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Recycling of steelmaking slag fines by weak magnetic separation coupled with selective particle size screening

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A B S T R A C T

Steelmaking slag fines are leftover materials generated in routine slag processing and their particle sizes are usually smaller than 12.5 mm. The steelmaking slag fines can include desulfurization (DeS) slag fines, basic oxygen furnace (BOF) slag fines, electric arc furnace (EAF) slag fines and ladle metallurgy furnace (LMF) slag fines. Low iron grades, high impurity concentrations and inappropriate particle sizes are major barriers for recycling of the steelmaking slag fines back into ironmaking and steelmaking processes. Current slag processors have failed to solve this problem in an economic way. As a result, steelmaking slag fines are either being disposed of at landfills or being stored on the ground in large quantities, not only adding a considerably heavy financial burden to steelmaking plants, but also causing enormous value losses and potential environmental liabilities. A recycling technology of weak magnetic separation coupled with selective particle size screening has been developed at ArcelorMittal Global R&D – East Chicago Laboratories, targeted at solving the problem in a cost-effective way. Samples of steelmaking slag fines from three ArcelorMittal Americas steelmaking plants were collected, characterized and tested with weak magnetic separation coupled with selective particle size screening. Test results show that existing slag processors' magnetic separators are ineffective in separating iron from steelmaking slag fines. Using the technology of weak magnetic separation coupled with selective particle size screening, steelmaking slag fines can be effectively separated to produce cleaner iron-rich products with sufficiently high iron contents and low levels of impurities to be reused.

1. Introduction

In an integrated steel production process, steelmaking generally includes three integrated unit operations: hot metal desulfurization (DeS), basic oxygen furnace (BOF) refining and ladle metallurgy furnace (LMF) refining. In a mini-mill steel production process, electric arc furnace (EAF) melting is followed by LMF refining. In these steelmaking unit operations, not only steel products are produced, but also various slags are generated. A steelmaking slag is often given a name corresponding to a specific unit operation, such as DeS slag, BOF slag, LMF slag or EAF slag. Recycling of these slags in economic ways has been a very challenging task and has attracted broad attention for decades (Alanyali et al., 2006; Dippenaar, 2004; Menad et al., 2014; Murphy et al., 1997; Shen and Forssberg, 2002; Topkayya et al., 2004; Wang et al., 2012).

Due to different working conditions in steelmaking unit operations, steelmaking slags from different unit operations are all different in chemical compositions and physical properties. For instance, since BOF and EAF smelting temperatures are around 1600 °C, BOF and EAF slags are in a molten state when they are discharged from BOF vessels and EAF furnaces, while desulfurization slag and LMF slag have experienced much lower temperatures and are often in a half-molten, half-solid state when they are skimmed out of desulfurization containers and LMF furnaces. Slags produced at high temperatures have good fluidity, and hence decantation can effectively separate metallic iron from the slags, while iron in partly solidified slags is difficult to separate by decantation. In general, iron in BOF slag and EAF slag often occurs as iron oxides, but iron in desulfurization slag and LMF slag often occurs as metallic iron (Hwang et al., 2006; Yildirim and Prezzi, 2011); BOF slag contains higher phosphorus than desulfurization slag, but desulfurization slag contains higher sulfur; EAF slag and LMF slag may contain higher levels of heavy metals like chromium and lead than other slag fines.

After being discharged from unit steelmaking operations, steelmaking slags undergo several operations including

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conditioning in slag pots, dumping on the ground, watering with sprays, cooling, crushing, magnetic separation and sizing. There are various slag processing facilities in the steel industry and many of them involve various steps of intensive and repetitive crushing and grinding for iron recovery as described in the literature (Horri et al., 2013; Shen and Forssberg, 2002; Topkayya et al., 2004).

The slag processing procedures at ArcelorMittal Americas plants differ from those described in the above literature. Generally, the procedures used at ArcelorMittal Americas steelmaking plants do not include intensive and repetitive crushing and grinding. After hot steelmaking slags are poured onto the ground in the slag yard and sprinkled with cooling water, front-end loaders are used to scoop up the slags in order to disintegrate the slags and accelerate cooling. The hot-state scooping up effectively prevents extensive formation of large slag particles over 300 mm in size, and avoids the need for excessive crushing.

After the slags are cooled, drop-ball crushing is sometimes used to break both the large slag particles over 300 mm in size and the iron skulls removed from slag pots. Cooled slags are then swept by grizzly magnetic cranes to separate high-purity steel from the slags. This steel scrap is normally recycled back into steelmaking or sold on the open market without issues. The slags remaining are then charged to magnetic separators (drums or belts) followed by a series of screening steps. Magnetic portions of the slags are often screened into three products: above 75 (or 50) mm, between 75 (or 50) mm and 12.5 (or 9.5) mm and below 12.5 (or 9.5) mm. The non-magnetic portions of the slags are screened into various size ranges for different uses.

The three magnetic slag products are given names of “A” scrap for the large-size particles, “B” scrap for the medium-size particles and “C” scrap for the fine-size particles. The “C” scrap is also called “C” slag fines. “A” scrap is often recycled back into the steelmaking process. “B” scrap is either recycled in the blast furnace ironmaking process or sold on the open market. Both “A” scrap and “B” scrap, in general, do not have any problem in recycling. However, due to the low iron grades, high impurity concentrations, and small particle sizes, “C” slag fines cannot be economically or environmentally recycled back into ironmaking and steelmaking processes in significant amounts without further treatment. Current slag processors have failed to solve this problem in an economic way. As a result, the “C” slag fines have been either disposed of at landfills or stored on the ground in large quantities, not only adding a heavy financial burden to steelmaking plants, but also causing enormous value losses and potential environmental liabilities.

At ArcelorMittal Americas steelmaking plants, large particles of the non-magnetic (NM) portions of the steelmaking slags mostly have been recycled into blast furnaces as flux substitutes. However, small particles of the NM steelmaking slags are difficult to recycle and face the same problem as “C” slag fines. The “C” slag fines and the fine NM steelmaking slags together are called steelmaking slag fines.

Methods to upgrade steelmaking slag fines in order to recycle the slag fines back into ironmaking and steelmaking processes have not been widely reported. Alanyali et al. reported a study using a 1650 G magnetic drum separator to treat <10 mm steelmaking slag fines, but did not report how effective their treatment was in terms of quality of magnetic concentrates (Alanyali et al., 2006). Wang et al. studied use of a wet magnetic separation tube device under a magnetic field intensity of 1200 A/m to recover iron from BOF steelmaking slags which were sampled when the slags were being tapped. In a laboratory, the slag samples were re-melted and cooled under several cooling conditions, and the slag samples were subsequently crushed to 70% passing 74 μm (200 mesh). The slag samples were mixed with water and the slurry was fed into the tube device. Magnetic particles adhered to the glass wall and non-magnetic particles bypassed with water. The best result in Wang et al.'s study was that the slag sample with 24.59% Fe was upgraded to a magnetic concentrate with 40.38% Fe with 26.13% yield (Wang et al., 2012). Abd El-Rahman started with large pieces of BOF slag, 50 mm × 100 mm, and crushed the sample down to 95% passing 10 mm and conducted a series of grinding, wet screening, and magnetic separation tests. A 13,000 G magnetic separator was used first and the concentrate product was further separated with a lower intensity magnetic separator whose surface magnetic field strength was not revealed (Abd El-Rahman, 2006). Menad et al. recently reported their research work on treating BOF steelmaking slag through various crushing, grinding, screening, and dry and wet magnetic separation stages beginning with 18,000 G for high-intensity magnetic separation and 900–16,200 G for low-intensity magnetic separation (Menad et al., 2014).

In mineral processing, in terms of surface magnetic “strength”, magnetic separators are divided into three categories: high-intensity magnetic field, medium-intensity magnetic field and low-intensity magnetic field depending upon the types of magnets used and the method of attaining the field intensity. It should be mentioned that intensity of magnetic field strength is measured in oersteds or A/m and magnetic flux density or induction is measured in gauss (or Tesla where $1\ T = 10^4\ G$). Due to historical reasons, the terminologies of magnetic field strength and magnetic flux density are often confused. However, magnetic flux density is proportional to magnetic field strength outside magnets. Gauss is often used to measure magnetic field “strength” (actually magnetic flux density) because of the ease of measurement with a gauss meter using Hall-effect probes. The unit of gauss is used throughout this paper as a measure of surface magnetic field strength.

Magnetic fields can be generated electrically or with “permanent magnets”. Surface magnetic field strengths for high-intensity magnetic separators are generally between 10,000 and 20,000 G, for low-intensity magnetic separators are between 1000 and 3000 G, and for medium-intensity magnetic separators are in between (EPA, 1994; Hopstock, 1985). Actual surface magnetic field strengths or intensities of existing slag processors' magnetic separators are not widely available. Magnetic field strengths in the literature cited above were all more than 1000 G.

In this research work, representative samples of DeS slag fines, BOF slag fines, EAF slag fines and LMF slag fines were collected from three ArcelorMittal Americas steelmaking plants. These samples were first characterized for physical and chemical properties. The characterization of these steelmaking slag fines has led to the development of a technology of weak magnetic separation (between 200 G and 800 G of surface magnetic field strength) coupled with selective particle size screening to upgrade the steelmaking slag fines for producing clean products with high iron grades, low impurity concentrations, and appropriate particle size distributions without relying on intensive grinding.

2. Materials and methods

2.1. Samples of steelmaking slag fines

Samples of steelmaking slag fines were taken from three ArcelorMittal Americas steelmaking plants, abbreviated as X, Y and Z steelmaking plants. X and Z steelmaking plants are BOF plants and Y steelmaking plant is an EAF plant. The following samples were obtained: fresh DeS “C” slag fines, fresh BOF “C” slag fines and fresh BOF NM slag fines from X steelmaking plant; fresh EAF “C” slag fines, fresh LMF “C” slag fines, fresh EAF NM slag fines and mixed “C” slag fines from a legacy pile which was a long-term mixture of EAF “C” slag fines and LMF “C” slag fines from Y steelmaking plant;