UTILIZATION OF PIG IRON IN THE ELECTRIC ARC FURNACE

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INTRODUCTION

Typical Pig Iron for use in the EAF

The production of steel via the EAF route continues to grow both in North America and worldwide. The past 5 years has seen additional growth both in the supply and use of alternative iron materials (pig iron, hot briquetted iron (HBI) and direct reduced iron (DRI)) for use in the EAF. Though initially, the demand for alternative iron materials was based on a need for a lower residual product from melting operations, many EAF operations now use alternative iron materials for other reasons as well. As demand for alternative iron materials has grown, more materials have become available on the merchant market and the number of choices facing EAF operators has grown. In fact, in another 5 years, it is expected that several new processes will be in commercial operation, further increasing the number of options available to steelmaking operations. More and more EAF operations are turning to the use of alternative iron materials as feedstock for the EAF. In particular, many operations have turned to the use of pig iron as it offers distinct advantages over other types of alternative iron feeds. In addition pig

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iron can be blended with materials such as HBI to improve yield and provide improvements to the steelmaking process.

On average, cold pig iron (CPI) now makes up between 5 – 10 % of EAF scrap feed worldwide. However, in some parts of the world where scrap is scarce, CPI may be used in quantities up to 60 % (1, 2). Many operations in China and India also use hot metal as a major component to the EAF charge. If these operations are taken into account, pig iron makes up between 15 and 20 % of the total scrap charge to the EAF. The choice of raw materials at any given facility is clearly based on a keen understanding of specific objectives and goals and cannot be applied universally to other facilities. However, there are several key qualities of pig iron that make it an ideal charge material for any EAF operation. These are discussed in the following paper.

GENERAL ADVANTAGES OF ALTERNATIVE IRON

Generally speaking, pig iron, hot briquetted iron and direct reduced iron are grouped together by EAF steelmakers into a scrap category called alternative iron (AI) materials. Many advantages have been attributed to the use of alternative iron materials in the EAF including:

- Dilute residuals – AI materials contain low levels of residuals
- Lower N content in steel – AI materials are low in nitrogen content and thus result in low bath melt-in nitrogen content. If the AI material results in elevated bath carbon levels, CO formed in the bath during decarburization will strip nitrogen from the bath.
- Consistent chemistry – AI materials are consistent in their chemistry. Thus utilization of AI materials will tend to offset the wide chemistry fluctuations common in obsolete scrap.
- Consistent C recovery – recovery of carbon from AI materials typically exceeds 90 %. Charge carbon recovery can vary widely (20 – 80 %) and some charge carbon is also high in ash content (up to 14 %) and sulfur content.
- Better slag foaming – slag chemistry is more consistent when properly using AI materials. The period of CO evolution is typically extended as compared to conventional EAF operations. These factors lead to more optimum slag foaming conditions.
- Greater slag volume – greater slag volume can lead to higher Fe losses but may be beneficial for slag foaming especially for DC operations and AC operations utilizing long arc practices in the EAF.
- Consistent EAF operations

Alternative iron sources can take on many different forms. Even within a single product type such as DRI, variations in chemistry and metallic content can greatly affect the way in which the material can be used in the EAF. One of the biggest concerns facing EAF operations is to meet product quality and productivity requirements at minimum cost. Without a clear understanding of the effect of scrap characteristics on EAF operations, it will be difficult for any EAF facility to determine the least cost mix of scrap to melt in the furnace. The choice of raw materials at any given facility is clearly based on a keen understanding of specific objectives and goals and cannot be applied universally to other facilities. However, there are several key qualities of pig iron that make it an ideal charge material for any EAF operation and which distinguish it from other alternative iron materials. The following table provides a summary of some of the key advantages of pig iron over other forms of alternative iron materials that can be used in the EAF process.

Attribute	**Pig Iron**	**HBI**	**DRI**
Dilute Residuals	Yes	Yes	Yes
Reduce N content in steel	By dilution and also through CO evolution in the steel bath	By dilution only	By dilution only
Consistent Chemistry	Small variations in Si and Mn content	More variable than PI	More variable than PI and changes can take place in metallization during storage
Gangue Content	Very little dirt content – Si oxidized to SiO2 during steelmaking	More dirt + gangue internal to the HBI	More dirt + gangue internal to the DRI – small pellets tend to pick up more dirt if stored on the ground
Metallization	100 %	88-94	88 - 94
Consistent C recovery	Essentially all of the carbon content is supplied to the steelmaking process – Very high recovery to steel bath – very consistent recovery	Carbon content mostly used to balance FeO content – only supplies small amount of carbon to the steelmaking process	Carbon content mostly used to balance FeO content – only supplies small amount of carbon to the steelmaking process
Better slag foaming	Control of FeO levels in the slag is much more consistent leading to improved conditions for slag foaming	If FeO and C levels in the HBI vary, can upset stability of the slag – can affect slag foaming	Get natural foaming effect if DRI is roof fed – if pellets loose metallization during storage, slag FeO levels can vary considerably leading to loss of slag foaming
Greater slag volume	Smaller effect on slag volume	Generally tends to result in an increase in total slag volume	Generally tends to result in an increase in total slag volume

Consistent EAF Operations	Use of PI results in greatly stabilized EAF operations and increased productivity if oxygen utilization can be increased. Residuals can be greatly decreased.	HBI can help stabilize bath chemistry and lower residuals	DRI can help stabilize bath chemistry and lower residuals

These attributes are discussed in detail in the following sections of this paper.

KEY PARAMETERS FOR EVALUATION OF SCRAP

In order to fully understand the benefits of pig iron as a scrap feed material to the EAF, it is helpful to understand the key parameters by which scrap materials can be evaluated. Key parameters that have been identified in the past as measures of the quality/value of alternative iron materials (AI) include:

- Metallization
- Carbon content
- Gangue content

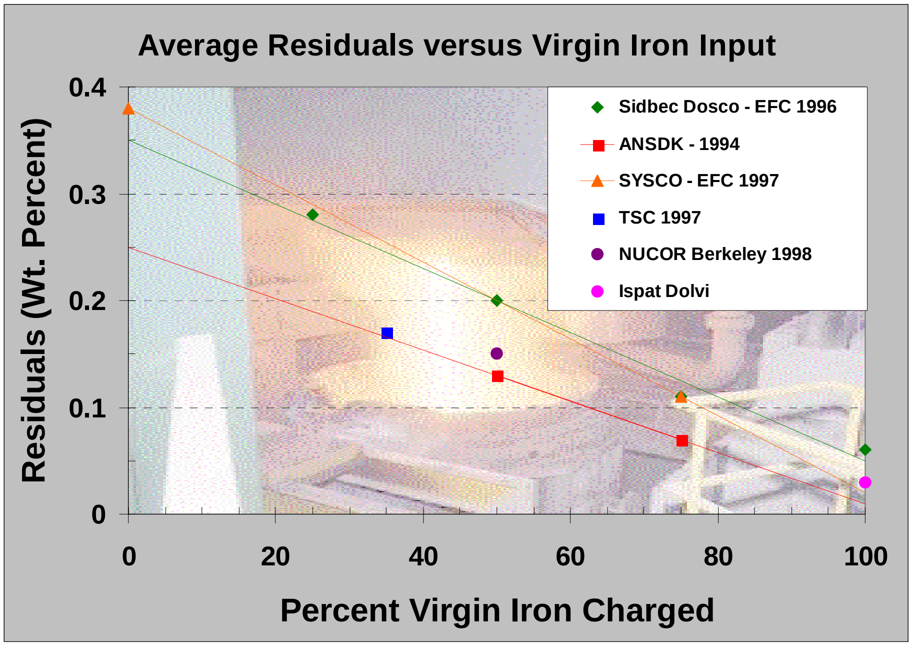
In addition, several other parameters have been identified in recent years as having an effect on value-in-use of AI materials. These include:

- Yield
- Iron, silicon and aluminum content
- Sizing
- Density
- Propensity to generate fines

In fact, it can be shown that all of these parameters can in fact be used to classify any type of metallic feed for the steelmaking process.

RESIDUALS

The major emphasis in EAF steelmaking has been related to achieving maximum energy efficiency in the EAF. In addition, material feed-stocks are also influencing the design of electric arc furnaces and the way in which they are operated. The use of alternate iron sources is the biggest driving force in this area. This includes pig iron (either solid or as hot metal), direct reduced iron (DRI), hot briquetted iron (HBI), and iron carbide. The demand for these “clean iron units” is brought about by the desire to lower the levels of tramp elements (residuals) in the steel. Tramp elements (or residuals) cannot be refined from the steel during processing. Therefore, the amount of these elements in the product is a direct function of the amounts of these elements charged to the steelmaking process in the scrap. Levels of these residual elements (copper, tin, nickel, chrome and molybdenum) are high in obsolete scrap and can affect both casting operations and rolling operations. Residuals may also affect product quality if the levels in the steel are not maintained at sufficiently low levels. One option is to use only high quality scrap in the EAF but this has major cost implications and with the additional flat rolled EAF capacity coming on line worldwide, it is expected that there will continue to be a shortage of high quality prompt scrap. Alternatively by adding clean iron units as part of the scrap mix along with obsolete scrap, the levels of these residuals in the liquid steel can be reduced to acceptable levels through dilution. The following graph shows the dilution effect of using clean iron units in the scrap charge.



(Courtesy K.Cotchen SMS-Demag (3))

LOWER NITROGEN CONTENT

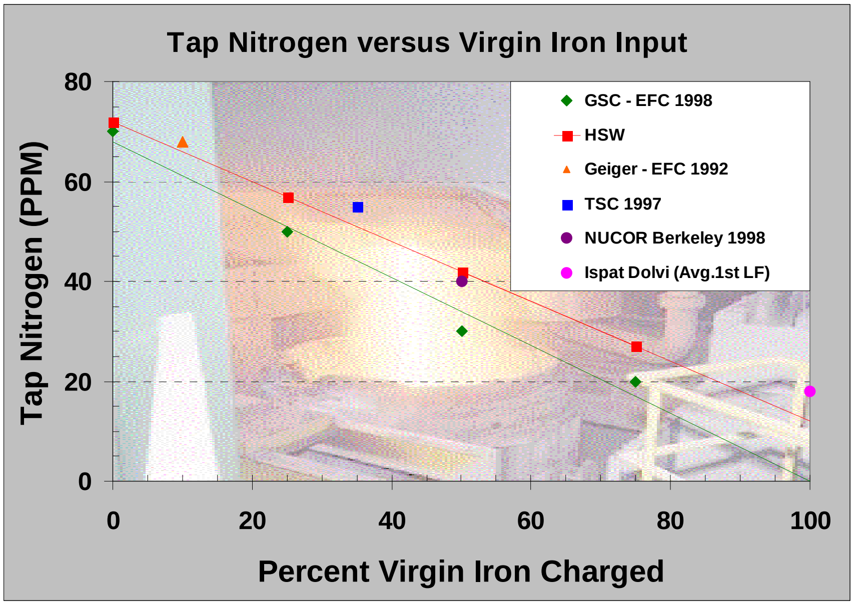
A recent EU study indicated that dissolved gases in steel have a greater effect on product quality and formability than residuals. Dissolved nitrogen has a very large effect on steel casting operations. Typically, steels produced in the EAF are tapped at between 90 and 120 ppm of nitrogen. In order to produce steels suitable for flat product production, nitrogen levels need to be reduced to the range of 40 – 80 ppm depending on the steel grade being made. Nitrogen level in the steel can be reduced by extra processing of the steel in a degassing unit, but this results in additional costs and processing time.

When carbon monoxide gas (CO) is evolved within the steel bath through the decarburization process (i.e. oxygen is injected into the steel to react with carbon), it helps to remove dissolved nitrogen from the steel. Decarburization is also beneficial for the removal of hydrogen. It has been demonstrated that decarburizing at a rate of 1 %

per hour can lower hydrogen levels in the steel from 8 ppm down to 2 ppm in 10 minutes.

Pig iron is generally used to supply consistent carbon recovery to the steel bath and allow for greater use of oxygen in the EAF process. In many cases, pig iron is used to supply additional carbon the steel bath. In such cases, more oxygen can be used which supplies more chemical energy to the steelmaking process. The amount of CO generated in the steel bath is greatly increased as compared to operations using no pig iron and as a result, steel with much lower nitrogen levels can be produced. Pig iron is also naturally low in nitrogen content and therefore helps to produce lower nitrogen levels in the steel through a dilution effect.

Typically, the apparent density of DRI is 3.5 g/cc as compared to that of steel that has a density of 7.8g/cc. Thus DRI will tend to float in the slag or at the bath slag interface. Thus the CO generated from the reduction FeO in the DRI does not assist in removing nitrogen from the steel, because the CO that is generated does not pass through the steel bath, as is the case if this reaction takes place in the steel bath. The lower nitrogen levels achieved with DRI use are attributed to a dilution effect (4), (i.e. the DRI contains very little nitrogen and dilutes the nitrogen contained in the scrap). The DRI does however promote a foamy slag, which is beneficial for preventing additional nitrogen pick-up from air entering the furnace. HBI can also be continuously fed to the EAF though due to its higher apparent density (5g/cc) (5), it tends to sink deeper into the bath and may take longer to melt in. In the case of HBI, some CO evolution may take place in the bath though as the briquettes melt, they tend to break up and the pieces float to the bath slag interface.



(Courtesy K.Cotchen SMS-Demag (3))

Thus HBI and DRI tend to lower the nitrogen content of steel through a dilution effect. Pig iron provides a dilution effect but also results in generation of CO within the steel bath leading to even lower nitrogen content in the steel. If pig iron is used in the EAF charge, the resulting nitrogen levels in the steel at tap will be lower than if a similar quantity of DRI or HBI were used. The graph above depicts tap nitrogen levels for EAF operations utilizing high levels of alternative iron in the charge mix.

PRODUCTIVITY IMPROVEMENT

The use of alternative iron in the EAF scrap charge can have quite varying effects depending on the type of alternative iron used. Typically, the use of HBI or DRI will result in decreased EAF productivity, decreased iron yield, increased energy consumption and longer processing times. Using pig iron in the charge will lead to increased productivity, shorter tap-to-tap times, improved iron yield and reduced electrical energy consumption which is balanced off against greater oxygen consumption.

Operations using high levels of cold pig iron (CPI) (>30 %), have found improved steel quality, better EAF operating consistency, improved iron yield and generally a significant reduction in energy consumption (2). With 35 % CPI in the scrap mix, energy consumption on the order of 390 kWh/tonne liquid steel has been achieved (2). Typical energy savings lie in the range of 3.1 – 3.6 kWh/ % pig iron in the charge. Using hot metal increases the savings to 4.8 kWh/% hot metal (6).

CONSISTENT CARBON RECOVERY

In electric furnace steelmaking, carbon is required in the steel in order to react with oxygen and iron oxide in order to help foam the slag. Some carbon in the steel is also beneficial for lowering the melting point and to meet product requirements. Some carbon is contained in conventional scrap feed materials, though the level will generally be low (between 0.05 and 0.30 weight %). The amount of carbon contained in these EAF feeds will generally be considerably lower than desired level in the steel at flat bath and typically, some additional carbon is charged to the EAF. Alternative iron materials such as pig iron, DRI and HBI can contain much higher levels of carbon than conventional scrap (up to 4.5 weight % in pig iron).

Carbon is also injected during slag foaming operations. This material is typically very fine in nature and may be blended with fluxes (CaO, MgO) to assist in the slag foaming process. This material does not contribute significantly to the steel bath carbon level and should not be confused with charge carbon. Injection of foamy slag material will typically lie in the range of 5 – 15 kg/tonne of steel produced.

In the past carbon was charged to the furnace to ensure that the melt-in carbon level was above that desired in the final product. As higher oxygen utilization has been implemented as a standard EAF practice, additional carbon is required in EAF operations as a fuel to balance out the increased oxygen use. The reaction of carbon with oxygen within the bath to produce carbon monoxide results in a significant energy input to the process and has lead to substantial reductions in electrical power consumption in EAF operations. The generation of CO within the bath is also integral to achieving low concentrations of dissolved gases (nitrogen and hydrogen) in the steel as these are flushed out with the carbon monoxide. The CO gas bubbles which are generated also help to foam the slag (create an emulsion) which helps to contain the electric arc and improve energy transfer to the steel (radiative heat losses from the arc can be contained so that the energy is transferred to the steel bath instead of to the furnace shell). Many EAF operations aim for a melt-in carbon level of approximately 0.2 to 0.3 weight %.

The amount of charge carbon used in a given EAF operation will be dependent on several factors including:

- Carbon content of scrap feed
- Projected oxygen consumption/oxygen availability
- Desired tap carbon level
- The economics of iron yield versus carbon cost
- Offgas system capacity

In general, the amount of charge carbon used will correspond to a carbon/oxygen/iron balance, as the steelmaker will try to maximise the iron yield. Typical charge carbon rates for medium carbon steel production lie in the range of 2.5 – 12.5 kg/tonne liquid steel.

Many different materials can be used for charge carbon from coal to coke to rubber tires. The majority of operations use coal. It is important to note that the fixed carbon in charge carbon materials can vary significantly and ash content can be as high as 12 %. The method of placement in the charge bucket can have a major impact on carbon recovery in the furnace. In addition, several operators have found that the size of the material also has a big effect on carbon recovery. Coal can have fixed carbon levels ranging from 60 to 80 % and recoveries in the EAF also vary from 20 to 80 % depending on the coal size and method of addition to the furnace.

One of the biggest problems encountered by EAF steelmakers is the variability of recovery for charge carbon. Analysis has shown carbon recoveries ranging from 20 to 80 % within a single operation. The fluctuation in carbon recovery can lead to an imbalance in the C/O/Fe balance leading to slag characteristics that are unsuitable for good slag foaming. This can lead to poor energy efficiency, yield losses, damage to the EAF, higher steel nitrogen content, reduced productivity and much higher processing costs.

When large quantities of pig iron are used, it may not be necessary to add charge carbon at all. A tonne of pig iron with 4 % C content supplies 40 kg of carbon to the steel bath. Thus for a furnace with a total 100 tonne charge weight, every 1 % of pig iron in the charge supplies 0.40 kg per ton of charge carbon (assumes 4 % C in pig iron). Thus 20 % pig iron in the charge would supply the equivalent of nearly 8kg/charge tonne scrap. Now if we consider for a moment that this furnace usually requires 10 kg of charge carbon per charge tonne, and that the recovery is 40 % and the actual carbon content of the charge carbon is only 80 %, we can calculate, the actual carbon requirement to be supplied from the pig iron:

Carbon Requirement = 10 * 40 % * 80% = 3.2 kg carbon per charge ton

This amount of carbon could be supplied by using 8 % pig iron in the charge since the recovery of the carbon in the pig iron is essentially 100 %:

Pig iron % = 100 charge tonnes *3.2 kg charge C/charge ton/ 40 kg C per 1 % pig iron = 8 %

If more oxygen is available to this facility, they could consider using in excess of 8 % pig iron in the charge in order to utilize more chemical energy in the EAF. This would reduce tap-to-tap time, increase productivity, reduce energy losses, reduce electrical power consumption and reduce production costs.

Carbon content in pig iron or hot metal varies considerably depending on the process source. Typically pig iron will contain between 3 and 4.5 %. It is easy to see that use of large amounts of high carbon materials must be balanced with oxygen availability in order that decarburization time is not extended. The maximum practical decarburization rate in the EAF is much less than in the BOF due to the shallow metal bath. Exceeding a rate of 0.1 % C per minute typically results in excessive metal splashing and increased fume losses to the offgas system. Typical decarburization rates in the EAF range from 0.06 % C to 0.1 % C. Too high a carbon level in the charge materials may actually extend the tap-to-tap time due to oxygen blowing limitations.

Many EAF operations now choose to use higher levels of oxygen injection into the EAF in order to increase productivity. As a result, it is necessary to add more charge carbon in order to maintain a high Fe yield. This has resulted in a secondary problem for those operations using large quantities of charge carbon. Coal typically contains from 2 to 20 % ash. This ash may contain up to 50 % Alumina (Al_2O_3). Alumina will combine with other flux materials in the EAF to form slag. The chemistry of this slag must be controlled in order to maintain conditions that are conducive to slag foaming. Once the alumina content in the slag climbs above 6 % it begins to have a bigger effect on slag viscosity. As a result, additions of CaO and MgO must be increased to balance out the Alumina. This can result in increased power consumption and extended tap-to-tap time. The carbon contained in pig iron contains no ash and thus does not contribute to higher alumina levels in the EAF slag.

Many claims have been made in the past as to the benefits of carbon contained in DRI. In the case of DRI, carbon levels in the product material are controlled by injecting a hydro-carbon gas in the cooling section of the reduction shaft. Production of high carbon DRI will negatively impact the productivity of the MIDREX reduction furnace and will displace iron units. Carburization potential is related to iron oxide type. If carburization is increased, the percent metallization will decrease unless the production rate is reduced.

Usually, sufficient carbon is provided to balance the FeO content in the DRI (approximately 1 % C for every 6 % FeO). If the DRI has insufficient carbon content to reduce the FeO contained in the DRI, the slag FeO level may become too high making it aggressive to furnace refractories and making it difficult to regain good slag foaming in the furnace. This is frequently the case for merchant DRI, as the material oxidizes during transport and also during storage, especially if it is stored on the ground.

MIDREX has carried out an extensive study with several of its' clients and has concluded that high carbon levels in the DRI are not beneficial to the EAF steelmaker (7). HYL has presented a different view of carbon levels in DRI and claims that high carbon levels can be very effective in supplying energy to the EAF (7).

When DRI is charged to the EAF, the carbon in the pellet is used to reduce the FeO contained in the pellet. This reaction is endothermic and actually increases the energy requirements for steelmaking. The carbon in the DRI pellet is typically not available as a source of carbon for the steel bath. MIDREX found that increasing carbon levels in DRI up to 1.8 % aided in creating and sustaining a good foamy slag, but this reaction does not provide energy to the steel bath. In operations utilizing 20 % or more DRI in the scrap blend, the DRI is usually fed through the roof and tends to float in the slag because it has a low density compared to the steel and slag (see comments in previous discussion on nitrogen control).

Most merchant HBI contains between 0.8 and 1.5 % carbon content. This may be related to the fact that at carbon levels above 2 % in the DRI, the material becomes very difficult to briquette. Thus for the merchant HBI market, high carbon HBI might not be readily available. HBI is somewhat denser than DRI and will tend to float at the bath/slag interface. Again, the bulk of the carbon content in HBI is required to balance out the FeO content in the briquette. The small remaining amount of excess carbon can contribute to the bath carbon requirements for the EAF though the amount is very small in comparison to that which can be supplied from pig iron.

IMPROVED SLAG FOAMING

At the start of meltdown the radiation from the arc to the sidewalls is negligible because the electrodes are buried in the scrap. As melting proceeds the efficiency of heat transfer to the scrap and bath drops off and more heat is radiated from the arc to the furnace sidewalls. By covering the arc in a layer of slag, the arc is shielded and the energy is transferred to the bath. When foamed, the slag cover increases from 4 inches thick to 12 inches or more (10 – 30 cm). HYL also indicates that at high carbon removal rates and 80% DRI, the foamy slag thickness can be as high as 40 inches (102 cm) (8). Claims for the increase in energy transfer efficiency range from an efficiency of 60 - 90 % with slag foaming compared to 40 % without. The following table shows results for efficiency of electrical energy transfer for different levels of arc shielding by the slag (9).

Table II Electrical Energy Transfer Efficiency for Various Slag Conditions in the EAF

Type of Arc	**Electric Energy Transfer Efficiency %**
Free burning	26
Partly surrounded by foamy slag	65
Totally surrounded by foamy slag	93
Partly resistance heating	97
Totally resistance heating	100

It can be seen that totally immersing the arc in the foamy slag has a huge effect on electrical energy transfer efficiency. Slag foaming results in greatly improved thermal efficiency and allows the furnace to operate at high arc voltages even after flat bath is reached. Burying the arc helps to prevent nitrogen from being exposed to the arc where it will dissociate and will enter the steel.

In the case of DC furnaces, it is even more critical to ensure that the arc is buried because, typically, these furnaces tend to operate at much greater arc voltages than conventional AC furnaces.

Consistent recovery of charge carbon is critical to the control of FeO levels in the slag. If FeO levels are too high, the slag will be very fluid and will not retain the CO gas bubbles generated from oxygen injection. If the FeO level is too low, the slag with be extremely thick and viscous and will not be cable of forming an emulsion with the CO gas bubbles. Control of carbon recovery in the EAF is integral to maintaining the correct C/O/Fe balance that will provide optimal energy efficiency (through slag foaming) and optimal yield which has the biggest effect on melting costs.

CORRECT SLAG VOLUME

In order to have efficient EAF operations, it is necessary to have sufficient slag to bury the arc but not an excess of slag. This is because metallic iron losses to the slag increase as the amount of slag increases. Generally speaking, AC furnace operations typically aim for a slag volume of about 6 – 12 % of the tap weight. Thus if an EAF is tapping 100 tons, they would aim for a total slag amount of 6 to 12 tons (likewise an EAF with a tap weight of 100 tonnes would aim for 6 – 12 tonnes of slag). Of course, sometimes the operator will end up with excessive slag due to dirt levels in the scrap or high ash content in the charge carbon. DC EAF operations typically use a longer arc length and thus try to have a deeper slag and aim for a slag volume of about 8 – 16 % of the tap weight. If an EAF has a deep furnace bottom, they may try to promote slag carryover from heat to heat.

The total amount of slag generated will be a function of the amount of silica (SiO_2) and alumina (Al_2O_3) that enters the EAF in the scrap feed and other charge material. Lime and MgO are deliberately added by the steelmaker so that the ratio of lime / (silica + alumina) is between 1.5 and 2.2 (this ratio is called the B3 ratio). A value in this range coupled with the correct FeO level and MgO level usually results in a good foamy slag. In the case of DRI and HBI, the amount of silica and alumina in the material may be as much as 4 %. Thus the slag volume may be much higher and the amount of lime and MgO which must be added increases. Pig iron contains silicon which when oxidized in the steel bath will generate energy but will also form silica. However, the amount of silicon in most merchant pig iron is usually below 0.7 weight % and this does not contribute to as large an increase in slag volume.

In many EAF operations producing flat products, the scrap that is used is too clean. It contains very little dirt and very low levels of silicon. In some cases, there is insufficient slag generated and in order to have sufficient slag to bury the arc, some operations have to add sand to the furnace. In such operations, using pig iron can provide a huge benefit as not only is the correct amount of silica produced but the operation also gains the energy benefit from the silicon reacting in the steel with oxygen to form silica. This can lead to better slag foaming due to early formation of a slag conducive to foaming.

SCRAP SIZING AND DENSITY

Sizing of the scrap can have a significant effect on melting operations. The acceptable scrap size is generally a function of the size of the furnace and the power rating of the transformer. Many operations have reduced their use of scrap bundles because they take too long to melt and tend to cave in, resulting in electrode breakage and lost operating hours.

Generally speaking, smaller scrap melts faster than larger pieces due to the relatively larger surface to volume ratio. Similarly, bulk scrap volumes with higher density take longer to melt than similar volumes of less dense scrap. Despite the melting rate advantage, a 100% charge of small scrap pieces is not advisable since it might result in excessive scrap cave-ins and arc instability.

Results for a Brazilian EAF operation utilizing high levels of CPI have identified the following (2):

- CPI is normally charged in the last 1/3 of the bucket in layers of no more that 7 tonnes
- To avoid arc deflection back to the roof, CPI should never be in the top layer of the bucket

- CPI should be surrounded with light scrap such as bushellings and turnings
- Oxygen blowing must commence shortly after power-on in order to decarburize the heat without incurring a delay
- With 35 % CPI, nitrogen levels in the steel were less than 50 ppm

Usually, a maximum of 20 – 25 % cold pig iron is used in the EAF. Furnace operators prefer small “pigs” which will melt in along with the scrap in the charge. If the CPI consists of very large pieces, it will take longer to melt in and may result in fluctuations in steel bath chemistry during processing. If higher percentages of pig iron are used, the oxygen blowing profile must be adjusted to ensure that decarburization delays do not result. Some operations have witnessed large un-melted pieces of pig iron when tapping. If the CPI is loaded too high in the scrap bucket, it may stick to the furnace walls and may also cause arc deflection back onto the EAF roof. Pig iron should be placed in the bottom half of the first charge bucket so that it will melt into the bath early in the heat. This allows for adequate decarburization time, (thus avoiding the possibility of an extended tap-to-tap time), and allows for maximum recovery of energy from CO post-combustion to cold scrap in the furnace.

DRI consists of small pellets and these will typically melt in quickly. However, when charged in the scrap bucket, they have a tendency to form clumps in the EAF which may stick on the furnace walls. These clumps may fall into the bath later in the heat and may cause small explosions and ejection of material from the EAF. HBI tends to have fewer problems with regards to sticking together as long as it is charged in layers (i.e. layered in the scrap bucket).

Utilization of pig iron in the scrap bucket can frequently lead to a reduction in the number of back charges required due to the high density of the CPI. Every time the furnace roof is raised and swung for charging, radiative energy losses of 10 – 20 kWh/tonne occur. By making the charge denser, the number of back charges can be reduced. DRI and HBI have a lower density than pig iron and as such provide a smaller benefit.

CONSISTENT SCRAP YIELD

Total metallic yield Fe for pig iron will typically be in the range of 94 – 96 % which is comparable to #1 prompt scrap. The only reason why the yield is not higher is because the silicon, manganese and carbon content are oxidized in the steel bath to generate chemical energy for the process and assist with slag formation for foaming. DRI and HBI typically have a yield of between 88 and 92 %. Analysis of the wide variation in yield of various scrap types indicates that total iron content in some conventional scrap may be as low as 70 % and for most conventional scrap types will lie in the range of 88 – 92 %. Even #1 grade scrap will typically contain surface coatings and oil and grease, which will result in a total iron yield of less than 96 %.

Percent metallization refers to the % of iron in the scrap, which is present as metallic Fe:

% Met = [(% Fe metallic)/(% Fe Total)] * 100

Typically steelmakers prefer a metallization of about 92 % or higher for alternative iron materials. **Useable iron** content refers to the amount of metallic iron present in the feedstock (% Fe metallic) and is an indication of the amount of the feed, which will directly contribute to the steel bath. Any iron that is not in this form will be present as iron oxide and must be reduced in the bath to recover the iron units. This will require both energy input and a source of reductant, usually carbon. In pig iron, 100 % of the Fe content is metallic Fe. In HBI and DRI, typically the metallic Fe is only 88 – 92 %. As a result, pig iron is a much better source of iron units than DRI or HBI.

Metallization in conventional scrap materials may be fairly high, though the yield of metallic iron to the finished product can be quite low compared to pig iron. This is because many melting operations overlook the actual iron content of the scrap and do not account for extraneous materials such as oil, grease, dirt, coatings, moisture, plastic and other foreign materials which all contribute to yield losses. Pig iron does not typically have any of these materials associated with it. In pig iron, the iron content is very high and is 100 % metallic. The Fe content in pig iron is easily identified and this fact explains why it is used as a quality control parameter.

SCRAP STORAGE

Pig iron is a relatively inert, dense material that is easy to ship and easy to store. Pig iron does not tend to absorb moisture when stored in the open. Pig iron does not tend to break up during shipping and handling and thus fines generation leading to yield losses does not occur. Many steelmaking operations do not consider how well a scrap type can be stored when they evaluate scrap. In addition to not storing well, some scrap types exhibit significant yields losses when handled during shipping and at the scrap yard. Several users of DRI have measured fines generation during shipping due to handling of the pellets and estimate that the –1 mm fraction typically increases by 3-5 %. DRI can absorb 10 to 15 % moisture if it is stored uncovered in wet weather (10). HBI has a much lower surface area and several re-oxidation tests indicate that it re-oxidizes at approximately 30 % of the rate experienced by DRI pellets. HBI tends to absorb 3 to 5 % moisture when stored uncovered (10). Another issue with DRI and HBI stored on the ground is that they become easily contaminated with dirt as the piles are reclaimed. This leads to even higher levels of acid gangue materials when charged to the EAF.

Other conventional scrap types such as borings and turnings will also tend to be very reactive when stored on the ground and will readily oxidize in wet conditions. These materials also suffer from dirt contamination in a similar manner to DRI and HBI.

BLENDING OF SCRAP MATERIALS

It has been found that proper layering of the materials in the charge is very important for yield, energy consumption and to prevent sticking of these materials. In some high quality applications, it may be necessary to charge up to 50 % alternative iron in order to meet residual and nitrogen requirements in the product. Recently, several operators have discovered the benefits of charging DRI/HBI in close proximity to pig iron. Several operations have found that this resulted in lower power consumption and greatly improved yield (in some cases the HBI yield improved more than 5 %). The reasoning behind this phenomenon is that the HBI melts in thus releasing FeO, which is then reduced due to the high carbon content resulting from the pig iron. The net result is that almost all of the iron content in the DRI/HBI is recovered.

In general, it has been found that good blending of the DRI/HBI with pig iron and conventional scrap results in improved yield and reduced power consumption while minimizing the negative melting aspects of these materials.

Table IV Projected Power and Oxygen Consumption for Mixed CPI/HBI Use in the EAF

% (CPI + HBI)	Power Required kWh/tonne	Oxygen Required Nm3/tonne	Flux Requirement kg/tonne
0	466.6	10.4	23
20	466.8	13.6	33
40	467.9	16.9	44
60	469.0	20.3	55

MORE CONSISTENT EAF OPERATIONS

The key to high productivity in the EAF is to achieve uniform, consistent operation from one heat to the next. Many high productivity EAF shops have adopted the practice of tapping a uniform heat of steel with respect to chemistry and then making the desired steel grade in the ladle. This has resulting in significant improvements in EAF productivity but it is easy to see that the fluctuations that occur in the scrap mix with respect to density, scrap sizing, carbon content and silicon content cause considerable disturbances in EAF operations leading to:

- Variations of +/- 10 % in tap-to-tap time
- Variations of +/- 5 % in power consumption
- Variations of +/- 5 % in oxygen consumption
- Variations in tap temperature of +/- 15 C
- Wide variations in slag chemistry leading to poor foaming efficiency
- Damage to the furnace sidewalls and roof resulting from arc flare

- Over-loading of the EAF offgas system

Several comprehensive scrap management models have been developed and are in use in some EAF meltshops. These models tend to focus on residual requirements for the steel grade being made, the properties of the scrap materials, the actual inventory of materials on hand at the plant and plant logistics (11). Approximately 75 % of prompt scrap is available as identified, unmixed material that is low in residuals (11). The amount of variation in the chemistry and physical properties of such scrap is minimal.

Obsolete scrap however, originates from a wide variety of sources – automobiles, appliances, structural steel, miscellaneous sheet products etc. (11). The level of variation in these materials is considerable. Not only does obsolete scrap tend to contain high levels of residuals but also these levels will fluctuate considerably based on the source of the scrap. Most obsolete scrap is supplied to the EAF facility based on sizing and density – thus the EAF operator is faced with considerable fluctuation in scrap chemistry, sometimes from one heat to the next.

Utilization of pig iron can have a significant effect on minimizing the effects of fluctuations in obsolete scrap chemistry. Traditionally, pig iron has been used in steelmaking operations producing higher quality products. However, recent evidence has shown that pig iron can be very cost effective for operations using high levels of obsolete scrap purely due to its stabilizing effects on the operation.

CONCLUSIONS

Since the first steel was made, pig iron in one form or another has been an integral component material. Though the face of steelmaking has changed considerably over the past 40 years, the utilization of pig iron as a raw material for steel production has grown. With the growth of EAF steelmaking which was focused on the recycle of steel scrap as opposed to making steel from virgin iron units, one might suspect that they demand for pig iron would have declined. However, as EAF steelmakers expanded their product offerings to include low residual flat and long products, they found that pig iron was an ideal raw material for use in the EAF and that it provided increased flexibility to the EAF process. Through the utilization of pig iron in the EAF, EAF steelmaking has evolved to take advantage of the flexibility to use large quantities of both electrical and chemical energy in the process.

The benefits of pig iron include:

- High density
- Dilute residuals – Pig iron contains essentially no residuals – very effective at diluting residuals introduced in lower grade scrap types
- Consistently high metallic yield and improved yield of other scrap types when used with pig iron
- Better slag foaming consistency

- Excellent carbon recovery to the bath – possibility to utilize more chemical energy in the EAF with consistent results
- Increased EAF productivity
- Improved Efficiency of EAF operations
- Better nitrogen control than other scrap types
- Easy handling compared to other scrap types
- Ease of storage for long periods of time – metallization not affected

Though some other raw materials provide some of these benefits, no other material provides all of the benefits that pig iron supplies to the EAF. Thus it is not surprising that pig iron has become a material of choice for EAF steelmakers.

THE AUTHOR

Jeremy Jones is currently Director of Operations and Engineering working with Nupro Corporation. Jeremy received his Bachelor's and Master's degrees in Chemical Engineering from Queen's University at Kingston, Canada, in 1983 and 1985, respectively. Following several years at Hatch Associates Limited, Jeremy held key positions at Nupro Corporation and at Ameristeel. In September 1995, Jeremy joined Bechtel Corporation as principal engineer for Iron and Steel projects worldwide. In March of 1998, Jeremy joined AG Industries as the vice-president of business development for the Steelmaking Technology Division. Jeremy's previous consulting roles have involved many international assignments focused on ferrous and non-ferrous process technologies including process plant improvement, review and development of environmental systems (including the design/retrofit, installation and start-up of more than 25 offgas systems), development of process control systems and plant start-ups. Recently, Jeremy has focused on EAF technologies under development and alternative iron feedstocks including new ironmaking technologies. Jeremy is a regular participant in both AISE and ISS training seminars and has authored over 50 papers in the field of EAF steelmaking. Jeremy was the primary author for the EAF steelmaking chapter in the recently updated volume of "Making, Shaping and Treating of Steel". Jeremy is past-chairman of the ISS Continuing Education Committee and also sat on the ISS Advanced Technology Committee and the ISS Energy and Environment Committee. Jeremy is currently a member of the AIST Electric Furnace Operating Committee. Jeremy has been a presenter each year since the conference began in 1995.

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