1. Introduction

In a typical semi electric arc smelting furnace operation for manufacturing silicomanganese alloy, production of 1 kg of silicomanganese alloy is accompanied by generation of about 1.2 kg of silicomanganese slag. Currently, about 84,000 tons of silicomanganese slag is produced each year from semi electric arc smelting furnace during the production of silicomanganese alloy at Dongbu Metal Company in Korea, which is simply used as a road pavement material or discarded at dump sites. Since the natural manganese oxide concentrates are becoming low grade and complex and the use of manganese continues to increase in the special steel industry, the amount of the slag generated in the silicomanganese slag discarded at dump sites. Since the natural manganese oxide concentrates are becoming low grade and complex and the use of manganese continues to increase in the special steel industry, the amount of the slag generated in the silicomanganese slag will increase concurrently. The discarded slag usually contains 10–14 mass% Mn that can be recovered. It was thus highly desirable to develop a novel process for recovering manganese from the slag in order to utilize effectively manganese resources and minimize the environmental problems caused by the slag of which the generation amount will increase in the future.

Recycling of silicomanganese slag back into the silicomanganese alloy smelting furnace would not only reduce an environmental liability caused by its dumping site but also decrease manganese ore consumption by recovering manganese contained in the slag. However, the gangue materials contained in the slag beside manganese have to be removed prior to feeding the slag into the silicomanganese alloy smelting furnace. This is due to the increase in slag volume, which can cause detrimental effects in the smelting operation. Thus, the upgrading of manganese from the silicomanganese slag must be required to recycle the slag back into the silicomanganese alloy smelting furnace. So far, a few hydrometallurgical processes to recover manganese from secondary manganese sources like waste batteries and spent electrodes, spent catalysts, steel scrap, sludge and ferromanganese slag are suggested. However, very little data on the utilizing of silicomanganese slag as a manganese resource are available. Specially, the upgrading of manganese from silicomanganese slag by physical separation processes has not been reported in literature.

Therefore, the present research is concerned with experimental investigations for the upgrading of manganese from silicomanganese slag by a physical separation process that is relatively simple and without generating any water wastes. The proposed process involves grinding and magnetic separation steps. It is thus thought that the physical separation process is relatively simple and low cost investment compared with conventional hydrometallurgical processes. The aim of this study is to investigate a feasibility process for the upgrading of manganese from silicomanganese slag to utilize it as a manganese resource for manufacturing silicomanganese alloy.

2. Experimental

The raw material used in the experiments was a silicomanganese slag discarded from semi electric arc smelting furnace during the production of silicomanganese alloy at Dongbu Metal Company in Korea. The slag was verified to has a complex amorphous structure with a composition mainly of MnO-SiO$_2$-CaO-Al$_2$O$_3$ system by X-ray analysis. Table 1 shows the average chemical compositions of the slag. The main ingredients contained in the slag are 14.1 mass% Mn, 38.6 mass% SiO$_2$, 15.7 mass% CaO and 14.8 mass% Al$_2$O$_3$. In the study, the slag was first ground by a jaw, hammer and pulverizer. The particle size of the powder ranged under 500 µm. The powder was then
sieved to four sizes, +0.280 mm, +0.200 mm, +150 mm and +75 mm. After that, dry magnetic separation was conducted at a magnetic field range of 5,000~10,000 Tesla for each the particle sizes. The dry magnetic separator used was one of the cross-belt types made by ERIEZ manufacturing company (Model: H.C.B), of which the maximum magnetic field strength was 15,000 Tesla. Figure 1 is a schematic diagram of the magnetic separator apparatus. In the magnetic separation experiment, the particles were continuously fed into magnetic field by an induced roll. Then, non-magnetic particles were thrown off the roll into the tailings compartment, whereas magnetic were gripped, carried out of the influence of the field and deposited into the magnetic compartment. Figure 2 shows the experimental flow sheet. Samples before and after the separation experiments were analyzed for Fe by a potassium dichromate titration method and Si by the loss in weight on volatilization with hydrofluoric acid. Also, Mn, Al, Ca, Mg, Zn, K and Na were determined by the inductively coupled plasma (ICP) method (JY-38 plus, Horiba Ltd., Kyoto, Japan). The solution for ICP analysis was prepared by decomposition with concentrated inorganic acids. Also, the morphological characterization of the samples was performed using a scanning electron microscope (SEM, JSM-6380LV, JEOL Ltd., Tokyo, Japan) equipped with an energy dispersive X-ray spectrometer (EDS, Link Isis 3.0, Oxford Instrument plc, Oxon, U.K).

3. Results and Discussion

It is already known that manganese minerals are separated in commercial magnetic separators.3,4) The magnetic separation technology was thus chosen to separate and concentrate manganese from waste silicomanganese slag in this study. In order to feed the silicomanganese slag into the dry magnetic separator, the slag was first ground into under 500 µm, and then the powder was sieved into several sizes. Figure 3 shows the relationship between the contents of manganese and iron and the percentage yield of each particle sizes. The figure shows that the contents of manganese and iron for all particle sizes are almost steady to be 14–15 mass% and under 1 mass%, respectively. Thus, it was verified that the particle separation on the upgrading of manganese form silicomanganese slag is not effective.

The magnetic separation for the upgrading of manganese form silicomanganese slag was carried out at a magnetic field range of 5,000~10,000 Tesla using the dry magnetic separator. Figure 4 shows the relationship between the contents of manganese and iron and the percentage yield of magnetic particles with the magnetic field strength for each the particle sizes. Shown in the figure is that the contents of manganese and iron in the magnetic particles separated increases with decreasing in the magnetic field strength for all particle sizes. This might be the reason why most of manganese contained in the raw silicomanganese slag exists in a mixture consisting of Mn, Mn-Fe, MnO and Mn-Fe-O compounds which are para-magnetic.3,4) Figure 5 shows SEM-EDS results of the raw silicomanganese slag particles.
The figure indicates that manganese-rich particles (particles 4-6) contain relatively much iron compared with manganese-poor particles (particles 1-3), while the manganese-poor particles (particles 1-3) contain a lot of gangue minerals like silicon, calcium and aluminum instead of iron. Thus, it was thought that since the manganese-poor particles which are relatively non-magnetic tend to be separated into the magnetic particles at strong magnetic field, the contents of manganese and iron in the magnetic particles separated decreases with increasing in the magnetic field strength. But, it was very difficult to measure experimentally the magnetic strength for each particle in the study. From Fig. 4, it was also examined that the content of manganese in the magnetic particles separated from all particle sizes is over 20 mass% at a magnetic field of 5,000 Tesla. Thus, the magnetic particles separated should be used as a manganese resource for manufacturing silicomanganese alloy because manganese rich slag containing over 20 mass% has been used for production of silicomanganese alloy in the duplex processing. Based on the magnetic separation experimental results, Fig. 6 shows the relationship between the content of manganese, the percentage recovery of manganese and the percentage yield of magnetic particles with the magnetic field strength. From the figure, manganese rich slag containing over 20 mass% manganese was calculated to be obtained from a magnetic field of 5,000 Tesla. Thus, the magnetic particles separated should be used as a manganese resource for manufacturing silicomanganese alloy because manganese rich slag containing over 20 mass% has been used for production of silicomanganese alloy in the duplex processing. Based on the magnetic separation experimental results, Fig. 6 shows the relationship between the content of manganese, the percentage recovery of manganese and the percentage yield of magnetic particles with the magnetic field strength. From the figure, manganese rich slag containing over 20 mass% manganese was calculated to be obtained from the magnetic separation process under the condition of a magnetic field of about 6,000 Tesla for the silicomanganese slag ground into the particle size range of 500 µm ~ 75 µm. At the conditions, the percentage recovery of manganese and the percentage yield were calculated to be 33% and 24%, respectively. Under the experimental con-

![Graph](image_url)
ditions considered in the study, the relationship equation for the percentage recovery of manganese and percentage yield of magnetic particles at each magnetic field strength is also given

\[ R_{Mn} = 0.071 \times Y_{mp} \cdot C_{Mn} \]  

(1)

where \( R_{Mn} \) is the percentage recovery of Mn, \( Y_{mp} \) is the percentage yield and \( C_{Mn} \) is the content (mass\%) of Mn in the magnetic particles separated. Therefore, it was considered that the process developed is a possible method to separate and concentrate manganese from the siliconmanganese slag discarded from semi electric arc furnace during the production of siliconmanganese alloy.

Fig. 6 The relationship between the content of manganese, the percentage recovery of manganese and the percentage yield of magnetic particles with the magnetic field strength. (Particle size: \( -500 \mu m \sim +75 \mu m \)).

4. Conclusion

A physical separation process to separate and concentrate manganese from siliconmanganese slag discarded from semi electric arc furnace during the production of siliconmanganese alloy was suggested in the study. The proposed process consisted of two major steps, grinding and magnetic separation steps. The content of manganese in the magnetic particles separated by the magnetic separation process was over 20 mass\% for the particle size range of \( -500 \mu m \sim +75 \mu m \) at a magnetic field strength of 5,000 Tesla. Using the process suggested, the manganese rich slag containing over 20 mass\% manganese from the siliconmanganese slag was calculated to be obtained at a magnetic field of about 6,000 Tesla for the siliconmagnese slag ground into the particle size range of \( -500 \mu m \sim +75 \mu m \).

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REFERENCES