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Process design for the magnetic recovery of iron from desulphurised hot metal slag

Mogiba, Sbongumusa

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Process Design for the Magnetic Recovery of Iron from Desulphurised Hot Metal Slag

MSc Research Report

Prepared by

SM Mogiba (366807)

Submitted to

School of Chemical and Metallurgical Engineering, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, South Africa

Supervisor: Prof V Sibanda

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DECLARATION:

I, Sbongumusa Mogiba student no: 366807 declare that this report is entirely a result of my work and efforts unless where stated otherwise.

_____

Signature

Date: 2018.11.30

Abstract

Desulphurised Hot Metal Slag (DHMS) from ArcelorMittal South Africa Newcastle Works was beneficiated using a drum magnetic separator under dry conditions. DHMS particle sizes from -1400µm to 106µm were classified into nine size classes and their behaviour under basic magnetic separation parameters was observed. The nine size classes were then consolidated into four classes; -1400+850µm, -850+300µm,-300+106µm and -106µm size respectively. The aforementioned particle size classes were used to study the effects of magnetic separation parameters on iron recovery in more detail.

It was observed that low intensity dry magnetic separation did not work effectively for particle sizes that are 106µm and below. Particles in this size range i.e. below 106µm were found to have a relatively low iron content of < 18% in the feed and after magnetic separation, their magnetic stream was only upgraded to 25% Fe, which is below the satisfactory grade thresh hold. The most optimal magnetic recovery was achieved when particles below 106µm were excluded and the remaining size classes of the DHMS were collectively upgraded from 55.26% Fe to 69.47% Fe. However, the sulphur content in the final product stream was still relatively high at 2.58% S compared to the 2.91% S initially in the feed. The aforementioned results were obtained at a feed rate of 11g/s, splitter position at 75% fully open and at a magnetic field strength of 641 gauss. The test work was considered a success since the final product has sufficient iron content for use as a high-sulphur source of iron during the production of high sulphur steel grades in the steel making process.

A conceptual process flow sheet to achieve this level of beneficiation of DHMS was proposed and a high level feasibility study indicates that the capital expenditure for the process is approximately R3.1 million with a one year payback period. The net present value was positive at R1.71 million while the internal rate of return (IRR) was found to be 23%. This indicates that this project would be worthwhile for operations that are currently disposing at least 18 375 tons of DHMS per year which could otherwise be economically recovered.

DEDICATION:

I dedicate this work to my amazing parents who have been nothing but a blessing in my life.

ACKNOWLEDGEMENTS:

I would like to thank the individuals who have contributed greatly to this work. Professor V. Sibanda for all the guidance, insight and supervision. Bright Ndlovu has consistently availed himself for test work at Eriez magnetics. Sipho Magudulela, the BOF Manager at AMSA Newcastle, made obtaining approval to conduct the research on ArcelorMittal slag possible. His contribution is highly appreciated. Lastly, I would like to thank Kobie Herholdt the lab manager at AMSA Vanderbijlpark for allocating time and resources for the analysis.

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1. Introduction

This work explores the possibility of recovering iron (Fe) from desulphurized hot metal slag (DHMS) by applying the dry magnetic separation technique. A high level economic evaluation of such a recovery plant was also conducted. It is envisaged that the effective recovery of Fe from DHMS will improve iron ore utilization in steelmaking plants and minimize volumes of unusable slag that would otherwise be disposed in slag dump facilities.

DHMS is a by-product of the desulphurization of hot metal (also referred to as pig-iron) which is produced in the blast furnace by reducing hematite (Fe2O3) into sponge Fe using coke as a reducing agent and adding fluxes such as lime for slag formation. Upon cooling, pig iron may be re-melted to produce cast iron. However, the high carbon levels (Table 1.1) make it too brittle for practical applications and therefore pig iron is considered to be an intermediate metal product which has to be converted and refined into steel by reducing the carbon content to levels below 2wt%.

Table 1.1 Typical pig iron analysis

Fe	C	Mn	P	S	Si	Ti	Cr	Ni	Mo	Nb	Cu
94.044	4.316	0.812	0.105	0.059	0.589	0.033	0.025	0.010	0.001	0.001	0.005

Molten pig iron is transported from the blast furnace to the steel making plant by torpedoes. Treatment of the pig iron to reduce sulphur levels to be as low as 0.01% is a pre-requisite for the production of low sulphur steel grades [1]. Upon arrival in the steelmaking plant, pig iron undergoes the desulphurization process. The desulphurized metal is then charged into the basic oxygen furnace and converted into steel via the oxygen blowing process. The resultant slag (DHMS) is skimmed off and disposed. The general desulphurization reaction follows equation 1.1 below [2]:

$$[S] + MeO \leftrightarrow MeS + [O] \quad (1.1)$$

[S] and [O] respectively represent the dissolved sulphur and the dissolved oxygen within the hot metal.

Calcium sulphide (CaS) is the predominant compound in DHMS. The typical mass composition of CaS is around 40wt%. The second most abundant component in DHMS is FeO at about 30wt% while the total sulphur content makes up around 3wt% of DHMS. Although the sulphur level may seem relatively low, it should be noted that sulphur is the single most important factor that is currently restricting DHMS from being utilised in the steel and construction industry due to its tendency to induce brittleness in materials.

The tendency of DHMS to disintegrate makes it unsuitable for use as a supplement to portland cement or for use as ballasting material in the construction industry. The two aforementioned applications are typical uses of iron making slag and Basic Oxygen Furnace (BOF) slag respectively. Furthermore, unlike the iron making slag and the BOF slag, DHMS does not get charged directly into the Basic Oxygen Furnace (BOF) as a metal scrap supplement or as iron ore replacement since it will increase the sulphur content of liquid steel, thus defeating the purpose of desulphurization. Sulphur in liquid steel tends to react with calcium to form solid inclusions such as calcium sulphides, which induce clogging during casting. In the absence of sufficient manganese, excess sulphur also readily combines with iron to form iron sulphide (FeS), a low melting point compound that promotes bloom brittleness at high temperatures. This phenomena is termed hot-shortness. Sulphur also tends to lower mechanical properties such as toughness in final steel products.

Due to its lack of practical applications, DHMS is generally classified as waste material that is subsequently disposed despite Fe unit losses of about 0.6-0.8 wt% per ton of pig iron which goes through the desulphurization process. The disposal of DHMS is however not aligned with the national waste management strategy, which states that waste disposal of any material ought to be the last resort after all possibilities of reuse and recycling have been explored and exhausted [4]. As a result, the DHMS would have to undergo some level of beneficiation in order to improve its chemical and physical consistency so that it may be classified as a suitable input material for steelmaking operations. The general perception has been that the treatment of DHMS is un-economic due to the low slag volumes produced during the hot metal desulphurization process and hence no effort or research has been seriously undertaken to develop a process to achieve this.

The steel industry is in need of a simple and economically viable process to recover Fe from DHMS. A recovery unit will improve profit margins for steel producers and reduce the quantity of slag that ends up on the slag disposal facilities. The recovered Fe can be used as metal scrap supplement or as iron ore replacement in converting units. As a supplement to raw iron ore in the BOF, the iron recovered from DHMS can mitigate some of the negative effects of raw iron ore such as its tendency to increases the risk of Fe spillage from the furnace during the oxygen blowing phase. This phenomenon is termed slopping and it results in Fe yield losses, equipment damage, production losses as well as environmental pollution [3]. The benefits of using iron recovered from DHMS are theoretically numerous. However, without a cost-efficient iron recovery process in place, these possibilities will remain unexplored.

Although iron recovery from blast furnace slag and BOF slag is common practice, academic literature with a focus on the optimization of magnetic separation parameters during slag reprocessing is limited, and consequently, comparison of the test work results with prior scientific studies on this subject matter is minimal. However, this research shall endeavour to determine the optimum parameters for the magnetic separation of DHMS by identifying the most efficient DHMS size classes to recover, along with the corresponding magnetic separation conditions at which these size classes maybe optimally recovered. The recovery of iron from the desulphurised hot metal slag will minimise disposable slag volumes while increasing the overall iron yield during the steel-making process. A simplified flowsheet depicting the required metal recovery plant set-up shall be developed and a high level economic evaluation shall be conducted in order to assess the viability of the recovery process. This work hopes to affirm the conclusion reached by R.T that the recovery of metals from slag is an environmentally and economically viable option [4].

This work was driven by two major hypothesis, one being that for liberated slag particles, iron recovery by magnetic separation will be directly proportional to the DHMS particle size, and the other being that magnetic parameters such as the magnetic field strength, splitter position, particle size and the feed rate have a significant influence on the efficiency of the DHMS magnetic separation process.

The major unknowns this work endeavoured to uncover was whether DHMS particles which are very fine (≈75μm) will show relatively poor recoveries compared to coarser DHMS particles and whether sulphur content of the magnetically recovered stream meet the specification threshold required for the recovered iron to be usable as a steelmaking supplement. The main objectives of this research are summarised below:

- To characterise the desulphurised hot metal slag (DHMS) from ArcelorMittal operations in Newcastle
- To study the liberation characteristics of the DHMS
- To study the factors affecting the magnetic recovery of iron from the slag
- To develop a process flow sheet for iron recovery from DHMS and perform a high level economic evaluation of a potential plant

2. Literature review

The manufacturing of iron in the blast furnace and steel in the basic oxygen furnace and subsequent refining stages employ the use of raw materials which contain valuable minerals and gangue material and/or impurities. The gangue is usually detrimental to the quality of the final product and is therefore removed using fluxing agents. The fluxing agents react with the impurities to form a by-product called slag. Steel making slag consists mostly of CaO and SiO_2 while blast furnace slag may consist of Al_2O_3 and MgO. The difference emanates from the fluxing agents used and the effect is evident in the different properties that each type of slag possesses.

Due to the very high volume of iron and steel slag produced annually, steel plants around the world attempt to recover the iron so that the by-product slag can be used as a product in its own right instead of it occupying land unproductively. Table 2.1 below shows the rough estimate of the annual worldwide production of various types of slag. The table further illustrates that the steel industry far exceeds all the other industries combined in terms of slag generation [4]. From an environmental point of view, this can be seen as a reflection of 300 million tons worth of environmental concern. However, from this study's perspective some of the 300 million tons may present economic benefits to the steel producing plants if the iron units in the DHMS could be successfully recovered.

Table 2.1: Worldwide slag production *(RT Jones, 2004)*

Type of slag	World production(million tons/annum)
Iron and steel	300
Ferromanganese	19
Nickel	15
Copper	14
Ferrochromium	4.4
Zinc	9
Lead	3
Titanium	2.4
Platinum group metals	2.4

A high percentage of steel slag is produced in the basic oxygen furnace and the ladle furnaces. However, small portions of slag may also be produced at steel degassing stations. As an alternative for scrap, BOF slag is limited by size. Fine particles (5 ≈mm) are deemed to have insufficient iron content (40 – 50% Fe). Larger particles are used to varying extents. In general, the larger the particle, the more interest there is to recover the iron content. As a result, the stockpile of the finer particles has been accumulating over the years. Furthermore, it should be noted that the slag produced by the desulphurization process contains fine particles, which are high in sulphur. As a result, DHMS gets very little to no beneficiation. There is therefore an existing potential that can be explored particularly on the fine DHMS particles for the benefit of the steelmaking industry.

Iron slag is typically produced in the blast furnace. The majority of blast furnace slag undergoes the granulation process by being rapidly cooled down from 1500°C with jets of high pressure water. Granulated blast furnace slag is vitreous and sandy in appearance. It has a chemical composition comparable to that of cement and therefore it is often used as a raw material in the cement making process. When iron slag is used as a substitute for limestone, the benefit is not only limited to the conservation of limestone, but it also reduces the energy requirements of rotary kilns [4]. The process of slag granulation generates steam which in turn can be utilized in power generation, thereby reducing energy requirements across the plant [5].

The portion of blast furnace slag which does not undergo granulation gets air-cooled and it tends to resemble crushed stone in appearance and characteristics. The air-cooled blast furnace slag has the capability to reinforce the load-bearing capacity of surfaces and therefore is typically used as concrete aggregate or road base for road construction. De-metalized steelmaking slag is also used as road ballast or as aggregate for asphalt mixtures due to its high hardness and good wear resistance properties while the magnetically recovered metal component is recycled into the BOF as a source of iron [6].

The applications of iron and steel-making slag have been well understood and universally accepted. Although DHMS is produced within the iron and steel industry, it is technically not correct to classify it as either iron slag or steel slag because of its distinct chemical and physical properties.

The formation of DHMS takes place after iron slag generation but prior to steel slag production. Therefore, DHMS contains iron particles and is void of particles steel particles. However, because desulphurization normally takes place at steel making sections of the production plant, DHMS is stored alongside steel slag and is categorised as such. At Newcastle Works, attempts to recover iron from DHMS have been attempted by processing the DHMS on a metal recovery plant which is designed to recover steel slag. The iron recoveries are generally poor for smaller sized particles (below 2mm). The larger DHMS particles are predominantly metallic (solidified carry over hot-metal) and are recoverable by using the magnetic separation configuration, which is designed for the recovery of steel components from BOF and ladle furnace slag. Magnetic separation parameters for the optimal recovery of iron components from DHMS need to be determined in order to maximise metal recovery from the slag.

It is however important not to limit slag utilization to traditional applications; research and development have unveiled slag application outside the norm. A case in point is the studies conducted in the 1990s aimed at finding an alternative to utilizing natural sand as a medium during the sand compaction pile method which was applied to help improve soft ground in coastal regions of Japan [6]. From these studies, a new sand compacting pile method which allowed slag to replace sand was devised. The technology displayed superior compaction properties and thus natural sand was conserved. The Japan success story evidently proves that non-conventional uses of slag are possible if we are able to develop technologies that will enable us to use slag characteristics in our favour.

Another example that shows how slag can be used outside of the normal application is its use in the agricultural industry. In 1964 tests were conducted on the effects of air-cooled blast furnace slag in agricultural products. The slag was found to increase the yield of paddy rice due to its silicic acid content, which prevents bad bacteria and harmful insects from damaging the leaves and culms of the rice plants. The slag was also found to promote photosynthesis by keeping the rice leaves in an upright position, thus improving the sun-light receiving efficiency of the plants. The slag was officially recognized as a silica fertilizer upon the revision of the fertilizer control law. BOF slag was approved in 1981 as a lime-based fertilizer [6].

At production rates in excess of 300 million tons per annum, iron and steel slags need to have as many applications as possible and DHMS should contribute towards the percentage of slag that has economic benefits.

In liquid steel, sulphur is generally considered to be an inclusion former (free-cutting grades are an exception) due to its high tendency to react with dissolved calcium forming calcium sulphides (CaS) or with iron to form iron sulphides (FeS). CaS is a non-metallic solid inclusion that induces clogging in the submerged entry nozzles of casting machines. This phenomenon results in excessive plant instabilities and consequently production capacity is reduced [7]. In solidified steel products, sulphur weakens mechanical properties such as toughness. Removal of sulphur from steel is thus a pre requisite for good casterbility as well as for the enhancement of mechanical properties of final steel products. It is however difficult to remove sulphur after the BOF oxidation process and therefore hot metal is desulphurized either inside torpedoes or at desulphurization stations prior to the converting process.

Desulphurization agents generally have high sulphur affinities. Compounds such as calcium carbide (CaC_2), soda-ash ($NaCO_3$) and magnesium (Mg) are typical examples of good desulphurization agents. The desulphurization reactions occur at hot metal temperature ranges of 1300ºC to 1400ºC [2]. Depending on the desulphurization method applied, either equation (2.1) and equation (2.2) , equation (2.3) or equation (2.4) may be followed.

Soda ash (NaCO3) has been the preferred desulphurization agent for Newcastle Works due to its availability and relatively low cost. The desulphurization of hot metal using soda ash begins when it decomposes upon contact with the hot metal to form Na_2O and CO_2. Na_2O reacts with dissolved sulphur to form Na_2S. Na_2O also gets reduced by dissolved carbon to form Na(g), which reacts with sulphur. The reactions are shown in Equation (2.1) and Equation (2.2).

$$Na_2O(l) + [S] \leftrightarrow Na_2S(l) + [O] \quad (2.1)$$

$$Na(g) + [S] \leftrightarrow Na_2S(l) \quad (2.2)$$

The use of soda ash for desulphurization is a major health and safety concern due to the violent gas evolution that occurs during the desulphurization process.

Furthermore, soda ash causes respiratory tract damage when inhaled and the risk of inhaling it is high in areas surrounding the desulphurization station. In addition to soda ash being a health and safety risk, it is also an environmental hazard as it tends to fly out of desulphurization ladles and accumulate on overhead structures such as walking platforms and staircases. This phenomenon results in bad housekeeping. Due to these health and environmental concerns, the soda ash desulphurization process was discontinued and subsequently replaced by a calcium carbide - magnesium desulphurization process as shown in (equation 2.3)

$$CaC_s(s) + [S] \leftrightarrow CaS(s) + 2[\mathrm{C}] \quad (2.3)$$

The main concern of using calcium carbide as a desulphurization agent is that the DHMS produced gets classified as hazardous waste as a result of the toxicity of calcium carbide. The environmental permit required to recover material from hazardous waste requires considerate time and effort to obtain such that it may be considered a barrier to setting-up a recovery plant. The absence of a hazardous waste recovery permit has been one of the major reasons why Newcastle Works has not commissioned a plant dedicated to the recovery of iron from DHMS.

The generation of calcium carbide based DHMS and soda ash based DHMS is declining as more and more plants such as Newcastle Works are adopting the magnesium – lime co-injection desulphurization process in order to mitigate the safety and environmental risks associated with soda ash and calcium carbide. Magnesium is a more powerful desulphurization agent compared to calcium carbide or soda ash as it has capabilities to achieve lower sulphur contents in hot metal. The disadvantage of using magnesium as a desulphurization agent (Equation 2.4 & 2.5) is that it has a high vapour pressure and therefore it forms Mg bubbles upon injection into the hot metal melt. For this reason, fluidised lime is blended with the magnesium and the resultant mixture does not only result in less violent reactions, it also has improved flow-ability, which results in decreased material blockages at the desulphurization stations.

$$Mg(g) + [S] = MgS(s) \quad (2.4)$$

$$\Delta G^{\circ}{}_{MgS} = 203\,604.6 - 35.0237T^{26.27}\left(\frac{j}{mol}\right) \quad (2.5)$$

Lime (CaO) in its own right is a desulphurizing agent and its reaction with sulphur follows the equation 2.6 below:

$$CaO(s) + [S] = CaS(s) + [O] \quad (2.6)$$

The corresponding Gibbs free energy change for lime desulphurization by lime is given below:

$$\Delta G^{\circ}_{CaS} = 105\,786.6 - 28.72T^{25.26}\left(\frac{j}{mol}\right) \quad (2.7)$$

The equilibrium constant for the CaO reaction can be expressed as follows:

$$k = \frac{a_o . a_{CaS}}{f_s . [\%S] . a_{CaO}} = e^{-(\frac{\Delta G}{RT})} \quad (2.8)$$

The equation can be re-arranged to show the amount of sulphur dissolved in hot metal as follows:

$$[\%S] = \frac{a_o . a_{CaS}}{f_s . k . a_{CaO}} \quad (2.9)$$

a_o and a_s represent the activity of dissolved oxygen and sulphur in the hot metal respectively. a_{CaO} and a_{CaS} represent the activity of CaO and CaS in the slag. F_s is the activity co-efficient of sulphur in hot metal and %S is the sulphur content dissolved in hot metal. [8]

Mg has approximately 20 times the capacity of CaO to remove sulphur [9] and therefore the lime injected at Newcastle has no significant effect on the desulphurization reaction; in fact it is used more as a magnesium carrier. This is consistent with the work of Zborshchik et al., [10] on the effectiveness of fluidized lime in the desulphurization of hot metal in 300 ton casting ladles. Hot metal is received from the blast furnace at around 1200°C-1300ºC with initial sulphur content of 0.03-0.07%. In order to achieve the desired sulphur levels, the deep desulphurization is then carried in 160t ladles by co-injecting granulated magnesium and fluidized lime. Final sulphur levels of 0.014% are normally attainable after the desulphurization process. Desulphurization is favoured by low oxygen activity in hot metal [11].

The desulphurization process is considered to follow equation 2.10 and equation 2.11.

Equation 2.10 is technically considered an insignificant desulphurization reaction due to the formation of calcium sulphide (CaS) and calcium silicate ($CaSiO_2$) precipitates that cover the lime (CaO), thus forming a thick barrier which reduces the rate of the reaction.

In addition to calcium sulphide (CaS), oxygen gas (O) is also produced. Equation 2.11 depicts the primary desulphurization equation, where S is the sulphur in the hot metal and MgS is magnesium sulphide, which is the desulphurization product that reports to the slag phase.

$$CaO + S = CaS + O \quad (2.10)$$

$$Mg(s) + S = MgS(s) \quad (2.11)$$

The sulphide capacity (C_S) i.e. the ability of molten slag to absorb sulphur is considered to be defined in equation 2.13 below.

$$\frac{1}{2}S_{2(g)} + O^{2-} = \frac{1}{2}O_{2(g)} + S^{2-} \quad (2.12)$$

$$C_s = \frac{K.ao^{2-}}{f_{s^{2-}}} = (\%s) \times \sqrt{\frac{Po2}{Ps2}} \quad (2.13)$$

Where K is the equilibrium constant of equation 2.10, $ao^{2-}$is the activity of oxygen in the slag

phase, $f_{s^{2-}}$ is the activity coefficient of sulphur in steel and % S is the content of sulphur in

the slag phase. P_{O2} and P_{S2} are respectively the partial pressures of oxygen and sulphur gases present in the slag produced during emulsion. Cs is often expressed in log units, the less negative the logarithmic unit, the better the sulphur removing capacity of the slag. (Posch, 2002).

The rate at which desulphurization takes place is defined as follows:

$$\frac{d[\%S]}{dt} = k\left([\%S] - [\%S_{eq}]\right) \quad (2.14)$$

Where [%S] is the sulphur content at time t and [$\%S_{eq}$] is the content of sulphur at equilibrium and k is the desulphurization rate constant.

The magnesium sulphide produced during desulphurisation reports to the slag along with other non-metallic elements and compounds such as Carbon(C), lime (CaO), silica (SiO2) and calcium sulphides (CaS). As a result, desulphurised hot metal slag is a crusty molten solution of metal oxides and sulphides that float on top of pig iron after it undergoes desulphurization. The iron in DHMS is present as metallic Fe and as iron oxide (FeO).

Calcium sulphide (CaS) is the most predominant compound contained in DHMS and its typical mass is about 40wt%. The second most abundant component of DHMS is FeO at about 30wt%, sulphur makes up around 3wt% of DHMS.

The selection of a suitable desulphurizing agent is one aspect to consider in order to have efficient hot metal desulphurization. Several other conditions have to be satisfactory for effective sulphur removal. Parameters such as operating temperatures, hot metal vessels, deslagging techniques and a reducing environment are as equally important [12]. Once the desulphurization has taken place, the slag must be removed from the hot metal ladle before the hot metal can be transferred to the basic oxygen furnace. To achieve slag removal the skimming process is used (Figure 2.1). The process uses a raking system that consists of an articulated arm and a paddle to skim off the slag. The technique has two major short falls; firstly, it is not robust enough to remove all the slag from the ladle, and this causes sulphur reversion into the hot metal. Secondly skimming is not selective, a significant amount of hot metal is paddled off along with the DHMS with each stroke of the paddle. Bottom bubbling hot metal ladles increase the amount of slag removable from the ladle but does not completely eliminate Fe losses.

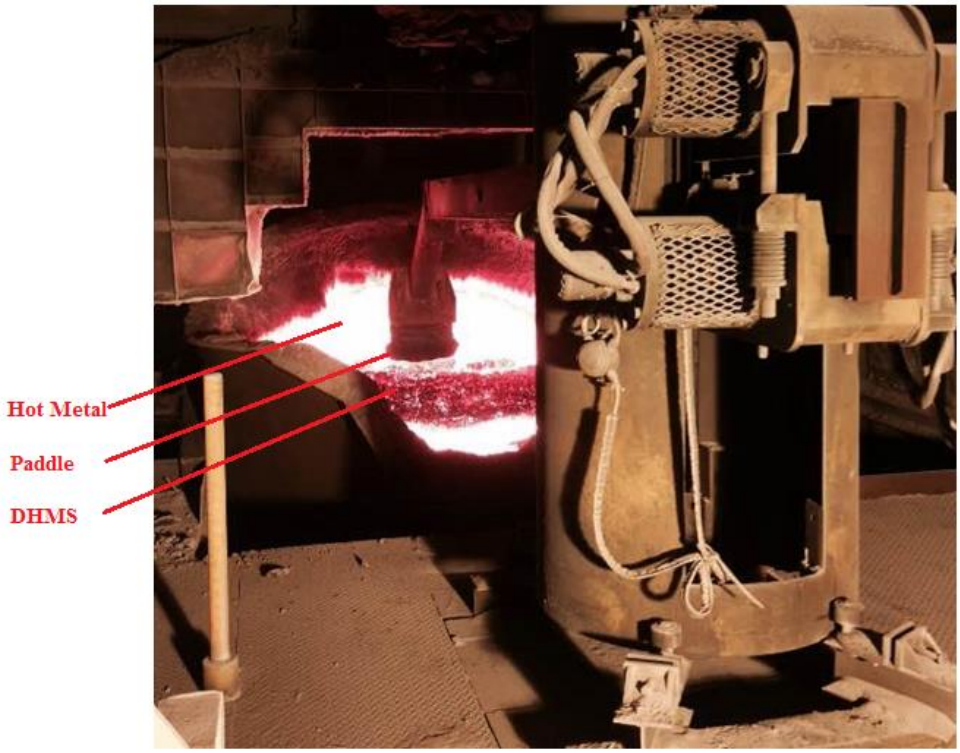


Figure 2.1: Skimming and deslagging technique

Slag removal ranges at 15-20kg per ton of hot metal desulphurised. The total Fe yield losses amount to an average of 1% with metallic content in the slag at about 39wt%. The quantity of the hot metal raked is directly proportional to the viscosity of the hot metal and the retention of Fe droplets in the slag increases as temperature drops [7].

De-slagging efficiencies may be improved by either using slag coagulators which essentially bond the slag together for ease of removal, or by using fluxing agents such as cryolite which decrease the viscosity of the slag, resulting in easier slag skimming. These coagulators and fluxes come at a high cost and therefore the techniques are not widely applied. Stirring lances have been tried with the aim of decreasing de-slag losses they are also not popular due to refractory failure. The loss of iron particles during the deslagging process is inevitable, thus the recovery of these Fe units from the DHMS is required in order to increase iron yield in steel-making.

Figure 2.2 is a block flow diagram showing the desulphurization process which occurs between the blast furnace and basic oxygen furnace.

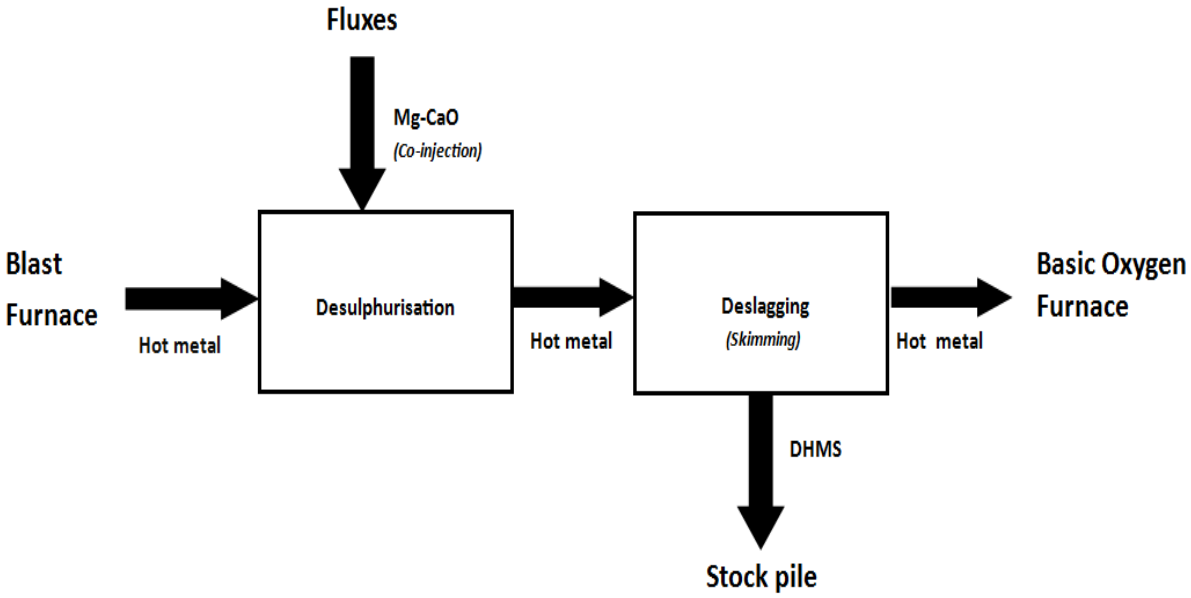


Figure 2.2 The desulphurization block flow diagram

DHMS from ArcelorMittal has a specific gravity of approximately 2.5 and it is ferro-magnetic. The presence of sulphur makes DHMS particles weakly bonded such that they disintegrate to some extent from their molten state upon cooling to room temperature [13].

The slag colour varies from grey to black depending on its Fe content and its texture is generally crusty. The particle size distribution of DHMS varies from very fine particles i.e. below 75µm to coarse particles that are well above 2cm. The DHMS is classified as waste and the National Environmental Management Waste Act of 2008 stipulates that the holder of waste must take all reasonable measures to avoid generation of waste and where such generation cannot be avoided, the toxicity and amounts of waste generated must be minimized. Disposal of waste should be the last resort after recycling and re-use opportunities have been explored [14].

The Waste management act stipulates that no person may commence, undertake or conduct a waste management activity listed in the waste management activity schedule unless a license is issued in respect of that activity.

The minister is the licensing authority for waste management activities that involve the establishment, operations, and cessation or decommissioning of facilities at which hazardous waste has been or is to be stored, treated or disposed of [15].

Failure to comply with environmental regulations may lead to a fine not exceeding R10 000 000 or imprisonment for a period of not more than 10 years or both [16].

Due care for the environment used to be an act of good will from corporations but in recent years, stringent legislations have been put in place and companies are now legally obliged to meet the set environmental standards. The choice of a desulphurization agent is important from the environmental perspective since it has a direct impact on the toxicity levels of the DHMS produced which in turn has a direct impact on the possible applications of DHMS. The move towards less toxic desulphurization agents is encouraging Newcastle Works to explore potential applications for DHMS. These potential uses for DHMS have become an urgent requirement due to the increased need for desulphurization in the steel industry as a result of the high demand for clean steels.

Iron recovery from DHMS will decrease the amount of final slag dumped by steel companies and thus put those companies in better standing in terms of their environmental compliance. The recovery of iron may be achieved by applying magnetic separation principles since the presence of iron in DHMS promotes ferromagnetism which results in DHMS being highly magnetic. Ferromagnetic materials have strong magnetization intensities due to the strong interaction of their adjacent atoms [17]. Sulphur is also known to induce magnetic fields that are in the opposite direction to externally applied magnetic fields. This property is termed diamagnetism [18]. The magnetic characteristic of iron and the non-magnetic nature of sulphur in DHMS is thus the most important physical property of the slag, which can be utilized to effectively recover the iron bearing components from the slag.

The use of magnetic separation to remove ferrous contaminants in an industrial environment dates back to the 17th century. In 1700, magnetic separation was applied to remove iron debris which was contaminating cassiterite. At that point in time, magnetic separators were hand held during the operation. Today cassiterite is separated using dry high intensity magnetic separation [19] . In 1972 an application for a patent for the separation of iron using a magnet was applied for. The first magnetic separator with magnetic polarities alternating along the direction of the material moved was proposed in 1854. The major breakthrough for industrial application of magnetic separation was the introduction of electromagnetic separators in 1855 [20]. In the 1940s, Orange Merwin developed a flat magnetic product to help farmers trap and remove metal contaminants from grain chutes [21].

Today some form of magnetic separation is applied in all the industries where magnetism is a distinguishing property.

Iron ore feedstocks with particle size below $45\mu m$ have been successfully recovered using wet high intensity magnetic separation (WHIMS). The work by Dworzanowski (2012) also showed that magnetic flocculation, which is the agglomeration of ferromagnetic particles as a result of their magnetization using an external magnetic field, helps maintain magnetic recovery even for particles below 10µm. For hematite particles below 200µm, the mass yield during wet high-intensity magnetic separation is better when the entire batch is recovered in one stream than when it is subdivided into several particle size classes with the iron recovered separately from each class [22]. Paramagnetic particles adhere to a magnetic matrix in accordance to the equation below.

$$f_m = \frac{k}{\mu_0(VB\nabla B)} \tag{2.15}$$

f_m is the magnetic force on the particles, k represents the volumetric magnetic susceptibility of the particles, μ_0 is the magnetic permeability of the vacuum, V is the volume of the particle, B represents the external magnetic induction, and ∇B is the gradient of the magnetic induction. From Eq (2.15) it is apparent that the smaller the particle size, the higher will be the resulting magnetic force. Magnetic force competes with the gravitational force, inertia, hydrodynamic drag and inter-particle forces under WHIMS conditions.
The most prevalent competing force is the hydrodynamic drag which is given in the equation below.

$$f_d = 6\pi\eta b v_p \tag{2.16}$$

Where f_d is the hydrodynamic drag force, η is the dynamic viscosity of the fluid, b is the particle radius and v_p is the relative velocity of the particle in respect to the fluid. For optimum recovery of fine particles, the hydrodynamic drag must be reduced and the magnetic force maximized [22].

Test work ought to be conducted on DHMS to determine which of the above mentioned principles are applicable and to what extent.

The test work on DHMS must however take cognisance of the fact that the iron in DHMS and run-of-mine iron may have different levels of magnetic susceptibility. Fortunately, a range of magnets exist with varying magnetic strengths. Barium ferrite magnets are on the weak side of the spectrum while rare earth magnets are on the opposite end. Magnets also range in complexity, from simple permanent magnets to large scale electromagnetic magnets which require air or oil cooling such as those used in heavy industrial applications for coal processing and limestone production among other aggregates. The iron compounds present in DHMS are strongly attracted to relatively weak magnetic fields such as barium ferrites [21] . The principle of magnetic separation can thus be applied to separate iron compounds from the non-magnetic components of DHMS. The operating conditions of the magnetic separation set-up will determine to what extent iron recovery from DHMS can be achieved. Considerations to be taken into account when selecting magnets include operational temperature range, DHMS flow rate, magnetic strength etc. The temperature ranges at which the magnet will be operating under is crucial because as temperature is elevated, permanent magnets tend to lose their magnetic strength. Magnetic strength losses can be reversed upon cooling in certain magnets while in other magnets, once a magnet has surpassed a certain temperature, the loss in magnetic strength cannot be recovered. The flow rate of the feed plays an important role in magnetic separation efficiencies. Most magnetic separators are driven by a motor with variable speed drives to adjust the speed and hence the feedrate. Thin burden or bed depth also allows the magnetic field to have the best opportunity to attract the magnetic particles. Magnetic intensity can also be used to control the grade and recovery of DHMS.

Eriez magnetics, an original equipment manufacturer (OEM) has developed a vast number of magnetic separators for both dry and wet processes. Wet magnetic separation is recommended for finer particles (+/-75µm) whilst the dry separation is effective for particles above 75µm. Magnetic separation has been found to be optimum when the particle size distribution of the feed material is narrow. An understanding of a specific size class provides insight which can be used to optimise the efficiency of the bulk feed during magnetic separation [23]. It is proposed that dry magnetic separation of DHMS should be the primary beneficiation process after crushing and/or screening to liberate the values from the slag.

The iron recovered from DHMS can be briquetted and charged as a coolant in BOF operations. This role is currently played by metal scrap and iron ore.

Metal scrap is expensive and the target scrap feed into the Basic Oxygen Furnaces ranges from 18-20% of the hot metal charged. This works out to be +/-30 tons/heat for Newcastle furnaces. Although recovered iron cannot completely eliminate the use of metal scrap, it can significantly reduce the amount of metal scrap required and the cost advantages will be realized. Iron ore increases the risk of slopping during oxygen blowing. Slopping results in yield losses, equipment damage and is a safety hazard. If iron recovered from DHMS has a less pronounced effect on slopping than raw iron ore, then the utilization of the recovered iron will lead to safer and more stable BOF operations. The recovered iron may contain traces of sulphur and thus may be used as a source of sulphur at the ladle furnaces and/or de-gassing stations. Contrary to the general practice of steelmaking, high Sulphur levels are a requisite in the production of free-cutting steel grades. However, the sulphur required to produce free-cutting steel grades is only added at the refining stages of secondary metallurgy. At that point of the production process, alloying materials must be of high quality i.e. the alloying material must consistently deliver the expected yield. Should an alloying material produce a lower or higher yield than expected, the entire batch of steel produced is likely to have incorrect specification resulting in the batch being rejected due to quality concerns. DHMS falls short of the high standards expected of alloying materials and for this reason it may not be used as an additive in the steelmaking process. Magnetic recovery of the iron from DHMS will result in a more defined and consistent product specification, enabling the usage of the recovered Fe in steel refining environments

The applications of the recovered iron are of interest to the steel industry. Likewise, the potential applications of the non-metallic components of DHMS ought to be also considered and evaluated. The non-metallic components should predominantly be calcium sulphides (CaS). The CaS decomposes upon contact with water to form $Ca(OH)_2$ and H_2S gas. $Ca(OH)_2$ can be used as an insecticide and H_2S gas forms a weak acid when dissolved in water. Apart from its ability to be processed to elemental sulphur, H_2S can be used as an analytical chemical to detect metallic elements in solutions though care must be taken since H_2S is very toxic. Depending on the CaS content after Fe recovery, the sulphur may have to be recovered and sold as a secondary product. The rest of the slag, which would largely be inert after metal recovery can be used as filler in construction or as ladle cover in steel-making.

The most important parameters in magnetic separation are material composition, applied magnetic field strength, particle size, flow rate [24]. Over the past few years, focus has been on upgrading the operability and separation efficiencies of magnetic separators. The main areas of focus have been the improvement of magnetic separation efficiency of fine particles, addressing of shortcomings associated with high temperature (120°c - 150°C) operating conditions, particle collection capacity of wet high intensity magnetic separators and feed system constraints, amongst other challenges. M.Dobbins notes that particles below 74 µm become increasingly inefficient to process which results in lower grade and/or recoveries below a certain size threshold. M.Dobbins further observes that fine particles behave in the same manner irrespective of whether they are a result of a crushing process or are naturally fine from the ore deposit. The behaviour of crushed versus uncrushed DHMS must be evaluated to affirm this finding. The extent of crushing must be controlled to minimize the amount DHMS fines.

Fine particles have been associated with static-charge build up. The higher the static charge present, the less efficient the magnetic separation. This is attributed to the rubbing together of fine non-magnetic, non-conductive particles, which would often adhere to the conveyor belt surface. This tribo-electric charging effect requires ionizers to correct and in many cases the efficiency of the ionizers is not enough to have a significant improvement on the magnetic separation efficiency. The fine particles tend to have a low particle collection capacity in wet high intensity magnetic separating units. Studies indicate that this observation is due to the drag force being stronger than the magnetic attraction force. A higher magnetic field gradient is thus required for the less magnetic fines. Dust control remedies which have been employed in recent years include the de-dusting of the feed prior to the magnetic separation and the introduction of purge air during the magnetic process. The best dust control technologies involve specifically designed door and hopper systems that contain the fines. These systems are usually equipped with dust extraction capabilities and generally result in cleaner and safer operations.

Handling of fine particles is further complicated by their negative effects on the human respiratory system.. Dust masks are therefore prescribed as personal protective equipment in stockpiles. Amongst all types of slag, magnetic recovery of larger particles tends to be more favoured than the recovery of finer particles. For DHMS, the optimum size threshold for optimum recovery is still to be identified [25].

The particle size of DHMS will have a significant impact on the magnetic strength required for optimal Fe recovery. In order to compensate for variations in DHMS particle size, the magnetic strength can be varied by altering the distance between the magnetic poles.

Forces (P) exerted by two magnetic poles whether repulsive or attractive can be expressed by the equation below:

$$P = \frac{KM_1M_2}{r^2} \tag{2.17}$$

M1 and M2 represent the pole strength and the r represents the distance between the poles. K is the proportionality constant that is inversely proportional to the permeability of the medium [26]. The Resultant field intensity (H) of the magnetic measured in Oersteds can be determined by summing the South Pole (S) and the North Pole (N) and is represented by the following equation:

$$H = km\left(\frac{1}{r_N^2} + \frac{1}{r_S^2}\right) \tag{2.18}$$

For solenoid interior with known length (l), current (i) and turns (n) the formulae below can be used,

$$H = \frac{ni}{l} \tag{2.19}$$

Within a magnetic field, the magnetic force is represented by magnetic force lines which run from the South Pole to the North Pole. The exerted force can either attract or repel objects placed in the magnetic field.

The extent to which objects are attracted to or repelled from a given magnetic field is utilized in the magnetic separation process to distinguish objects which exhibit one or more differences in physical properties and/or chemical properties. The temporary magnetism of an object is termed the magnetic moment. Magnetization (I) in turn is defined as the magnetic moment per unit volume.

Magnetic susceptibility (X) is the ratio of the Magnetization (I) to the applied magnetizing field intensity (H). By definition, the equation below then follows:

$$X = \frac{I}{H} \tag{2.20}$$

The magnetic susceptibility per unit mass is referred to as specific susceptibility and it is measured in $10^{-8}\mathrm{m}^3/\mathrm{kg}$. Specific susceptibility varies significantly from one mineral to another. Calcite for instance, has specific susceptibility of -0.3 to -0.4 while pyrrhotite can have a specific susceptibility between 10 and 30 000. The quincke's method can be used to determine magnetic susceptibility of diamagnetic or paramagnetic substances [27].

Magnetic behaviour of material can be classified into the following categories:

- Diamagnetic : Weak negative susceptibility
- Paramagnetic : Weak positive susceptibility
- Ferromagnetic : Strong positive susceptibility
- Ferrimagnetic : Strong positive susceptibility
- Anti-ferromagnetic: Moderate positive susceptibility

Although both ferromagnets and ferrimagnets have strong positive susceptibilities, their magnetic structures differ in lattice orientation. Ferromagnetic materials exhibit a parallel alignment of atomic moments whilst ferromagnetic materials have an antiparallel arrangement of atomic moments or sub-lattices. As a result of the sub-lattice orientation, ferromagnetic materials generally have stronger magnetic fields than ferromagnetic materials of the same size. Ferromagnetic material also have higher curie temperatures compared to ferromagnetic materials, as an example cobalt has a curie temperature of 1131°C while magnetite, a ferromagnetic material has a curie temperature of 580°C [28]. DHMS is ferromagnetic, as such it has a strong positive magnetic susceptibility and thus a relatively low intensity magnet may be utilised to recover Fe from the desulphurized hot metal slag. Table 2.2 below provides an indication of the magnetic susceptibility of iron relative to other materials.

Table 2.2: Magnetic susceptibility of minerals

Mineral/element	Chemical formula	Magnetic susceptibility kappa [10-5 SI]
Diagmagnetic		
Quartz	SiO2	-15
Feldspar	[Ca,Na,K][Al,Si]4O3	-13
Calcite	CaCo3	-12
Paramagnetic		
Dolomite	CaMg[CO3]2	100
Olivine	[Fe,Mg]2SiO4	100
Ferromagnetic		
Iron	Fe	220,000,000
Cobalt	Co	180,000,000
Nickel	Ni	61,000,000
Ferromagnetic		
Magnetite	Fe3O4	200,000 - 570,000
Maghemite	gamma Fe2O3	140,000 -220,000
Titano-magnetite	Fe3O4-Fe2TiO4	85,000 -150, 000
Pyrrotite	Fe7S8	23,000
Antiferromagnetic		
Hematite	alpha Fe2O3	100 – 900
Goethite	alpha FeOOH	100 – 400

Magnetic susceptibility should not be used as the sole indicator when predicting the potential for iron recovery from DHMS. During magnetic separation, several competing forces will act on the DHMS particles. These forces include but are not limited to gravitational force, inertia and inter-particle forces. Magnetic recovery is obtained when the magnetic force is greater than the sum of the competing forces acting on the particles.

If the magnetic force is too high, relative to the competing forces, selectivity of the particles tend to be poor due to the loss in distinction in magnetisable particles. The operating conditions of the magnet as well as the choice of the magnet itself play a crucial role in the balancing of the magnetic and competing forces. The particle size has an influence on the competing forces, however, this influence is minimal on dry magnetic separation due to the particle size dependence of the magnetic force and that of gravitational force being identical.

For industrial application magnetic separators are divided into two basic types; wet magnetic separators and dry magnetic separators. These two types are further classified either as low intensity or high intensity magnetic separators. Magnetic separators are classified as low intensity if they produce maximum field intensity below 2000 gauss. High intensity magnetic separators have field strengths in the region of 10 000 to 20 000 gauss. The lower the magnetic susceptibility of the material which needs to be recovered; the higher the magnetic intensity required in order to achieve the desired magnetic separation.

Dry magnetic separators are easier to control and operate than wet magnetic separators. This is attributed to the use of air as a medium of separation instead of water, which is utilized in wet magnetic separators. Water introduces drag forces resulting in a much more complicated separation of particles. In general, dry magnetic separators tend to have a lower capital cost and lower maintenance cost than wet magnetic separators [29]. The common types of magnetic separators are listed below.

Common types of magnetic separators are as follows:

i. **Ore cobbing magnetic pulleys** – also called concentrating pulleys, they are capable of handling large amounts of magnetic material by utilizing a high number of poles across the pulley width, thus developing a uniform field depth.
ii. **Magnetic drums** – used to concentrate ferromagnetic minerals and ideal for feed material less than 2.5cm in diameter. The drum speed can be varied from 20-200 rotations per minute depending on the design.
iii. **Induced roll magnetic separators** – produce high intensity magnetic fields, can be used to recover minerals that are weakly magnetic such as glass sands and phosphate rocks.
iv. **Cross-belt high intensity magnetic separators** – used for selective mineral concentration of weakly magnetic minerals.

v. The belt travels across the electromagnetic pole allowing the magnetized points to attract the magnetic material as it passes.

vi. **Ring type magnetic separators** – similar in design to the cross-belt magnetic separator. However, they use a magnetized steel ring instead of a cross belt.

vii. **Low intensity wet drum magnetic separator** – used to concentrate fine particles (≈3mm and below) such as magnetite media and taconite ores.

viii. **Wet high intensity magnetic separators** - typically operates at 15 000 to 20 000 gauss and applied in cases where weakly magnetic materials require recovery. The feed material should be in a slurry phase.

ix. **High gradient magnetic separators** – use a uniform field of solenoid with a matrix of secondary poles to obtain a high gradient. Typically operates at 20 000 gauss. Usually applied in the recovery of paramagnetic particles.

x. **Super conducting separators** – they are usually small laboratory super conducting solenoids which can achieve magnetic fields in the region of 60 000 gauss. They are used in the production of permanent magnetic fields.

Selecting a suitable magnetic separator should be done with caution as it is not always a straight forward process. The configuration of the magnetic separation unit is equally important. A company was applying a rare-earth drum circuit to recover chromite from chromite bearing sands, however the product stream recovery was 16% with grades in the region of 20%. Upon investigation, it was discovered that by introducing a rare earth roll separator with two additional magnetic passes, product recoveries were improved by an additional 51% at a 46% Cr_2O_3 grade [29]. The first pass ran at 400 rpm and was designed to maximize the recovery of magnetite along with magnetic slag. The next two passes ran at 300 rpm. The success of the magnetic roll was attributed to its higher magnetic strength compared to the rare-earth roll. The rare-earth roll had a magnetic strength well over 800 gauss whilst the rare-earth drum was slightly below 800 gauss. Furthermore, the magnetic roll could be run at much higher speeds without compromising the product grade. This case show how optimizing the configuration of magnetic circuits can enable a much cleaner separation of material.

Studies have shown that even the most advanced magnetic separation techniques and configurations thereof, may not always be adequate for the efficient recovery metals. A case in point is the hematite ore with iron content of 30.5% and limonite ore with iron content of 38.11% that were crushed to -2mm size particles.

The concentrates had a grade of 41 % Fe and 43% Fe respectively; these results were achieved by using a wet high intensity magnetic separator. A hydrophobic flocculent was introduced to the same feed under the same operating parameters and the resultant concentrates had 56% Fe grade and 66% Fe grade. These results indicate that magnetic recovery of iron using magnetic separation can be significantly enhanced if it can be complimented by other metallurgical techniques i.e. an appropriate chemical treatment [6]. Deep reduction of copper slag coupled with magnetic beneficiation has been used to recover up to 91.82% of the feed iron at an iron grade of 96.21%. This recovery is remarkable when taking into account that the copper slag contains 41.1% FeO and 13.2% Fe_3O_4 as the only sources of Fe [30]. Hydrometallurgical routes have also been employed to recovery ferrous metals. Manganese is recovered from ferromanganese slag by leaching with ammonium carbamate [31] or ferric chloride followed by either electrowinning or precipitation [32]. Ferrochrome slag, by contrast, is subjected to solvent extraction principles to achieve optimum chromium recovery [30]. The most appropriate methodology for separating metal from the feed material depends not only on the desired mineral's properties but also on the properties of the undesired components of the feed material.

Alternative mineral recovery methodologies have been compared with magnetic separation, with magnetic separation being more effective in some cases than in others. For limonite ores with iron content of 39%, magnetic separation was found to be more effective than the use of jig concentrators. [33]. Jig concentrators rely on the relative densities of the particles to achieve separation. Since metals are usually heavier than non-metals, jig concentrators are perceived to be the ideal substitute for magnetic separation. Lead, on the other hand, is recovered via the flotation of metallurgical slag, which contains 16.9% lead oxide (PbO) and 41.6% Fe_2O_3 [34]. Despite the difference in magnetic susceptibilities of PbO and Fe_2O_3, magnetic separation is not the recovery methodology of choice in the lead recycling industry due to the amount of fine particles present on the lead-bearing metallurgical slag.

A study conducted by Braga et.al in which 51.9% of the sample was below 37µm revealed that such fines particles are difficult to recover through magnetic separation. One of the greatest limitations of magnetic separators is their inability to distinguish between middlings. Bikbov et.al categorizes middling particles into three types. The first is the rich inter-grown particles; these are the particles that predominantly consist of the desired mineral by weight%.

The second type is the middle inter-grown particles. The middle inter-grown particles typically have a 50%-50% split between gangue and target mineral. The third type is the poor inter-grown particle; this type of middling particles is predominantly gangue by weight % [20]. Current magnetic separators often fail to be fine-tuned to the level where one can determine which % of valuable mineral should report to the magnetic stream. As a result, most magnetic separation units are preceded by one or more crushing units and/or size classification units. The incorporation of the aforementioned units increases the capital, operational and maintenance cost of metal recovery plants.

A prototype of a magnetic separator which can be more precisely set to select particles with a certain % of the required metal has been developed and the results are promising. The unit achieves the desired recoveries by applying alternating magnetic fields of increased frequency compared to standard models. [20]. The applications of these selective separators (also termed super-concentrators) in industrial applications remain to be seen. With all the advancements in magnetic separation technologies as well as the potential benefits which can be realised by incorporating auxiliary metallurgical processes for the recovery of iron from DHMS, it is important to bear in mind that the steel industry is in need of cost-efficient cost solutions.

A cost-efficient recovery process is one that requires low capital injection, has minimal maintenance and operational costs as well as a relatively long lifespan. The net present value and internal rate of return can be used as indicators for an economically viable project. Magnetic separators have been successfully applied in the recovery of iron containing material in cost efficient manners. Since DHMS is highly magnetic due to the presence of iron and iron oxides in the slag matric, magnetic separation can be an attractive technique to separate the Fe from the non-metallic components of the slag.

In order to minimize operational costs and the complexity of handling slurries, the dry magnetic separation technique will be explored as opposed to wet magnetic separation. The test works conducted in the context of this project seek to provide insight on the parameters which influence the recovery of iron from DHMS and to determine the operational parameters, which would result in the optimal recovery of the iron.

3. Methodology

The DHMS at ArcelorMittal SA Newcastle operations has a distinct physical appearance; the colour of the slag varies from light grey to dark grey with some reddish particles. The slag particle size varies from fines to chunks. The particle size distributions of the insitu DHMS is displayed in Figure 4.1

Sampling procedure

Using a 3kg shovel, samples were extracted from 3 various parts (top, middle and bottom) of a stockpile and placed into a 20L bucket. The samples were mixed manually in the bucket and spread out onto a canvas sheet where the cone and quartering sampling method was used to obtain a representative sub-sample. The sample was passed through a Gilson screen to obtain the PSD analysis and a riffle splitter was used to cut out DHMS samples for use in the magnetic separation test work.

Magnetic separation of DHMS

Sample preparation was carried out by manually crushing DHMS sample from the riffle splitter using a pestle and mortar. The crushed DHMS sample was screened and classified according to the following particle sizes classes: -1400+850 µm, -850 +300 µm, -300 +106 µm and -106 µm. From each particle size class, 30g of DHMS was placed aside for chemical analysis and the remaining sample was measured using a lab scale and placed in a container which would later serve as a hopper during the magnetic separation experiments.



(a) **(b)**

Figure 3.1: Gilson screen (a) sub sampling riffle splitter (b)

Experimental Set-up for the magnetic separation test work

A barium ferrite (BaFe) low-intensity dry magnetic drum separator from Eriez magnetics (Figure 3.2) was used for the magnetic separation test work. The magnetic drum was 250mm wide and 380mm by diameter with a rating of 525volts.



Figure 3.2: A dry magnetic drum separator

Two trays were placed underneath the drum separator, one for the recovery/collection of the magnetic components and the other for the recovery/collection of the non-magnetic components. The splitter position was manually set to a 20 cm distance away from the magnet. The vibratory feeder was adjusted manually to control the flowrate of the feed material. The magnet was manually positioned to the required position for each test.

Each of the following experimental parameters was varied individually during the test work; the splitter position, , flow rate and the magnetic field strength (Appendix A Figure 9.3) and the distance of particles away from the magnet (Appendix A Figure 9.4). The splitter on the magnetic separation equipment may be set to favour either mass recovery by increasing the gap between the splitter and the magnet, or to favour grade recovery by closing the gap between the splitter and the magnet. The splitter position was varied from 10% to 90 % distance away from the magnet for all three particle size classes that were used for this testwork i.e.-1400+850µm, -850+300µm, -300+106 µm. The distance between the magnet and the point at which the DHMS material falls is measured by positioning the chute from 1 cm to 3 cm away from the point at which magnetic stream recovery occurs.

The DHMS feed rate into the magnetic separation drum was varied between 1 g/s – 50g/s by adjusting the rotations per minute on the feeder speed drive. The material collected on the magnetic and non-magnetic stream trays was weighed and the magnetic stream's mass was divided by the mass of the feed DHMS in order to calculate the mass recovery/mass pull achieved. The mass pull profiling is one of the strategic methodologies applied to optimise flotation banks [35]. A similar profiling methodology was adopted for this study since mass recovery is anticipated to have a significant impact on grade recovery.

The magnetic field strength was varied from 148 gauss to 1351 gauss by adding rubber liners to weaken the magnetic field strength and using a gauss meter to measure the effective strength. For the second series of test work a wider range of particle size classes was tested i.e. -1400+1000 µm; -1000+850µm; -850+600µm; -600+425µm; -425+300µm; -300+212µm; -212+106 µm. It was important to maintain a mono layer condition throughout all the experiments in order to ensure that all particles experience the same magnetic field for a given run.

The dry magnetic drum separator was operated as follows: The magnetic drum was allowed to run for 1 minute before the DHMS was slowly poured onto the vibrating feeder in order to ensure that the slag particles formed a near mono-layer by the time the particles reached the magnetic drum.

The time it takes to pour out a specific mass of the slag material onto the vibrating feeder trough was monitored to provide the federate. The weight of the magnetic and non-magnetic components of the sample were measured using a lab scale after each run. The magnetic component and the non-magnetic component samples from each experimental run were stored in separate air-tight bags and marked accordingly and sent for chemical analysis.

Characterization

As indicated in literature, magnetic separators function best when the variation of particle size classes is narrow because different particle sizes vary in their magnetic susceptibility and as such, the fit-for-purpose particle size class needs to be identified for any given material that is being separated by magnetic methods [23]. The particle size classes of DHMS that show a high magnetic recovery were determined as follows: Four size classes shown in Table 3.1 were selected based on their visual physical characteristics as explained in the observation column of the table.

Table 3.1: Particle size classes selected to identify an optimum size class for magnetic recovery

Particle size class	**Particle size (**μm)	**Observation**
Size class 1	+850-1400	Conglomerated particles which are distinguishable by colour (black particles conglomerated with light brown particles)
Size class 2	+300-850	Uniform colour of particles, indication of improved liberation from size class 1 (predominantly black particles)
Size class 3	+106-300	Observably similar in characteristics to size class 2
Size class 4	-106	Particles are very fine, dust form (predominantly light brown particles)

The difference in the visual appearance of particles in different size classes is noticeable, see Figure 3.3 below:



Figure 3.3: Visual appearance of different particle size classes in sieves

SEM Analysis

Scanning Electron Microscopy (SEM) Analysis was performed to obtain the morphology characteristics and elemental compositions of samples as follows: A dry sub sample from each of the 4 size classes was mounted on a carbon pad/stub and a conductive coat was applied to it before being analysed using the SEM-EDS technique. A Carl Zeiss Sigma Field Emission Scanning Electron Microscope (FE-SEM) was used where imaging is performed with a Secondary Electron (SE) or a Back Scatter (BS) detector. Elemental analysis was done on this microscope by Energy Dispersive X-Ray Spectroscopy (EDS) with a Silicon Drift Detector (SDD).

Chemical Analysis

Chemical analysis of DHMS was carried out to determine the total iron content in each sample using the potassium permanganate titration method (equations 3.1, 3.2 & 3.3) and the carbon and sulphur contents were obtained using leco analysis.

Sample preparation was carried out by riffle splitting the sample to generate an unbiased test sample which was milled to 100% -75µm using an RJM swing mill and a sub-sample weighing 0.2g was taken from the product of the swing mill and determination of total iron content on this sample size was conducted by titration using potassium permanganate.

This iron analysis was done at the SANAS accredited ArcelorMittal lab by a competent laboratory technician using ISO procedures.

Titration procedure

The titration analysis was conducted using an experimental set up indicated in Figure 3.4. This procedure was performed by adding 0.2g of < 75µm iron powder into a beaker and pouring 250mL of hydrochloric acid solution, followed by placing the solution on a hot plate and allowing it to heat up until vapour bubbles start to form at around 80°C. Drops of $SnCl_2$ solution were added to the iron solution until the yellowish colour disappeared. The solution was then cooled to room temperature and 10ML of mercury chloride droplets were added. The solution was then placed in flask containing a solution of 400mL of distilled water with 25mL of Reindardt-zimmermann solution. The resultant solution was titrated using potassium permanganate until a pink-purple colour persisted. Volume readings from digital burette were taken and inserted to a chemical analysis computer programme to find the % Total Fe of the specimen.



Figure 3.4: Set up to determine the total iron content by the titration technique

Titration Chemical Reactions

$$2FeCl_3 + SnCl_2 \rightarrow 2FeCl_2 + SnCl_4 \quad (3.1)$$

$$SnCl_2 + 2HgCl_2 \rightarrow SnCl_4 + Hg_4Cl_2 \quad (3.2)$$

$$5Fe^{2+} + MnO_4^- + 8H^+ \rightarrow 5Fe^{3+} + Mn^{2+} + 4H_2O \quad (3.3)$$

4. Results and Discussion

4.1 DHMS particle size classification of the stockpile material

Figure 4.1 below shows the particle size classification of the insitu DHMS sample collected from the stockpile before crushing.

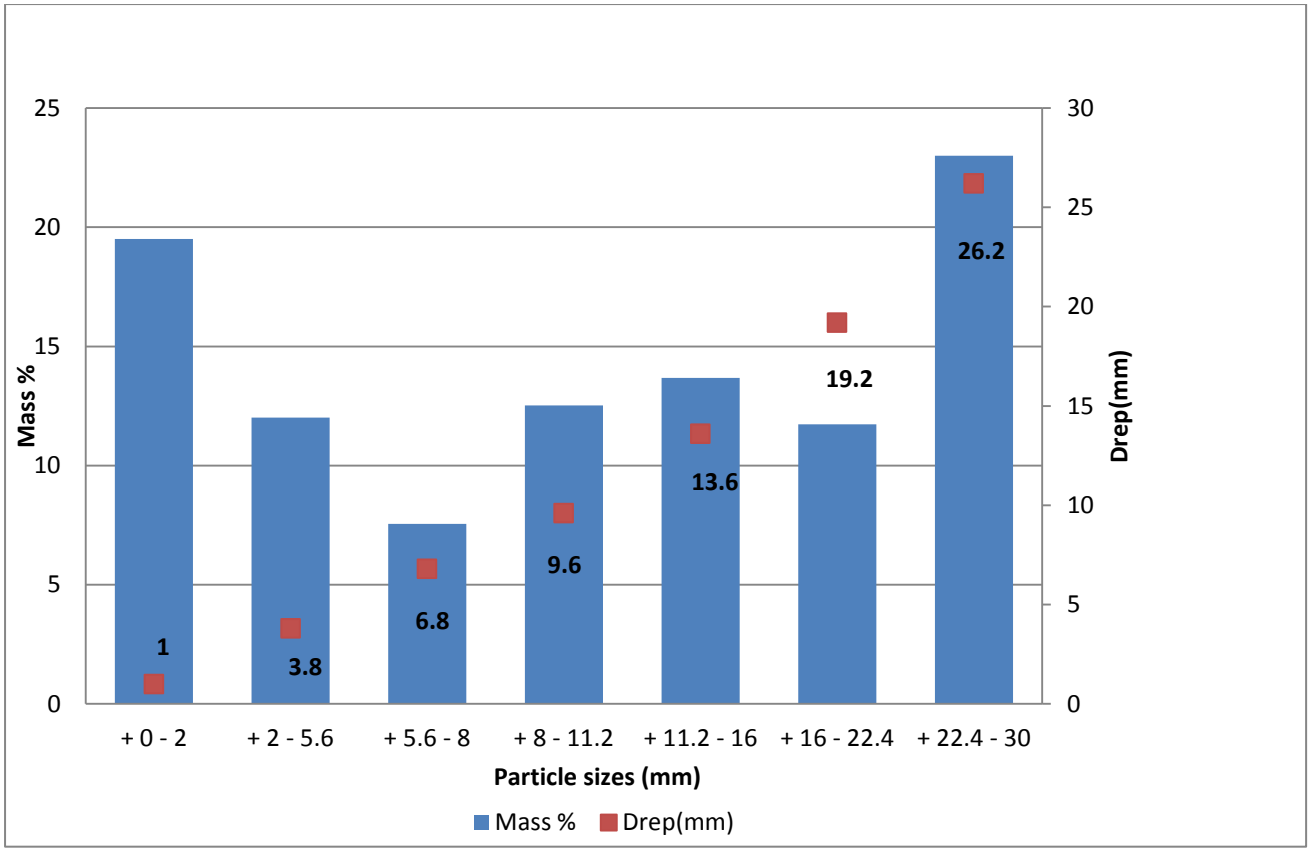


Figure 4.1: Particle size distribution of the DHMS stockpile before crushing

The original material stockpile consists of about 27% of coarse particles with a representative diameter (drep) of ≈ 26.2mm and about 20% of fine particles with drep ≈ 1mm. The particles greater than 5.6mm look like solidified iron chunks which could have resulted from excessive and unintentional carry-over of hot metal into the slag during the skimming process. The solidified chucks look and feel like typical solidified iron. In this exercise, the slag material will be crushed as the above particles are too large to be processed by bench scale magnetic separation equipment and crushing is expected also help in liberating the less liberated particles by releasing the entrapped iron.

4.2 DHMS particle size classification of crushed sample material

The slag material from the stockpile was initially crushed and screened into 4 sub-classes; -1400+850µm; -850+300 µm; -300+106 µm and -106 µm. The primary purpose of placing the particles in these broad size classes was to assess the effect of DHMS particle size on magnetic separation under mono-layer conditions at a high level using fewer particle size ranges. Knowledge of the particle size class that generally gives higher recoveries would guide further the investigations that will zoom in on the particle size class that show better performance. Once a preferred size class is identified more sub-classes in that range can be created so as to establish the optimum particle size that will give the highest possible recoveries and grades.

The influence of particle size on recovery during magnetic separation has been widely reported in literature and it varies from material to material. Generally, fine particles have been found to be more difficult to recover than coarse particles in magnetic separation. Therefore, successful recovery of the finer particles will be an indication of the success of the project. Coarse slag particles have generally been recovered to satisfactory levels.

Figure 4.2 shows the results of particle size and mass distribution done on the DHMS material after pestle and mortar crushing. The use of a pestle and mortar to crush DHMS particles was not technically evaluated for effectiveness as a crushing method since the objective was to reduce the size of the slag particles for test work purposes. Pestle and mortar grinding is common practice and it has been satisfactorily used in batch testing of lead slag [36] . The crushing process produced a significant amount of particles in the -850+300 µm size class i.e. about 44% and another 40 % is made up of particles < 300 µm. DHMS, in general, is grindable with the exception of the solidified iron pieces, which hampered efforts to mill the DHMS by being too hard for the grinding media. These results suggest that components of the slag which are easy to crush tend to have more gangue & sulphur, furthermore, since the crushed particles become finer, the particle size class that emerges as a dominant size class contains more solidified iron content. It therefore follows that screening the crushed material in itself will achieve a good degree of concentration.

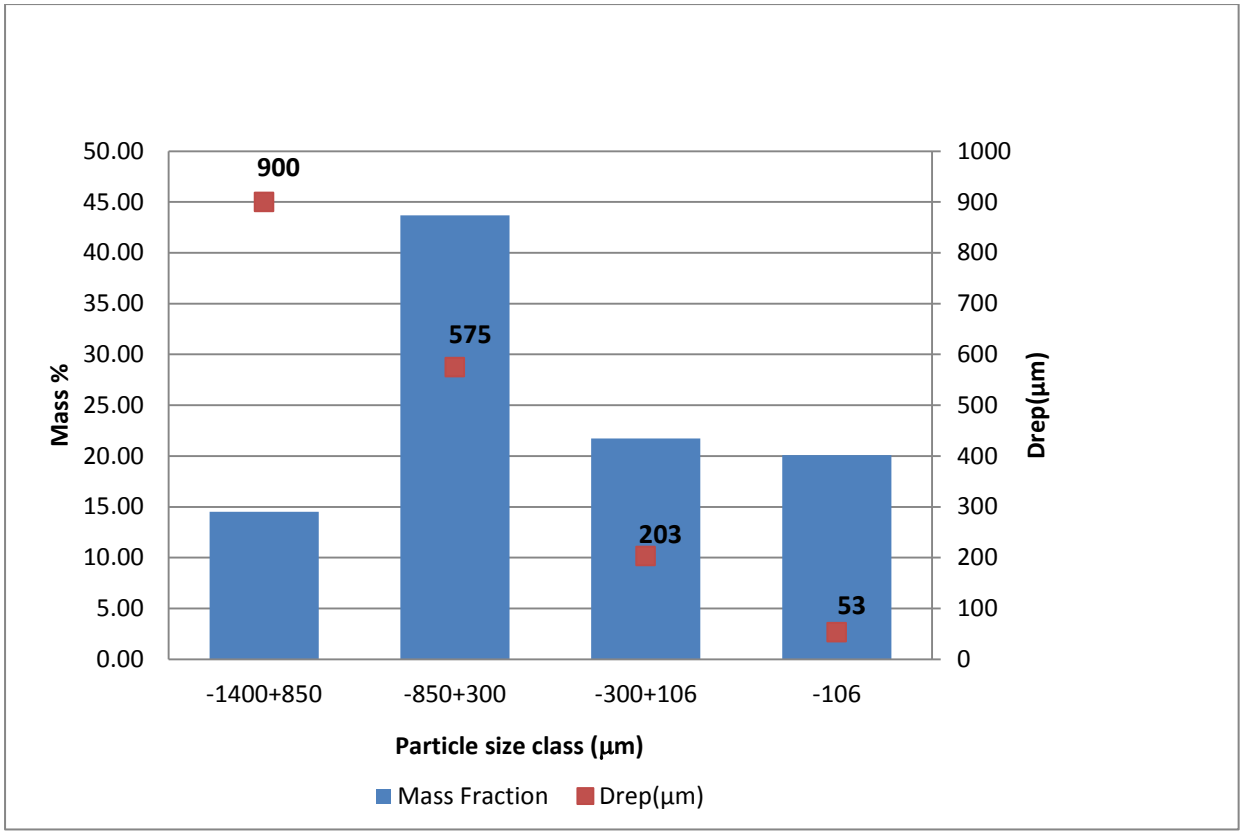
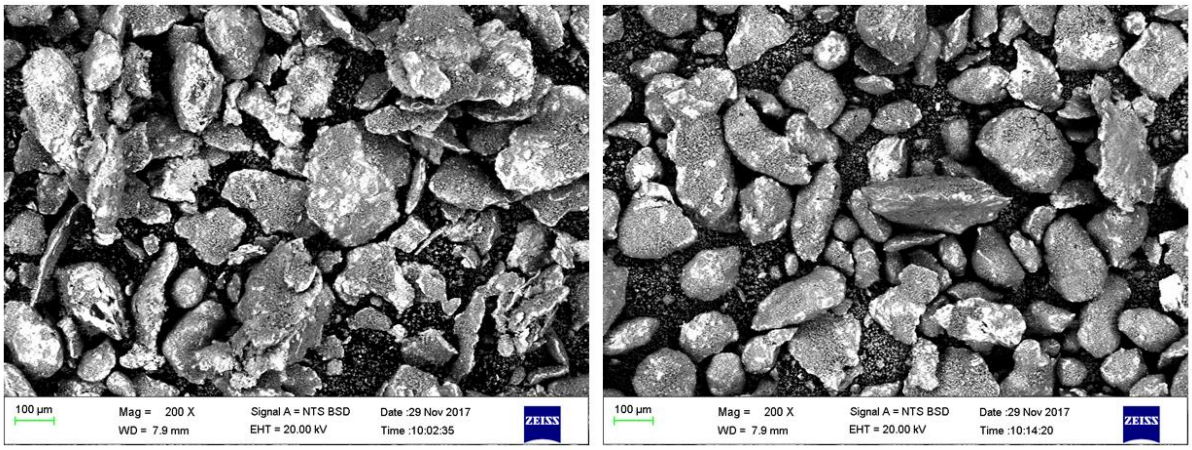


Figure 4.2: Particle size distribution of crushed DHMS

Figure 4.3(a) **(b)**

Figure 4.3 (a) and (b) show the scanning electron micrographs (SEMs) for the DHMS slag material after and before crushing i.e. SEM (a) after crushing and SEM (b) before crushing.



(a) **(b)**

Figure 4.3: SEM micrographs of (a) crushed DHMS and (b) uncrushed DHMS sample

It can be observed that a crushed sample shown in SEM (a) shows particles which are visibly less smooth and most particles are apparently more flat or flaky in shape than the uncrushed sample. The flattening of particles of the DHMS during crushing is indicative of particles being more ductile and malleable than brittle hence they flatten on impact. Malleability and ductility exhibited by the DHMS points to the presence of significant amounts of metallic components, i.e. Fe in the material.

Figure **4.4** a, b, c & d are the scanning electron micrographs (SEMs) for the DHMS samples in the various size classes.

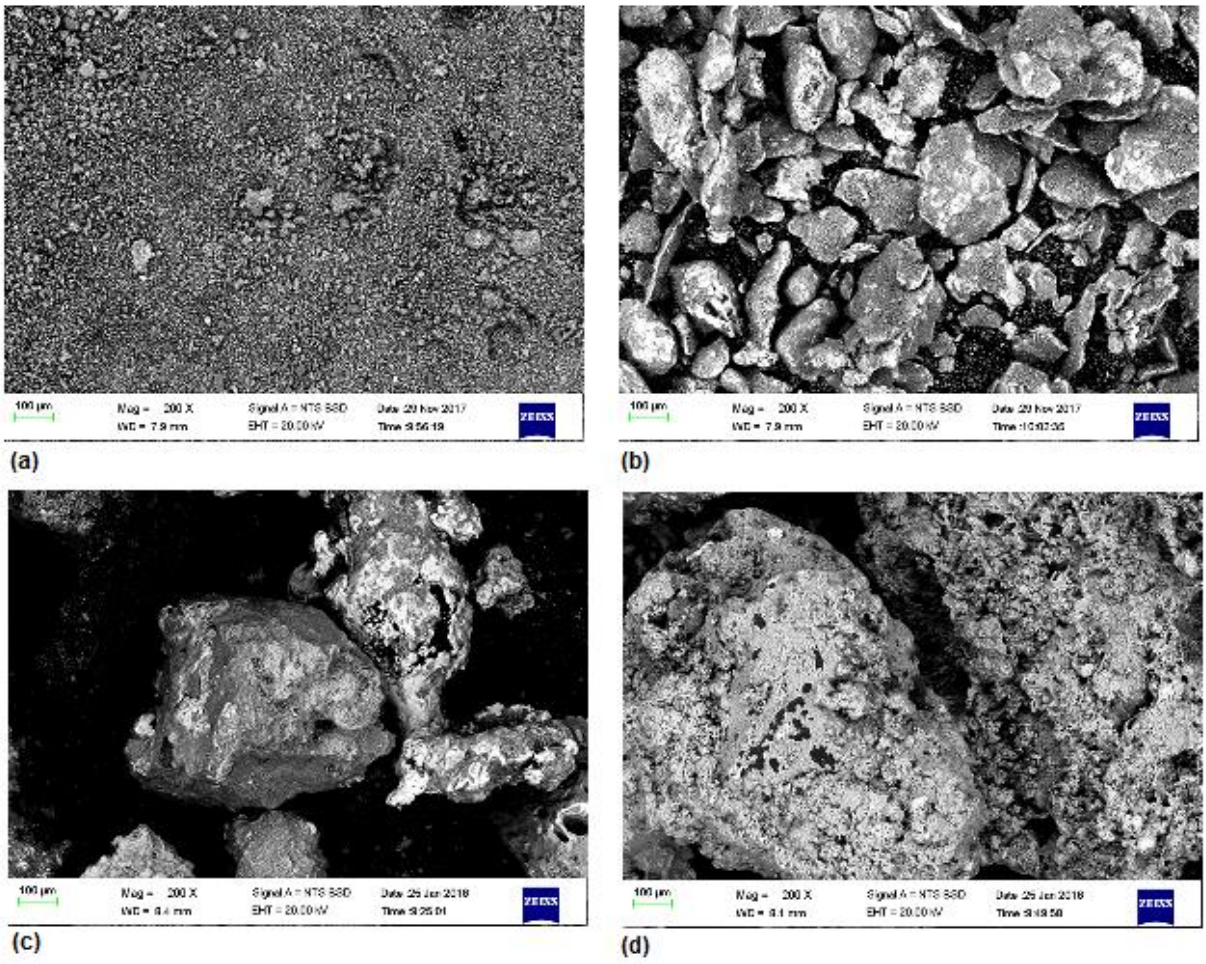


Figure 4.4: SEM micrographs of (a) -106 µm (b) +106-300µm, (c) +300-850µm and (d) +850-1400µm particles

Figure 4.4 image (b & c) show that the -300+106 µm and -850+300µm particles exists as physically distinct and discrete particles separated from each other whilst the -1400 +850µm particles in image (d) appear combined as lumps even after crushing and they also exhibit a shiny lustre indicative of high metal content.

Particles in the size class -106µm (image (a) in Figure 4.4 above) are not ideal for use in a steel making process due to the challenges associated with the handling of very fine particles in furnaces. The particles would ideally need to be screened-off and disposed. The disposal of these fine particles has an adverse impact on the environment, and sustainable ways of handling such fines is needed. From a commercial stand-point though, the fines also contain iron which can increased the steel production yield, which presents an opportunity for their recovery and possibly followed by agglomeration to make them amenable for use in furnaces.

For the above reasons the -106µm particle size class was also magnetically separated in order to evaluate how efficiently these fines can be upgraded and also to quantify the iron and sulphur content present after magnetic separation.

4.3 Effect of magnetic separation parameters on yield

4.3.1 Effect of splitter position on magnetic stream recovery

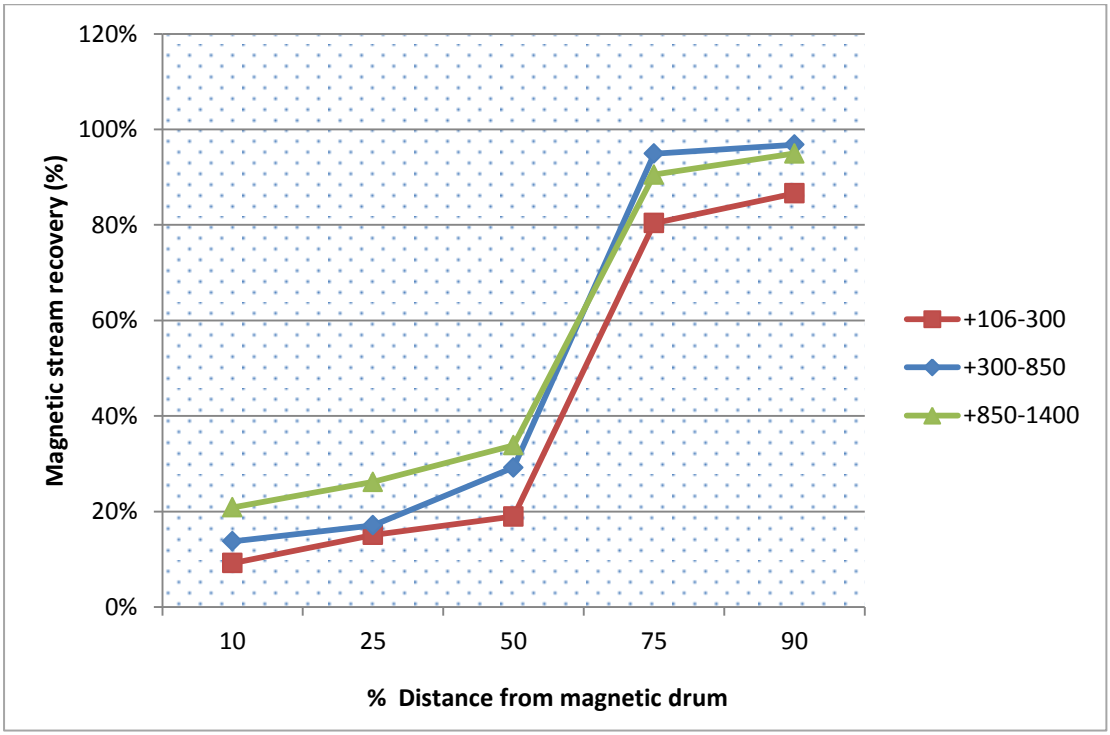


Figure 4.5: Effect of splitter position on magnetic stream recovery

As anticipated, the further the splitter position is from the magnet, the more the DHMS reports to the product stream (Figure 4.5). The increase in the magnetic stream recovery shows a linear correlation from 10% - 50 % splitter gap with the larger particles i.e. -1400+850µm being recovered at a higher rate than the finer particle size classes. Between the splitter gap of 50 % to 75% there is a sudden steep increase in the magnetic stream recovery which suggests that the gap is now too large, indicating that a substantial proportion of unwanted non-magnetic material is being recovered.

These results suggest that a 50% splitter gap, in this equipment, maximum recovery without excessive dilution of the product stream with non-magnetic material is achieved. The splitter position is therefore an important parameter in magnetic separation as it can be used to control product grade and mass pull of the product.

A product stream recovery or yield of 80% with at least 60% iron grade was the targeted in this project as the mass pull and quality that will make this process attractive and viable. An iron grade of 60% is acceptable for sinter plant operations while an iron grade of 64% is comparable to hematite and can be utilized in blast furnace and/or steelmaking operations. Since it will be difficult to achieve both the grade and mass recovery targets solely from dry magnetic separation, grade recovery will take precedence over mass recovery within this exercise.

The results from Figure 4.5 show that a mass pull of 80% and above can only be achieved at splitter opening of 75% and higher. This experiment was not conducted to determine the best splitter position but rather to understand the relative impact that splitter position has on mass recovery and if this impact is size dependant. It can be deduced that the splitter position has a similar effect and to a similar extent, on all the particles +106µm and - 1400µm. For optimal utilisation of a DHMS iron recovery unit, the splitter should be mechanically adjustable in order to allow flexibility in handling of the various DHMS size classes.

4.3.2 Effect of altering the DHMS discharge point on the magnetic stream recovery

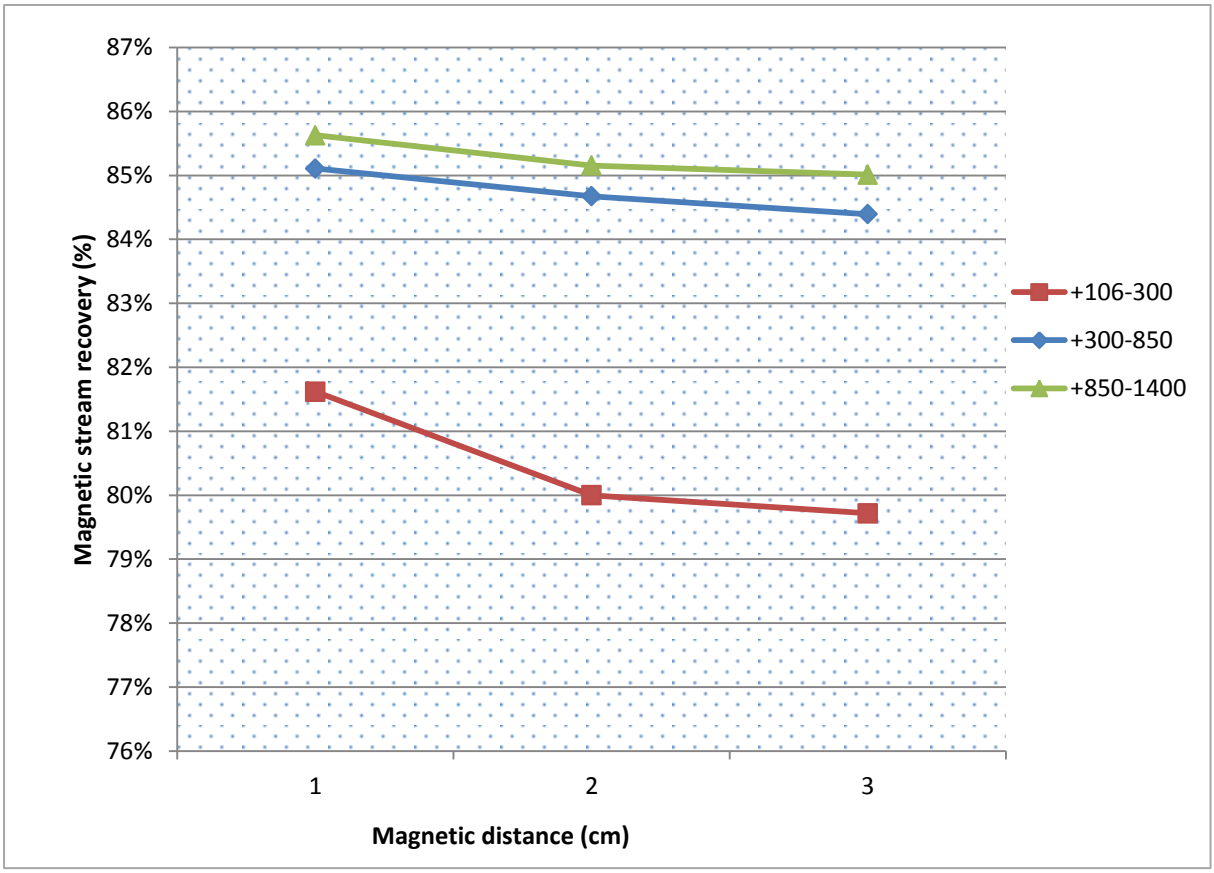


Figure 4.6: Effect of magnetic strength caused by altering magnet distance on mass pull

The results show that the further away the DHMS discharge point was from the magnet the less the mass recovery to the magnetic stream for all the particle size classes involved. The finer particle size class of -300+106µm exhibit much lower recoveries and tend to be much more affected by the distance from the magnet than larger particles as shown by the gradient of the graph of recovery, as the distance increases (Figure 4.6). This observation can be attributed to the lower iron content of the -300+106µm size class compared to the sizes classes with particles above 300µm. It can however, be observed from the graph that the difference in magnetic stream mass recovery as a function of the magnet's distance from 1cm to 3cm is negligible and for this reason, an industrial magnetic separator can be designed with the magnet mounted at a fixed position away from the conveyor belt which will be carrying the DHMS particles during the iron recovery process.

4.3.3 Effect of feed flow-rate on magnetic mass recovery and iron grade

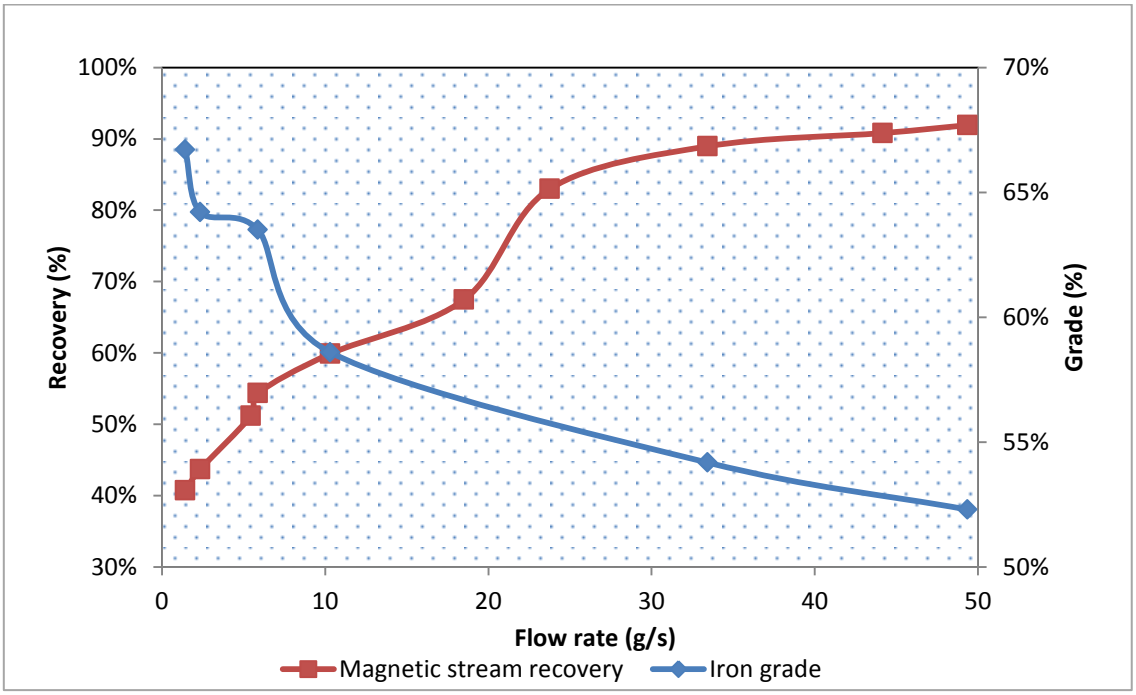


Figure 4.7: Effect of flowrate on iron grade and mass recovery

The results in Figure 4.7 show an approximately linear increase in the magnetic stream recovery with increase in the feed rate of the DHMS up to the feed rate of 25g/s after which the increase in the mass recovery slows down and almost plateaus off at feed rate of 35g/s.

A high Fe grade of about 68% was recorded for the magnetic streams collected between 1g/s – 7 g/s. The grade of magnetic stream samples collected at higher feed rate then decreases after 7g/s to about 50% for feed rate of 50g/s. In the event that particle monolayer conditions are maintained and the particles remain unobstructed from the magnetic field, an increase in the feed rate should result in an increase in mass recovery but still produce a product of similar grade. However, in this test work, the grade of the product is only comparable for feed rate between 1 – 7 g/s suggesting that in this feed rate range monolayer conditions still prevail; hence an increase in the mass recovery does not diminish the product grade. However, at higher feed flow-rates it is likely that the probability and severity of particle entrapment increases, resulting in the recovery of some particles that should not be recovered in the magnetic stream. This causes a drop in the product grade.

Recovery by physical entrapment is the phenomenon that is likely to be happening between the feed rate 7 – 25g/s. At feed rate above 25g/s i.e. between 25 – 50 g/s, it is likely that the momentum that the belt gives to the material is so high that the material over-shoots the splitter and more of it reports to the non-magnetic stream, consequently reducing the rate of magnetic recovery. These results indicate that feed flowrate has a pronounced effect on both the grade and mass recovery during the magnetic separation process.

The curves above are limited to the understanding of recovery trends as a function of change in flow rate and the corresponding figures cannot be directly extrapolated and applied in the design of an industrial magnetic separator. Eriez magnetics confirmed that the formulae used to predict industrial scale flow rate is based on particle density, magnetic field strength as well as particle size distribution. Figure 4.7 has however illustrated that the flow rate has a significant impact on both the grade and recovery of DHMS particles. An industrial magnetic unit therefore requires a motor with adjustable speed functionality and/or a feeder with capabilities to control material flow rates. i.e vibratory feeders.

4.3.4 Effect of magnetic field strength on the recovery of different size classes

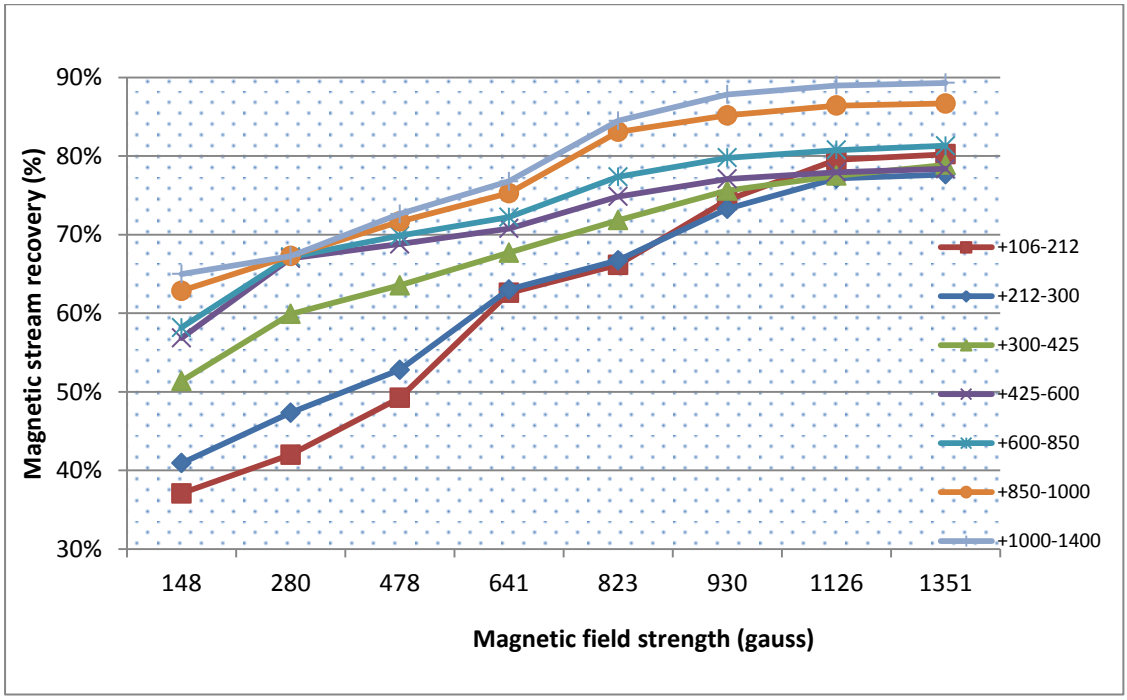


Figure 4.8: Effect of magnetic field strength on mass pull

The results show that as the magnetic strength is increased, the magnetic stream recovery generally increases for all the size classes that were considered (Figure 4.8). Generally at any given magnetic strength value, the larger size classes recorded higher magnetic stream recoveries. The curves also show that the increase in the recovery does not go on indefinitely with the increase in the magnetic field strength.

At a certain point, for all the particle size classes, the recovery stops increasing as the field strength is increased. At the magnetic field strength of around 930-1126 gauss, the recovery completely plateaus off. The smaller particle size classes i.e. - 300µm, show a more marked increase in the recovery for an incremental change in the field strength than coarser particles. Figure 4.8 also demonstrates that the target 80% mass recovery is achieved at different magnetic field strengths for different particle size classes i.e. it is achieved around 730 gauss for particles in the range + 850 µm, around 930 gauss for particles in the range + 600 µm, at 1351 gauss for particles below 300 µm.

For each magnetic field strength applied, the larger the particle size, the more material was recovered. It therefore follows that larger particles are easier to recover than finer particles. This observation is consistent with literature. It can be deduced from Figure 4.8 that above a certain threshold the magnetic stream recovery remains relatively constant for each size classes despite an increase in magnetic strength. This observation implies that a single magnetic strength may be selected for the recovery of all the particle size classes as one batch of a wider particle size i.e. +106-1400µm during an industrial magnetic separation process.

4.3.5 Effect of magnetic field strength on the composite stream recovery and grade

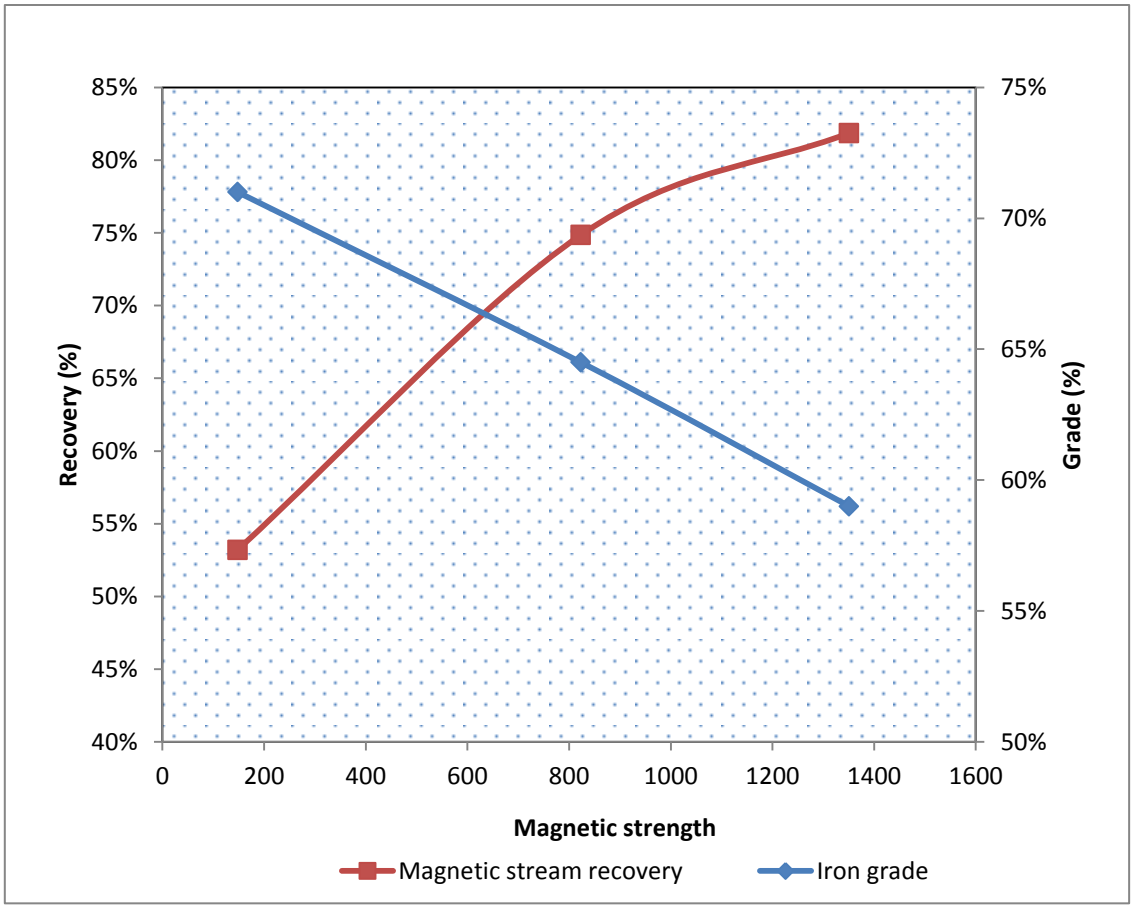


Figure 4.9: Effect of magnetic strength on mass recovery and iron grade on +106-1400µm

Figure 4.9 above indicates a decrease in iron grade with an increase in magnetic recovery. Since steel-making processes require feedstocks with iron content of above 65%, the maximum attainable mass recoveries are about 75% which corresponds to approximately 700 gauss. Observations from Figure 4.8 indicates that recovery of particles generally increases with increase in magnetic strength up-to approximately 820 gauss region, beyond which the recovery slows down due magnetic entrapment.

Therefore operating this process at a magnetic strength of about 700 gauss results in an acceptable grade of iron feed material of about 65% at a reasonable yield of about 75 %, which is marginally lower than the target yield of 80%.

4.4 Effect of optimum magnetic separation parameters on iron and sulphur recoveries

Figure 4.10 shows Fe and S deportment across the different size classes that were magnetically separated under optimal conditions as determined from the preceding test work results. The magnetic field strength was set at 641 gauss, the flow rate at 11g/s and the splitter opening at 75%.

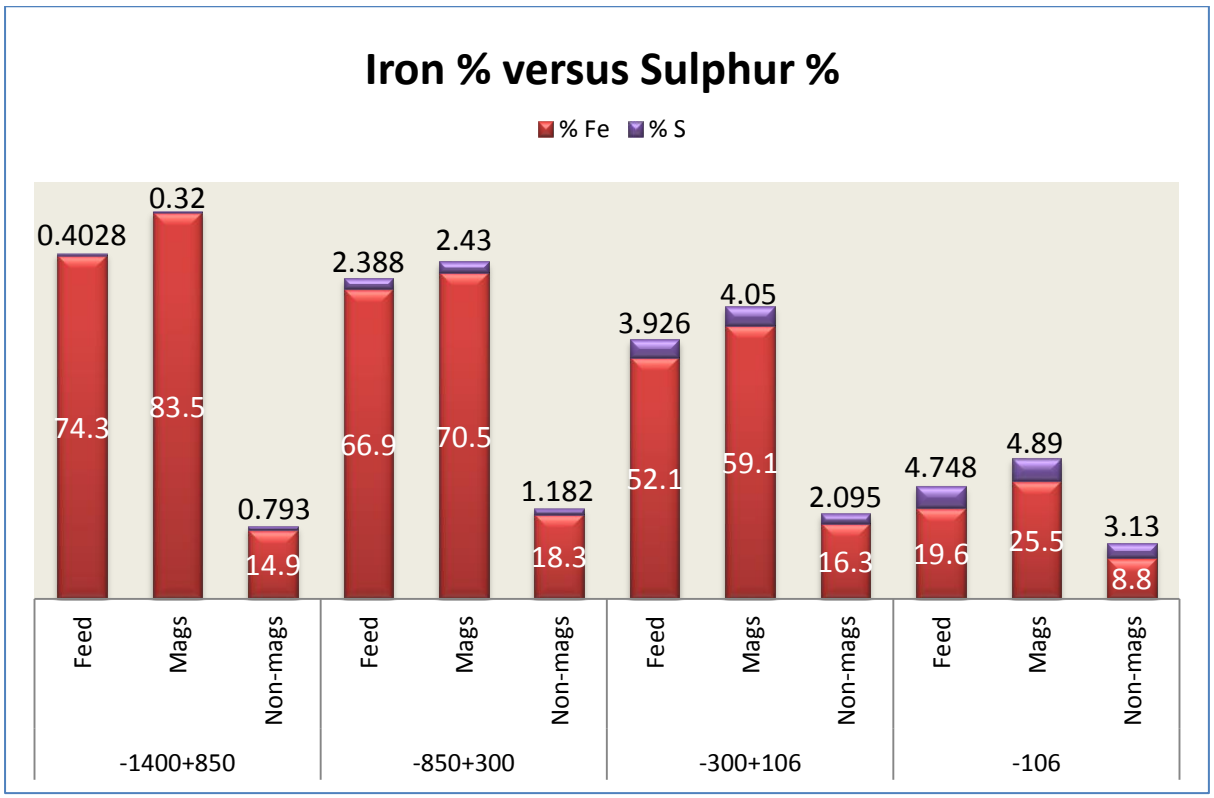


Figure 4.10 :Iron and sulphur deportment for the different size classes

The sulphur content was observed to increases with the decrease in particle size in all the size class streams i.e. feed, magnetic and non-magnetic streams. This is consistent with the fact that sulphur-containing compounds are generally more brittle and tend to break down into smaller fragments much easier than iron-bearing compounds during crushing. It is also observed that more sulphur reports to the magnetic stream than to the non-magnetic stream except for the largest size class, which is contrary to expectations since sulphur is generally non-magnetic.

This might suggests that more of the sulphur remains intricately bonded to the magnetic components or the iron-bearing minerals in the minerals unliberated or it may be that sulphur is weakly magnetic and gets recovered to a higher degree than the bulk of the gangue.

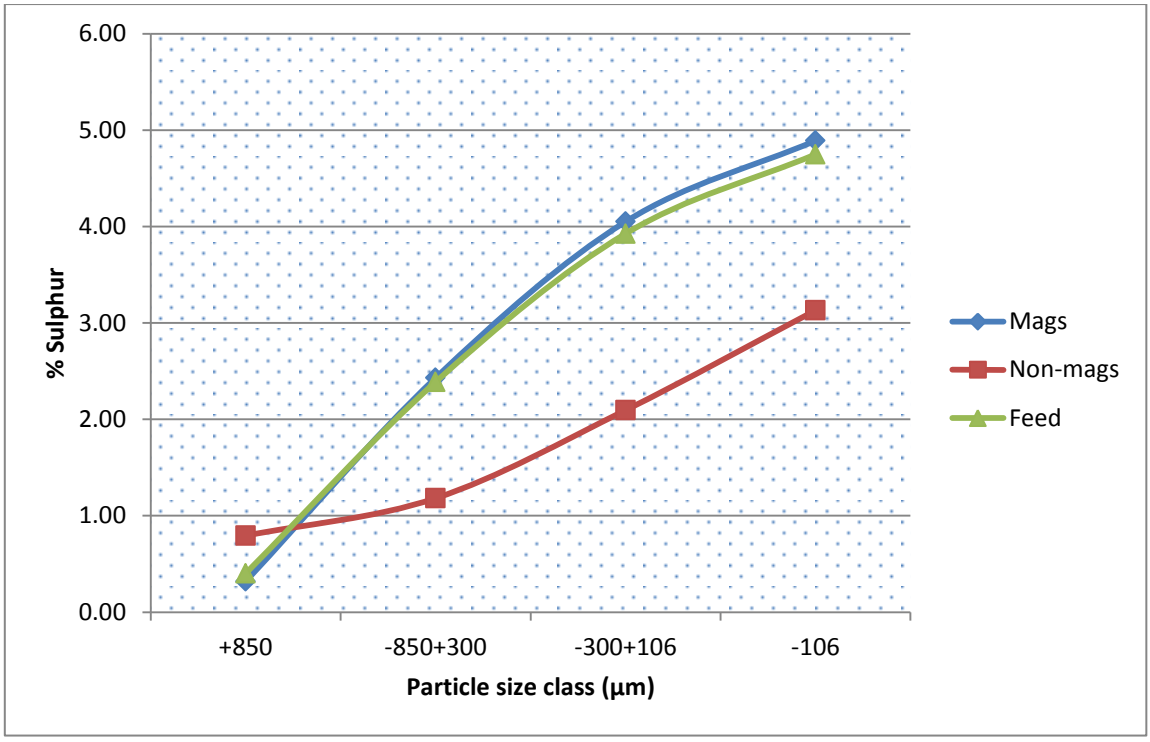


Figure 4.11 : Sulphur content per size class for mags, non-mags and feed streams

The sulphur present in the feed was not significantly reduced by applying magnetic separation under the test work conditions explored within the scope of this exercise. In general, the non-metallic components of DHMS tend to be present as fine particles while the iron rich particles tend to coarse and bonded to the sulphur even after liberation by crushing. This implies that while magnetic separation improves the iron content of DHMS, it is not effective for sulphur removal. To remove sulphur from DHMS alternative metallurgical routes should be explored. Alternative design configurations and/or technologies will have to be identified and trialled as shown in the cases presented in the literature review section. The DHMS iron recovered by magnetic separation may still be suitable for some applications within the iron and steel making environment.

Table 4.1: Prime product versus feed product

	Feed	Extrapolated product based on Figure 4.9	Analysed product
%Fe	55.26	65	69.47
%S	2.91	-	2.58

Table 4.1 indicates the prime product from the test work, which is essentially the combination of the magnetic streams above 106 µm as shown in Figure 4.10. It was therefore determined that crushing and magnetic separation of DHMS can be successfully used to improve the Fe content from 55.26% to 69.47% while decreasing the sulphur content from 2.91 % to 2.58%. The Fe content is marginally higher than that of hematite ore while the sulphur content is unsuitable for most steel grades. The difference between extrapolated and analysed iron content suggests that a fully operational iron recovery plant should not rely solely on extrapolated figures as they may be notably different from the actual analysis.

4.5 Evaluation of DHMS for use in steel making

Table 4.2: Steelmaking input materials that DHMS can potentially substitute/compliment

Parameter	Iron ore (Hematite)	Hot Metal	Directly reduced iron	sulphur wire
% Fe, tot	66.4-67.6	96	91.5-92	Encapsulation purposes only
% Sulphur	0.005-0.03	0.08-0.12	0.005	99
Usage	Blast furnace/BOF	BOF	Blast furnace/BOF	Ladle furnace
Suitability of Prime product as a replacement or supplement	Suitable for use in blast furnace operations	Suitable for use as supplementary sulphur source on high sulphur grades	Not suitable due to DHMS having significantly lower iron content	Suitable for use as supplementary sulphur source on high sulphur grades, low yields to be expected

From the material specifications above, it can be observed that the high sulphur content limits the scope of application for the DHMS products. Recently, steel plants have been blending their DHMS with fine BOF slag and using the mixture as an iron source during the sintering process.

Table 4.2 also indicates that sulphur can be a desirable element for some steel grades and consequently DHMS may be a used as a sulphurizing agent at the ladle furnace for medium to high sulphur steel grades. Briquetting of the DHMS would be necessary for this application because larger input material tend to have better yields during alloying than finer material.

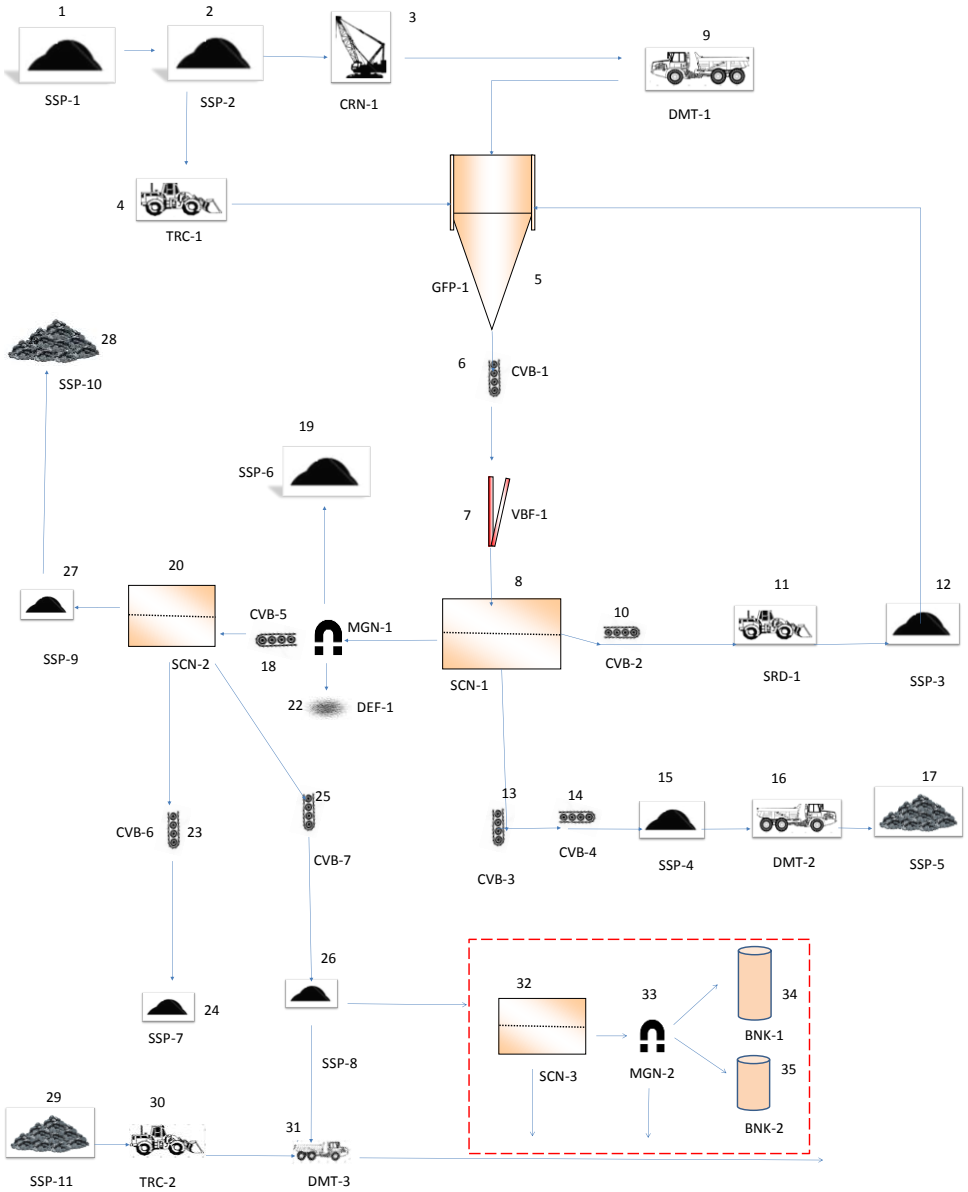
Precaution ought to be taken when introducing input material to liquid steel on downstream processes since this is where the ultimate chemical properties of the final product are refined. For this reason, input material consistency is much more critical than in upstream processes such as the sintering plant. The role of magnetic separation in the recovery of DHMS thus becomes more of a means to classify the DHMS into different sulphur groups which can be blended to give a consistent product of 2.5% sulphur content. It should be noted that the solution above is applicable for plants that produce free machining steel grades and each plant has to have unique operating conditions.

5. Preliminary process design and rationale

5.1 Process Flow Diagram (PFD)

Figure 5.1 below is a simplified representation of the Newcastle slag handling set-up. The additional screening unit, magnetic separator and two bunkers which are proposed for the successful recovery of iron from DHMS have been incorporated and are enclosed in the red-dotted boundary on the process flow diagram.

Slag handling operations



EQUIPMENT LIST		
ITEM NO.	Code	Description
1	SSP-1	SLAG BAY
2	SSP-2	BOF SLAG STOCK PLIE
3	CRN-1	CRANE
4	TRC-1	FRONT END LOADER
5	GFP-1	GRIZZLY FEEDER PLANT
6	CVB-1	CONVEYOR BELT
7	VBF-1	VIBRATORY FEEDER
8	SCN-1	SCREEN
9	DMT-1	DUMP TRUCK
10	CVB-2	HORIZONTAL CONVEYOR
11	SRD-1	FRONT END LOADER
12	SSP-3	SLAG STOCK PILE
13	CVB-3	WASTE CONYEYOR
14	CVB-4	BRICKS CONVEYOR
15	SSP-4	WASTE STOCK PILE
16	DMT-2	DUMP TRUCK
17	SSP-5	HAZARDUS WASTE
18	CVB-5	C-CONVEYOR
19	SSP-6	C STOCK PILE
20	SCN-2	SCREEN
21	MGN-1	MAGNET
22	DEF-1	D AND E FINES
23	CVB-6	E CONVEYOR
24	SSP-7	D STOCK PILE
25	CVB-7	D CONVEYOR
26	SSP-8	E STOCK PILE
27	SSP-9	G4, G5 MATERIAL STOCK PLIE
28	SSP-10	NEW SLAG STORAGE SITE
29	SSP-11	C,D,E STOCK PILE
30	TRC-2	FRONT END LOADER
31	DMT-3	DUMP TRUCK
32	SCN-3	SCREEN
33	MGN-2	MAGNET
34	BNK-1	BUNKER
35	BNK-2	BUNKER

Figure 5.1: Metal recovery PFD depicting the DHMS iron recovery unit

5.2 Process rationale

Test work from this investigation has shown that DHMS particles can be upgraded from 55% to 69% Fe. To achieve similar results under operational conditions would require the incorporation of the following units into the existing process configuration.

Vibrating Screens (SCN-3):

A well designed screen should take into account material factors such as particle morphology, density, moisture content as well as size distribution. These properties will determine the most suitable machine factors such as the screening media, screen motion requirements (i.e. shaking, stationary or vibrating) as well as other factors that affect the screenability of particles [37]. The test work has shown that magnetic recovery of DHMS is a function of particle size. The smaller the particle size the more stringent the parameters should be in order to achieve optimum iron grade and mass recovery.

Additional screens are required (SCN-3) in order to classify the finer DHMS particles that would otherwise not be recovered by the parameters set-up for magnetic separator MGN-1. The screen (SCN-3) main purpose is to discard particles below 106µm and classify the feed to the magnetic separator (MGN-2) into 106µm - 300µm, 300µm - 850µm and +850µm-1400µm. A multi-deck vibrating screen with a capacity of 5-10 tons/hour would be suitable for the efficient screening of DHMS particles.

Vibrating screens provide good accuracy of sizing, they require less maintenance per ton of material handled, less installation space and they weigh less than other types of screening equipment. The screen surface can be inclined at any angle between 20 and 40 degrees and the vibration frequency can vary from 15 000 to 72 000 per minute [38]. High degrees of inclination and high vibration frequencies have been used to overcome screen blinding of DHMS particles, particularly plugging, which is a form of blinding which occurs when near-sized particles wedge into the screen aperture thus preventing the passage of undersize material. This form of blinding would be more prevalent in DHMS screening than coating, which is a form of blinding which occurs when sticky or moist material is being screened. As a reactive measure, mesh cleaning devices such as balls or rings can be utilised to eliminate or reduce the blinding. The most optimum screening operating conditions for DHMS will have to be identified through test work.

Magnetic separator (MGN-2):

Magnetic separation is the core unit for the iron recovery process. The magnetic separator MGN-1 is tuned for large particles of BOF slag. Iron-rich fine particles of BOF slag are lost into the non-magnetic stream due to the size bias of magnetic unit. However, the BOF iron recovery is beyond the scope of this exercise.

A dry low intensity magnetic separator which can process 5-10 tons/hour would be the most suitable selection for the application. Wet high intensity magnets have proven to be more efficient in recovery of fine particles. However, the handling of liquid and/or slurry is generally more costly than the handling of dry solids. Since cost efficiency is one of the requirements for a viable solution, the dry magnetic route is much more favourable.

A strong magnet would attract almost all the DHMS into the recovery stream since DHMS is highly magnetic. The aforementioned scenario would defeat the purpose of magnetic separation. The actual magnetic strength should be approximately 650 Gauss as this is the optimal strength for separating most of the particle sizes, which would be separated during the operational life of this magnet. The splitter position and feed-rate should be variable in order to allow for flexibility in cases where the incoming slag chemistry is outside the normal specification. All other magnetic parameters may be kept constant.

Storage bunkers (BNK-1 & BNK-2):

The upgraded DHMS will find use in the downstream steel processing such as ladle furnace where input material's yield consistency is a prerequisite, therefore one of the two critical elements should be kept constant. Since the sulphur would be the element of interest, it makes more sense to keep it at a fixed percentage i.e. 2%. The product from MGN-2 would be stored in either Bunker 1, for sulphur content above 2% or bunker 2 for sulphur content below 2%. The recovered iron products from the two bunkers would be blended proportionally to achieve the required sulphur specification.

6. Economic evaluation

The introduction of a DHMS recovery unit shall be complimentary to the already existing BOF slag recovery plant. Based on the relatively low tonnages of DHMS compared to BOF slag, additional man-power will not be required. The DHMS recovery plant will share resources, including personnel with the BOF recovery plant. Insurance costs will also not be accounted for separately as it is covered by the company's umbrella insurance. The cost implications for the recovery of iron from DHMS therefore relate to the direct capital (Table 6.1) as well as operational and maintenance requirements (Table 6.2)

Table 6.1: Capital cost

Equipment		Quantity	Cost/Unit (R)	Total Cost (R)
Vibrating screens		1	R 210 000.00	R 210 000
Magnetic separator		1	R 345 000.00	R 345 000
Storage bunkers		2	R 185 000.00	R 370 000
	Total Machinery and Equipment Cost			**R 925 000**
	Installation Factor		2.04 Solids Handling	
	Total Installed Cost (TIC)			**R 1 887 000**
	Direct field cost (DFC)			R 1 887 000
	Indirect field cost @ 5% OF DFC			R 94 350
	Home office cost @ 1% OF DFC			R 18 870
	Sub Total			**R 2 000 220**
	Contingency @ 5%			R 100 011
	Capital cost (total installed value)			R 2 100 231

The equipment vibrating screen and magnetic separator can handle 5-10 tons of material per hour. About 9.375 tons/hour of slag is expected to be processed per day, at a maximum of 8 hours per day and for 350 days per year. The current manpower is on 65% utilization per shift which implies that they can incorporate this task as part of normal day-to-day operations without the need for additional man-hours i.e. overtime or extra personnel. The process of identifying suitable equipment suppliers, tendering and commissioning of the plant can take 5 to 7 months from the date the project is approved.

Table 6.2: Operational cost

Item	Unit	Annual consumption	Unit Cost (R)		Annual Cost (R/a)
Variable costs:					
Electricity	Kwh	38500	R 0.75		R 28 875.0
Briqueting	Tons	18375	R 400		R 7 350 000.0
Other consumables		5% of variable cost			R 368 943.75
		Total Variable Cost			**R 7 747 818.8**
Fixed Costs:					
Analytical	PM	12 service fees	R 55 000		R 660 000.0
Maintenance		5% of capital cost			R 105 011.6
		Total Fixed Cost			**R 765 011.6**
Operational cost					**R 8 512 830.3**

NB: *Vat excluded*

Although the recovered Fe shall be used as a supplement to iron bearing ores and alloys, the cost benefit is the amount which shall be saved by processing 26 250 tons of DHMS to produce 18 375 tons of product to be used as a high sulphur iron source during the production of free-machining steel grades. Briquetting of the iron recovered from DHMS increases the variable cost of the recovery operation significantly however the overall operating cost is still lower than the cost of disposing the DHMS slag. The current disposal rate is in the region of R655/ton of DHMS. The figure includes material handling costs, transportation costs and disposal fees. The economic evaluation was conducted without taking into account the impact of tax and depreciation.

Table 6.3: Economic evaluation

Year	0	1	2	3	4	5
Capex	2.10					
working capital	7.75					
Revenue		12.04	12.04	12.04	12.04	12.04
Operating cost		8.51	8.51	8.51	8.51	8.51
Gross profit		3.52	3.52	3.52	3.52	3.52
CASH FLOW	-9.85	3.52	3.52	3.52	3.52	3.52
IRR, 20	23%					
NPV,15%discount rate, 5 years	1.71					

NB: *All amounts in table 9 are in million rands*

The Internal Rate of Return (IRR) is on the high side at 23% and the Net Present Value (NPV) is positive at R1.71 million (Table 6.3). Both indicators suggest that the project makes financial sense. In the steel industry, projects are however not approved solely on their own merit, they are instead weighted against other projects that require capital expenditure.

In general, projects with high NPVs and low IRR are favoured over projects with High IRR and Low NPVs. This practice is mainly because NPV is considered a better indicator of the shareholder value created [39]. The low NPV may explain why most steel plants have not commissioned metal recovery plants dedicated to the recovery of iron from DHMS.

7. Conclusion and Recommendations

DHMS particles which are less than 106µm have an iron content in the region of 20%. Magnetic separation of the -106µm particle size class achieved a product stream with 26% iron . The -106µm particle size class was therefore determined to be uneconomical to recover using dry magnetic separation. For DHMS particle size classes 1400+850µm; -850+300µm; and -300+106 µm, iron recovery showed a direct proportion to size class. Particles between 106µm and below 1400µm were beneficiated from 55% iron to 69% iron by operating at 641 gauss and 11g/s at a mass recovery of approximately 70%.

The magnetic stream of DHMS was found to be sulphur rich and has potential to be used as a sulphur source during the refining stages of free-machining steel grades. An additional screen, magnetic separator and two storage bunkers would need to be incorporated into the existing AMSA Newcastle slag recovery system to allow DHMS to be optimally recovered. The additional process units required can easily be sourced, are simple to operate and economically justifiable to commission. The lab scale test work shows promising results, however a pilot plant needs to be set-up to affirm that similar results could be attained from a full scale recovery unit.

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9. Appendix A: Data



Figure 9.1: Gauss meter

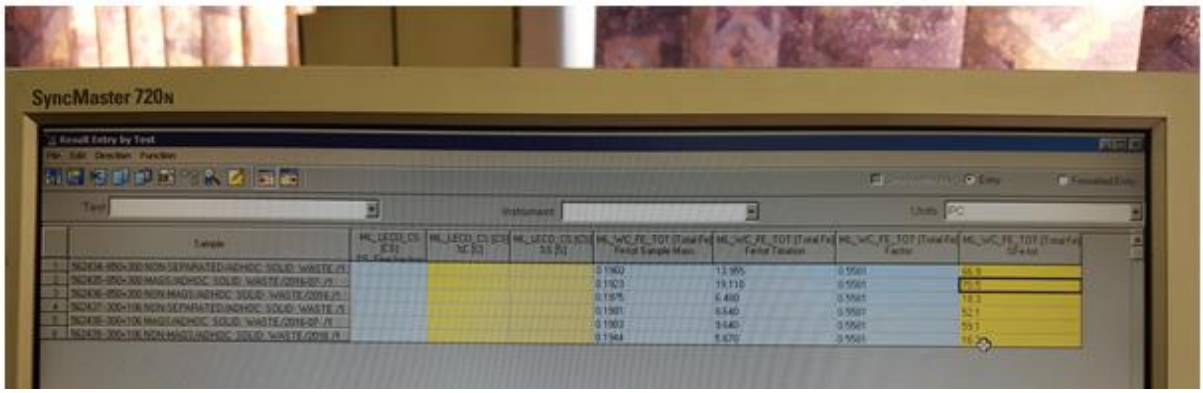

Figure 9.2: Lab analysis software

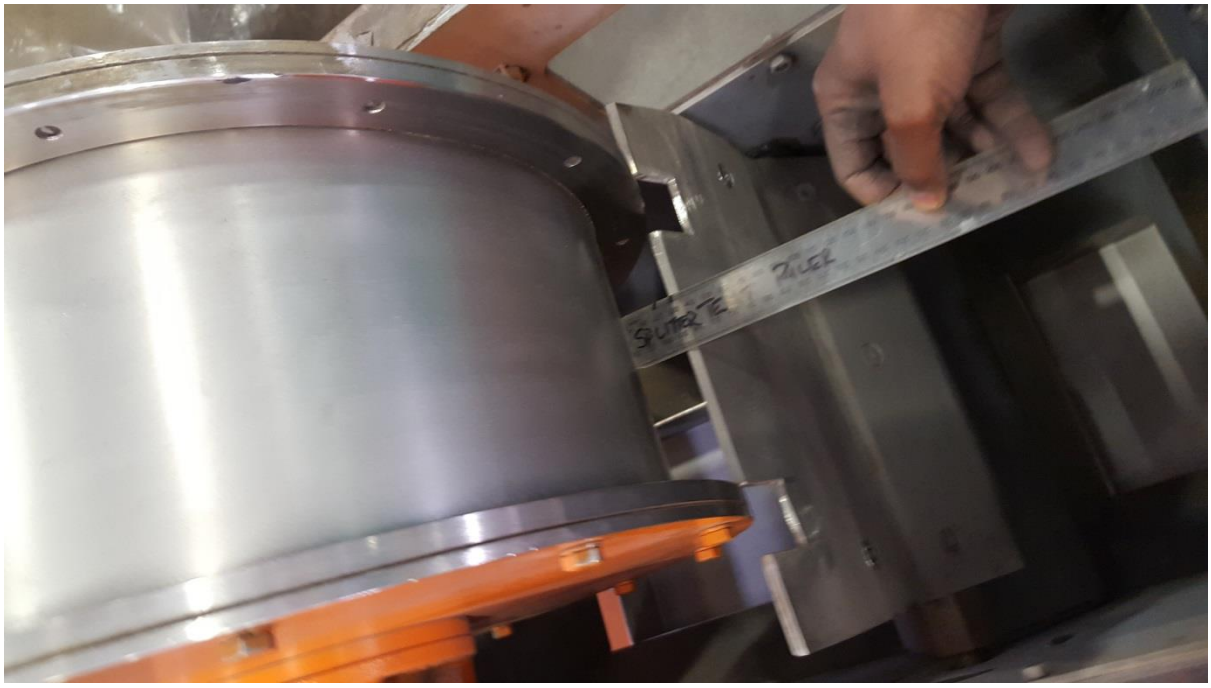

Figure 9.3: Magnetic drum –Splitter position

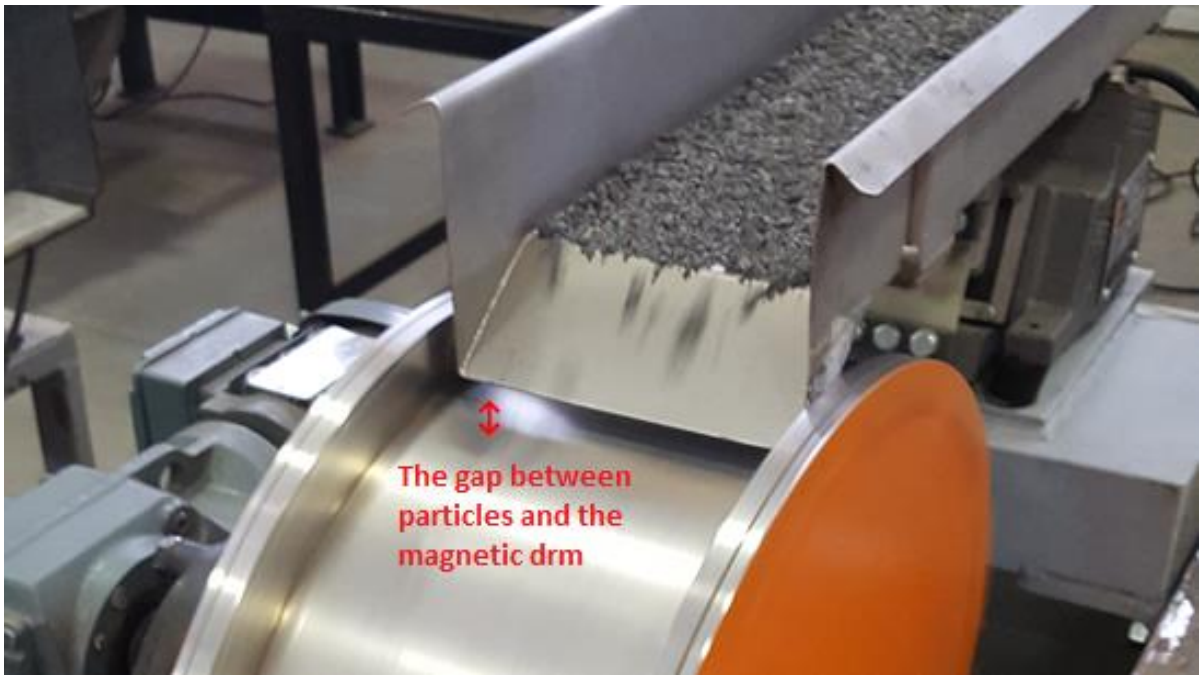

Figure 9.4: Distance between particles and magnetic drum



Figure 9.5: Specimen before and after titration

Table 9.1: Lab results

SAMPLE ID	SAMPLE No.	LAB No.	%Fe-tot
+850 non-separated	562431	16/0303	74.3
+850 mags	562432	16/0303	83.5
+850 non-mags	562433	16/0303	14.9
-850+300 non-separated	562434	16/0303	66.9
-850+300 mags	562435	16/0303	70.5
-850+300 non-mags	562436	16/0303	18.3
-300+106 non-separated	562437	16/0303	52.1
-300+106 mags	562438	16/0303	59.1
-300+106 non-mags	562439	16/0303	16.3
-106 non-separated	562440	16/0303	19.6
-106 mags	562441	16/0303	25.5
-106 non-mags	562442	16/0303	8.8