

Article

Optimization of the Matrix in a Transverse-Field High-Gradient Magnetic Separator for an Improved Ilmenite Separation

Jianguo Liu ^{1,2,3,4}, Huixin Dai ^{1,*}, Lili Yu ^{2,3,4}, Chenghang Wang ^{2,3,4,5}, Jiaying Feng ^{2,3,4}, Peilun Li ^{2,3,4,5} and Shaohua Xu ^{2,3,4}

¹ Faculty of Land Resources Engineering, Kunming University of Science and Technology, Kunming 650093, China; liujianguo@grre.gd.cn

² Institute of Resources Utilization and Rare Earth Development, Guangdong Academy of Sciences, Guangzhou 510650, China

³ State Key Laboratory of Separation and Comprehensive Utilization of Rare Metals, Guangzhou 510650, China

⁴ Guangdong Key Laboratory of Mineral Resources Development and Comprehensive Utilization, Guangzhou 510650, China

⁵ Southwest United Graduate School, Kunming 650092, China

* Correspondence: dhx6688@sina.com

Abstract: Transverse-field high-gradient magnetic separators (HGMSs) are an important complement to longitudinal-field HGMSs in mineral processing due to their several advantages. However, the processing capacity of the transverse-field HGMS is smaller than that of the longitudinal-field HGMS. Consequently, research on the optimization of the matrix box for improving the processing capacity is essential. This work investigates the optimization of the matrix box for the SSS[®] HGMS to enhance the ilmenite separation efficiency and processing capacity. The results show that the matrix's influence on separation performance is primarily influenced by the diameter of the rod matrix, the filling ratio, the depth of the matrix in the direction of slurry flow, and the ore unloading efficiency. Ilmenite pre-concentration tests are carried out using a test sample ore from Panzhihua, China. Pilot-scale validation research is carried out. The test results indicate that the depth of the matrix box should not be considerably thick, as an excessive number of layers increases the capture zone, but simultaneously reduces the unloading efficiency. The depth of the matrix box should neither be considerably thick nor particularly thin, as this would result in low processing capacity. Meanwhile, the segmented multi-layer matrix box should be used to balance the capturing and unloading performance. Finally, an optimal double-layer matrix ring is applied to the industrial transverse-field HGMS, and its inner and outer rings are equipped with matrix boxes with $\phi 3$ mm and $\phi 2$ mm rods, respectively, which improves its pre-concentrate efficiency and processing capacity. The concentrate indexes of the transverse-field HGMS is achieved with a TiO_2 grade of 18.01% and a recovery of 87.28%, which is better than the separation indexes of the longitudinal-field HGMS.

Keywords: transverse magnetic field; high-gradient magnetic separator; magnetic matrix; ilmenite; separation efficiency



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1. Introduction

High-gradient magnetic separation is one of the most effective physical separation techniques, and high-gradient magnetic separators (HGMSs) have been widely used for separating essential metal ores, removing magnetic impurities of non-metallic ores, and eliminating suspended solids and other impurities in wastewater or waste gas [1–6]. The

longitudinal-field HGMS [7] and transverse-field HGMS [8] are typical HGMSs in industrial applications. The transverse-field HGMS serves as an important complement to the longitudinal-field HGMS in mineral processing due to its several advantages, such as reduced susceptibility to corrosion of the magnetic system, lower probability of magnetic matrix blockages, and longer service life. To date, the main transverse-field HGMSs include the SSS-I series wet high-intensity magnetic separator (WHIMS), the SSS-II series double-frequency double-vertical-rings pulsating WHIMS [9], the SSS-III series double-frequency double-layer vertical-rings pulsating WHIMS [10], and the SSS-IV series horizontal-ring non-pulsating WHIMS. The SSS-II series transverse-field HGMS has been used for limonite processing and ilmenite processing in China. The SSS-II-1750 transverse-field HGMS has been used for limonite processing at Nanjing Meishan Metallurgical Development Co., Ltd., Nanjing, China. Mining Brach since 2009; this system has successfully resolved the issues of magnetic system corrosion and magnetic matrix blockage of the original longitudinal-field HGMS [11]. The SSS-II-2000 transverse-field HGMS has been used for ilmenite processing at Pangang Group Mining Co., Ltd., Panzhihua, China. Titanium Dressing Plant since 2012. The concentrate grade is 1.58%, and the concentrate recovery is 5.08% more than the indexes achieved using the longitudinal-field HGMS [9].

The magnetic field in a transverse-field HGMS is oriented horizontally. In contrast with the longitudinal-field HGMS through industrial application practice, the slurry and magnetic systems in a transverse-field HGMS are independently configured, preventing direct contact between the slurry and the magnetic system. Consequently, the magnetic system is protected from corrosion, leading to a longer service life [12]. Furthermore, the magnetic matrix in a transverse-field HGMS is arranged in a rectangular lattice, offering a smoother slurry flow path compared to the rhombic lattice arrangement in the longitudinal-field HGMS. This configuration reduces the probability of particle sedimentation on the magnetic matrix, thereby preventing blockages in the matrix box. Consequently, the capturing and unloading performance are improved, and the durability of the matrix box is enhanced [13].

However, the width of the sorting ring and the volume of the matrix box are limited by the magnetic system's spacing, resulting in a reduced processing capacity. The equipment must be improved to increase the processing capacity. Numerous factors related to the magnetic matrix still influence the separation performance of transverse-field high-gradient magnetic separation, including the matrix's shape, the diameter of the rod matrix, filling ratio, the depth of the matrix in the direction of slurry flow, and the discharge efficiency of the captured particles [14–20]. Professors Luzheng Chen and Dongfang Lu have conducted extensive and fruitful work on HGMS. This work presents the findings of a study on matrix box optimization in transverse-field HGMSs to improve the processing capacity for ilmenite pre-concentration. Titanium is an important element in ilmenite, which has been extensively used in the fields of aerospace, petrochemical, and automobile manufacturing [21]. Ilmenite in China is considered low grade, with grades typically ranging from 5% to 10%, necessitating pre-concentration. Magnetic separation is a key pre-concentration method, and HGMS has been widely used in the beneficiation of ilmenite. Lu et al. [22] studied a novel method for the efficient recovery of ilmenite by HGMS coupling with magnetic fluid. Chen et al. [23] used a new type HGMS (CHGMS) for ilmenite separation. In their study, ilmenite from Panzhihua was used to conduct pilot-scale validation research and an industrial application for the pre-concentration of ilmenite. The matrix box was improved, the processing capacity was significantly increased, and the ore unloading rate and separation index were increased.

2. Materials, Equipment, and Methods

2.1. Experimental Sample

The experimental sample consists of tailings from the separation of vanadium–titanium magnetite (Panzhihua, Sichuan, China) as the primary ilmenite. The TiO_2 content of the sample is relatively low, and its mineral composition is complex. The results of the multi-elemental analysis and particle size distribution for this sample are presented in Tables 1 and 2, respectively. The data in the tables indicate that the TiO_2 grade of the sample is 9.90%, which is relatively low, thereby necessitating a pre-concentration process. The predominant particle size of the sample is +0.074 mm, with a corresponding yield of 70.57%. This result shows that the sample has a moderate particle size distribution, neither excessively coarse nor fine. Additionally, the liberation degree of the sample is 90.70%, which exceeds 90%, illustrating an excellent level of mineral liberation suitable for the pre-concentration process.

Table 1. Multi-elemental analysis of the experimental sample (%).

Element	TiO_2	TFe	V_2O_5	SiO_2	Al_2O_3	CaO	MgO	S
Content	9.90	28.08	0.19	29.60	9.74	5.27	12.17	0.12

Table 2. Particle size distribution of the experimental sample (%).

Grain Size (mm)	Yield	TiO_2 Grade	TiO_2 Proportion	Liberation Degree
+0.25	6.04	8.49	5.18	44.39
−0.25 + 0.20	7.86	8.81	6.99	87.07
−0.20 + 0.15	18.50	10.15	18.97	88.27
−0.15 + 0.10	20.16	10.11	20.59	92.18
−0.10 + 0.074	18.01	9.92	18.05	95.63
−0.074 + 0.043	11.55	12.35	14.41	97.95
−0.043 + 0.038	11.23	8.91	10.11	99.08
−0.038	6.65	8.51	5.70	99.25
Total	100.00	9.90	100.00	90.70

The mineral composition analysis, the equilibrium distribution of TiO_2 in the minerals, and the dissemination relationship of ilmenite in some large mineral particles are illustrated in Figure 1, Figure 2, and Figure 3, respectively. The data presented in these figures reveal that ilmenite, a valuable mineral, constitutes 13.58% of the experimental sample, with 70.42% of the TiO_2 distributed within it. The theoretical TiO_2 grade of ilmenite is 51.35%, which is slightly lower than the value of 52.66% derived from the chemical formula. This discrepancy may be attributed to the lattice substitution effects from magnesium, manganese, and other impurity elements. The primary gangue minerals identified in the sample include plagioclase, olivine, titanite, chlorite, and quartz, with contents of 24.62%, 15.17%, 14.05%, 10.99%, and 10.68%, respectively. The undissociated ilmenite is mainly intergrown with amphibole and chlorite or Ti-magnetite, which would interfere with the TiO_2 grade of pre-concentrate of HGMS. Ilmenite belongs to the group of weakly magnetic minerals with relatively strong magnetic properties, and most of them can be captured using a high-gradient magnetic matrix box and enter the magnetic products under the background magnetic field strength of 0.4–0.6 T.

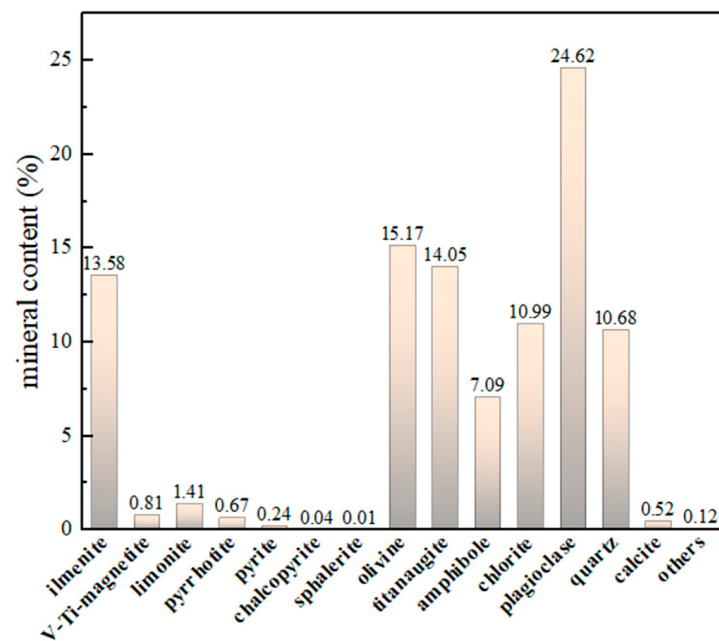


Figure 1. Mineral composition analysis of the experimental sample.

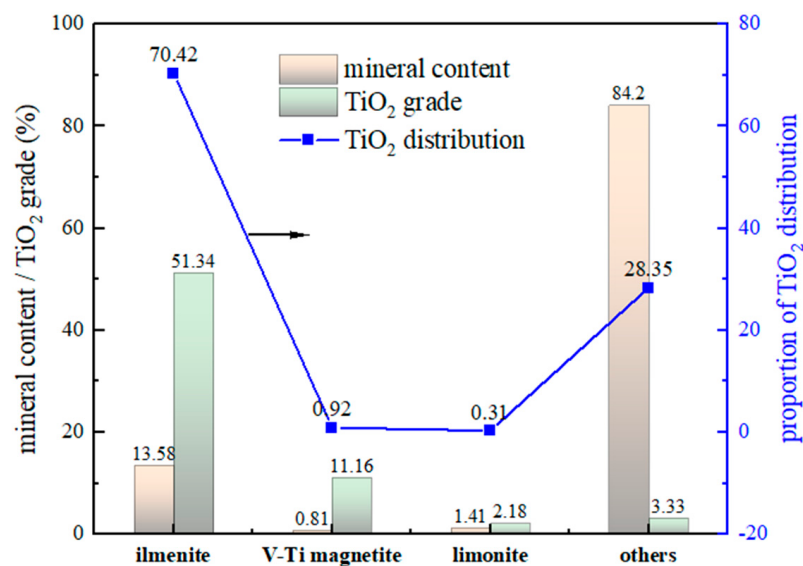


Figure 2. Equilibrium distribution of TiO₂ in these minerals.

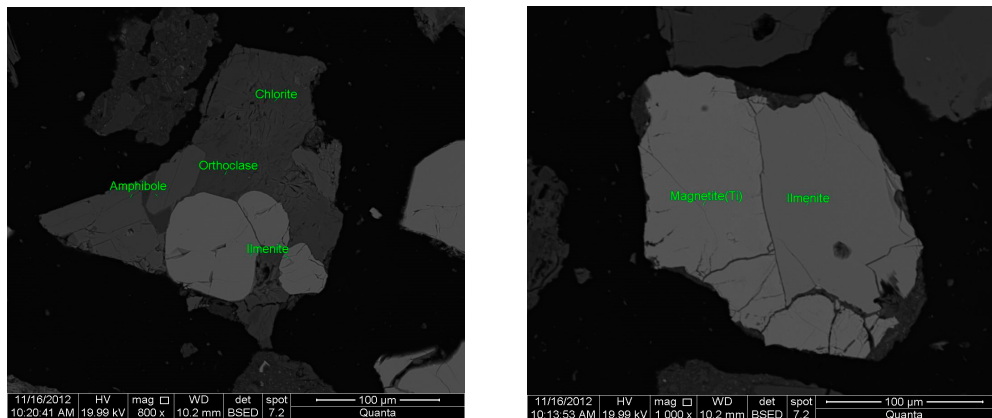


Figure 3. Dissemination relationship of ilmenite in some large mineral particles.

2.2. Material Properties of the Magnetic Matrix

The conventional matrix used for separating metal ores in HGMSs is a rod with a circle cross-section, and its diameter is typically 3, 2, or 1.5 mm. In this work, the magnetic matrix material from Dalian F.T.Z. Special Steel Product Factory (Dalian, China) is selected for the laboratory investigation and industrial application research. The steel type is Cr10NiTiMo, and its chemical composition and mechanical properties are shown in Table 3; the B–H testing curve of the magnetic matrix Cr10NiTiMo is shown in Figure 4.

Table 3. Chemical composition contents and tensile strength of the magnetic matrix.

Element	Fe	C	Si	Mn	P	S
Content (%)	88.86	0.010	0.260	0.080	0.016	0.004
Element	Cr	Ni	Mo	Ti	Tensile Strength (MPa)	
Content (%)	10.100	0.240	0.210	0.220	880,980	

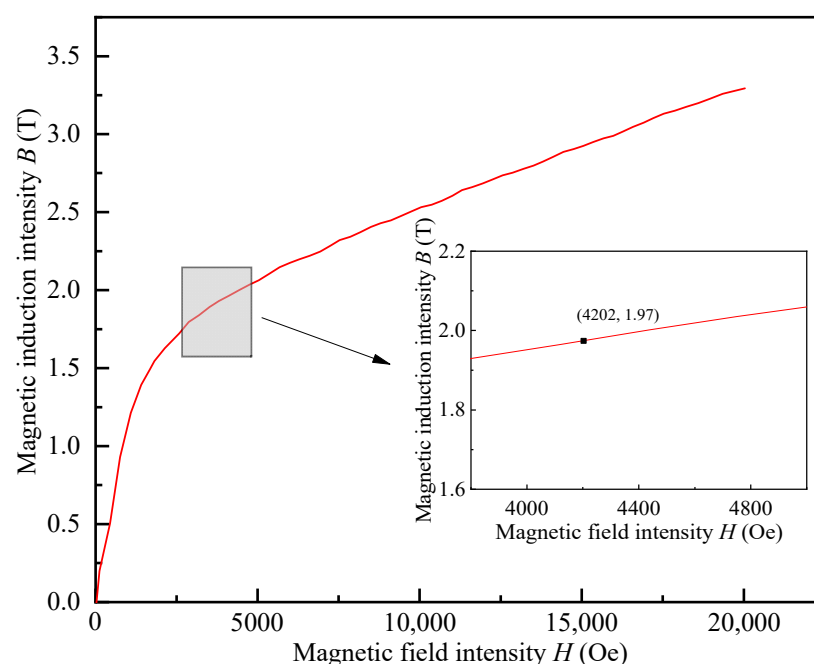


Figure 4. B–H testing curve of magnetic matrix Cr10NiTiMo.

2.3. Pilot-Scale and Industrial-Scale Transverse-Field HGMS

The pilot-scale separator used is the SSS- $180 \times 80 \times 250$ cyclic transverse-field HGMS, with an effective separation chamber volume of $180 \times 80 \times 250 \text{ mm}^3$. The structural diagram and equipment photograph are provided in Figure 5. The entire separation principle of this device is similar to that of the SLon cyclic pulsating HGMS, with the primary distinction being the orientation of the magnetic system.

The industrial-scale separator used is a typical SSS vertical ring transverse-field HGMS. The structure of this separator is shown in Figure 6. The equipment is primarily composed of a pulsating mechanism, an iron yoke, vertical rings, a gas–water combined ore unloading device, a magnetic matrix box, a ring driver, exciting coils, and magnetic poles.

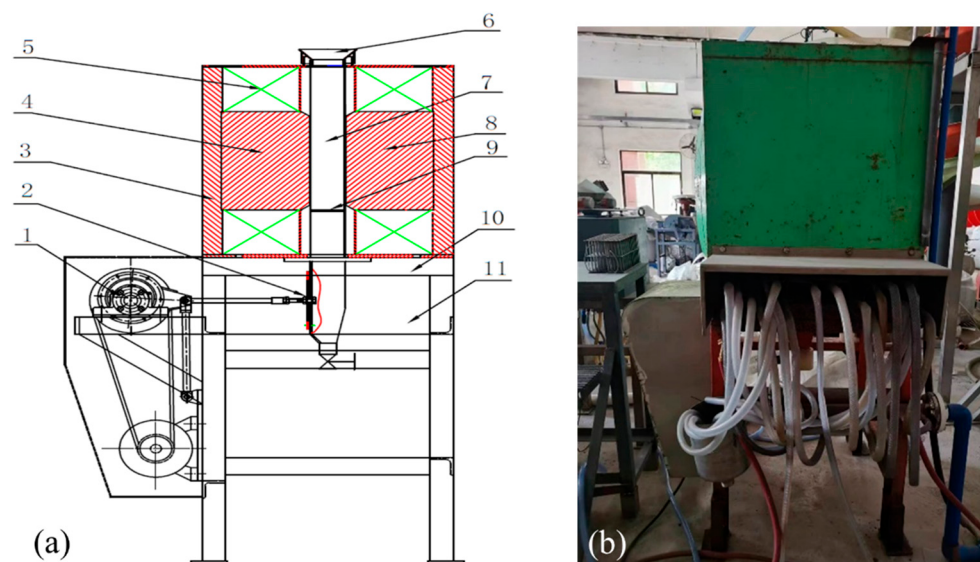


Figure 5. Equipment structure diagram (a) and physical diagram (b). 1—Gearing; 2—pulsating tympanic membrane; 3—magnetic system; 4—left magnetic pole; 5—exciting coils; 6—feed bin; 7—separation chamber; 8—right magnetic pole; 9—magnetic matrix box holder; 10—equipment frame body; 11—cooling water inlet and outlet area.

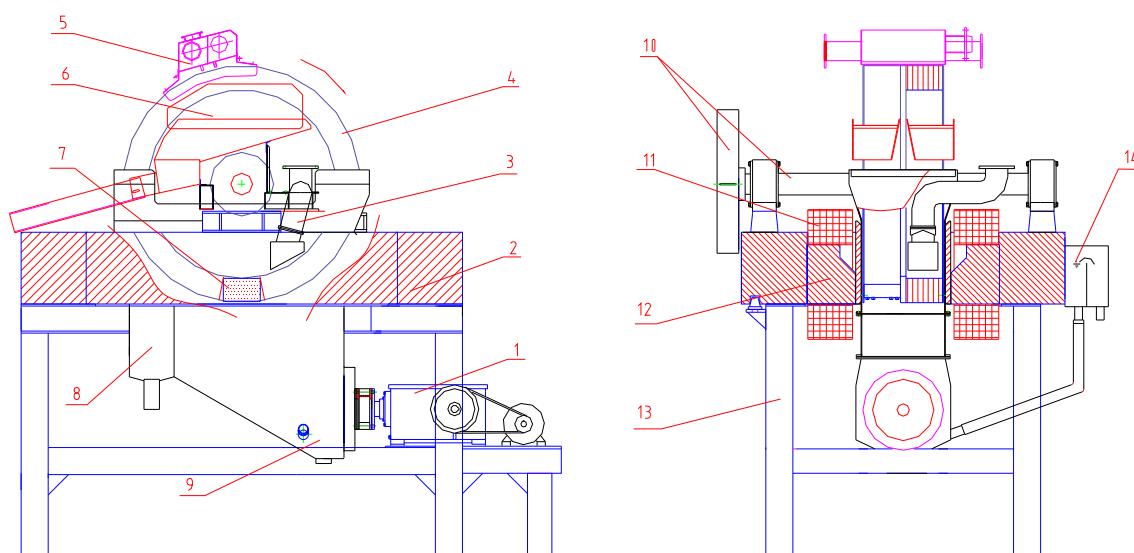


Figure 6. Structure of a typical SSS vertical ring transverse-field HGMS. 1—Pulsating mechanism; 2—iron yoke; 3—feeding pipe; 4—rotating rings; 5—gas–water combined unloading device; 6—concentrate bucket; 7—magnetic matrix box; 8—middling hopper; 9—tailings hopper; 10—ring driver; 11—excitation coils; 12—magnetic pole; 13—rack; 14—liquid level bucket.

The slurry, introduced through the feed pipe, passes an arc-shaped separation zone formed by opposing magnetic poles. Within this zone, magnetic mineral particles are attracted to and captured on the surface of the matrix. Meanwhile, non-magnetic particles, unaffected by the magnetic field, pass through the matrix units and enter into the tailings hopper. The pulsating mechanism, with adjustable frequency and stroke, creates an up-and-down scouring motion in the slurry to avoid matrix blockage, which aids in loosening and removing gangue that has deposited on the matrix surface, facilitating its flow into the tailings hopper. The remaining magnetic particles, still adsorbed on the matrix, rotate with the matrix ring and gradually exit the magnetic field. In the top region without magnetic field, a gas–water combined unloading device is utilized to wash the magnetic particles off the matrix surface, which are then collected in the concentrate hopper,

forming the magnetic product. This process can effectively separate magnetic particles from non-magnetic particles.

The design of the transverse-field HGMS effectively isolates the magnet from the ore slurry, thereby preventing abrasion and corrosion caused by the high-speed pulp. This isolation simplifies the maintenance of the matrix rings, allowing for the detached ring to be easily hoisted for servicing. A key feature of this separator is the “moving-cleaning” capability of the magnetic matrix, which significantly reduces the risk of incrustation on the matrix’s surface and delays matrix blockage. In practical applications, the feed always contains strongly magnetic particles, such as magnetite and tramp iron. These particles alternately move between the capture and discharge steps, as illustrated in Figure 7. When the matrix ring rotates into the arc-shaped magnetic zone, magnetic particles adsorb to both sides of the rod matrix. The weakly magnetic particles are flushed into the concentrate bucket as the ring moves to the unloading area. Meanwhile, the strongly magnetic particles remain trapped at the bottom of the rod matrix due to residual magnetism. Upon returning to the magnetic zone, the strongly magnetic particles are re-mobilized to a horizontal position, preventing the formation of a fixed deposition. This continuous movement of the strong magnetic particles effectively cleans the rod matrix’s surface, preventing magnetic minerals from staying in one place and without moving, which can be described as a “moving-cleaning” process. Thus, no deposition occurs on the surface of the rod matrix, and the pulp path remains unblocked.

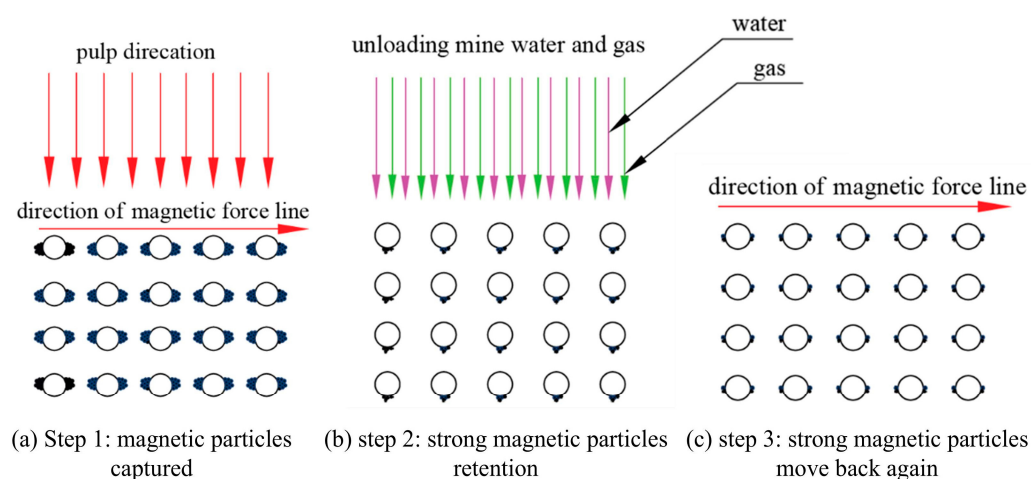


Figure 7. Process of magnetic matrix capture–washing–recapture (moving–cleaning).

2.4. Methods of Matrix Box Optimization

As previously mentioned, the factors that affect the separation performance and processing capacity of the magnetic matrix mainly include the diameter of the rod matrix, the filling ratio, and the depth of the matrix in the direction of slurry flow. The rod diameter is closely related to the distribution of the magnetic field within the background magnetic field. The matrix filling ratio affects the capture capacity and the efficiency of ore unloading. The depth of the matrix in the direction of slurry flow affects the smoothness of slurry flow, thereby influencing the processing capacity and concentrate indexes.

The relationship between the rod diameter and the mineral particle size is typically expressed as Equation (1), according to the research result [19] and test experience:

$$K = \frac{D_a}{D_b} > 10 \quad (1)$$

where K is a specific value, D_a is the rod diameter, and D_b is the particle size of the recoverable minerals.

The ore unloading efficiency is defined by the following equation:

$$U = \frac{Q_0 - Q_1}{Q_0} \times 100\% \quad (2)$$

where U is the ore unloading efficiency, Q_0 is the total quantity of concentrate adsorbed by the matrix, and Q_1 is the residual concentrate quantity remaining in the matrix after ore unloading.

The recovery of particle-sized fraction in the concentrate is a critical factor in assessing the separation performance of the magnetic matrix. This factor is defined as follows:

$$\xi = \frac{\varepsilon \times \gamma}{\kappa} \times 100\% \quad (3)$$

where ξ is the recovery of the particle-sized fraction, ε is the recovery of concentrate, γ is the metal proportion of a certain size of fraction in the concentrate, and κ is the metal proportion of a certain size of fraction in feeding.

3. Experimental Results and Discussion

3.1. Magnetic Matrix Optimization

The particle size fraction of the sample is primarily distributed in $-0.25 + 0.10$ mm and $-0.10 + 0.043$ mm, and the corresponding yields are 46.52% and 40.79%, respectively. Consequently, the suitable rod diameters are more than 2.5 and 1.0 mm because $K > 10$. The $\phi 3.0$ mm rod is suitable as the matrix for separating the $-0.25 + 0.10$ mm fraction. Meanwhile, the optimal rod diameter for separating the $-0.10 + 0.043$ mm fraction remains to be determined. The maximum magnetic induction strength measured on the surface of rods with different diameters under varying exciting currents is presented in Figure 8. The test data are measured in the unmoving state of the device.

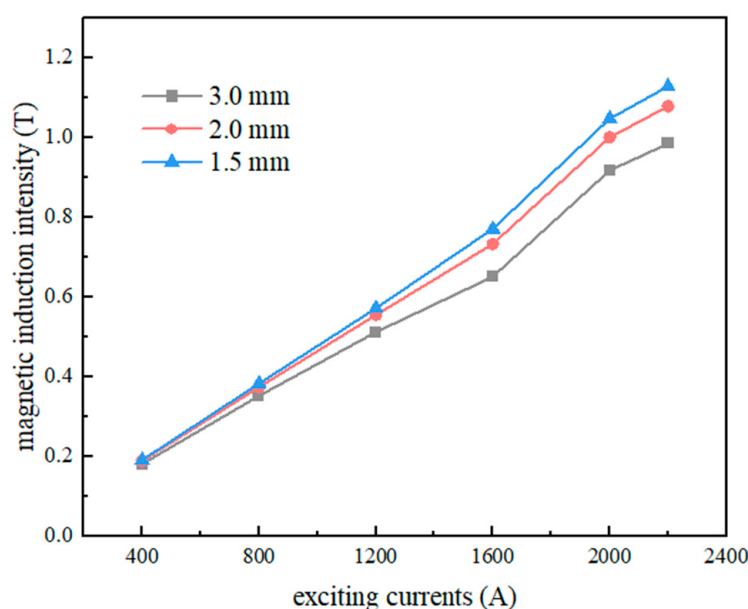


Figure 8. Maximum magnetic induction strength measured on the surface of rods with different diameters under varying exciting currents.

The results presented in Figure 8 indicate that the difference in magnetic induction intensity on the surfaces of rods with different diameters becomes pronounced with the increase in the excitation current. Specifically, the magnetic induction field of the $\phi 3.0$ mm rod is lower than that of the $\phi 2.0$ and $\phi 1.5$ mm rods. Under a large current, the magnetic

induction intensities of the $\phi 2.0$ and $\phi 1.5$ mm rods are similar, with the former slightly lower. Considering the stability of the mechanical properties and the induction field, the $\phi 3.0$ mm magnetic matrix rod is suitable for separating coarse particle size fractions with stronger magnetism, and $\phi 2.0$ and $\phi 1.5$ mm are suitable for separating relatively fine particle size fractions with weaker magnetism. This inference can be verified by the models of particle tracking with different diameters of rod matrixes in Figure 9, as well as the capture probability of particles using rod matrixes in Figure 10.

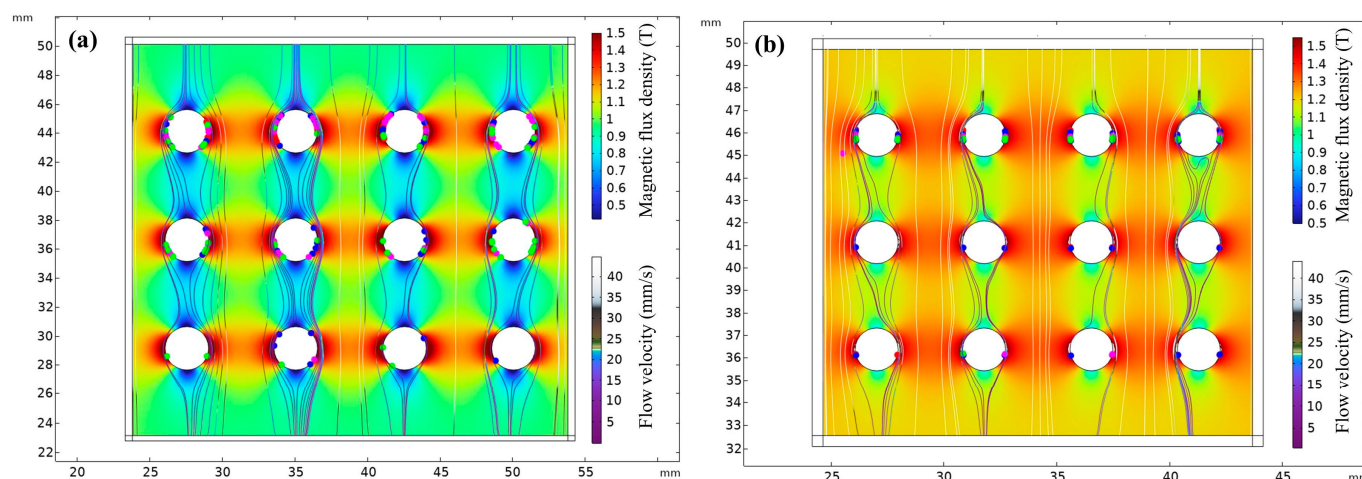


Figure 9. Particle tracking models for rod matrixes with diameters of $\phi 3$ mm (a) and $\phi 1.5$ mm (b). Note: the background magnetic field intensity is 0.42 T, the particle size is $-0.25 + 0.10$ mm and $-0.10 + 0.043$ mm, the relative permeability of the particle is 1.006, and the initial velocity is 40 mm/s.

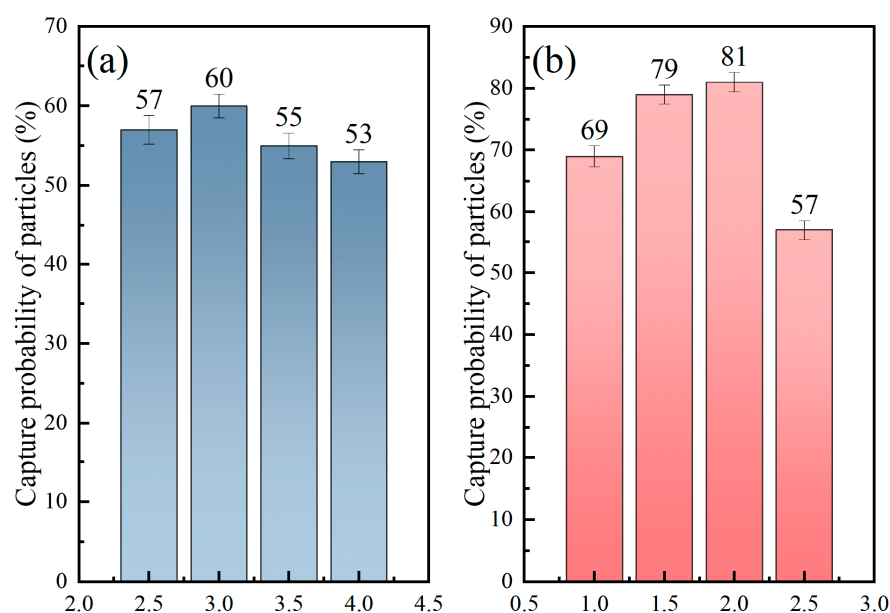


Figure 10. Capture probability of particles by rod matrixes of different diameters. Capture probability for separating (a) $-0.25 + 0.10$ mm fraction and (b) $-0.10 + 0.043$ mm fraction.

Figure 10 shows that the highest particle capture probability of 60% is achieved for the $-0.25 + 0.10$ mm fraction when the diameter of the rod matrix is $\phi 3.0$ mm. When the diameter of the rod matrix is $\phi 2.0$ mm, the capture probability for the $-0.10 + 0.043$ mm particles is a maximum of 81%, which is very close to the 79% capture probability for a diameter of $\phi 1.5$ mm.

In addition to the diameter of the rods, their filling ratio also affects the magnetic field distribution. Taking the magnetic matrix rod of $\phi 2.0$ mm as an example, the maximum

magnetic induction strength measured on the surfaces of rods with different filling ratios under varying exciting currents is shown in Figure 11.

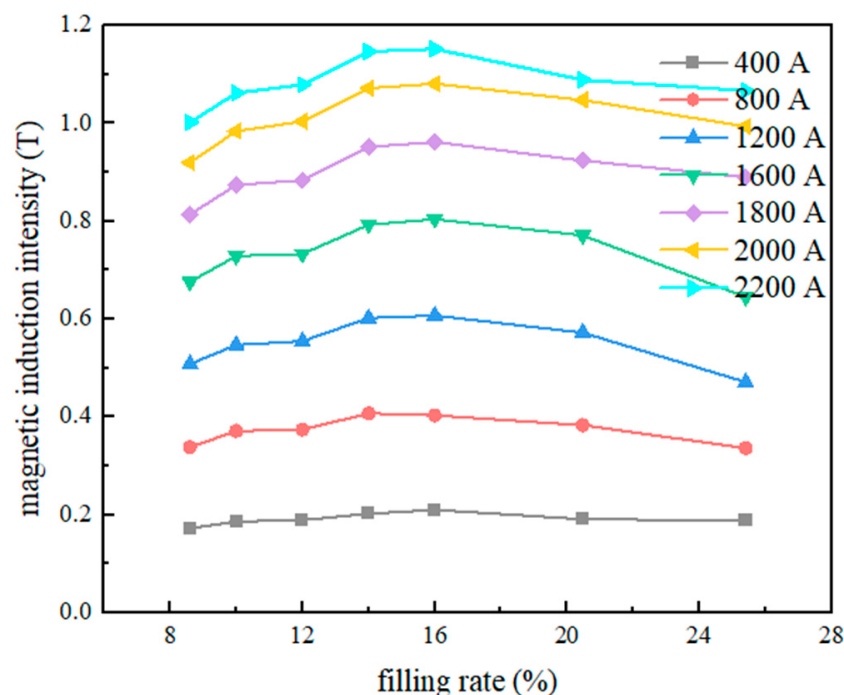


Figure 11. Maximum magnetic induction strength measured on the surfaces of rods with different filling ratios under varying exciting currents.

Figure 11 demonstrates that the magnetic induction strength initially rises with the increase in the filling ratio and then declines. The filling ratio always falls in a range from 14% to 16% when the maximum magnetic induction intensity is achieved at various excitation currents. A higher magnetic induction intensity corresponds to a stronger ability to capture magnetic minerals. Therefore, an optimal filling ratio of approximately 16% is chosen.

The number of arranged layers (also referred to as “depth”) in the magnetic matrix is closely correlated with the capture capacity and the unloading efficiency of magnetic particles. A typical matrix box utilized in the transverse-field HGMS is depicted in Figure 12, with a depth of 248 mm, a length of 140 mm, a width of 78 mm, and a rod diameter of 2.0 mm as an example. The depth of the matrix box is high, resulting in a large processing capacity. The optimal test conditions are as follows: feed quantity of 1500 g, stroke of 14 mm, pulsating frequency of 240 r/min, and magnetic field intensity of 0.42 T, which are obtained through condition tests. The experimental results of the ore unloading efficiency with different flushing water quantities are presented in Table 4. The findings show that ore unloading efficiency ranges from 75.59% to 85.78% as the flushing water flow rate increases from 3 L/min to 12 L/min. Despite the higher flushing water volumes, the ore unloading efficiency remains suboptimal. This notion suggests that the commonly used magnetic matrix box, characterized by a considerable depth, is inherently limited in its ability to achieve high ore unloading efficiency.



Figure 12. Typical matrix box in a pilot-scale transverse-field HGMS with a diameter of 2 mm.

Table 4. Experimental results of the ore unloading efficiency with different flushing water quantities.

Flushing Water (L/min)	Production	Yield (%)	TiO ₂ Grade (%)	TiO ₂ Recovery (%)	Q ₀ (g)	Q ₁ (g)	U (%)
3	Concentrate	41.26	16.85	70.23	618.90	151.10	75.59
	Tailings	58.74	5.02	29.77			
	Total	100.00	9.90	100.00			
6	Concentrate	43.65	17.16	75.66	654.75	123.41	81.15
	Tailings	56.35	4.28	24.34			
	Total	100.00	9.90	100.00			
9	Concentrate	44.26	17.22	76.99	663.90	101.56	84.70
	Tailings	55.74	4.09	23.01			
	Total	100.00	9.90	100.00			
12	Concentrate	44.85	17.31	78.42	672.75	95.67	85.78
	Tailings	55.15	3.87	21.58			
	Total	100.00	9.90	100.00			

The element matrix method is utilized to assess the capture of magnetic particles at various positions within the matrix box (from top to bottom) and further investigate the potential for reducing the depth of the matrix box. In this method, the matrix box is divided into five elements (A~E) (Figure 13). The steps to obtain the amount of ilmenite particles captured by each layer of matrix (A~E) are as follows: restore the process of capturing ilmenite particles in the magnetic matrix box in the stationary state; when the feeding is finished, keep the original background magnetic field strength unchanged (0.42 T) until there is no liquid outflow at the bottom of the matrix box; and then reduce the background magnetic field strength to 0.1 T, although, at this time, the ilmenite particles are subjected to the magnetic force of the substrate decreases, but the particles are still captured on the surface of the substrate under the action of the capillary force of the liquid. Immediately after that, perform a layer-by-layer slow removal of the matrix and collection of ilmenite particles in the order of A~E. Multiple experiments were conducted, and the data were statistically processed. The experimental results, summarized in Table 5, suggest a gradual decrease in the capture weight and the TiO₂ grade as one moves from element A to E. Specifically, the capture weight and TiO₂ grade of element A are 252.60 g

and 16.19%, whereas those of element E are only 55.65 g and 11.82%, respectively. These findings indicate that the capture efficiency in the lower elements of the matrix box is significantly reduced, thus supporting the feasibility of minimizing the number of layers in the matrix box.

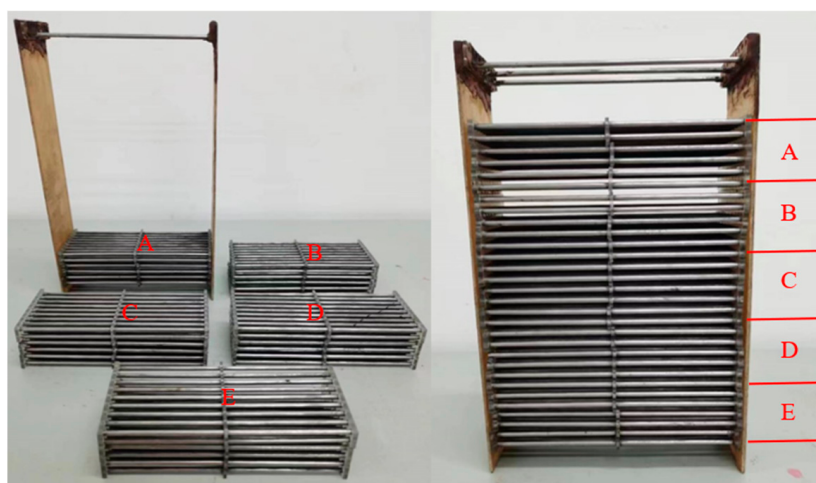


Figure 13. Magnetic matrix box divided into five elements (A~E).

Table 5. Experimental results using the element matrix method.

Matrix Box Element	Production	Weight (g)	Yield (g)	TiO ₂ Grade (%)	TiO ₂ Recovery (%)
A	Concentrate1	252.60	16.84	16.19	27.55
B	Concentrate2	258.90	17.26	18.24	31.81
C	Concentrate3	110.25	7.35	16.61	12.34
D	Concentrate4	94.35	6.29	13.93	8.85
E	Concentrate5	55.65	3.71	11.82	4.43
	Tailings	728.25	48.55	3.06	15.01
	Total	1500.00	100.00	9.90	100.00

In summary, Tables 4 and 5 indicate that the matrix box should not be considerably deep, as this would hinder the efficient unloading of ore and prevent the achievement of optimal capture performance. Therefore, the typically used deep, integrated matrix box must be segmented to balance capturing and unloading efficiencies, allowing for independent unloading in each segment.

3.2. Pilot-Scale Validation Research

Segmented short magnetic matrix boxes with rod diameters of 3, 2, and 1.5 mm are fabricated to validate the results of the magnetic matrix box optimization, as illustrated in Figure 14a–c. The typical combinations of these short matrix boxes used in pilot-scale HGMSs are demonstrated in Figure 15. The rod diameter of the upper-layer matrix box is intentionally larger than that of the lower-layer matrix box, facilitating the early capture of relatively coarse and strongly magnetic particles. The upper and lower-layer matrix boxes are connected via a holder (Figure 14d). The experimental results for the typical combination of the double-layer matrix box are presented in Table 6. The combination of matrix boxes with rod diameters of $\phi 3$ and $\phi 2$ mm yields the optimal performance for ilmenite separation. This configuration achieves a TiO₂ grade of 18.46% and a recovery of 87.32%. Additionally, this configuration exhibits the highest ore unloading efficiency, at 94.07%. The separation index and ore unloading efficiency surpass the results presented

in Table 4 that were obtained using the traditional integrated matrix box. The suitable magnetic matrix box combination is $\phi 3$ mm and $\phi 2$ mm. This notion means that the two-layer ring can be used in industrial equipment. The inner ring is configured with a magnetic matrix box of $\phi 3$ mm rod. Meanwhile, the outer ring is configured with a magnetic matrix box of $\phi 2$ mm rod.

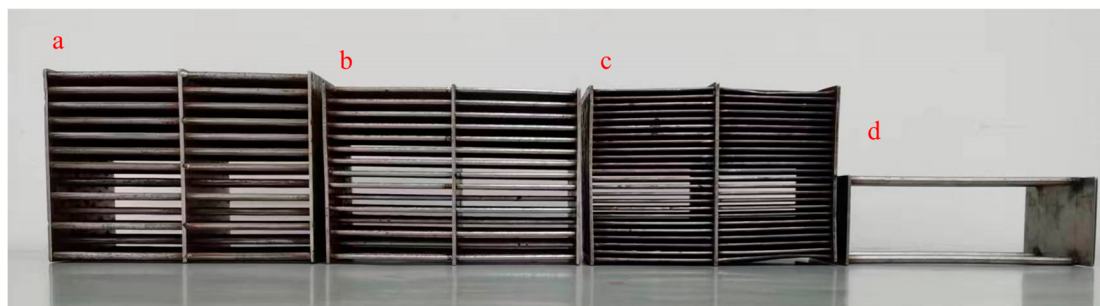


Figure 14. Magnetic matrix boxes and a holder: (a)— $\phi 3$ mm rod; (b)— $\phi 2$ mm rod; (c)— $\phi 1.5$ mm rod; (d)—holder.

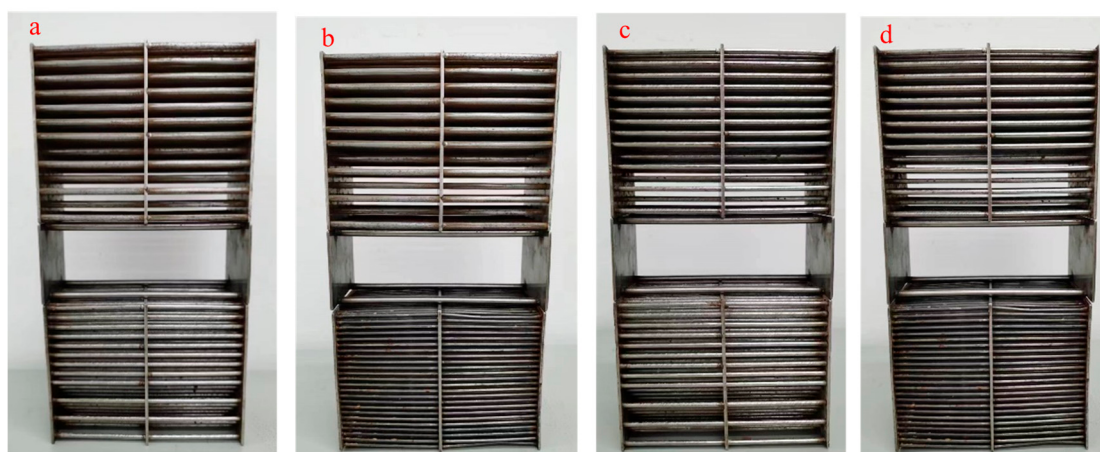


Figure 15. Segmented magnetic matrix boxes with different rod diameter combinations: (a)— $\phi 3$ mm and $\phi 2$ mm; (b)— $\phi 3$ mm and $\phi 1.5$ mm; (c)— $\phi 2$ mm and $\phi 2$ mm; (d)— $\phi 2$ mm and $\phi 1.5$ mm.

Table 6. Experimental results of the typical combination of the double-layer matrix boxes.

Combination Form of the Box	Production	Yield (%)	TiO ₂ Grade (%)	TiO ₂ Recovery (%)	Q ₀ (g)	Q ₁ (g)	U (%)
$\phi 3$ and $\phi 2$ mm	Concentrate	46.82	18.46	87.32	702.30	41.63	94.07
	Tailings	53.18	2.36	12.68			
	Total	100.00	9.90	100.00			
$\phi 3$ and $\phi 1.5$ mm	Concentrate	44.83	17.35	78.55	672.45	61.57	90.84
	Tailings	55.17	3.85	21.45			
	Total	100.00	9.90	100.00			
$\phi 2$ and $\phi 2$ mm	Concentrate	45.30	18.31	83.76	679.50	51.38	92.44
	Tailings	54.70	2.94	16.24			
	Total	100.00	9.90	100.00			
$\phi 2$ and $\phi 1.5$ mm	Concentrate	43.88	17.26	76.48	658.20	68.25	89.63
	Tailings	56.12	4.15	23.52			
	Total	100.00	9.90	100.00			

The specific results of the screen analysis for the optimal concentrate and size fraction recovery are listed in Table 7. These results indicate that the recovery of the size fractions ranging from -0.15 mm to $+0.038$ mm is relatively uniform, with a value of approximately 90%. However, the recovery of the coarser fraction ($+0.15$ mm) and the finer fraction (-0.038 mm) is comparatively low. The lower recovery of the coarser fraction can be attributed to poor dissociation. Meanwhile, the reduced recovery of the finer fraction is due to the insufficient magnetic attraction resulting from the small particle size. Therefore, these pilot-scale experimental findings provide strong evidence that supports the validity of the magnetic matrix optimization.

Table 7. Particle size distribution in the concentrate and size fraction recovery.

Size Fraction (mm)	Yield (%)	TiO ₂ Grade (%)	TiO ₂ Proportion (%)	Size Fraction Recovery (%)
+0.25	6.26	13.17	4.47	75.27
$-0.25 + 0.20$	8.18	13.56	6.01	75.05
$-0.20 + 0.15$	18.43	17.22	17.19	79.12
$-0.15 + 0.10$	20.75	19.51	21.93	92.99
$-0.10 + 0.074$	17.11	20.64	19.13	92.53
$-0.074 + 0.043$	12.19	23.19	15.31	92.78
$-0.043 + 0.038$	10.86	17.56	10.33	89.21
-0.038	6.22	16.76	5.65	86.49
Total	100.00	18.46	100.00	87.32

3.3. Industrial Application Case

The industrial testing machine is developed based on the success of the pilot test. The two-layer sorting ring for the transverse-field industrial HGMS is demonstrated in Figure 16. The volumes of the magnetic matrix boxes in the outer and inner rings presented in Table 8. The rod diameter of the outer ring is 2 mm, while that of the inner ring is 3 mm. The data in Table 8 indicate that the magnetic matrix volumes of the transverse-field and longitudinal-field HGMSs are comparable when using the same vertical ring diameter. The transverse-field industrial HGMS with the two-layer ring used in the beneficiation plant is shown in Figure 17.

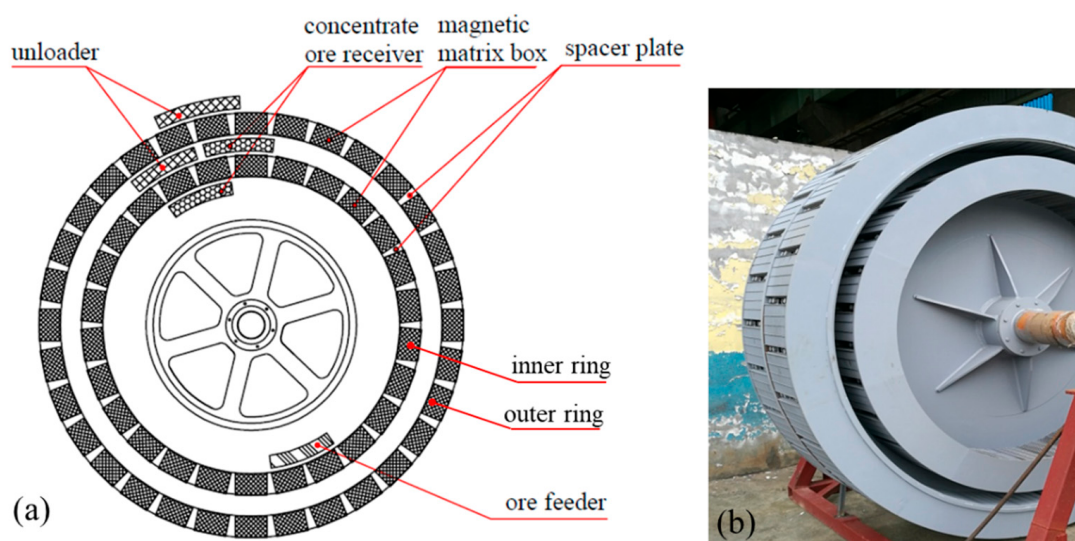
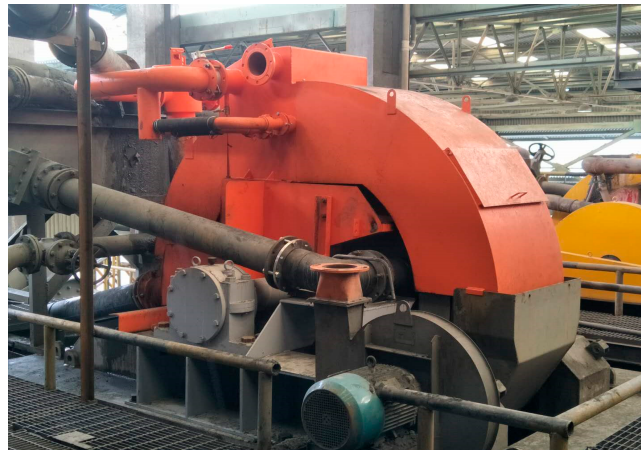


Figure 16. Diagram of the two-layer ring (a) and physical image (b).

Table 8. Volume of the magnetic matrix boxes of the HGMSs.

Type of HGMS	Model	Magnetic Rings	Box Size (L × W × H) (mm)	Box Number	Volume (m ³)	Total (m ³)
Transverse magnetic field HGMS	2750	Outer	330 × 174 × 226	80	1.04	1.65
		Inner	330 × 156 × 184	64	0.61	
Longitudinal magnetic field HGMS	2750	One	300 × 182 × 174	176	1.67	1.67

**Figure 17.** Industrial equipment of the SSS-III-2750 two-layer ring transverse-field HGMS used in the beneficiation plant.

The industrial best operating parameters of the transverse-field HGMS (SSS-III-2750) are as follows: vertical ring speed of 4.0 r/min, magnetic field intensity of 0.45 T, pulsating stroke of 10 mm, and pulsating frequency of 120 r/min. The industrial best operating parameters of the longitudinal-field HGMS are as follows: vertical ring speed of 4.0 r/min, magnetic field intensity of 0.50 T, pulsating stroke of 14 mm, and pulsating frequency of 170 r/min. The comprehensive index for a 1-month stable production is provided in Table 9. The result indicates that the separation index for the transverse-field HGMS outperforms that of the longitudinal-field HGMS. The production achieved a TiO₂ grade of 18.01% with a recovery of 87.28% after a roughing separation. The particle size distribution in the concentrate and size fraction recovery of the two-layer ring transverse-field HGMS is shown in Table 10. The size fraction recovery is more than 91% when the size fraction is from −0.15 mm to +0.043 mm, similar to the result in the pilot plant test.

Table 9. Industrial test results of the two-layer ring transverse- and longitudinal-field HGMSs.

Type of HGMS	Model	Production	Yield	TiO ₂ Grade	TiO ₂ Recovery
Transverse magnetic field HGMS	2750 (two-layer ring)	Concentrate	47.98	18.01	87.28
		Tailings	52.02	2.42	12.72
		Total	100.00	9.90	100.00
Longitudinal magnetic field HGMS	2750	Concentrate	50.61	16.73	85.49
		Tailings	49.39	2.91	14.51
		Total	100.00	9.90	100.00

Table 10. Particle size distribution in the concentrate and size fraction recovery of the two-layer ring transverse-field HGMS.

Size Fraction (mm)	Yield (%)	TiO ₂ Grade (%)	TiO ₂ Proportion (%)	Size Fraction Recovery (%)
+0.25	6.52	12.77	4.62	77.95
−0.25 + 0.20	8.76	13.12	6.38	79.74
−0.20 + 0.15	18.93	16.85	17.72	81.54
−0.15 + 0.10	20.52	19.07	21.73	92.17
−0.10 + 0.074	16.94	20.16	18.97	91.76
−0.074 + 0.043	11.89	22.89	15.12	91.59
−0.043 + 0.038	10.13	17.48	9.83	84.94
−0.038	6.31	16.06	5.63	86.22
Total	100.00	18.01	100.00	87.28

4. Conclusions

The transverse-field vertical ring HGMS is a suitable industrial magnetic separator used in the ilmenite separation of pre-concentrations. This separator can be used as an important supplement to the longitudinal-field vertical ring HGMS in mineral processing due to its features, including no magnet wear and corrosion and the natural magnetic matrix “moving-cleaning”. However, the processing capacity should be improved. This work carried out the optimization of a matrix box in pilot-scale and industrial transverse-field HGMSs to improve the pre-concentrate efficiency and processing capacity of ilmenite. The obtained conclusions are as follows.

The diameter of the rod matrix, the filling ratio of the rod matrix, and the depth of the matrix box influence the pre-concentrate’s efficiency and processing capacity. The processing capacity can be increased with the increase in the depth of the matrix box. The depth of a single matrix box should not be considerably deep, as this would result in a low ore unloading rate, which can be divided into different thinner matrix boxes, for example, two-layer matrix boxes with $\phi 3$ and $\phi 2$ mm rods combined, which can improve the pre-concentrate’s efficiency and processing capacity.

A two-layer sorting ring is fabricated in the industrial transverse-field HGMS based on the research results. The inner ring is configured with a matrix box of a $\phi 3$ mm rod, which is used to separate the coarse fraction products. Meanwhile, the outer ring is configured with a matrix box of $\phi 2$ mm rod, which is used to separate the fine fraction products. The industrial test results indicate that the pre-concentrate efficiency and processing capacity are improved. Moreover, the separation index of the transverse-field HGMS is better than that of the longitudinal-field HGMS.

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