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# Study on the demarcation of applied magnetic induction for determining magnetization state of matrices in high gradient magnetic separation

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ABSTRACT

High gradient magnetic separation (HGMS) has been widely applied in many scientific and industrial fields. The performance of matrix in HGMS varied greatly before and after reaching magnetization saturation. Particle capture models of unsaturated and saturated matrices had been established in previous studies. Problems remained that how to determine the demarcation of applied magnetic induction for selecting the right capture models in specific studies. This is remarkably essential for the investigation of effect of matrix shape (aspect ratio) on performance of matrix in HGMS. In the present paper, magnetization process of circular matrix with increasing applied magnetic induction was investigated through numerical simulation and theoretical calculations. A convenient method to determine the demarcation point was proposed. The internal magnetic induction of matrix is equal to magnetization before reaching saturation and has the same growth rate as applied magnetic induction after reaching saturation. The demagnetization of matrix is half of the magnetization before and after reaching saturation. Validity of the coefficients adopted in the particle capture models in the whole range of applied induction is investigated with the internal magnetic induction, aiming to determine the demarcation point for selecting the right particle capture models. Results showed that the demarcation of the applied magnetic induction for circular matrix is $M_s/2$. Particle capture models of unsaturated and saturated matrix should be selected when applied magnetic induction is lower and higher than $M_s/2$, respectively.

## 1. Introduction

High gradient magnetic separation (HGMS) is an effective method for separation or purification of weakly magnetic materials. Due to its high efficiency and eco-friendly characteristics, HGMS has been widely applied in mineral processing (Zeng and Xiong, 2003; Li et al., 2014; Singh et al., 2015; Tripathy et al., 2017) and some other scientific and industrial fields such as water purification (Wang et al., 2012; Nomura et al., 2012), biological entities separation (Jung and Han, 2008; Lindner et al., 2013) and waste management (Kim et al., 2015; Okada et al., 2011). Consequently, the basic principles of HGMS have also attracted much attention from scientific researchers. Magnetic matrices and applied magnetic field are key components of HGMS system. The most commonly used matrices in HGMS are circular cross-section cylinders of high susceptibility.

For the basic principles behind HGMS, previous researchers had focused on capture of particles by matrices and some particle capture models were established. Watson and Gerber modeled particle capture of circular cross-section matrices in three configurations (longitudinal, transversal and axial) of HGMS (Watson, 1973; Gerber, 1978; Kanok and Mayuree, 2013; Abbasov et al., 2016). Based on the particle capture models, we investigated particle capture of fine weakly magnetic minerals in HGMS (Zheng et al., 2015a, 2015b) and we also modeled particle capture of elliptic cross-section matrices in HGMS (Zheng et al., 2016a, 2016b, 2016c). However, all these particle capture models were based on the premise that matrices were saturated by applied magnetic field. In our subsequent studies, it was found that some experimental results could not be explained by these particle capture models. Then we expanded particle capture models of circular and elliptic cross-section matrices (circular and elliptic matrices for short hereafter), considering both the case that the matrices were saturated and unsaturated by applied magnetic field. Analyses with expanded particle capture models agreed well with experimental results in axial and transversal configurations (Zheng et al., 2017a, 2017b).

The performance of matrices in HGMS varied greatly before and after reaching magnetization saturation and coefficients in the particle

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**Nomenclature**

| | |
|---|---|
| $H_0$ | applied magnetic field, A/m |
| $B_0$ | applied magnetic induction, T |
| $B_{in}$ | internal magnetic induction of the matrix, T |
| $H_{in}$ | internal magnetic field of the matrix, T |
| $M$ | magnetization, T |
| $M_s$ | saturation magnetization, T |
| $H_d$ | demagnetization field, A/m |
| $\mu_0$ | vacuum permeability, H/m |
| $\mu$ | magnetic permeability, H/m |
| $\mu_r$ | relative permeability, – |
| $\kappa$ | magnetic susceptibility, – |
| $d$ | radius of the circular matrix, m |
| $r$ | polar coordinate, m |
| $\theta$ | polar angle ccodinate, – |

capture models for saturated and unsaturated matrices should be selected accordingly. Thus it is vitally important to determine when matrices reach magnetization saturation with increasing applied magnetic field. Although we had established the expanded particle capture models of circular and elliptic matrices in HGMS and had declared that matrices reached saturation at certain magnetic induction, no explanations or judging methods were provided. Moreover, for studying performance of matrices with different aspect ratio in HGMS, the magnetization state of matrices changes with varying aspect ratio in a constant magnetic field. Although there are many methods of measuring magnetism (Cavanough et al., 2006; Yu et al., 2017), only the basic magnetic properties of the material such as B-H curve or susceptibility can be obtained. Till now no methods focus on the relation between the magnetization state of a magnetic sample (unsaturated or saturated) and the given magnetic induction. In HGMS, the applied magnetic induction is a key adjustable parameter. It is quite necessary to develop a method for rapidly judging whether matrices have reach magnetization saturation or determine how to exactly adopt particle capture models at specific magnetic induction.

In the present paper, magnetization process of circular matrix was studied with increasing applied magnetic field using numerical simulation. The variations of related magnetization coefficients of matrix were investigated. Theoretical calculations were conducted for investigation of generalized condition. A method of determining the demarcation of applied magnetic induction for exactly adopting particle capture models (models for saturated and unsaturated cases) was proposed.

## 2. Numerical simulation of the matrix's magnetic field

### 2.1. Related magnetization coefficients and magnetization rules

Magnetization state of the matrices varies with the applied magnetic induction. To provide an intuitive observation of the magnetization process of matrix with increasing magnetic induction and investigate the variation of related magnetization coefficients, numerical simulation of the magnetic field generated by matrix under different magnetic induction was conducted firstly. Magnetization rules describe the interrelation of related magnetization coefficients such as internal magnetic induction $B_{in}$, internal magnetic field $H_{in}$, magnetization $M$, magnetic permeability $\mu$, relative permeability $\mu_r$, magnetic susceptibility $\kappa$, and demagnetization field $H_d$. Magnetization of matrix follows the following rules (Zheng et al., 2017c):

When matrix is unsaturated by the magnetic field:

$$B_{in} = \mu_0 H_{in} + M \tag{1}$$

When matrix is saturated:

$$B_{in} = \mu_0 H_{in} + M_s \tag{2}$$

where $M$ and $M_s$ are magnetization and saturation magnetization of the matrix material, respectively. For both the case that matrix is unsaturated and saturated, relationship between magnetization and internal magnetic field:

$$M = \mu_0 \kappa H_{in} \tag{3}$$

where $\kappa$ is susceptibility of the matrix. Typically, the material of the matrices applied in HGMS is ferromagnetic, the susceptibility is not a constant and varies with the applied magnetic induction. Using Eqs. (1)–(3), relation of internal magnetic induction and magnetic field can be obtained, as shown of Eq. (4).

$$B_{in} = \mu_0 (\kappa + 1) H_{in} \tag{4}$$

where $\mu_0$ is vacuum permeability. The relations among the susceptibility $\kappa$, the relative permeability $\mu_r$ and the permeability $\mu$ of matrix are shown by Eqs. (5) and (6).

$$\mu_r = \kappa + 1 \tag{5}$$

$$\mu = \mu_0 \mu_r \tag{6}$$

With Eqs. (4)–(6), relation between the internal induction and internal field can be simplified as Eq. (7).

$$B_{in} = \mu_0 \mu_r H_{in} = \mu H_{in} \tag{7}$$

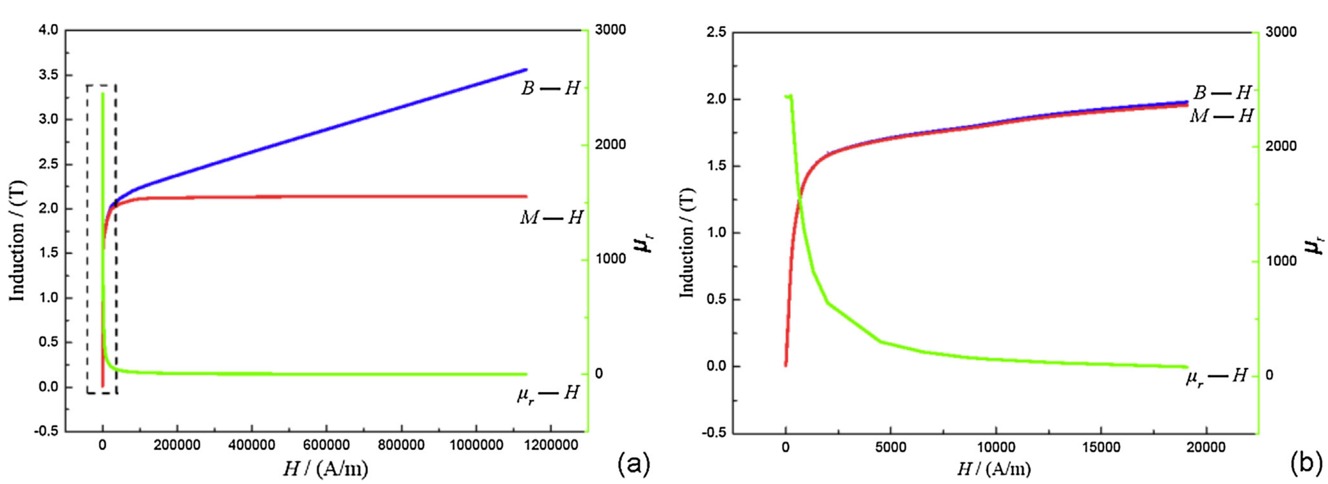


**Fig. 1.** B-H curve of pure iron.