pISSN 1229-3008 eISSN 2287-6251
Progress in Superconductivity and Cryogenics
Vol.19, No.1, (2017), pp.22~25 https://doi.org/10.9714/psac.2017.19.1.022

Superconducting magnetic separation of ground steel slag powder for recovery of resources

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(Received 23 February 2017; revised or reviewed 13 March 2017; accepted 14 March 2017)

Abstract

Steel slag has been considered as an industrial waste. A huge amount of slag is produced as a byproduct and the steel slag usually has been dumped in a landfill site. However the steel slag contains valuable resources such as iron, copper, manganese, and magnesium. Superconducting magnetic separation has been applied on recovery of the valuable resources from the steel slag and this process also has intended to reduce the waste to be dumped. Cryo-cooled Nb-Ti superconducting magnet with 100 mm bore and 600 mm of height was used as the magnetic separator. The separating efficiency was evaluated in the function of magnetic field. A steel slag was ground and analyzed for the composition. Iron containing minerals were successfully concentrated from less iron containing portion. The separation efficiency was highly dependent on the particle size giving higher separating efficiency with finer particle. The magnetic field also effects on the separation ratio. Current study showed that an appropriate grinding of slag and magnetic separation lead to the recovery of metal resources from steel slag waste rather than dumping all of the volume.

Keywords: High-gradient magnetic separation, recovery, steel slag, environmental application, superconducting magnet

1. INTRODUCTION

Separation is a common processes in environmental technologies including water and wastewater treatment, contaminated soil treatment, and hazardous waste management. High gradient magnetic separation (HGMS) is one of the major applications of the superconductivity and the magnetic separation can be applied on several environmental area [1-4].

Steel making is a fundamental industry which has been a basement for manufacturing industry and construction. Industrially advanced nation has iron mills. Melting iron ore is the main steel making process and produces steel slag as by-product. Steel slag includes some valuable elements such as iron, silica, phosphorous and calcium, however it also has toxic heavy metals such as copper, zinc, lead, and cadmium. The steel slag has been considered as hazardous waste due to the small amount of heavy metal contents which could be leached into soil and water environment from the landfill site where slag has been dumped.

Human faced to several environmental crises including climate change and short of valuable resources. Therefore, current environmental policy focused on the recovery of valuable resources, reuse, and minimization of the waste to be dumped. These policies could be resulted in saving the landfill area. The minimization of waste is more important in countries whose land area is small and population density is high such as Korea and Japan. The minimization of dumping is also important to avoid the secondary pollution of soil and eco-system from the soil contamination around the landfill area. The ocean disposal has been banned by international regulation. Therefore the minimization of dumped waste is a method to prevent environmental and human from the toxic waste and recovery of valuable resource for economical reason.

Kim et al. reported on separation of steel slag from landfill waste for the purpose of decontamination using a HGMS system [5]. They successfully separated the highly slag containing part from soil and minimized the volume to be treated intensively. Lin et al. published a paper regarding the separation and recovery of phosphorus from p-bearing steelmaking slag using a magnetic separation system [6]. MgO, MnO, Na_2O and CaF_2 have little effect on the phosphorus recovery whereas SiO_2, Al_2O_3 and TiO_2 have great effect on phosphorus enrichment in slag and magnetic separation. Nadirov et al. studied on the recovery of value metals such as zinc, copper, and iron from copper smelter slag by ammonium chloride treatment [7]. Furthermore, manifold researches for recovery of valuable resources such as high grade iron, cobalt, nickel, and vanadium were carried out to date [8-13].

The objective of current study is to evaluate a superconducting magnetic separation system for recovery of valuable resources from a steel slag and at the same time concentration of toxic metals into the other side. We expect the successful usage of superconducting magnetic

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separation system as natural resource recovery technology. The technology could be an efficient alternative for recovery of metal resources such as iron and others. The metal content variation and size distribution are compared before and after the magnetic separation. Cryo-cooled Nb-Ti superconducting magnet with 100 mm room temperature bore and 600 mm of height was used for the magnetic separator.

2. EXPERIMENTAL METHODS

2.1. Materials

Standard Solution of Pb, Fe, Zn, and Cu were purchased from Kanto and the concentration of each metal was 1000 mg/L. Nitric acid (36%), and hydrochloric acid were obtained from Merck. All chemicals and materials were used without further purification.

2.2. Steel Slag from Steel Making Company

Steel slag was obtained from a steel making company in Korea. The slag was in granular type with diameter of 5-7 mm and the slag was milled before the magnetic separation. The ground slag powder was sieved with a 200 mesh sieve and the finer than 75 µm was used for the magnetic separation experiment. The particle size distribution of slag was analyzed by a particle size analyzer (Mastersizer 2000, Malvern) and the size distribution is shown in Fig. 1. The particle size ranged from 0.3 to 75 µm.

2.3. Magnetic Separation

A HGMS system was used in current experiments and the HGMS was equipped with a 6-Tesla cryo-cooled Nb-Ti superconducting magnet. The bore size of the magnet was 100 mm in diameter and sample channel, which is made of acrylic pipe, was fitted into the bore. The magnetic filter was wound steel mesh and it is made from stainless steel mesh. The steel mesh filter was placed into the acrylic pipe which to be fitted into the pore of the magnet. The magnetic filter size and interval were 10 mesh (0.254 mm) and 10 mm.

Slag particles could be caught by the magnetic moment generated per unit volume of the slag material. The magnetic force in slag particles is given by [14]:

$$F_m = (1/\mu_0)\rho\chi VB\nabla B \quad (1)$$

Where μ_0 is permeability in vacuum ($4\pi \times 10^{-7}$) (H m^{-1}), χ is the specific magnetic susceptibility (m^3/kg), ρ is the specific gravity (kg/m^3), V is the volume of particle (m^3), B is magnetic induction (T).

The magnetic separation experiments were conducted in a manner of batch process. The sieved slag powder was suspended into distilled water and the liquid to solid ratio was 1000:1. The prepared slag slurry was introduced into the acrylic pipe, in which the steel mesh was placed. The separated particle captured on the steel mesh by magnetic force was collected by removing the pipe and steel mesh from the bore after a set of experiment. The ratio of collected slag to the part passed through steel mesh was calculated. The experiments were repeated in variable magnetic field ranged from 1.0 T to 6.0 T

2.4. Analytical Methods

The morphological features of steel slag were studied using a scanning electron microscope (Vega II LMU, Tescan). The particle size distribution was analyzed by a particle size analyzer (Mastersizer 2000, Malvern). X-ray fluorescence spectrometer, XRF (ZSX Primus II, Rigaku), and inductively coupled plasma atomic emission spectroscopy, ICP-AES (720 series, Agilent), were used for measurement of major mineral and metallic elements of steel slag. The accuracy and precision of the analytical methods were verified against reference samples.

The characteristics of the slag collected by the magnetic force were compared with the portion passed through the separation system.

3. RESULTS AND DISCUSSION

3.1. The Ratio of Captured to Passed Slag at Variable Magnetic Force

The particle size distribution was monitored before and after the magnetic separation as shown in Fig. 1. The finest particle is about 0.3 µm in diameter and the biggest particle was about 100 µm in diameter. There are no big difference between the particle size before separation and that of captured particle. However, the passed particle is relatively very fine particle smaller than 40 µm and the most of the particle was between 1.2 and 17 µm. This indicates the passed ones have different particle size distribution from the captured one. This means that successful separation could be possible in fine particle which allow separation of high iron content particle from nonmetallic slag contents such as silica and calcium. For more detail discussion, major element analysis of captured and passed particle will be necessary.

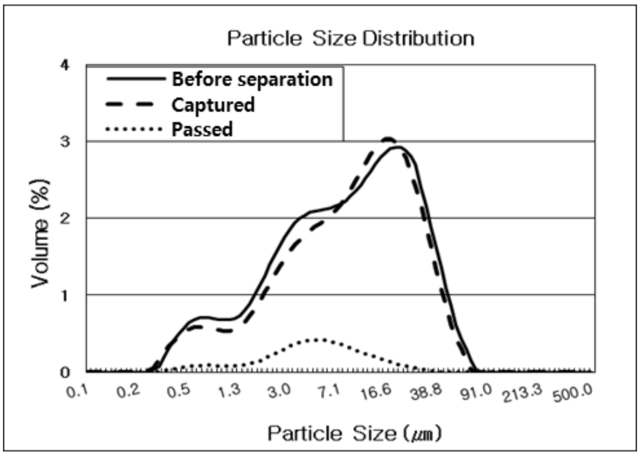

Fig. 1. Particle size distribution before and after magnetic separation at 6.0 T.

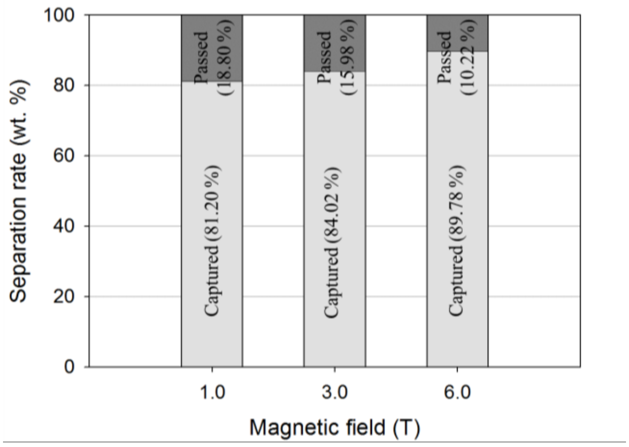

Fig. 2. Magnetic separation rate of steel slag (Velocity of flow=0.2 m/s).

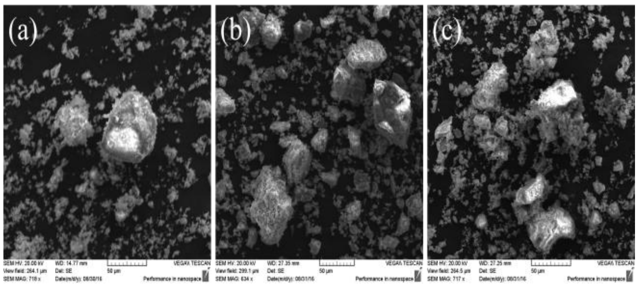

Fig. 3. SEM images of steel slag, (a) before magnetic separation, (b) captured at 6.0 T, (c) passed at 6.0 T.

The collected portion of the slag was ranged from 81.20% at 1 T of magnetic field to 89.78 % at 6T of the magnetic field as shown in Fig. 2. The recovery rate was relatively high since the slag contains iron as a main content. Therefore, the increase of the collection rate was not big even the magnetic field increased from 1 T to 6T. The captured rate also is function of the flow rate of the slag slurry. In current study the flow rate was 0.2 m/s which is not so fast if considering water is a low density liquid.

The surface of slag particle and particle distribution was observed by the SEM as shown in Fig. 3. There are no significant difference between the captured particles and the passed particles. The shape of particles is also almost same before and after the magnetic separation.

3.2. Concentration of Resources by the Magnetic Separation

The concentration effect of the magnetic separation for some concerning element was expected. XRF analysis was conducted and results were summarized in Table I. Calcium oxide and iron oxide is the major component of the slag surface as shown in Table I. In comparison between before and after the magnetic separation, magnesium oxide, manganese oxide and iron oxide were concentrated in captured portion. However, aluminum oxide, silica, phosphorus, and calcium oxide was concentrated in the passed portion. The analytical results from XRF are just about surface and semi-quantification method. ICP-AES is more accurate quantification method for metallic elements.

TABLE I
XRF ANALYSIS RESULT FOR MAJOR MINERALS. (WT. %)

	MgO	Al_2O_3	SiO_2	P_2O_5	CaO	MnO	Fe_2O_3
Before Separation	3.65	3.57	13.8	2.29	37.32	3.19	33.92
Passed at 6.0 T	2.89	4.80	15.21	2.70	53.00	1.72	17.38
Captured at 6.0 T	3.99	3.61	14.29	2.27	33.24	3.57	36.67

TABLE II
ICP-AES ANALYSIS RESULT. (MG/KG)

Passed at 6.0 T	As	Cd	Co	Cr	Cu	Fe
	43.29	ND*	ND	3637	140.8	67856
	Ni	P	Pb	Ti	V	Zn
	ND	8035	1267	2801	1385	971.3
Captured at 6.0 T	As	Cd	Co	Cr	Cu	Fe
	38.65	17.68	ND	8767	88.25	187468
	Ni	P	Pb	Ti	V	Zn
	ND	6984	2566	2880	2023	986.6

* ND = Not detected

After a pretreatment through dissolution of the slag particle into acid solution, ICP-AES was employed for the quantification of major elements and some heavy metals as shown in Table II. Iron and vanadium was concentrated into the captured portion while copper and phosphorus was found in passed portion relatively high concentration. This indicates that the magnetic separation could concentrate some valuable elements either captured or passed portion. However, it is not confirmed that the element concentration is high enough for raw material for economic aspect. The magnetic separation also concentrates some heavy metal which is the main reason why the slag is considered as hazardous waste. If the heavy metal is concentrated into one part and the concentration is thin the other side, the volume of waste to be treated would be reduced. The volume reduction of waste is one favorable technique in environmental engineering field. Appropriate operation of the HGMS for fine slag particle could result in the reduction of waste and recovery of valuable element. Previous studies also showed a positive result of concentration of phosphorus through magnetic separation with a HGMS [6].

3.3. Magnetization of the Slag before and after the Magnetic Separation

The slag particle captured and passed portion by magnetic field was tested for the magnetization and the results showed in Fig. 4. The slag particles magnetically separated in a magnetic field showed a high magnetization trend but the particles passed through the magnetic field showed a relatively small magnetization.

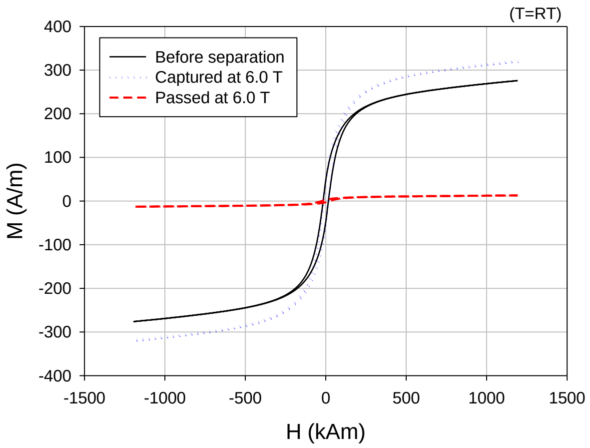

Fig. 4. Magnetic hysteresis loop of the steel slag.

3. RESULTS AND DISCUSSION

Steelmaking slag has been considered as hazardous waste to be safely treated but the slag contains some valuable resources such as iron, zinc, and phosphorus. The slag also contains some toxic heavy metals which cause adverse effect on human and environment when the heavy metal is leached into soil and water environment. A HGMS system was applied on slag particles suspended in water for concentrating the valuable metals and heavy metals.

About 81.20~89.78% of steel slag was captured at 1.0~6.0 T of magnetic fields despite relatively fast flow velocity (0.2 m/s) showing the slag contains iron or iron oxide in high concentration. Magnetic separation efficiency is greatly affected by the particle size of slag. Separated particles show a dissimilar mineral content, captured particles have an increased iron oxide content while passed particle have a higher calcium oxide content. This proved that magnetic separation could concentrate both of the valuable metals and the heavy metals. Cd and Cr such as environmental contaminants are concentrated in the captured particle. The concentration effects of some valuable minerals (P, Ti, and V) are not significant. The effect of particle size should be tested in detail and cost vs. benefit should be considered at the same time for the treatment of slag.

ACKNOWLEDGMENT

This research was supported by GAIA project from Korea Environmental Industry & Technology Institute (KEITI 2015000550008).

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