Minerals Engineering 78 (2015) 122–127

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

High gradient magnetic separation in centrifugal field

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ARTICLE INFO

Article history:
Received 25 January 2015
Revised 16 March 2015
Accepted 19 April 2015
Available online 16 May 2015

Keywords:
Centrifugal high gradient magnetic separation
Fine weakly magnetic ores
Hematite
Ilmenite

ABSTRACT

High gradient magnetic separation (HGMS) in centrifugal field, termed a Centrifugal High Gradient Magnetic Separation (CHGMS), has been developed to concentrate fine weakly magnetic particles such as hematite and ilmenite. In this investigation, the principle of CHGMS is theoretically discussed and a cyclic pilot-scale CHGMS separator was tested to concentrate a fine (−74 μm) hematite ore, to study the effect of key variables such as magnetic induction, rotation speed of matrix, feed flow rate and feed mass on the separation performance of the separator. The results of investigation indicate that changes in the magnetic induction and the rotation speed of matrix had the most significant influences on the performance. An increase in the rotation speed improved concentrate grade but reduced iron recovery, while the reverse was observed for changing the magnetic induction. A too low feed flow rate resulted in an extremely high recovery but a lower concentrate grade. For a given matrix configuration, there was an upper limit for feed mass as the capture area of magnetic elements in the matrix was fixed, and this limit was correlated to the rotation speed of matrix. When the variables were optimized, the CHGMS separator achieved a superior separation performance to pulsating HGMS, achieving a separation efficiency of 72.50% compared to 56.41%, respectively. It was thus concluded that the CHGMS provides a potential technique for the production of high-grade magnetic concentrate from fine weakly magnetic ores.

1. Introduction

High gradient magnetic separation (HGMS) is a powerful and useful technique for the recovery of fine weakly magnetic particles (Svoboda, 2001). In the recent decades, HGMS has undergone significant advancements and its applications has expanded with the beneficiation of hematite, limonite, ilmenite and rare earth minerals, and the purification of quartz, feldspar, fluorite and kaolin (Xiong et al., 1998). The magnetic force is the main mode by which particles are separated, although hydrodynamic drag and gravity may assist (Svoboda and Fujita, 2003). Due to technical difficulties, it is not possible to produce a high-grade magnetic concentrate from weakly magnetic ores, and achieving a concentrate grade greater than 60% Fe from hematite ores is very difficult for HGMS in a single pass. The reason is caused by magnetic encapsulation of gangue which along with low-grade composite magnetic material deteriorates the quality of magnetic concentrate (Chen et al., 2009). In practice, HGMS is widely used to preconcentrate fine weakly magnetic ores, and is processed by flotation or gravity processes to produce a marketable high-grade concentrate (Zeng and Xiong, 2003). However, flotation has a relatively high energy, reagent consumption and environmental pollution considerations, while gravity concentration has characteristic low throughput rate.

In the past, laboratory attempts to produce high-grade concentrate from fine weakly magnetic ores were investigated through HGMS process, after size enlargement of magnetic particles in the form of flocs (Song et al., 2002) or polymer flocculations (Arol and Aydogan, 2004), with limited success. A major challenge in using such methods lies in the fact that, it becomes very difficult even impossible to keep the magnetic flocs or flocculations in a stable state in the slurry, throughout the HGMS process. Recently, centrifugal concentration both in pilot-scale and full-scale has been tested with success to produce a high-grade concentrate, by cleaning the primary hematite concentrate from pulsating HGMS (Chen et al., 2010). This lies in the fact that centrifugal force is effective in removing magnetically low-grade intergrowths from the primary concentrate. But, a disadvantage of this is its low throughput rate, as it concentrates heavy particles in a flowing film of several millimeters thick (Chen et al., 2008).

Although the centrifugal force is effective in cleaning the primary hematite concentrate, its practical use is limited because of it low throughput rate. However, the increasingly stringent environmental restrictions and the demand for high-grade raw materials from the

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http://dx.doi.org/10.1016/j.mineng.2015.04.018
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steel making industry justify the efforts to find physical methods to produce high-grade concentrate from fine weakly magnetic ores. Thus, HGMS incorporating centrifugal action, which is termed Centrifugal High Gradient Magnetic Separation (CHGMS) (Chen, 2010), are continually being refined to concentrate hematite, limonite and ilmenite, with success for treatment of these fine weakly magnetic ores. In this investigation, the principle of CHGMS is theoretically discussed and a cyclic pilot-scale CHGMS separator was tested on fine (−74 μm) hematite ore, to study the effect of key variables such as magnetic induction, rotation speed of matrix, feed flow rate and feed mass on the separation performance of the separator. In addition, the separation results were compared with those of cyclic pilot-scale pulsating HGMS separator.

2. Cyclic CHGMS and its working procedure

A CHGMS separates particles via a cyclic process, as shown in Fig. 1. A matrix made of cylindrical bars of magnetic stainless steel rotates within a magnetic field and a centrifugal field is built up in that magnetic field. The sealed chamber is filled with water, and slurry is fed into the feed inlet and is radially thrown out of the rotating matrix as a result of centrifugal force. Magnetic particles are attracted onto the surface of matrix, while non-magnetic particles flow through the radial depth of matrix and flow downward to get a non-magnetic product, under the combined actions of magnetic force, centrifugal force and shear hydrodynamic resistance.

In the CHGMS process, the rotation of matrix stirs the slurry, keeping particles in the matrix in a loose state, thus improves the separation selectivity of magnetic capture. The rotation may cause the tumbling motion of captured particles over the magnetic elements in the matrix, thus facilitates the release of entrained non-magnetic particles. Moreover, the actual magnetic element layers of particles passing through the matrix significantly increases with increase in the rotation speed of matrix. This improves the collision efficiency of particles with the matrix, resulting in the increased recovery for magnetic particles.

This cyclic CHGMS process was operated in a batch mode. When a batch of feed was finished, the magnetic field was switched off and the magnetic particles captured onto the matrix were washed out with clean water to obtain a magnetic product.

3. Principle of CHGMS

3.1. Magnetic force for capture of magnetic particles

Fig. 2 illustrates the direction of forces acting upon a particle within the rotating matrix in the CHGMS process. Assume a

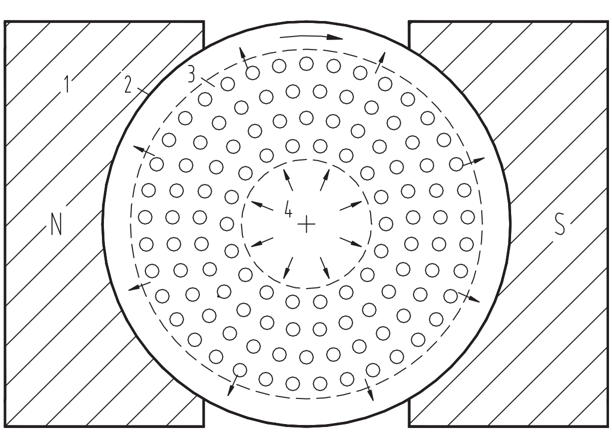

Fig. 1. Schematic diagram of a cyclic CHGMS process (plan view): 1 = magnetic poles, 2 = sealed chamber, 3 = magnetic matrix, 4 = feed inlet.

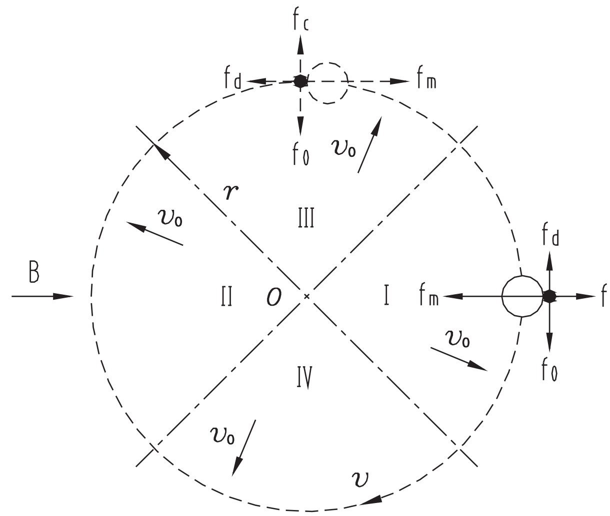

Fig. 2. Capture of magnetic particle in a CHGMS process (plan view).

particle of unit mass with diameter d was captured onto a magnetic element and revolves with the element at a radius r with linear velocity υ, it is subjected to a magnetic force f_m approaching to the element, a centrifugal force $f_c = \upsilon^2/r$ in radial direction, a shear hydrodynamic resistance $f_d = 18\mu\upsilon/d^2\rho$ (in laminar flow region) opposite to the linear velocity υ, and a friction force f_0 opposite to the centrifugal force or the shear hydrodynamic resistance as shown in Fig. 2.

If the particle was captured onto the horizontal outer surface of the magnetic element, which revolves in I or II areas as shown in Fig. 2, the friction force f_0 is written as:

$$f_0 = (f_m - f_c) \cdot \tan\theta \tag{1}$$

where θ is the friction angle.

Then, $f_0 \geqslant f_d$ should be met and we get:

$$f_m \geqslant \frac{18\mu\upsilon}{d^2\rho\tan\theta} + \frac{\upsilon^2}{r} \tag{2a}$$

where μ and ρ are the dynamic viscosity of fluid and the density of particle, respectively.

And, if the particle was captured onto the horizontal inner surface of the magnetic element, the above correlation is written as:

$$f_m \geqslant \frac{18\mu\upsilon}{d^2\rho\tan\theta} - \frac{\upsilon^2}{r} \tag{2b}$$

However, when the particle was captured onto the vertical surface of the magnetic element, which revolves in III or IV areas, then $f_0 \geqslant f_c$ should be met. In this case, if the particle was captured onto the downstream surface of the element as shown in Fig. 2, we get:

$$f_m \geqslant \frac{18\mu\upsilon}{d^2\rho} + \frac{\upsilon^2}{r \cdot \tan\theta} \tag{3a}$$

And, if the particle was captured onto the upstream surface of the element, the above correlation is written as:

$$f_m \geqslant -\frac{18\mu\upsilon}{d^2\rho} + \frac{\upsilon^2}{r \cdot \tan\theta} \tag{3b}$$

Comparing Eqs. (2a), (2b), (3a), and (3b), it is derivative that the critical magnetic force f_{mcr} required for the capture of magnetic particles in the CHGMS process may be written as:

$$f_{mcr} = k_1\frac{18\mu\upsilon}{d^2\rho} + k_2\frac{\upsilon^2}{r} = k_1 f_d + k_2 f_c \tag{4}$$