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Study on magnetic difference of artificial magnetite and natural magnetite

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Abstract: The magnetic differences of the artificial magnetite and the natural magnetite were studied to improve the magnetic parameters of artificial magnetite in the study. The effect of roasting conditions on the magnetism of artificial magnetite and the diffidence of magnetism and magnetic behavior of the artificial magnetite and natural magnetite was studied and compared. The results indicate that the magnetically strong artificial magnetite has been obtained under the optimized process parameters of the roasting temperature of 800°C, roasting time of 60min and the mass ratio of pulverized coal to ore (C/O ratio) of 2%. And the magnetic analysis shows that the magnetism of natural magnetite is stronger than that of artificial magnetite under the same conditions, but the remanence and coercivity of artificial magnetite is stronger than natural magnetite. With the decrease of particles, the magnetism of the artificial magnetite changes insignificantly, but the magnetization of natural magnetite decreases gradually; and the difference in the magnetism of two becomes smaller (from $1.53\times10^{-4}\cdot m^3\cdot kg^{-1}$ to $0.14\times10^{-4}\cdot m^3\cdot kg^{-1}$) with the decrease of particles. The gaps and impurities in the ore are the cause of the difference, which provides a theoretical basis for the further study the size-fractionated magnetic separation of artificial magnetite.

1. Introduction

The iron ore is difficult to exploit effectively for its fine particle distribution, complicated structure and low-grade in China[1-3]. And with the rapid development of iron and steel industry and increasing mining of iron ore in recent years, rich iron ore is gradually depleted[4,5], so it is essential to exploit refractory iron ore resources effectively. At present, magnetizing roasting is an effective method for the treatment of weakly magnetic refractory ores[6-8]. The ore is heated and reacted with oxidant or reductant during the process of magnetizing roasting. After that, magnetism of weak magnetic iron-containing minerals is significantly enhanced while magnetism of gangue minerals almost remains. Thus, iron can be successfully separated according to magnetic differences of iron-containing minerals and gangue minerals.

However, it was found that the diversity of magnetism and magnetic separation between artificial magnetite made by magnetizing roasting and natural magnetite, while the magnetic separation process of artificial magnetite was studied. Luo et al[9] studied on improving the beneficiation index of roasting magnetic concentrate, it indicated the ore with relative higher remanence will occur the phenomenon of magnetic agglomeration, which had bad effect on quality of the products from magnetic separator. Toomver[10] indicated the magnetite with the higher coercivity and remanence of artificial magnetite may become a strong magnetic aggregate containing non- magnetic particles resulting in the deteriorate of concentrate during magnetic separation process, which induced magnetism was greater in artificial magnetite compared to natural magnetite. Yuan et al[11] introduced that the artificial magnetite with relative higher coercivity was difficult to demagnetize in the process of magnetic separation. Therefor, in this study, the magnetic properties magnetic separation behavior of artificial magnetite and natural magnetite was studied to research the difference between the two. And it is hoped that the magnetic separation is performed effectively using the difference.

2. Experimental

2.1 Material

The artificial magnetite was made from specularite that was from JISCO (Jiuquan Iron & Steel (Group) Co., Ltd.; Gansu Province, China) by magnetizing roasting. Chemical compositions and phase compositions of specularite are listed in Table 1 and Table 2. The results show that the main metal minerals are iron in specularite, the content is 33.39 wt.%; the main gangue minerals are quartz, accounting for 27.85 wt.%, followed by Al_2O_3, MgO and CaO. Iron mainly exists in hematite and siderite, accounting for more than 95% of total, followed by magnetite, iron sulfides and iron silicate in specularite.

Table 1. Main chemical compositions of the specularite (wt.%)

Components	TFe	SiO_2	Al_2O_3	CaO	MgO	MnO	S	P
Content	33.39	27.85	5.64	1.50	3.05	1.26	0.99	0.24

Table 2. Analysis of iron chemical phases in the specularite (wt.%)

Iron Phase	Magnetite	Siderite	Sulfides	Silicate	Hematite	TFe
Iron Amount	0.50	7.05	0.21	0.88	24.75	33.39
Distribution rate	1.50	21.11	0.63	2.64	74.12	100.00

The natural magnetite was from Daye city, Hubei Province, China. Chemical compositions and phase composition of which are listed in Table 3 and Table 4. which shows that the main metal minerals are iron in natural magnetite, the content is 44.41 wt.%; the main gangue minerals are quartz, accounting for 11.46 wt.%, followed by CaO and MgO. Iron mainly exists in magnetite, accounting for 89.26 wt.% of iron and 40.30% of all, followed by iron carbonate, iron sulfides and iron silicate in natural magnetite.

Table 3. Chemical compositions of the artificial magnetite(wt.%)

Components	TFe	SiO_2	CaO	MgO	MnO	S	P	Cu
Content	44.41	11.46	8.25	3.31	0.15	3.51	0.052	0.45

Table 4. Analysis of iron chemical phases in the artificial magnetite(wt.%)

Iron Phase	Magnetite	Carbonate	Sulfide	Silicate	FeO	TFe
Iron Amount	40.30	1.52	1.28	2.00	0.05	45.15
Distribution	89.26	3.37	2.83	4.43	0.11	100

Coal was used as the reducing agent during the reduction reaction of magnetizing roasting. The proximate analysis of coal is shown in Table 5. Which shows it is a suitable reducing agent for its high content of fixed carbon and low content of ash and sulfur.

Table 5. Proximate analysis of coal(wt.%)

Components	**Fixed carbon**	**Ash**	**Volatile matter**	**S**	**Water**
Content	63.66	11.0	12.6	0.42	12.7

2.2 Procedure
The experimental process is shown in Figure 1.

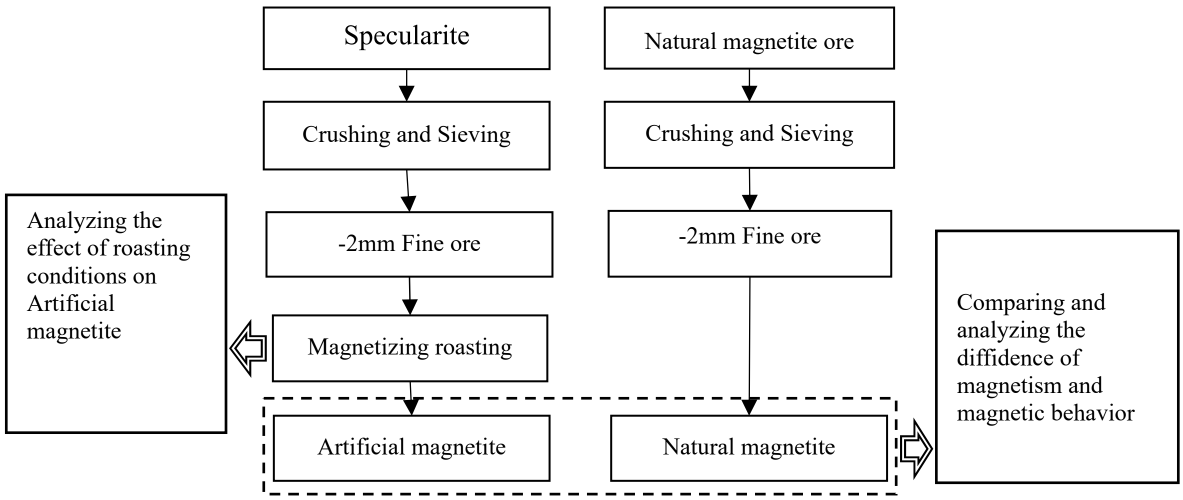


Figure 1. Process chart of experimental

The ore raw material were crushed to below 2mm size with a two-stage jaw crusher(model XPC-60×100) (Wuhan Exploring Machinery Factory, Wuhan, China) and a one-stage roll crusher(model XPS-Φ250×150) (Wuhan Exploring Machinery Factory, Wuhan, China). The artificial magnetite and natural magnetite were divided into four grades respectively with screening machine(model HLSDB-Φ200) (Wuhan Heng-le Mineral Engineering Equipment Co. Ltd., Wuhan, China).

2.3 Test methods
(1) Chemical composition of the sample was analyzed using inductively coupled plasma-atomic emission spectrometer(ICP)-atomic emission spectrometer (AES) performed on an IRIS Advantage ER/S instrument (Thermo Elemental, Waltham, MA, USA).
(2) X-ray diffraction(XRD) analysis of the sample was conducted by D/MAX-RB X-ray diffractometer (Rigaku, Akishima, Japan) using Cu K radiation.
(3) The magnetic properties of the sample were conducted using a VSM(Vibrating Sample Magnetometer; model JADW-2000D, Changchun City Yingpu Magnetic Technology Development Co. Ltd., Changchun, China).

2.4 Test indexes
(1) Iron grade(%); chemistry titration.
(2) Iron recovery(%); chemistry titration.
(3) Magnetization (M)= vector sum of magnetic moment($\sum$m)/ per unit volume(ΔV)
(4) Mass susceptibility(χ)= massic magnetic moment(σ)/intensity of external magnetic field(H)

3. Results and discussion

3.1 Preparation of artificial magnetite
The artificial magnetite was made from specularite by magnetizing roasting. The effects of roasting

conditions on the magnetism of artificial magnetite were investigated.

3.1.1 Effect of roasting temperature on artificial magnetite

When the roasting time is 60min, C/O ratio is 2%. The effect of roasting temperature on the magnetism of artificial magnetite was studied, as figure 2 showed. With the roasting temperature rising from 700°C to 800°C, the maximum mass susceptibility of artificial magnetite increases from $6.11\times10^{-4}\cdot m^3\cdot kg^{-1}$ to $7.11\times10^{-4}\cdot m^3\cdot kg^{-1}$, which indicates that the contents of magnetite of artificial magnetite increase resulting in its magnetism increasing. With the temperature continues to rise to 900°C, the maximum mass susceptibility of artificial magnetite reduces to $4.44\times10^{-4}\cdot m^3\cdot kg^{-1}$, which indicates that the contents of magnetite of artificial magnetite decrease resulting in its magnetism reducing. Therefore, the optimum temperature of 800°C for magnetizing roasting was determined in this experiment.

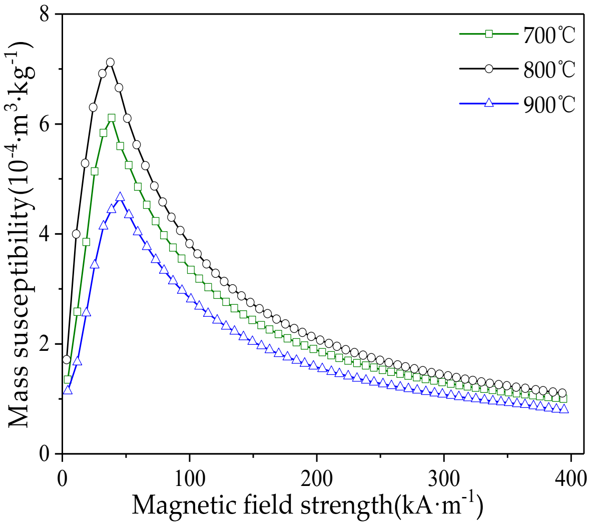


Figure 2. The effect of roasting temperature on the mass susceptibility of artificial magnetite

3.1.2 Effect of roasting time on artificial magnetite

When the roasting temperature is 800°C, C/O ratio is 2%, the effect of roasting time on the magnetism of artificial magnetite was studied, as figure 3 showed. When the roasting time is 60min, the maximum mass susceptibility of artificial magnetite is strongest of $7.12\times10^{-4}\cdot m^3\cdot kg^{-1}$. If the roasting time is not enough, the weak magnetic minerals are not reduced, so the magnetism of artificial magnetite is weak. However, if the time is too long, the magnetite will be reduced to weak magnetic minerals(Fe_xO) resulting in the magnetism of artificial magnetite weakening. Therefore, the optimum time of 60min for magnetizing roasting was determined in this experiment

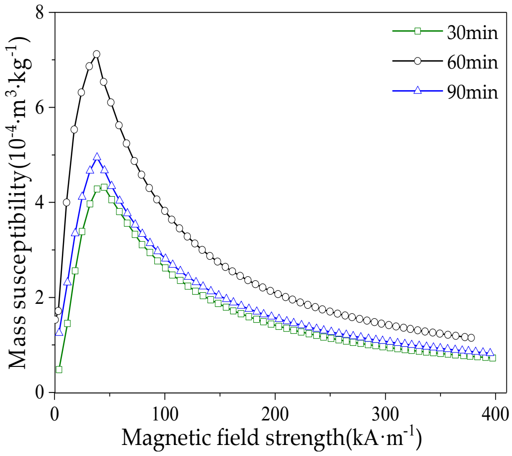


Figure 3. The effect of roasting time on the mass susceptibility of artificial magnetite

3.1.3 Effect of C/O ratio on artificial magnetite

When the roasting temperature is 800°C, roasting time is 60min, the effect of C/O ratio on the magnetism of artificial magnetite was studied, as figure 4 showed. The table 4 shows that with the C/O ratio increasing, the maximum mass susceptibility is strongest of $7.13\times10^{-4}\cdot m^3\cdot kg^{-1}$ when C/O ratio is 2%. The degree of ore reduction will be affected for too much or too little coal. Therefore, the optimum C/O ratio of 2% for magnetizing roasting was determined in this experiment.

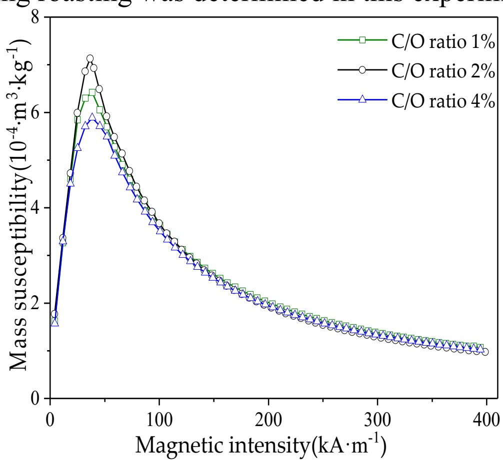


Figure 4. The effect of C/O ratio on the mass susceptibility of artificial magnetite

In summary, the roasting conditions of temperature of 800°C, time of 60min and C/O ratio of 2% are the optimum process system during the process of magnetizing roasting. Artificial magnetite can be obtained under the conditions.

3.1.4 Characterization of artificial magnetite

Chemical compositions and phase composition of the artificial magnetite are listed in Table 6 and Table 7. Hematite (Fe_2O_3) in specularite is reduced to magnetite (Fe_3O_4) while non-magnetism of gangue minerals almost remains no-change. The content of iron increases to 38.66%, because the water was off with high temperature. And iron mainly exists in magnetite, accounting for 92.52% of the iron and 35.50% of total, followed by iron carbonate, iron silicate and iron oxide in artificial magnetite.

Table 6. Chemical compositions of the artificial magnetite (wt.%)

Components	**TFe**	**SiO_2**	**CaO**	**MgO**	**MnO**	**S**	**P**	**Cu**
Content(%)	38.66	29.10	1.84	2.80	1.13	1.17	0.024	0.012

Table 7. Analysis of iron chemical phases in the artificial magnetite(wt.%)

Iron Phase	**Magnetite**	**Carbonate**	**Sulfide**	**Silicate**	**FeO**	**TFe**
Amount(%)	35.50	0.90	0.26	1.10	0.97	38.73
Distribution(%)	92.52	2.32	0.67	2.84	2.50	100

3.2 The magnetic separation behavior between the artificial magnetite and the natural magnetite

The magnetic separation test was carried out in order to study the difference of magnetic separation behavior between the artificial magnetite and natural magnetite.

3.2.1 Effect of grinding fineness on the magnetic concentrate indexes of magnetite

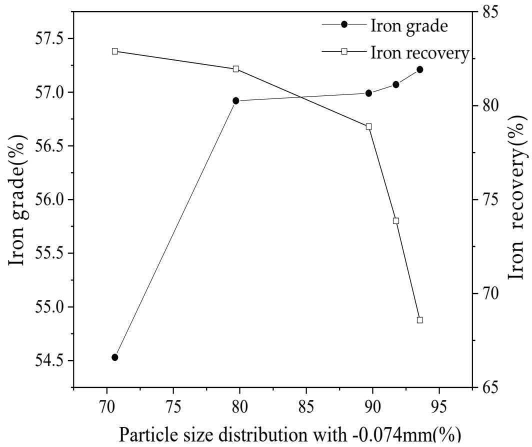


Figure 5. The effect of grinding fineness on the magnetic concentrate indexes of artificial magnetite

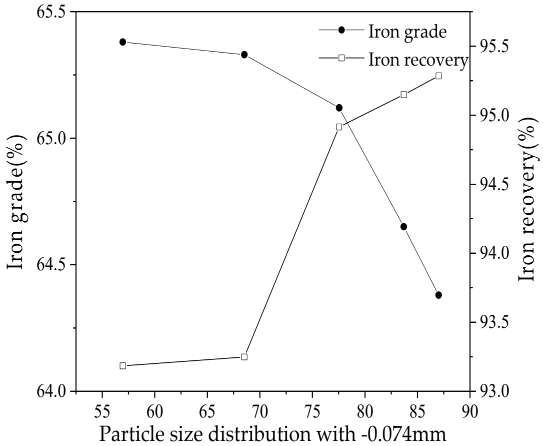


Figure 6. The effect of grinding fineness the magnetic concentrate indexes of natural magnetite

The figure 6 shows that with the decrease of particles, the iron grade of magnetic concentrate of artificial magnetite has been rising, but the rising trend slows down when the particle size distribution rate with -74μm of 79.9%; and the iron recovery of that decline gradually. The figure 7 shows that with the decrease of particles, the iron grade and iron recovery of magnetic concentrate of natural magnetite rise gradually, but the recovery of that declines when the particle size distribution rate with -74μm of 77.5%. Therefor the grinding fineness with -74μm of 79.9% of artificial magnetite and that of 77.5% of natural magnetite were determined.

3.2.2 Effect of magnetic intensity on the magnetic concentrate indexes of magnetite

The figure 7 shows that as the magnetic intensity increases, the iron grade of magnetic concentrate of artificial magnetite rises gradually while the iron recovery of that declines gradually, but the change rate of two slow down when the magnetic intensity of 91.56kA/m. The figure 8 shows that as the magnetic intensity increases, the iron grade of magnetic concentrate of natural magnetite rises gradually and the iron recovery of that rises first and then declines. Therefor the magnetic intensity of 91.56kA/m of artificial magnetite and that of 80 kA/m of natural magnetite were determined.

The magnetic concentrate of artificial magnetite with the iron grade of 56.92% and the iron recovery of 81.95% was obtained with the optimum conditions of the grinding fineness with -74μm of 79.9% and the magnetic intensity of 91.56kA/m; and that of natural magnetite with the iron grade of 64.65%% and the iron recovery of 94.62% was obtained with the grinding fineness with -74μm of 77.5% and the magnetic intensity of 91.56kA/m.

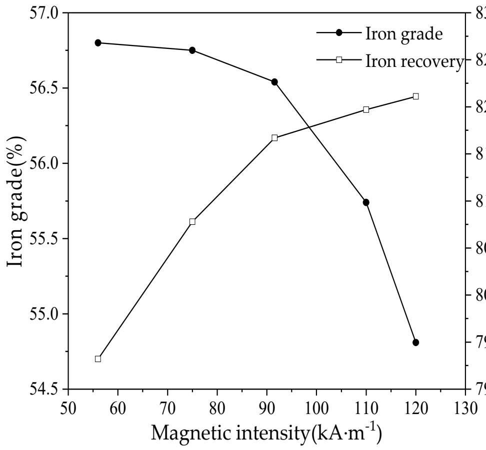


Figure 7. The effect of magnetic intensity on the magnetic concentrate indexes of artificial magnetite

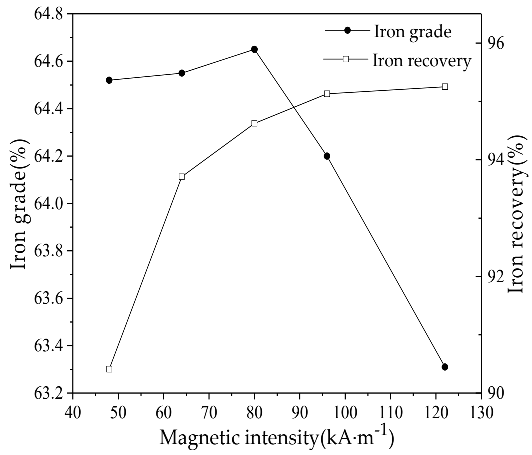


Figure 8. The effect of magnetic intensity on the magnetic concentrate indexes of natural magnetite

In summary, the magnetic separation indexes of natural magnetite are better than that of artificial magnetite.

3.3 The magnetic comparison between the artificial magnetite and the natural magnetite

In order to analyze the diffidence of magnetic separation behavior of artificial magnetite and natural magnetite, the magnetism of two was researched. And for the purpose of studying the effect of particle size on magnetism of two, the samples were divided into four particle sizes. As shown in the table 8.

Table 8. The sample of artificial magnetite and natural magnetite

Sample	Grain level /mm	Number	Magnetite /%	Density /$\times10^3$kg·m^{-3}
Artificial magnetite	-0.074~+0.048	A1	35.50	3.6988
	-0.048~+0.038	A2	34.81	3.7529
	-0.038~+0.025	A3	35.09	3.7458
	-0.025	A4	37.21	3.7067
Natural magnetite	-0.074~+0.048	N1	34.51	3.7916
	-0.048~+0.038	N2	34.19	3.8532
	-0.038~+0.025	N3	33.95	3.7554
	-0.025	N4	33.48	3.7832

3.3.1 Effect of grain size on the magnetism of artificial magnetite

The magnetization curve and hysteresis loop of artificial magnetite is shown in figure 9 and figure 10 respectively. The magnetic properties of that are listed in table 9.

As shown in figure 9, the magnetization of artificial magnetite is almost saturated when the magnetic intensity is about 150kA·m^{-1}, the mass susceptibility of which is maximum when the magnetic intensity is about 38kA·m^{-1}. The hysteresis loop is typical narrow S curve (figure 10).

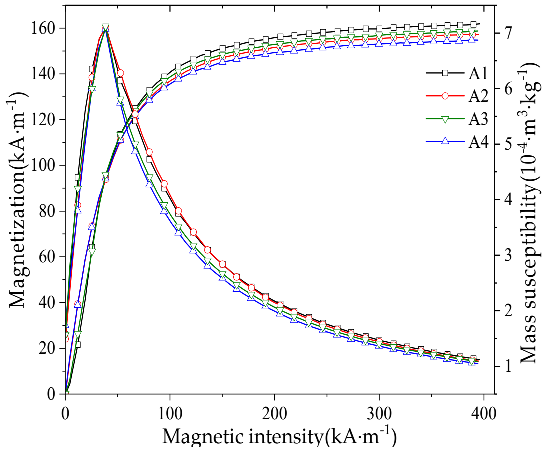


Figure 9. The magnetization and mass susceptibility with magnetic intensity of artificial magnetite

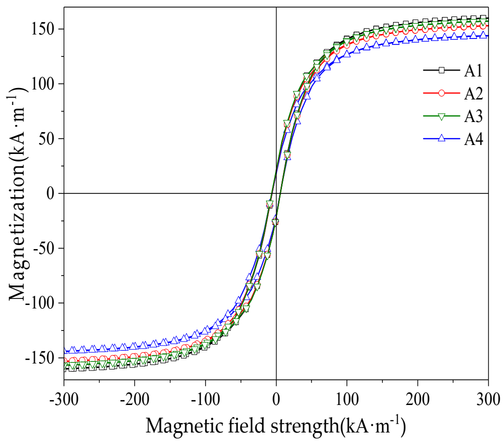


Figure 10. The hysteresis loop of artificial magnetite

Table 9. The magnetic properties of artificial magnetite

Grain size /mm	Saturation magnetization M_r /kA·m^{-1}	Residual magnetization J_r /kA·m^{-1}	Coercivity H_c /kA·m^{-1}	Maximum mass susceptibility χ/×10^{-4}·m^3·kg^{-1}
-0.074~+0.048	161.88	20.365	5.6588	7.11
-0.048~+0.038	157.27	19.452	5.7680	7.09
-0.038~+0.025	158.75	21.039	5.9133	7.09
-0.025	154.83	21,191	5.9408	7.05

With the decrease of particles, in general, the saturation magnetization and maximum mass susceptibility of artificial magnetite decrease gradually, while the residual magnetization and coercivity of that increase gradually, but the trend is not significant. It indicates that the magnetism of artificial magnetite changes little with the change of particle size.

3.3.2 Effect of grain size on the magnetism of natural magnetite

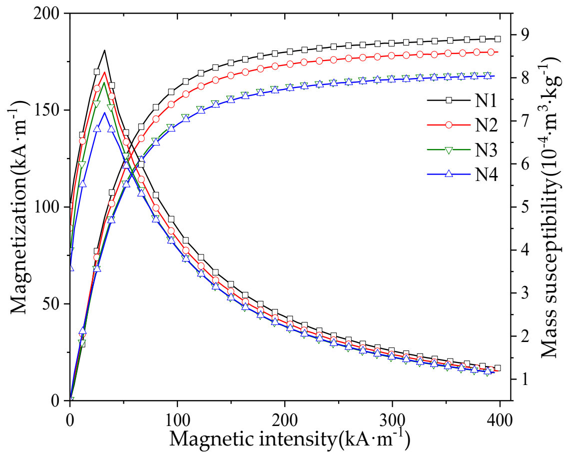


Figure 11. The magnetization and mass susceptibility with magnetic intensity of natural magnetite

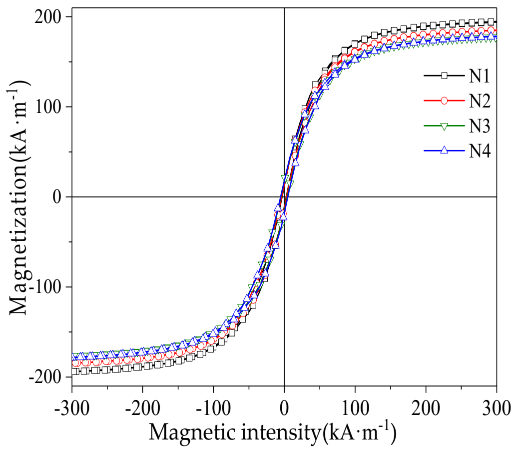


Figure 12. The hysteresis loop of natural magnetite

The magnetization curve and hysteresis loop of natural magnetite is shown in figure 11 and figure 12 respectively. The magnetic properties of that are listed in table 10.

As shown in figure 11, the magnetization of natural magnetite is almost saturated when the magnetic intensity is about 200kA·m^{-1}, the mass susceptibility of which is maximum when the magnetic intensity is about 32kA·m^{-1}. The hysteresis loop also is typical narrow S curve (figure 12).

Table 10. The magnetic properties of natural magnetite

Grain size /mm	**Saturation magnetization M_r/kA·m^{-1}**	**Residual magnetization J_r/kA·m^{-1}**	**Coercivity H_c/kA·m^{-1}**	**Maximum mass susceptibility χ/×10^{-4}·m^3·kg^{-1}**
-0.074~+0.048	186.72	11.488	2.9478	8.64
-0.048~+0.038	179.90	12.690	3.6114	8.13
-0.038~+0.025	168.29	15.279	4.3267	7.89
-0.025	167.57	17.971	5.0852	7.19

With the decrease of particles, the saturation magnetization and maximum mass susceptibility of natural magnetite decrease gradually, while the residual magnetization and coercivity of that increase gradually, the trend is obvious comparing that of artificial magnetite. It indicates that the magnetism of natural magnetite becomes weak with the change of particle size.

3.3.3 Magnetic comparison of artificial magnetite and natural magnetite

Comparing the magnetization curve and hysteresis loop of artificial magnetite and natural magnetite, we can know they both have similar magnetic characteristics (Saturation magnetization, Maximum mass susceptibility and narrow S hysteresis loop). But the artificial magnetite is easier to reach the magnetic saturation than the natural magnetite.

Comparing table 9 and table 10, under same conditions, the saturation magnetization and maximum mass susceptibility of natural magnetite is bigger than the artificial, but the residual magnetization and coercivity of former is smaller than the latter. It easy to occur in the phenomenon of magnetic agglomeration during the process of magnetic separation for the large remanence of artificial magnetite. So the magnetism of the natural magnetite is stronger than artificial magnetite under same conditions.

With the decrease of particles, the difference of maximum mass susceptibility of the artificial magnetite and natural magnetite decreases from 1.53×10^{-4}·m^3·kg^{-1} to 0.14×10^{-4}·m^3·kg^{-1} gradually(figure 13), which indicates that the difference of magnetism of two decrease gradually.

The effect of particle size on magnetism of the magnetite can be explained by magnetic domain theory[11,12]. The magnetic properties of the ore are derived from the effect of the movement of the magnetic domain walls and the rotation of the magnetic domain, but the effect of the movement of the magnetic domain walls plays a major role. With the decrease of particles, the number of magnetic domains reduce, so the effect of the movement of the magnetic domain walls decrease during the magnetization process. At this time, the effect of the magnetic domain rotation starts to play a major role. After the particle size reduce to the ore only contain one magnetic domain, the magnetic domain wall disappears, and the magnetic properties of the ore are all from the effect of the rotation of the magnetic domain. But the rotation of the magnetic domain requires much more energy than the movement of magnetic domain wall. Therefor the magnetism of the magnetite weakens gradually while remanence and coercivity increase with the decrease of particles. But the magnetism of the artificial magnetite and natural magnetite have different trends with the change of grain size. SEM-EDS analysis was performed for the purpose of analyzing the cause of differences.

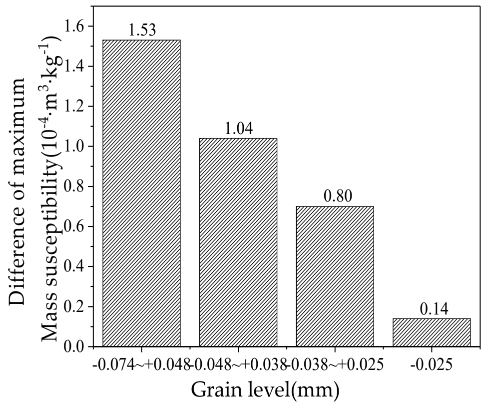


Figure 13. Difference of maximum mass susceptibility of two with the change of particle size

The SEM image (figure 14 and figure 15) shows that the surface of the artificial magnetite is loose and porous, there are so many gaps between the particles and; while the surface of the natural magnetite is smooth and dense and not too many gaps. Then the EDS spectra (figure 16 and figure 17) shows that the main impurity elements are Mg, Si and Mn which accounting for 6.86%, 3.43% and 1.25% of atomic ratio respectively, followed by Al and Ca in the artificial magnetite; and the main impurity elements are Mg and Si which accounting for 1.15% and 1.74% of atomic ratio respectively, followed by Al, Ca and Cl in the natural magnetite. The magnetic domain structure in the magnetite will make a big change if the magnetite contains gaps and impurities.

The presence of impurities and gaps cause a new localized magnetization around them[13,14], but the direction of magnetization is not same with that of the external magnetic field, so that total magnetic moment weaken resulting to the weakening of magnetism of magnetite. At the same time, the movement of magnetic domain wall is hindered for the gaps between the magnetic domain, it can't be restored to the original position after the magnetic domain wall moves, so that the remanence and coercivity become large. Which explains that the magnetism of artificial magnetite is weaker than that of natural magnetite, while the remanence and coercivity are larger than the latter.

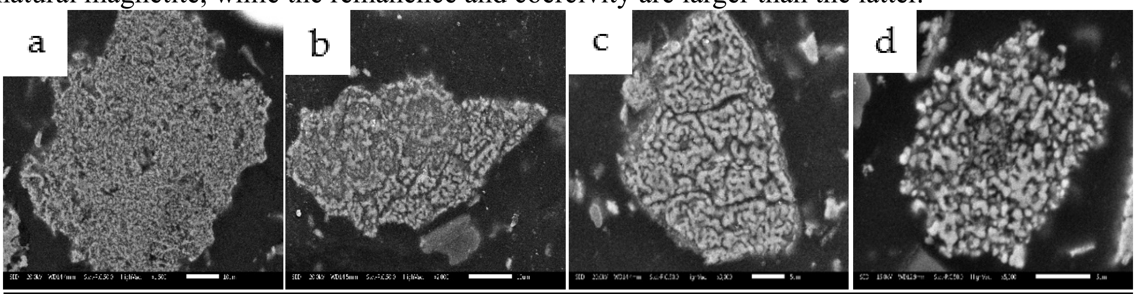


Figure 14. SEM images of the artificial magnetite. (a) Particle size distribution with -0.074mm ~ +0.048mm(×1500); (b) Particle size distribution with -0.048mm ~ +0.038mm(×2000); (c) Particle size distribution with -0.038mm ~ +0.025mm(×3000); (d) Particle size distribution with -0.025mm(×5000)

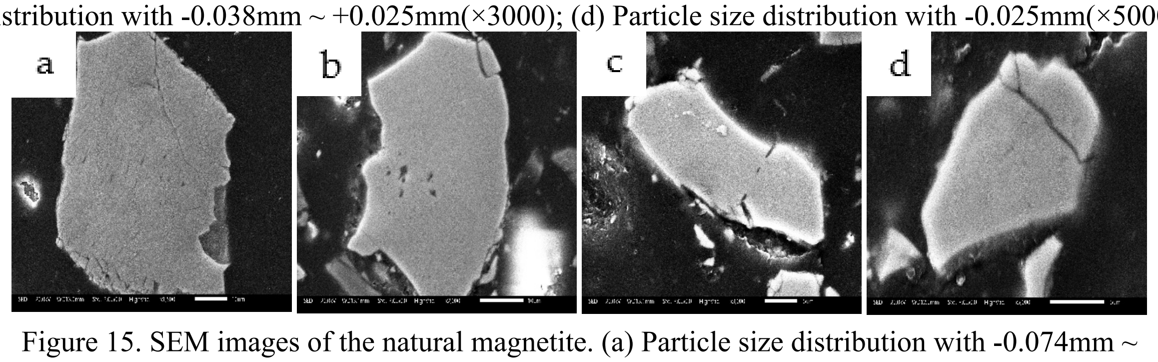
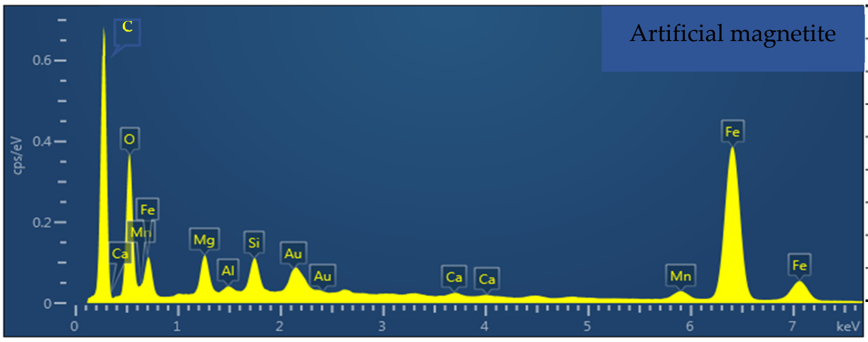
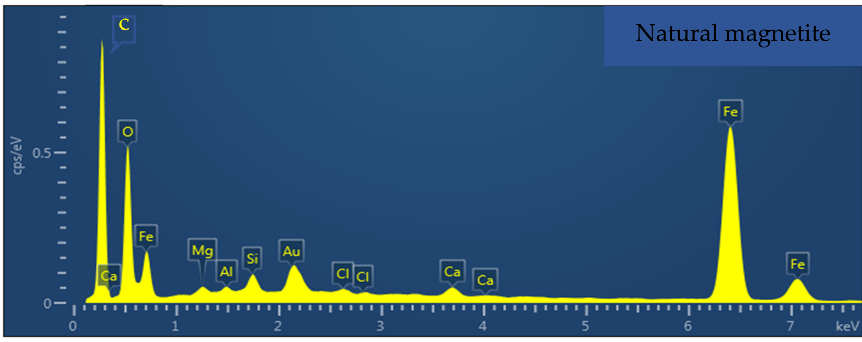


Figure 15. SEM images of the natural magnetite. (a) Particle size distribution with -0.074mm ~ +0.048mm(×1500); (b) Particle size distribution with -0.048mm ~ +0.038mm(×2000); (c) Particle size distribution with -0.038mm ~ +0.025mm(×3000); (d) Particle size distribution with -0.025mm(×5000)



Element	Wt./%	At./%
FeK	54.56	28.21
OK	32.78	59.16
MgK	5.78	6.86
SiK	3.34	3.43
MnK	2.34	1.25
AlK	0.71	0.76
CaK	0.46	0.33
Total	100	

Figure 16. EDS spectra of artificial magnetite with particle size distribution with -0.074mm~-0.048mm



Element	Wt./%	At./%
FeK	61.27	32.43
OK	34.02	62.85
MgK	0.94	1.15
SiK	1.66	1.74
AlK	0.63	0.69
CaK	1.02	0.75
ClK	0.46	0.39
Total	100	

Figure 17. EDS spectra of natural magnetite with particle size distribution with -0.074mm~-0.048mm

When the ore particles are bigger, the magnetism of natural magnetite is weakened by the decrease of the mass magnetic susceptibility with the decrease of the particles due to its single particle composition, smooth surface and compact structure; and the trend of decreasing the mass magnetization of artificial magnetite is not obvious for its internal stomatal structure and the complex impurity of some components which is not conducive to the movement of the magnetic domain. When the ore particle size is reduced to the ore only contains one magnetic domain, the magnetism of the magnetite is completely generated by the rotation of the magnetic domain, so the magnetic difference between the natural magnetite and the artificial magnetite is reduced.

As the magnetic properties of the artificial magnetite and natural magnetite are gradually approaching, size-fractionated magnetic separation will be further studied.

4. Conclusions

From above analyses and discussions, following conclusions can be drawn:

1. With the optimum conditions with temperature of 800°C, time of 60min and C/O ratio of 2%, artificial magnetite with iron grade of 38.66% was obtained. After magnetizing roasting, the compositions of Hematite/limonite reduced and that of magnetite increased gradually, indicate the effect is good. And the magnetic separation indexes of natural magnetite are better than artificial magnetite.

2. The artificial magnetite and natural magnetite both have similar magnetic characteristics. But the magnetism of the natural magnetite is stronger than the artificial magnetite, however the artificial magnetite is easier to reach the magnetic saturation when the magnetic intensity is about 32 $kA{\cdot}m^{-1}$ than the natural magnetite when the magnetic intensity is about 38 $kA{\cdot}m^{-1}$.

3. The difference of magnetism of the artificial magnetite and natural magnetite decreases from $1.53{\times}10^{-4}{\cdot}m^3{\cdot}kg^{-1}$ to $0.14{\times}10^{-4}{\cdot}m^3{\cdot}kg^{-1}$ gradually with the decrease of particles. The gaps and impurities in the ore are the cause of the difference of the natural magnetite and artificial magnetite. Which provides a theoretical basis for the further study the size-fractionated magnetic separation and the phenomenon of magnetic agglomeration of the natural magnetite and artificial magnetite.

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