

PLASTIC WASTE USE IN THE BLAST FURNACE AS A REDUCING AGENT

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Abstract

Steel is among the most essential materials in construction, making its manufacture equally important. Steel is manufactured either via an integrated iron and steel making route characterised by the Blast Furnace (BF) and a Basic Oxygen Furnace (BOF), smelting followed by a BOF or in an electric arc furnace. The objective of this paper explores the possibility of using plastic waste in Africa as an alternative reducing agent to coke in the Blast Furnace; a recycling practice that is commonly done in Japan and Europe. There are many benefits that can be accrued environmentally, operationally and economically when using waste plastics in the BF. The hydrogen content in waste plastics is almost three times more than that in pulverised coal making it a better reducing agent environmentally and economically. Plastic waste has a higher calorific value and less impurities, which results in energy savings and less dioxins and furans in the process. In addition, bearing in mind that over 130 million of tonnes of plastic waste are currently in Africa's landfills, utilising waste plastics in the BF will result in savings in landfills airspace, prevent financial losses incurred through dumping valuable recyclables, protect the environment and the public because if spontaneous fires start in landfills then toxic fumes such as furans and dioxins, cannot be generated if the landfills are plastic free. With such evidence on hand, plastic waste use in the BF presents an untapped beneficial opportunity not only for the continent of Africa but other continents such as North America where landfilling is rife.

Keywords: Blast Furnace, Coke, Landfill, Plastic waste,

1 INTRODUCTION

Steel is among the most essential materials in construction [1], making its manufacture equally important. Steel is manufactured either via an integrated iron and steel making route characterised by the blast furnace (BF) and a basic oxygen furnace (BOF), smelting followed by a BOF or in an electric arc furnace (EAF) as shown in Figure 1 [2].

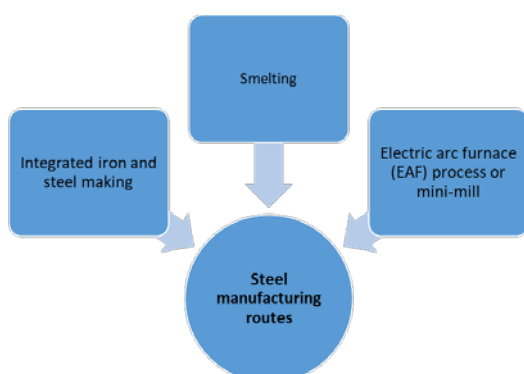


Figure 1: Steel making process routes [2]

In the integrated iron and steel process route, sinter, pellets or lumpy ore are used to provide

the iron while coke or pulverised coal act as the reducing agents which facilitate the reduction reactions occurring in the blast furnace. The resultant pig iron from the blast furnace is then further processed into steel in a BOF. Pig iron constitutes 70% of the feed into the BOF. It is important for the produced pig iron to be of consistent quality and as a result, the quality of reducing agents and iron-bearing feedstock should also be consistent. This route is the most preferred when demand for steel is high and there is an abundance of iron and coal/coke [2]. In smelting, iron ore is melted in a reactor in the absence of coke. The EAF is commonly used for small markets as well as where there is abundant scrap metal and relatively cheap electricity. Aside from scrap metal, direct reduced iron (DRI) or sponge iron is also used as a feedstock in the EAF. Direct reduced iron is produced from iron ore and reducing agents such as natural gas or non-coking coal. Figure 2 summarises these process routes and the various inputs used for steel making [2].

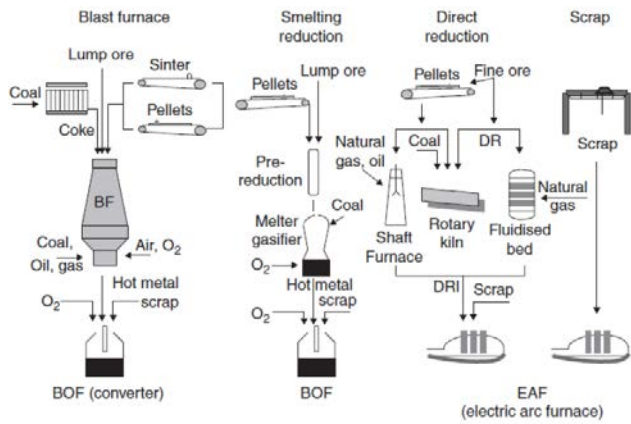


Figure 2. Steelmaking process routes and inputs. Credit: [1]
(Source: Adapted from Steel Institute VDEh, 2008).

Globally, the manufacture of steel via the integrated blast furnace route; which is the focus of this paper, is the leading route accounting for 61%, followed by the scrap metal and DRI routes with 36% and 4% respectively in 2005 [2].

1.1 Blast Furnace Route of Iron and Steel Making

The pig iron making process utilising the BF heavily relies on sintering, coke making and pig iron production in the BF. These processes consume the most energy of the whole steel making process accounting for approximately 65–75% of the total energy consumed in steel production. This energy is equivalent to ca. 11–12 GJ/t hot metal [1].

Carpenter [3] also reported energy consumption per unit process as shown in Table 1.

Table 1. Unit Processes and Energy Used During Integrated Iron and Steel Making

Unit process	Energy used (GJ/tcs)
Blast Furnace	10-13
Sintering	2-3
Coke making	0.75-2
Steel making	1.5-3
Ladle metallurgy and casting	0-1

* tcs – tonnes of crude steel

1.1.1 Sintering

Sintering is a process where fines that would otherwise have been landfilled or stockpiled are

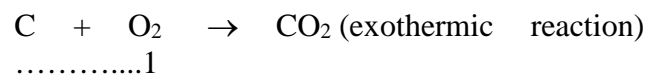
agglomerated or fused using heat, into a product called sinter that is suitable for the blast furnace. These fines are comprised of iron ore, coke and limestone among other materials from the entire plant.

1.1.2 Coke Making

Coke is the main reducing agent in the Blast Furnaces which releases gases that reduce iron ore as well as providing heat energy for the melting process and any other endothermic reactions that occur. Metallurgical grade or coking coals are used in the production of coke. The coking process is done in ovens, where the coal is heated to 1000–1100°C in the absence of air/oxygen for 12-36 hours; a process called carbonisation. As the temperature continues to rise, the coal exhibits plasticity and fuses, and re-solidifies to form coke [3,4]. The quality of the resultant coke is determined by the qualities of the coking coals used, as well as the coke plant operating conditions. Coke quality is dependent on the composition of the coal as well as its ability to behave like plastic on heating and re-solidifying to form coke and bituminous coals fall in this category. Good coke quality improves the productivity of the blast furnace [3,4]. The role of coke is also to mechanically support the BF burden or charge and to provide a permeable bed which allows, molten metal, slag and gases to flow.

1.1.3 BF Operations

The reactions below occur in the BF which is shown in Figure 3 [5].



In reaction 1, the coke undergoes combustion in the lower section of the furnace giving rise to temperatures as high as 2000°C. The CO₂ released then reacts with the carbon in coke to form carbon monoxide (CO), the reducing gas. This is known as the Boudouard reaction.



Due to the endothermic nature of the reaction, temperature is decreased to around 1700°C.

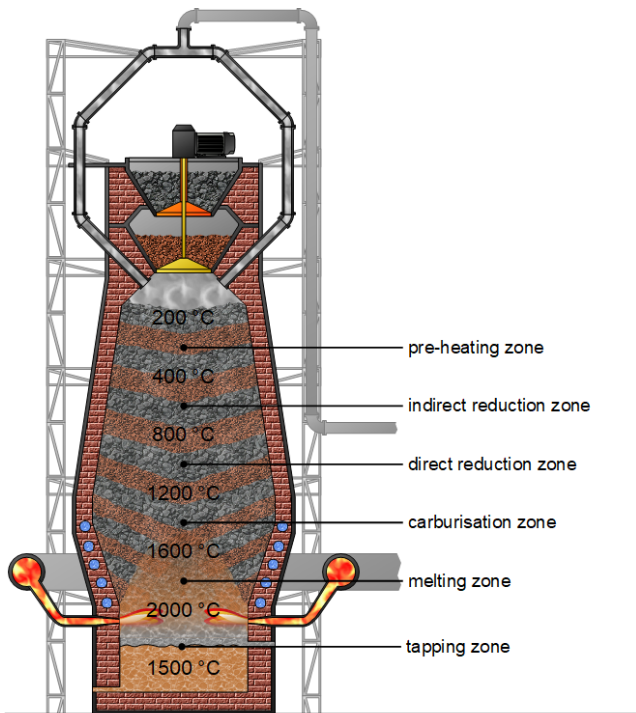
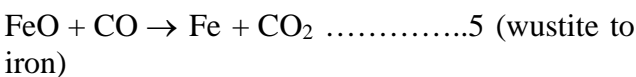
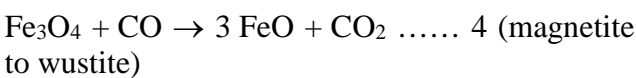
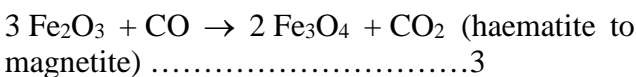


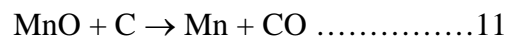
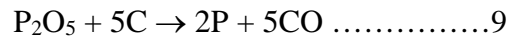
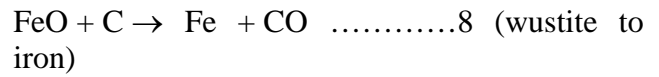
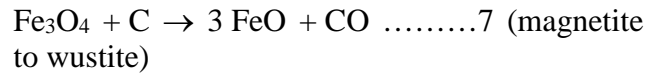
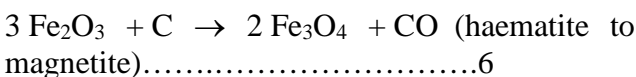
Figure 3. Blast Furnace Zones and Temperatures source: [5]

The gases generated from the combustion of coke then rise up and when they reach the throat of the furnace the temperature there is around 200°C. It is in the throat where the charged ore is preheated and dried.

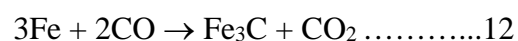
From the throat, the ore descends to the shaft where indirect reduction with carbon monoxide occurs as CO is oxidised to CO₂. Temperatures in this zone are between 400 – 800°C.



From the indirect reduction zone, the ores which have not been reduced are reduced in the direct reduction zone using carbon. Compounds of silicon (Si), manganese (Mn) and phosphorous (P) are reduced as well and react with lime to form slag. These reactions are all endothermic.



The formed iron reacts with carbon/carbon monoxide to form cementite which has a lower solidification temperature than pure iron (1536°C versus 1200°C).



Beyond the carburisation zone, is the melting zone where inner layers of the ore are then reduced as a result of the lowered solidification temperature. The reduction process, carburisation and melting of the iron are completed and the carbon remains in the molten metal.

Molten metal is denser than slag, therefore it settles at the bottom or hearth and is tapped off. The metal also contains approximately the following elements: 4.5% carbon, 2.5% silicon, 1.5% manganese, 0.5% phosphorus and 0.1% sulphur.

1.2 Problems Associated with the BF Route

The BF route leads to high energy consumption in steel making, the use of carbon based fuels and reducing agents, the high demand for steel; and also the release of significant amounts of CO₂ emissions in the process as compared to other industries which is a major concern as environmental regulations on emissions continue to be tightened in order to mitigate the impact of global warming [3]. In 2010, over 1414 Mt of steel were produced [3] and this is almost 5 times the amount of plastics produced in the same year [6]. Table 2 shows, the amount of CO₂ produced by the main unit operations [3].

Table 2. Unit Processes and CO₂ released

Unit Process	CO ₂ released (TCO ₂ /tIs)
Blast Furnace	1.14–1.4
Sintering	0.1–0.11
Coke making	0.06–0.07
Steel making	Up to 0.04
Casting	0.01
Rolling and finishing	0.2–0.29
Oxygen and power plants	0.12–0.21

*tIs – tonnes of liquid steel

The objective of this paper is to explore the possibility of using plastic waste in Africa as an alternative reducing agent to coke in the BF; a recycling practice that is commonly done in Japan and Europe [7].

The quality of hot metal and BF gas produced, and the BF performance is significantly influenced by the coke, waste plastics or iron ore quality and consequently deviations in quality cannot be tolerated. The combustibility of the plastic is also critical for the optimum performance of the BF and waste plastics consists of these highly combustible hydrocarbons which are organic chemicals made from hydrogen and carbon [8]; with only about 3% of total carbon remaining unused in the BF [7].

2 PLASTIC WASTE AS FEEDSTOCK IN IRON MAKING

Plastic waste can be used in iron making through 4 ways [7]: These are;

- Co-carbonisation with coal in coking ovens to produce coke
- Charging the plastic waste through the top. This however, results in the production of tar in the shaft as the plastics decompose.
- External gasification of the plastic followed by injection of the gas through the blast furnace tuyeres.
- Co-injection of pulverised plastic waste and coal through the tuyeres

2.1 Advantages of Using Plastic Waste in The BF

Hanrot, [9] conducted a study on the use of waste plastics in steel making and found that adding 2% of plastics by weight, in the coke

making process reduced CO₂ emissions by 2%. Furthermore, the production of synthetic gas from plastic wastes and its subsequent injection through the BF tuyeres reduced the CO₂ by 7%. Combining these 2 options, would therefore decrease the CO₂ emissions by 9%. Production costs were also found to be lower with plastic waste use even at a purchase price of US\$58 per tonne. The use of synthetic gas from plastic waste also reduces CO₂ emissions by 5%. A 30% reduction in CO₂ emissions can be realised when using plastic waste in the BF. Plastic also has a higher calorific value than coal as shown in Table 3 which then reduces the coke requirements as well as energy consumed by about 47 GJ/t vs 0 to 60 MJ/t saved through mechanical recycling [7].

Table 3. Calorific values of different fuels including plastic [10]

Material	Calorific value
Polyethylene	46,3 MJ/kg
Polypropylene	46,4 MJ/kg
Polystyrene	41,4 MJ/kg
Polyvinyl chloride	18,0 MJ/kg
Coal	24,3 MJ/kg
Liquefied petroleum gas	46,1 MJ/kg
Petrol	44,0 MJ/kg
Kerosene	43,4 MJ/kg
Diesel	43,0 MJ/kg
Light fuel oil	41,9 MJ/kg

Source: Mike Rycroft, EE Publishers

Plastics also have a low sulphur and alkali metal content and this reduces the amount of fluxing agent or calcite required in the process and energy requirements of the process in turn. Alkalis result in the degradation of the coke and sinter and destruction of the refractory lining. Generation of fines in the furnace shaft reduces the permeability of the bed and hinders effective gas flow which in turn results in operational problems such as “hanging” or “slipping” of the burden; scenarios in which adequate reactions do not occur leading to slow material descent or its fall down to the hearth respectively [2]. In addition, the same effect of increased hydrogen in the BF when natural gas is injected is also observed when plastic wastes are injected into the furnace [7].

Table 4 gives a summary of the advantages associated with plastic waste injection into the BF [1] [7], [9]

Table 4. Summary of Advantages of plastic waste as feedstock to the BF [1] [7], [9]

Environmental	Operational	Economic
<ul style="list-style-type: none"> •The quantity of plastic waste landfilled or incinerated is reduced. •Non-renewable coal reserves are preserved •The BF exhaust gas produced contains a negligible amount of furans and dioxins. •Less carbon dioxide emissions due to the high hydrogen to carbon ratio in plastic wastes 	<ul style="list-style-type: none"> •Plastic waste has less sulphur and alkalis compared to coal. Sulphur affects quality of pig iron, while alkalis can affect the coke and sinter quality as well as refractory lining in the furnace. •Blending of coal and plastic waste can improve the properties of the feedstock to the blast furnace allowing lower quality coals to be injected. 	<ul style="list-style-type: none"> •High energy efficiency of at least 80% and lower energy consumption due to the presence of more hydrogen which does not absorb a lot of heat unlike carbon monoxide (hydrogen is a better reducing agent).

2.2 Disadvantages of Using Plastic Waste in The BF

Plastic waste also has some disadvantages when considered for use in the BF. First, the complexities involved in their collection from various sources and management of post-consumer plastic can make the process expensive. In addition, these plastic wastes are varied with differing physical and chemical properties [7], and therefore require different treatments. For example, polyvinyl chloride (PVC) would require de-chlorination prior to its use in the BF, since chloride attacks can destroy the refractory lining of the BF leading to breakouts as well as the piping network in the BF gas cleaning plant. The chlorides can also lead to the formation of toxic dioxins. The de-chlorination adds to the costs associated with PVC use [7]. Plastic wastes cannot also wholly replace the coke in the BF as they not only lack the mechanical strength to support the BF charge or burden but also do not possess the required permeability necessary for efficient gas flow to occur in the BF and in turn reactions.

2.3 Types of Plastics Suitable for Use in the BF

Plastics can be classified as either thermosets or thermoplastics. Thermosets as the name suggests, permanently solidify upon heating and they cannot be softened once this is done. Examples of these plastics are polyurethanes (insulation), unsaturated polyesters (bath tubs), epoxy resins (glue) and phenol formaldehyde [11]. On the other hand, thermoplastics soften on heating, but this process is reversible as they can return to their original condition on cooling.

Thermoplastics can be moulded, extruded and pressed and this robustness has resulted in their use in a variety of applications such as food packaging. Examples include polypropylene, low and high density polyethylene used in food packaging (LDPE and HDPE), polystyrene for takeaway containers (PS), PVC for piping, polyethylene terephthalate (PET) for water bottles, among others [11] [7] [12]. Basing on these characteristics, thermoplastics are the plastics best suited to use in the BF [7] [12].

Table 5 shows the compositions of various plastics, mixed plastics, pulverised coal (PC) and fuel oil.

Table 5. Composition of various plastics, pulverised coal and fuel oil [7] [12]

Element	Unit	PE	PP	PS	PET	PVC	Waste plastic mixture	PC	Fuel oil
Carbon	%	85.6	85.75	92.16	64.71	41.40	77.80	79.60	85.90
Hydrogen	%	14.21	14.15	7.63	3.89	5.30	12.00	4.32	10.5
Sulphur	%					0.03	0.90	0.97	2.23
Ash	%	0.19	0.10	0.21	0.17	0.40	4.90	9.03	0.05
Chlorine	%					47.70	1.40	0.20	0.04
Potassium	%						0.05	0.27	0.001
Sodium	%						0.09	0.08	0.001

From Table 5, it can be seen that the carbon content in the various plastics except PVC and PET surpasses that in pulverised coal (PC) and compares relatively well with fuel oil. Moreover, the carbon content in waste plastic is almost similar to that in PC. Furthermore, waste plastics have a hydrogen content that is almost three times higher than that in PC while impurities such as ash, sulphur and potassium are higher in PC than in waste plastics. However, as afore mentioned the chlorine content is higher in waste plastics than in PC with the chlorine load being contributed by PVC.

Table 6 shows the specification for heavy metals and trace elements in plastics used by voestalpine Stahl involving shredded plastic waste as well as household and industrial packaging.

Table 6. Recommended specifications for moisture, heavy metals and trace elements in plastics [7]

Element	Value
Moisture, %	≤3 or less
Chlorine, %	< 2
Sulphur, %	< 0.5
Mercury, mg/kg	< 0.5
Cadmium, mg/kg	< 9
Lead, mg/kg	< 250
Zinc, mg/kg	< 1000
Copper, mg/kg	< 1000
Arsenic, mg/kg	< 5
Chromium, mg/kg	< 500
Nickel, mg/kg	< 500
Size	≤ 8

The presence of elements such as zinc can lead to the damage of the refractory lining as well as reduced slag viscosity and quality, which creates operational problems in the BF [13].

3 DISCUSSION

There are many benefits that can be accrued environmentally, operationally and economically when using waste plastics in the BF. The hydrogen content in waste plastics is almost three times more than that in pulverised coal making it a better reducing agent economically and environmentally as water is released during the reduction reactions instead of the greenhouse gas, carbon dioxide [7]. Plastic waste has a higher calorific value and has less impurities which results in energy savings and less dioxins and furans in the process.

In addition, bearing in mind that over 130 million of tonnes of plastic waste are currently in Africa's landfills [14], utilising waste plastics in the BF will result in savings in landfills airspace, prevent financial losses incurred through dumping valuable recyclables, protect the environment and the public because if spontaneous fires start in landfills then toxic fumes such as furans and dioxins, cannot be generated if the landfills are plastic free. The possibility of fires occurring in an uncontrolled landfill is high and these are rampant in Africa. There are two types of fires that can potentially occur at a landfill site and these are surface fires involving new material, which occur close to or on the surface of the landfill and are exacerbated by the presence of methane or underground fires

which are deep under the landfill surface and involve waste that is some months or years old [15].

In surface fires waste plastics can result in thick, black smoke due to the emission of volatile matter caused by the high temperatures that result. Surface fires can be caused by dumping waste that is smouldering, inadequate control of the methane gas released at the landfill, smoking at a landfill site either by personnel or the public, dumping of hazardous materials that can start a series of chain reactions, activities such as welding or drilling or sparks from vehicles in the presence of methane gas, uncontrolled intentional fires which can be started to increase the lifespan of the landfill or arson [15].

On the other hand, underground fires occur when significant amount of oxygen causes significant aerobic bacterial activity which in turn leads to increase in temperatures. These high temperatures coupled with methane presence result in underground fires, which can take weeks or months to extinguish. These prolonged fires lead to accumulation of toxic gases on and around the areas close to the landfill site. Toxic levels of carbon monoxide on the landfill surface or in landfill gas are strong indications of an underground fire. Therefore, since landfill fires are not uncommon, it becomes critical to divert plastic waste from landfills [15].

In addition, plastics in landfills can; contaminate the soil and ground water when additives such as Bisphenol-A (BPA) leach out from plastic, be transported by wind into the environment as well as degrade and generate microplastics [16] whose harmful effects on the environment, animals and possibly humans have been highlighted in an earlier publication by Mazhandu et al [16].

Lazarevic et al [17] also concluded that the use of unrecyclable plastic wastes as reducing agents (RA) has less environmental impact than incineration with energy recovery. In Wrap's study [18], RA outperformed pyrolysis in the global warming potential (GWP) and Abiotic depletion potential (ADP), which represents the use of non-renewable resources to produce energy [19]. In the Human toxicity potentials

(HTP), feedstock recycling was at par with pyrolysis and mechanical recycling; outperforming use in cement kilns (solid recovered fuel/SRF), incineration and landfilling. On energy use, although RA came second to SRF, it outperformed mechanical recycling, incineration, pyrolysis and landfilling. With regards to solid waste arising, RA came in third to incineration and SRF but had less environmental impacts than mechanical recycling, pyrolysis and landfilling. Overall, RA was more beneficial for the environment compared to landfilling and incineration.

Plastic waste injection in the BF not only prolongs the refractory lining due to less sulphur but also lengthens the life of coking ovens which are characterised by high capital and operating costs. This is as a result of reduced production of coke [7].

Despite all the potential benefits that plastics can offer in the blast furnace, it is important to note that, these plastics cannot wholly replace coke or pulverised coal but instead blending is required. This is mainly because; plastic lacks the physical strength required to support the heavy burden in the BF as well as the superior permeability that coke offers [3]. A ratio of 30% plastic waste to 70% coke has been recommended, although other studies have recommended 40% [7]. Further to this, it is clear that the reactions that occur in the BF are complex and as a result the quality of the blended feedstock should always be consistent in order to ensure steady operations of the BF [7] and avoid phenomena such as “hanging” and “slipping” or damages to the refractory lining which can cause dangerous “breakouts” where hot molten metal comes out through the furnace shell.

4 CONCLUSION

The three fundamental issues of concern associated with steel making via the Blast Furnace route are; high operating costs, high energy consumption and subsequent release of carbon dioxide from carbonaceous materials involved in the process. Plastic waste is an alternative that can be used by co-injecting it together with coal or coke in the BF. This results in improved economies of scale of the process, reduced energy consumption, as much as a 30% reduction in CO₂ emissions while

simultaneously reducing the amount of plastic waste that is either disposed in landfills where land is scarce or landfill cost or mismanaged through illegal burning or dumping. This also mitigates the effects of mismanaged plastic waste. With such evidence on hand, plastic waste use in the BF presents an untapped beneficial opportunity not only for the continent of Africa but other continents such as North America where landfilling is rife.

5 DIRECTIONS FOR FUTURE RESEARCH

There is need for an audit into the Blast Furnaces in Africa which are in operation and those that can be recommissioned; followed by life cycle assessments to determine the suitable plastic waste to coke ratios that can be used without compromising the furnace operations.

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