suggested that the presence of particles increases the rigidity of the bubble shell, reducing the effect of the turbulent oscillations that occur during coalescence that can lead to detachment. The results agree with findings from laboratory experiments carried out by Gourram-Badri et al. (1997), who studied selectivity during bubble coalescence for a mix of sphalerite and chalcopyrite particles from an industrial

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concentrate. They showed that the particles of lower hydrophobicity, indicated using induction time measurements, tended to become detached during coalescence. It should be noted, however, that the experimental systems in both studies, consisting of two bubbles submerged in solution, is more representative of the pulp phase, or the region of the pulp–froth interface, rather than towards the froth surface, where the liquid content is lower and the bubbles are more polyhedral in structure.

Rahman et al. (2013) scaled up a laboratory device that allowed the collection of particles dropping back through the froth, in addition to those reaching the froth surface, and tested it at a copper concentrator. The results showed that the grade of the particles collected in the drop back chamber was significantly lower than the concentrate grade, although higher than the tails grade, suggesting that the froth selectively rejects particles as a function of grade, in addition to size. The authors conclude that the particles dropping out of the froth were more likely to be middling particles.

Industrially, Yianatos et al. (1988) showed that mineral grade in the froth increased towards the froth surface by taking samples at different heights in a flotation column froth, however they found little difference in grade in shallower froths. Using in-pulp and froth surface sampling techniques, Seaman et al. (2004) found that there was little difference in the grade of attached particles between the pulp and the froth surface in cleaner cells and columns at a zinc concentrator, however in the retreatment circuit (cleaner-scavenger), the surface grade was higher than the grade of particles attached to bubbles in the pulp in the mechanical cells, but not in the final cleaner column. This suggests that for cells with higher feed grades (i.e. cleaner cells), there is little upgrading available within the froth possibly due to particles having similar liberation and/or size, however in cells where there is a lower feed grade, or a greater range of particles of different liberations, then there is selective rejection of lower grade particles. Mineral liberation is typically described as being the fraction of particle that is constituted by the mineral of interest.

More recently, Yianatos et al. (2014) compared the grade and size distribution of particles attached to bubbles in the pulp with the top-of-froth (TOF) grade down a bank of Cu rougher cells. They found that there was some upgrading between pulp and froth for the coarser size fractions, but that there was insignificant selectivity for the finer fractions. It should be noted that the method of collection of the TOF sample involves a shallow 'scoop' that skims off the top surface of the froth. This will collect not only attached particles but also unattached particles at the froth surface, which may be the reason for the contradictory results to Seaman et al. (2004), who use a more targeted sampling approach that collects material from an individual bubble surface. Yianatos et al. (2014) also show that the TOF grade decreased down the bank, which they attribute to the recovery of particles of lower liberation. The decrease in attached particle grade at the froth surface down the bank was also reported by Hadler et al. (2006), who showed additionally that the attached particle grade (or lamellae grade) was not affected by variations in operating conditions such as air flowrate. This observation had also been noted by Ventura-Medina et al. (2004) and Barbian et al. (2005) suggesting that the attached particle grade is more closely linked to the mineralogical characteristics of the feed. Yianatos et al. (2014) conclude that "the TOF measurement allows for an indirect identification of the liberation effects on the flotation process".

Although there is some contradiction in the literature on the selective nature of the froth in rejecting particles of poorer liberation and lower grade, the properties of the particles that remain attached at the froth surface, such as grade and size, can give an indication of the mineralogy and the liberation of the particles being recovered, which is in turn linked to flotation rate and recovery. In this paper, the link between cell feed grade and attached particle grade is explored further, and an empirical model describing the link between feed and attached particle grade is described.

2. Experimental methodology

The data presented in this paper are taken from two separate periods of experimental work, carried out at the same copper concentrator 5 years apart, the aim of which was to investigate the effects of operating conditions of froth stability and flotation performance. Details of the findings with respect to this aim can be found in Hadler et al. (2006, 2010).

The copper concentrator comprises a bank of four rougher cells and four scavenger cells, with a cleaner circuit, the tails of which recycle into the scavenger row. In addition to samples of feed, concentrate and tails for each cell being sampled, air recovery was measured using image analysis to determine the overflowing froth velocity, and manual measurements of the overflowing froth height. The effects of various operating conditions on air recovery and flotation performance were tested, including air rate. For each operating condition, samples were also taken of the attached material at the froth surface and in the pulp (Survey 2 only).

2.1. Surface sampling method

There are two key methods reported for collecting froth surface samples; touch sampling individual bubbles to collect only attached material (Sadr-Kazemi and Cilliers, 2000) and bulk 'top-of-froth' sampling; collecting material from the top 'layer' of froth only using a shallow 'scoop' (Yianatos et al., 2014). While the bulk top-of-froth (TOF) sampling has the benefit of allowing greater quantities of material to be collected over shorter time periods, enabling size-by-size analysis for example, it does not give a reliable measure of only attached particles. Typical flotation froths operate with air recoveries (the fraction of air entering the cell that overflows in unburst bubbles) of 50% or lower, often around 20% for rougher cells (Hadler et al., 2006). These low values mean that the majority of particles recovered to the concentrate are unattached (Hadler, 2006; Ventura-Medina and Cilliers, 2002). On the other hand, the touch sampling method is laborious, and, with each sample collecting in the order of 10 mg solids, time-consuming to collect sufficient material for assay.

In the studies presented here, the touch sampling method was used. The technique is described in detail in Ventura-Medina et al. (2004), and requires precision as collecting too much material from the Plateau borders can reduce the measured grade of the solids. Slower flowing and more highly coated bubbles are easier to sample in this way, and accurate sampling becomes more difficult further down the bank, where the loading of particles on bubbles decreases and air recovery drops (Hadler et al., 2006). For this reason, only the four cells of the roughers were sampled in this way. In order to collect sufficient sample, around 100 bubbles were sampled (Ventura-Medina et al., 2004). As each bubble 'print' had a mass of approximately 10 mg at the head of the bank, decreasing to 2 mg by the fourth cell, there was insufficient sample for size-by-size analysis. A typical bubble 'print' is shown in Fig. 1.

In addition to the surface samples, in during the second survey, samples were also taken of the attached material in the pulp using the Anglo Platinum Bubble Sizer, which is based on the design of Hernandez-Aguilar et al. (2004). The reliability of this measure is discussed in more detail later in the paper.