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Processing a rare earth mineral deposit using gravity and magnetic separation

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ABSTRACT

Rare earth (RE) mineral deposits are typically processed using several different unit operations including flotation, gravity, magnetic and electrostatic separation techniques. Two of the most important beneficiation techniques for RE minerals are gravity and magnetic separation. Many RE minerals are found alongside low specific gravity gangue minerals thereby permitting the use of gravity separations to concentrate the heavy value RE minerals. Magnetic separation is used primarily to remove ferromagnetic gangue minerals as well as to separate individual paramagnetic rare earth minerals.

This work investigated the use of a wet high intensity magnetic separation (WHIMS) in conjunction with gravity pre-concentration steps (Knelson and Falcon centrifugal concentrators) to beneficiate a rare earth ore. The results of these separation steps are related to the magnetic properties of RE minerals, based on literature and measurements conducted using a vibrating sample magnetometer (VSM).

1. Introduction

1.1. Rare Earth minerals

Rare earth (RE) element bearing minerals are composed of at least one of the fifteen lanthanide elements or yttrium. Rare earth elements are used in a diverse range of applications including high strength magnets, phosphors, alloying elements, catalysts and polishing compounds (Crow, 2011; Meyer and Bras, 2011; Preinfalk and Morteani, 1986). There are many different RE minerals and these minerals can be found in many locations throughout the world; the bulk of currently operating RE mines are located in China.

Recently, the Chinese government has begun imposing strict export quotas on the RE industry thereby driving RE exploration and mine development in many other regions of the world (Chen, 2011). The three most common RE minerals mined are bastnäsite, monazite and xenotime, however the new deposits under development contain many new minerals with unknown characteristics. Most RE mineral deposits are beneficiated through a combination of unit operations such as gravity concentration, magnetic separation and froth flotation (Zhang and Edwards, 2012). Due to their relatively high specific gravities (between 4 and 7) gravity separation can be used to concentrate RE minerals by eliminating low specific gravity gangue minerals such as quartz (Ferron et al., 1991). In the context of RE mineral beneficiation, magnetic separation is typically used for two purposes: low intensity magnetic separation is used to remove ferromagnetic gangue minerals such as iron oxides and high intensity magnetic separation is used to separate monazite and xenotime from other heavy minerals (Gupta and Krishnamurthy, 1992).

For further information on rare earth physical beneficiation recent reviews by Zhang and Edwards (2012) and Jordens et al. (2013a) should be consulted.

1.2. Gravity separation

Gravity separation is used in mineral processing to separate minerals based on differences in specific gravity. The most common and successful type of gravity separator used for fine particle sizes is a centrifugal gravity concentrator (Falconer, 2003). These separators introduce a mineral slurry into a rapidly rotating bowl to generate centrifugal forces on the particles that are much higher than the force of gravity and therefore decrease the lower size limit for effective gravity separation (Falconer, 2003). The centrifugal forces on the particles trap high specific gravity material against the sides of the bowl to become the gravity concentrate while lower specific gravity material is carried along with the flowing fluid to report to the gravity tailings (Falconer, 2003). These concentrators are operated in a semi-continuous mode where the accumulated

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concentrate is periodically removed by washing (Fullam and Grewal, 2001).

One of the most common centrifugal separators is the Knelson Concentrator, which employs an inclined bowl lined with collecting ridges where the heavy (specific gravity >4) value mineral is collected (Ferron et al., 1991; Fullam and Grewal, 2001). These ridges contain perforations through which water is pumped in order to fluidize the material collecting in the ridges and allow for the exchange of low specific gravity material (which may have initially reported to the concentrate) with high specific gravity material (Fullam and Grewal, 2001; Knelson, 1992). The Knelson Concentrator works very well for applications where the desired high specific gravity mineral is present in very low concentrations (ppm) but runs into operational difficulties processing ores with higher contents (typically >1%) of high specific gravity material as the concentrate accumulates very rapidly (Fullam and Grewal, 2001). If the accumulated gravity concentrate is not flushed promptly the selectivity of the separation will suffer significantly (Fullam and Grewal, 2001; Knelson, 1992). An additional limitation to the Knelson Concentrator is that the efficiency of the concentration step decreases with feed fineness (Laplante, 1993). Laplante (1993) suggested that for the specific case of gold particles, the poor performance of the Knelson Concentrator in treating fine feeds (<75 μm) is more likely attributable to the shape of the fine gold particles rather than their size.

The Falcon Ultra-Fine (UF) Concentrator is designed specifically to process very fine particle sizes. It lacks the fluidizing water used in other centrifugal concentrators; instead relying on the geometry of the bowl walls to retain the high specific gravity material (Lins et al., 1992). This design changes the mechanism of high specific gravity particle collection as there is no opportunity for particle exchange once a particle has been deposited on the wall of the spinning bowl (Kroll-Rabotin et al., 2011). Laplante et al. (1994) showed that there are three steps in a Falcon Concentrator separation: initial unselective deposition of material on the concentrate bed along the bowl wall, selective concentration until the concentrate bed is saturated, and finally minimal recovery as the concentrate bed is unable to accept additional particles. It can be seen from these three phases of material recovery that it is crucial to ensure that the concentrator is stopped at suitable time intervals to maximize the separator's efficiency by not operating with a fully-loaded bowl.

1.3. Magnetic separation

Magnetic separation of minerals is based on different behaviours of mineral particles when in an applied magnetic field. Unpaired electrons present in certain types of atoms cause magnetic dipoles which lead to the creation of magnetic moments in a material that can in turn result in a magnetic force on the material when these moments are aligned by an externally applied magnetic field. In mineral processing terminology there are three distinct behaviours that a mineral particle may exhibit: Ferromagnetic and paramagnetic mineral particles will both be attracted along the lines of an applied magnetic field whereas a diamagnetic mineral particle will be repelled along the magnetic field lines. The main difference in ferromagnetic and paramagnetic minerals is that a ferromagnetic material is able to much more rapidly align its magnetic moments so that the magnetisation (and consequently the magnetic force felt by the particles) is much higher at lower applied magnetic field strengths. An excellent introduction to magnetism in materials and other associated concepts can be found in the work of Jiles (1990).

The magnetic recovery in a magnetic separator is dependent on the applied magnetic field strength, the magnetic field gradient and the magnetic susceptibility of the mineral particles and accompanying fluid medium as can be seen in the following equation (Oberteuffer, 1974):

$$F_x = V(\chi_p - \chi_m)H\frac{dB}{dx} \tag{1}$$

In this equation F_x is the magnetic force felt by a particle (N), V is the particle volume (m^3), χ_p is the dimensionless volume magnetic susceptibility of the particle, χ_m is the volume magnetic susceptibility of the fluid medium, H is the applied magnetic field strength (A/m) and dB/dx is the magnetic field gradient ($T/m = N/Am^2$) (Oberteuffer, 1974; Svoboda and Fujita, 2003). The magnetic force on a particle in a magnetic separator may be controlled by varying the magnetic susceptibility of the particle/medium, the applied magnetic field or the magnetic field gradient.

The size range at which magnetic separation is effective depends on which of the three main forces on a particle (gravitational, magnetic and fluid drag) is dominant at a particular size (Oberteuffer, 1974). The fluid drag forces on a particle are proportional to the radius, r, while the magnetic force on a particle is proportional to r^2 (Oberteuffer, 1974). Similarly the force due to gravity can be shown to scale with r^3 so that for particles of very small radius the fluid drag forces are dominant while for a much larger particle radius gravitational forces are the most significant forces on a particle (Oberteuffer, 1974). The particle radius at which magnetic separation may be effective has been determined to be approximately 5 μm up to 1 mm (Oberteuffer, 1974) however the recovery of increasingly fine magnetic material (down to even nano-scale particles) is an area of active research (Chen et al., 2012; Ebner et al., 1997; Menzel et al., 2012; Roy, 2011).

1.4. Measuring the magnetic properties of materials

As stated in Section 1.3 all minerals may be classified (for simplicity) into three categories of magnetic behaviour. The specific behaviour of a single mineral may be analysed by looking at the magnetisation of the material as a function of applied magnetic field. One method of obtaining this information is by using a vibrating sample magnetometer (VSM) which suspends a small quantity of mineral from an oscillating rod (Foner, 1959). The material is then subjected to a series of uniform magnetic fields of varying strength and the changes in magnetisation within the material are measured by a series of detection coils (Foner, 1956). The direct measurement output of the VSM is the magnetic moment of the sample, which is converted to magnetisation by dividing by the volume of the sample.

An example of typical diamagnetic, paramagnetic and ferromagnetic behaviour may be seen in Fig. 1. A diamagnetic material, due to its unaligned magnetic dipoles, will be repelled along the lines of an applied magnetic field and as such it will exhibit a slightly negative linear variation of magnetisation with increasing applied magnetic field as shown in Fig. 1 (Jiles, 1990; Waters et al., 2007). On the same graph a paramagnetic material will show a positive linear increase in magnetisation as higher applied magnetic field strengths will cause more of the magnetic dipoles

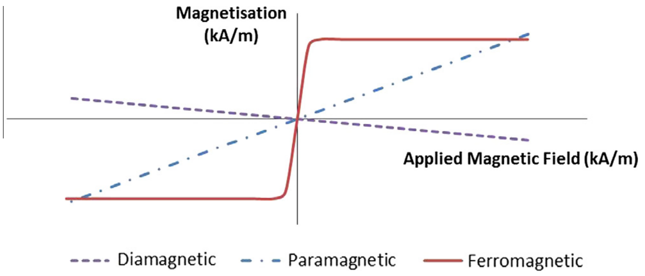

Fig. 1. Typical VSM results for diamagnetic, paramagnetic and ferromagnetic material.