DRY MAGNETIC SEPARATION TECHNOLOGY FOR THE RECOVERY OF IRON MINERALS IN FINE-GRAINED STEEL SLAG

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ARTICLE INFO	Abstract:
	Using the MagNet software package, a permanent magnetic circuit was simulated and a sectorially-spliced magnetic system was designed. Consequently, a new roller permanent magnetic separator with different magnetic field intensities in each roller was developed. The modular structural design allows fine-grained minerals with different magnetic susceptibility to be separated in one pass, according to their different processing characteristic. Steel slag, selected from a factory, was crushed, ground and sieved into different particle size ranges for the single-factor magnetic separation experiments. It was determined that the optimum value ranges for the particle size, magnetic separation distance and rotating frequency were 0.15 mm-0.3 mm, 10 mm-12 mm, 40 Hz～60Hz, respectively; using the chosen parameter values of 0.2mm, 11mm, and 40Hz, the concentrate recovery and concentrate grade of the new separation technology reached up to 52.78% and 64.74%, in comparisson with the existing technology. *Thus, it was demonstrated that the self-developed separation technology has the potential to improve the iron recovery of the fine-grained steel slag.*

1 Introduction

Steel slag is a type of solid waste emitted from the steel making process. It includes electric furnace slag, converter slag, and open-hearth furnace slag, with emissions account for around 15% to 20% of crude steel production. According to the World Steel Association (world steel), the world's crude steel production reached 1.6 billion tons in 2016; accordingly, it is estimated that at least 250 million tons of steel slag were produced, with a metallic iron content of up to 25 million tons [1]. In China alone, the crude steel production exceeded 804 million tons in 2016; taking into account a progressive increase of 0.8~0.9 million tons per year, the resultant emission of steel slag is over 100 million tons. The excessive accumulation of steel slag not only causes serious environmental problems in the form of land, water and soil pollution, but also results in wastage of iron resources [2]. This last

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problem is particularly pressing, as China still imports large quantities of iron ore.

It is expected that by 2018, China will account for 35% of the world's iron ore consumption. Iron is already one of the 10 kinds of mineral resources that China faces a shortage of. The recycling of steel slag not only protects the environment, but also promotes utilization ratio of resources. Hence, effective recycling of iron from steel slag, would not only alleviate environment pressures and improve economic efficiency, but would also reduce the industrial demand for iron ore in China [3-5].

Currently, the processing of steel slag from major plants in China is typically done by water quenching method. However, this method involves mineral-aggregate problems and a difficult subsequent handling process due to high iron content [6]. In universities and research institutes, the technique used for efficient recycling of iron mainly include dry magnetic separation of bulk slag, wet stage grinding and magnetic separation, wet magnetic separation for full grain level, fine-grained level flotation, and gravity separation [7-9]. The wet separation and electromagnetic separation technologies suffer from high power and water consumption, whereas by contrast, dry permanent magnetic separation is a relatively simple, no-drying, energy-saving technology. However, the limitations of the existing magnetic equipment result in lower mineral separation accuracies for fine-grained steel slag [10]. Development of technology for efficiently recycling iron resources from fine-grained steel is, therefore, of utmost importance.

In the present study, a new roller permanent magnetic separator with four magnetic rollers was developed. The magnetic rollers have different magnetic field intensity. Four-sorting experimental studies for fine-grained steel slag, were performed to determine the best value of sorting parameters through single factor experiments. The desired magnetic concentrate recovery indices were achieved through high temperature modification experiments. Finally, a concentrated index was used to characterize the feasibility of the recycling steel slag iron with a new roller magnetic separator. In this paper, we present a self-developed new multi-roller permanent magnetic separator, tailored to the physical characteristics of fine-grained steel slag. After separation, calculation of iron grade and recovery through titration experiment were performed so as to evaluate advantages and disadvantages of separator performance.

2   Experimental material and its properties

The selected steel slag was crushed to a particle size of 6mm, then ground to a particle size of 2mm, before being screened into particle size ranges for the magnetic separation experiments, as follows: 0.45 mm–2 mm, 0.3 mm–0.45 mm, 0.2 mm–0.3 mm, 0.15 mm–0.2 mm, 0.1 mm–0.15 mm, 0.074 mm–0.1 mm. The process is illustrated in the flowchart shown in Fig. 1.

The results of multi-element chemical analysis of the steel slag are shown in Table 1. The iron distribution of different particle sizes is shown in Table 2.

As Table 1 shows, the grade of the selected steel slag was low, with Fe% 21.84%. The SiO_2 and CaO content was higher, accounting for 15% and 43.69%, respectively, that also were the associated minerals disseminated into iron. In order to obtain a magnetite concentrate with a high grade index, the minerals should be fully dissociated during magnetic separation. It can be seen in Table 2 that the fine-grained steel slag has higher iron content and the significance of recovery is obvious. The composition of the steel slag in terms of the main iron minerals' and its theoretical grade were determined using the X-ray analysis, as shown in Table 3.

Table 3 shows that the strongly magnetic minerals contained in the steel slag mainly include metallic iron, magnetite and ilmenite, with a total iron share of 80.82% and a relative mean theoretical grade of 69.7%. This is the maximum theoretical value for the magnetic concentrate.

In principle, it is feasible to choose a weak-intensity magnetic separator to recover iron from steel slag. While, the hematite is weak magnetic mineral, and the iron share is 18.35%. So, the magnetic intensity should not be too low. Although quartz and plagioclase have high iron contents, their iron grade and iron share are relatively low and cannot be recovered in a weak magnetic field.

In view of the factors such as fine particle size and magnetic properties, a new magnetic separator is adopted to separate the steel slag. Finally, the paper optimizes the sorting parameter and lays the technical foundation for the steel slag treatment.
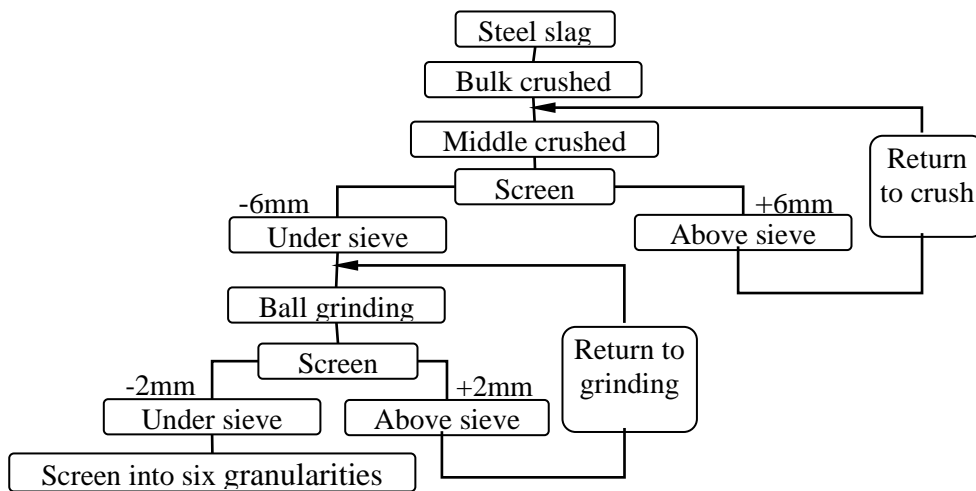
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Figure 1. Flow chart for preparation of fine-grained steel slag

Table 1. Chemical composition of steel slag

Chemical composition	SiO$_2$	Fe$_2$O$_3$	Al$_2$O$_3$	CaO	MgO	MnO	P$_2$O$_5$	FeO	S	TFe
Content/%	15	12.27	3.22	43.69	8.2	1.54	1.12	14.96	0.21	21.84

Table 2 Iron distribution for different particle size of steel slag

Particle size/mm	Yield /%	Grade /%	Fe% /%	Iron distribution /%
0.45–2	1.96	17.9	0.35	1.68
0.3–0.45	18.2	15.4	2.80	13.46
0.2–0.3	27.5	19.7	5.42	26.06
0.15–0.2	21.2	23.5	4.98	23.94
0.1–0.15	10.7	20.4	2.18	10.48
0.074–0.1	20.4	24.8	5.06	24.33
SUM	100	20.8	20.8	100

Table 3 Main iron mineral content and theoretical grade of steel slag.

Main iron minerals	Metallic iron	Magnetite	Ilmenite	Hematite	Quartz	Plagioclase	Total
Content/%	7.09	10.06	11.29	6.01	29.55	36.00	100
theoretical grade /%	100	72.40	36.80	70.00	0.64	0.39	24.78
Iron share /%	30.93	31.77	18.12	18.35	0.82	0.61	100

3 Self-developed multi-roller permanent magnetic separator

3.1 Magnetic system design

The key consideration when designing a magnetic separator is the performance of its magnetic system, as this directly affects the whole separation process. In this study, eight fan-shaped permanent magnets, with the N and S poles arranged alternately, were circumferentially distributed along the roller using the splicing technique, and the eight magnetic yokes were entrained in the middle of adjacent magnets to form a closed loop magnetic system structure.

Following this, the multi-set structures were radically arranged along the roller using extrusion technology, to form the magnetic roller. A simplified physical model of the magnetic system is shown in Fig. 2.
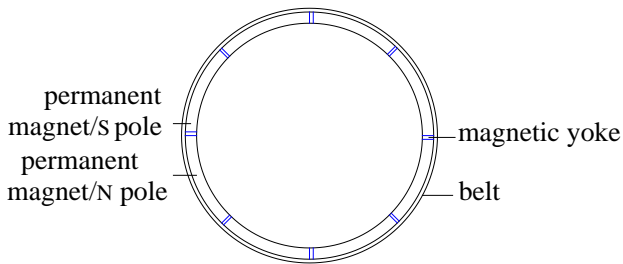
permanent magnet/S pole
permanent magnet/N pole

magnetic yoke
belt

Figure 2. A simplified physical model of the magnetic system

MagNet electromagnetic field analysis software is a low frequency electromagnetic analysis software,it is used to solve the problem of the magnetic field in aerospace, automobile, electric power, magnetic separation equipment, medical equipment, electronic products and other industries. The simulation results for the magnetic system, simulated using software package MagNet [11], are shown in Fig. 3.

Fig. 3 (a) shows that the magnetic force lines could effectively be gathered due to the magnetic yoke configuration, and the magnetic field intensity along the circumference of magnetic roller are relatively gentle, with a variation amplitude of 0.2 T. Also, it is evident that there was less magnetic flux leakage along the splicing line. All of these features are useful, for they enable the fine-grained steel slag to repeatedly flip during the sorting process so as to reduce the inclusions in the tailings and thereby improve the magnetic concentrate grade.

Fig. 3 (b) shows that the values of the magnetic field intensity are higher than 0.15 T, up to a maximum of 0.5 T, corresponding to a vertical distance of 0–50 mm from the surface of the magnetic roller. When the vertical distance is between 50 mm–150 mm, the magnetic field values are between 0.04 T–0.15 T. When the vertical distance is between 150 mm–350 mm, the values are between 0–0.04 T. When the vertical distance is over than 350 mm, the value of magnetic field intensity is 0. The results indicate that the magnetic system design has the characteristics of higher echelon change value of magnetic field intensity, large magnetic field separation space and deep magnetic separation distance. All of these are conducive to efficient enrichment of iron in fine-grained steel slag.
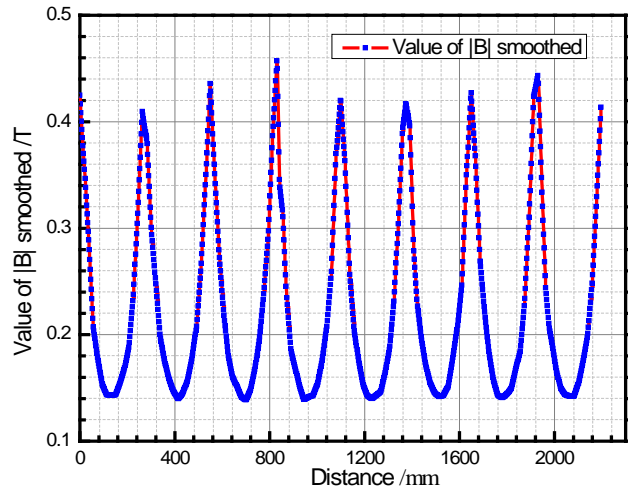
*(a)Magnetic field intensity along the circumference of magnetic roller*
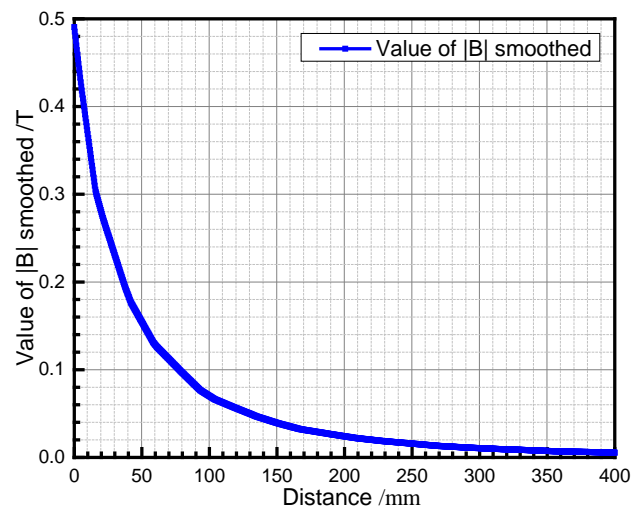
(b) Magnetic field intensity along the vertical distance of magnetic roller

Figure 3. Simulation results for the magnetic system of the new roller magnetic separator

3.2 The structure and sorting characteristic of magnetic separator

A reasonable mechanical design can improve technical performance of a magnetic separator to some extent, thereby realizing the maximum revenue possible for mineral separation [12]. The structure and sorting characteristic of the new roller magnetic separator are shown in Fig. 4.

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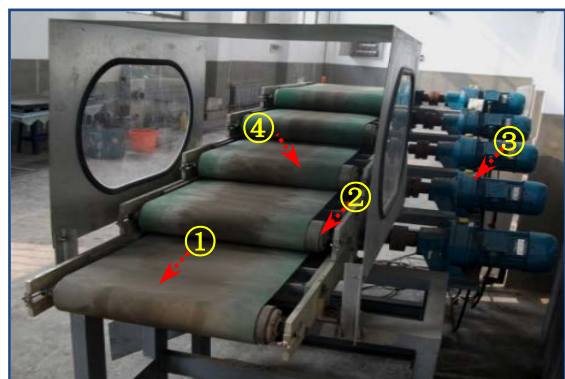
(①:belt; ②:magnetic roller I; ③:variable frequency motor; ④:magnetic roller II)
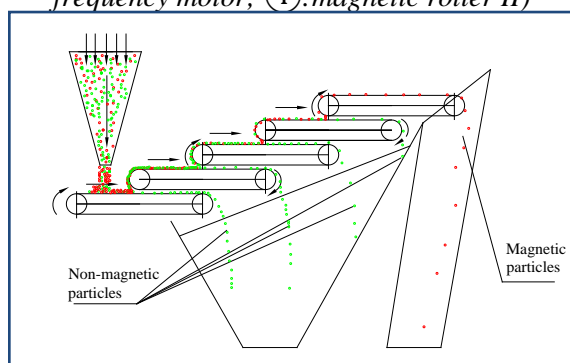

Figure 4. Structure and sorting characteristic of the new roller permanent magnetic separator

As can be seen in Fig. 4, the multi-level magnetic roller setting and modular structure design allow the separator to be adjusted according to the characteristics of the minerals being processed so as to achieve different sorting effects. Furthermore, by using multi-level and multiple sorting methods, combined with a circumferential magnetic field distribution, it is possible to significantly reduce inclusions of minerals in fine-grained steel slag. Moreover, the steel slag used in the experiment have complex magnetic mineral compositions and quite different magnetic properties. Therefore, adjusting the system according to the sorting characteristics can greatly simplify the separation process and improve the efficiency of minerals separation. Each of the different magnetic rollers has different magnetic field intensity; therefore, the four times separation process can not only achieve efficient separation of different compositions of iron magnetic minerals, but it can also greatly enhance the iron concentrate grade [13].

Compared with the conventional magnetic separator [14], the new roller permanent magnetic separator has the following advantages:1) it can achieve the separation of different magnetic compositions of

steel slag; 2) using the same background magnetic field, it can not only achieve the separation of useless mineral tailings in steel slag, but can also effectively remove the non-magnetic materials from the magnetic materials. In this way, the enrichment of useful minerals is enhanced, and the magnetic concentrate grade is improved, both through the alternating changed direction of magnetic field and by sorting with the multi-level magnetic roller.

In this study, we explored the influence of separation parameters on the magnetite concentrate grade and recovery by conducting the single factor experiments. The chosen factors included particle size, magnetic separation distance, and rotating frequency. In addition, the experiments helped definite the optimum separation parameters and improved the efficiency of the recovery process.

4 Results and Discussion

4.1 Experimental research of particle size influence to the concentrate index

Figure 5 shows the dissociation of mineral compositions in steel slag at different particle sizes, imaged using a stereo microscope. With a decrease in the particle size, the dissociation of mineral composition is apparent. At a particle size of 0.074 mm–0.15 mm, the minerals become agglomerated. The iron distribution for the different particle sizes is shown in Table 2, which indicates that the suitable particle size is confined to the middle classifier of 0.15 mm–0.3 mm. It can also be inferred from the images that most of the monomer dissociation and disseminated combined iron and iron oxide in the steel slag are grey-black, with some brightly-colored areas corresponding mainly to silicates and other non-magnetic minerals.

In order to further optimize the particle size, the particle size influence on the magnetite concentrate index was investigated. The experimental results for the relationship between the variables is shown plotted in Fig. 6.

Fig. 6 shows that the magnetic concentrate grade was higher than the feed grade, with a greatly improved amplitude value of about 30%; thus demonstrating that the new roller magnetic separator has excellent sorting properties. Fig. 6 illustrates that the value of concentrate grade gradually improved with a decreasing particle size, while under the same conditions the value of concentrate recovery dropped sharply. The reason for this is that

iron minerals and gangue contained in the bulk intergrowth minerals cannot be fully dissociated; instead, they may be recovered as a magnetic concentrate. Fig. 6 also shows that the concentrate recovery rebounds at a particle size of 0.074 mm–0.1 mm particle size, due to the phenomena of

mineral agglomeration. Here, we chose 0.15 mm–0.3 mm as the suitable particle size range for steel slag (as it represents a tradeoff between the values of concentrate recovery and concentrate grade),and we therefore present a comprehensive analysis of this size range.
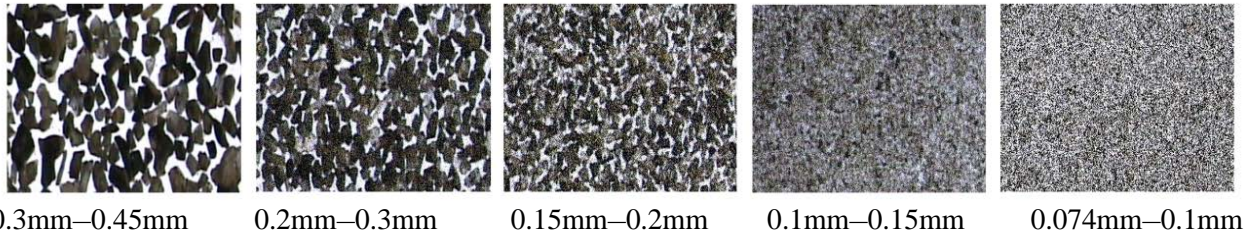

| 0.3mm–0.45mm | 0.2mm–0.3mm | 0.15mm–0.2mm | 0.1mm–0.15mm | 0.074mm–0.1mm |

Figure 5. The dissociation of mineral compositions in steel slag at different particle size

4.2 Experimental research of magnetic separation distance influence to the concentrate index

Taking the average value of the optimal particle size as 0.2 mm, the relationship between the magnetic separation distance and the concentrate index was investigated. This relationship is shown plotted in Fig. 7.

Fig. 7 shows that the value of concentrate grade increases gradually with an increase in the magnetic separation distance, and that the overall distribution of values is higher than the feed grade of 21.40%.

Figure 6. Relationship between concentrate index and particle size

From the data shown in Fig. 3, we know that the magnetic intensity, Hy, decreases exponentially with vertical distance y. Thus, an increase in the magnetic separation distance causes y to increase; hence, the magnetic field intensity sharply

decreases, along with the magnetization intensity of the magnetic minerals in the steel slag. This lowers the magnetic inclusion phenomenon and enhances the magnetite concentrate.
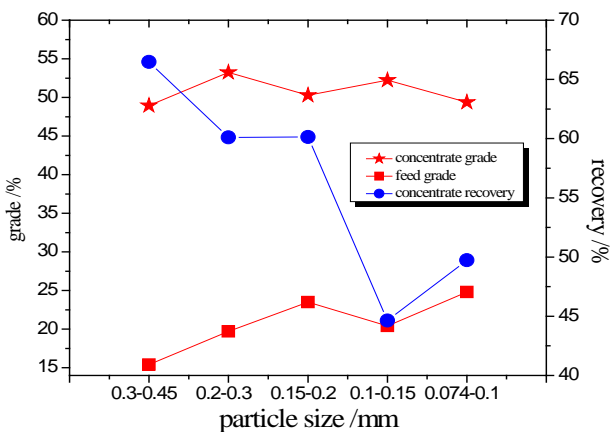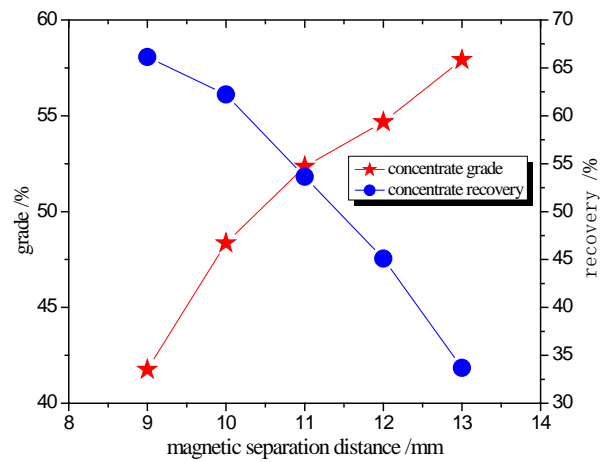

Figure 7. Relationship between concentrate index and magnetic separation distance

Nevertheless, for some weakly-susceptible magnetic minerals, the lowered magnetic force cannot meet the threshold value, causing the value of concentrate recovery to drop. When the magnetic separation distance is between 10 mm–12 mm, the concentrate grade and concentrate recovery are higher, with values of 52.35% and 53.64% respectively, at a separation distance of 11 mm.

4.3 Experimental research of rotating frequency influence to the concentrate index

In the present study, the relationship between the rotating frequency and the concentrate index was also investigated, at a particle size of 0.2 mm. This relationship is shown plotted in Fig. 8.

Fig. 8 shows that with an increase in the rotating frequency, the concentrate recovery shows a minimum value at 60 Hz. The value of concentrate grade, on the other hand, shows a maximum at 40 Hz; thereafter, it decreases, but with a smaller change in amplitude compared to the recovery.
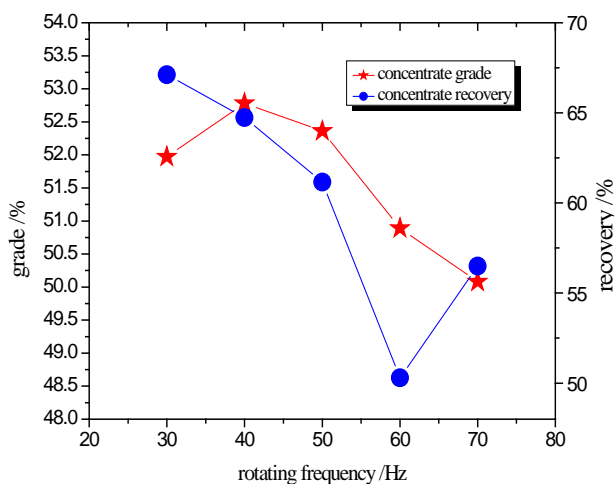

Figure 8. Relationship between concentrate index and rotating frequency

These observations can be attributed to the following reasons: the total iron composition of the strongly-susceptible magnetic minerals in steel slag is 80.82%, whereas the overall content of weakly-susceptible minerals, which have low iron content, is much higher. Therefore, the strongly-susceptible minerals will be magnetized instantly, and will form magnetic chains, which can produce a secondary magnetic field and display magnetic field superposition. Hence, the weakly-susceptible magnetic minerals will be magnetized by the new external magnetic field and will then be mixed up with or will attach to the surface of the magnetic chains.

As the rotation frequency is gradually increased, the residence time for magnetic chains becomes short; and the secondary magnetized time for weakly magnetic susceptibility minerals decreases. Also, the impact force of the surrounding particles increases and becomes higher than the binding force, causing them to be separated again. The non-magnetized and separated weakly-susceptible magnetic minerals will be lost to the tailings, and the magnetite concentrate recovery may therefore be reduced. However, for higher values of rotation frequency, the surrounding particles have a very short contact time with the magnetic chains. The separation of weakly magnetic minerals will be effectively adsorbed and enriched, therefore causing the value of concentrate recovery to increases lightly.

It should also be noted that there is inevitably some mixing of non-magnetic minerals in magnetic chains. As the rotating frequency increases and the residence time shorten, the tumbling time is not sufficient for concentrate recovery. This results in the mixed or attached minerals not being discharged in time, thereby lowering the concentrate grade. On the other hand, the loss of weakly-susceptible minerals can also lower the concentrate grade; however, their iron content tends to be very low, and thus the resultant amplitude reduction is not large.

The data presented in Fig. 8 also shows that as the rotation frequency increases, the mineral loss rate is higher. The analysis indicates that in the rotating frequency range of 40 Hz–60 Hz, there is a tradeoff, whereby the optimal concentrate recovery and concentrate grade values are reached; for example, at 40 Hz, these values were 64.74% and 52.78%, respectively.

The single factor experiments, conducted using the optimum the particle size range of 0.15 mm–0.3 mm, have thus enabled determination of the optimum magnetic separation distance and the rotating frequency ranges, which are 10 mm–12 mm and 40 Hz–60 Hz, respectively.

4.4 Comparative experiments

A set of experiments were also carried out to compare the recovery performance of a conventional roll magnetic separator and the self-developed magnetic separator in the separation of iron minerals in fine-grained steel slag. The experiments with the roll separator used a particle size of 0.2 mm and different rotating frequencies, whereas the experiments with the self-developed separator used the same particle size with a magnetic separation distance 11 mm, which corresponds to the former rotating frequency. The experimental results for both systems are compared in Fig. 9.
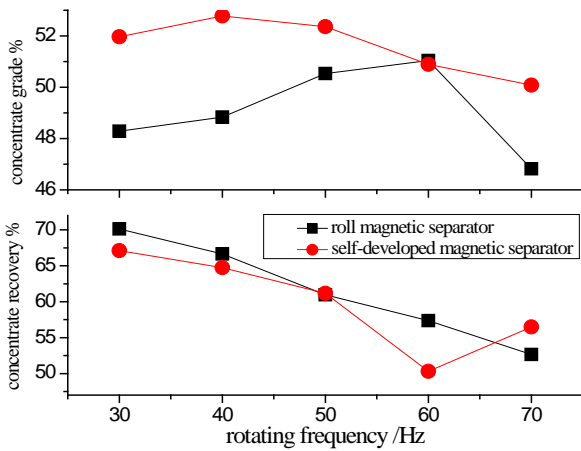
Figure 9. Comparative experimental results at different rotating frequency

Figure 9 shows that the value of concentrate grade obtained using the self-developed separator is higher than that obtained using the roll separator, at all the different rotating frequency used, except for 60 Hz where the performance of both separators is identical. Furthermore, the values of concentrate recovery for the two separation technologies are similar. Thus, we conclude that the new (self-developed) separation technology is more suitable for fine-grained steel slag, with the concentrate recovery and concentrate grade reaching 52.78% and 64.74%, respectively, using the optimized sorting parameters. The new separation technology clearly demonstrates a strong effect on the separation of magnetic minerals and the recovery of iron in waste slag.

4.5 Experimental results for the modified steel slag

Through the experiments in which the magnetic behavior of fine-grained steel slag was tested at different particle sizes, we observed that the suitable particle size range was 0.15mm–0.3 mm. The average magnetic concentrate recovery was 52.16%, the maximum magnetic concentrate recovery was 66.13% (which is a low value), and that the magnetic concentrate grade increased by 20–30%. Therefore, it is evident that the yield and the recovery of the magnetic concentrate needs to be improved. There is a certain proportion of weakly magnetic minerals in steel slag. Therefore, magnetic concentrate recovery will probably not be high, as these materials do not possess sufficient magnetism for the new magnetic separator to be effective. In order to verify this, we analyzed the magnetite content of the suitable particle size using a magnetic tube, which enabled calculation of the magnetite iron content.

This section describes how the desired magnetic concentrate recovery index was achieved through high temperature and high voltage modification experiments. ADC voltage device was used to shock the fine steel slag. After 10 minutes, 500 g of slag were sampled to analyze the magnetite iron content. The slag was then roasted, and after 60 minutes, another 500g were sampled for analysis. Table 4 shows the magnetite iron recovery before and after modification.

Table 4 Magnetite iron recovery with magnetic tube determination prior and after modification

Particle size/mm	High voltage modification		High temperature modification		The difference value /g	
	BM	AM	BM	AM	High voltage modification	High temperature modification
-0.3	107.70	92.21	107.70	131.56	-15.49	23.86
+0.1	100.60	89.24	100.60	122.85	-11.36	22.25
0.15-0.3	119.05	101.99	119.05	145.44	-17.06	26.39

"BM"stands for "Before Modification"; "AM"stands for "After Modification"

As Table 4 shows, the magnetite iron recovery of steel slag dropped by 13% on average and the fluctuation was large after the high-voltage modification. However, after the high temperature modification, the recovery increased by 22% on average, with a smaller fluctuation. The reasons for this are likely as follows: the specific susceptibility of moderately strong magnetic minerals will

decrease under high voltage, resulting in a decrease in the probability of adsorption of moderately strong magnetic minerals; on the other hand, high-temperature roasting can make some weakly magnetic minerals strongly magnetic, resulting in an increase in the magnetite iron content.

Using lignite as a reducing agent, the oxidation-reduction reaction of the best grade 0.15–0.3 mm steel slag was carried out in a high-temperature roaster. The C-content ratio is the ratio of carbon content in coal and the quality of steel slag in mineral. The resulting data are shown plotted in Fig. 10, and it was assumed that the grade of the raw ore was 25%.

As shown in Fig. 10, when the C-content ratio is 6:1, the concentrate recovery of the modified steel slag will drop 2.63 percentage points at 850℃; when the C-content ratio is 10:1, the concentrate recovery of the modified steel slag will increase 0.28 percentage points at 850℃; when the C-content ratio is 8:1 and the temperature is 1150℃, the magnetic concentrate recovery of the modified steel slag is 91.78%, which increases 24.66 percentage points and the effect is very obvious.
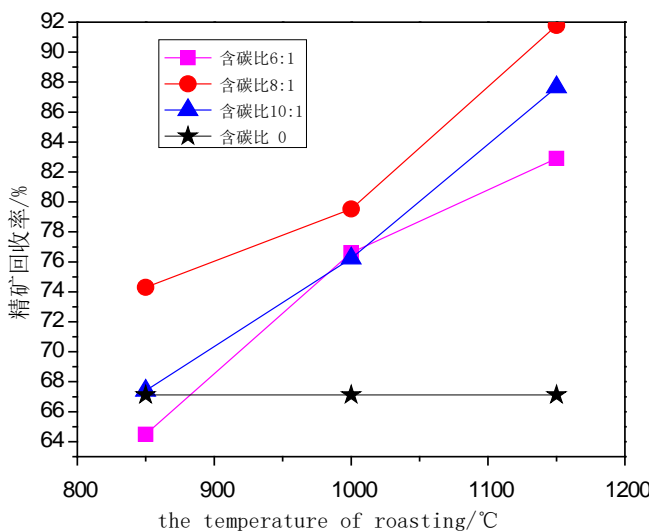

Figure 10. Dry magnetic behavior contrast of steel slag for different high-temperature roasting

As shown in Fig. 10, for a C-content ratio of 6:1, the concentrate recovery of the modified steel slag dropped by 2.63% at 850 ℃, whereas for a C-content ratio of 10:1, the concentrate recovery increased by 0.28% at the same temperature. On the other hand, when the C-content ratio and the temperature were 8:1 and 1150℃ respectively, the

magnetic concentrate recovery of the modified steel slag was 91.78%, which is an increase of 24.66%, clearly illustrating the temperature effect.

As it is widely known, steel slag is formed from liquid poured from a smelting furnace [15]. When the furnace liquid is poured, its temperature is about 1200℃, high enough to meet the requirements of roasting. By adding lignite to the cooling pool and controlling particle size, this technology may be used in industry to improve the moderately-strong magnetic mineral content, as well as the separation efficiency of iron minerals.

5 Conclusions

In the present study, a new magnetic separator was designed and magnetic separation experiments were carried out to optimize the main sorting parameters according to the characteristics of the selected steel slag. An efficient recovery of iron in the fine-grained steel slag was obtained. The main conclusions are:

(1) With designing the closed-loop permanent magnetic system by splicing and extrusion of eight fan-shaped permanent magnets, it was possible to realize the echelon changes of magnetic field intensity with higher values. The magnetic system thus produced displays characteristics such as more circumferential alternating times, minimal magnetic flux leakage, large magnetic separation space, and deep magnetic separation distance, thus efficiently contributing to iron enrichment in the fine-grained steel slag.

(2) The self-developed magnetic separator has a multi-roller setting and a modular structural design, enabling it to be adjusted to achieve different sorting effects depending on the characteristics of the minerals being processed. At the same time, these characteristics, combined with the circumferential distribution of magnetic field, enhance the probability of reducing mineral inclusions.

(3) A process was designed for the preparation of fine-grained steel slag, and four-sorting experiments were carried out on the recovery of steel slag iron. The single factor experiments enabled determination of the optimum value ranges of the particle size (0.15 mm–0.3 mm), magnetic separation distance (10 mm–12 mm), and rotating frequency (40 Hz–60 Hz). Correspondingly, a comparative experimental was carried out using parameter values of 0.2 mm, 11 mm, and 40 Hz, respectively. It was found that the concentrate recovery and concentrate grade reached 52.78% and 64.74%, respectively. Thus, the

new separation technology has a beneficial effect on iron recovery from waste slag.

(4) The magnetite iron recovery of steel slag was found to drop after high voltage modification and increase after high temperature modification. Furthermore, for a C-content ratio of 8:1 at a temperature of 1150℃, the magnetic concentrate recovery of the modified steel slag was 91.78%.

Acknowledgements

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