Improvements in Yield in an All-DRI-Fed EAF From Minimization of FeO Generation During Melting as Well as Post-Reduction of FeO From Residual Slag

In recent years, ArcelorMittal Mexico has focused on improving iron yield in the continuing challenging economic environment. Previous work highlighted recycling and briquetting direct reduced iron fines. This improved yield more than 2%. In that work, it was noted that additional yield savings were possible by a tighter control of ppm oxygen at tap to avoid excess generation of FeO. This also applies to generation of FeO during the heat. By delaying the initiation of lancing, the final slag %FeO can be reduced and yet meet aim carbon. Lower slag %FeO not only improves yield, directly lowering costs, but additionally leads to cost savings from using less aluminum after tap.

Over the past several years, the authors have reported significant progress on improving yield in all-direct-reduced-iron (DRI)-fed electric arc furnaces (EAFs).\textsuperscript{1–3} A significant breakthrough was realizing that subsized DRI pellets and fines were short-circuiting the furnace by floating out with the slag over the breast rather than getting ingested into the bath. This is attributed to Stokes’ Law, whereby the falling (terminal) velocity of the pellet decreases in proportion to the square of its diameter, so that the smaller the pellet, the greater its descent velocity through the slag on feeding. While this velocity never, by itself, can reach zero, in the furnace the falling DRI encounters an upward force from the evolution of CO from decarburization and reduction of carbon and FeO in the pellet. This phenomena effectively suspends the smaller DRI pellets and fines in the slag.

This has led to a successful strategy based on screening pellets and fines in the feed below 0.25 inch and recycling them as briquettes. As a result, yield has jumped some 2%, an enormous improvement for general improvement in yields.

Most recently, the authors explored factors related to fracturing of the DRI pellet in the first place, upstream of the EAF, focusing particularly on the DRI reduction units (Midrex and HYL). Generally at issue is a compromise between pellet strength during reduction and pellet porosity needed for good reducibility that is largely determined upstream by ore concentrate selection and the pellet production process. These phenomena are complex, suggesting they can be optimized. However, it was decided to not compromise metalization in any trade-off between compressive strength and porosity. Instead, a recycling practice was developed, although it does entail additional costs with regard to briquetting. However, in this case, the tremendous improvement in yield more than offsets these costs.

In previous papers, the authors elucidated the key factors affecting yield. Top of the list is slag volume because of the contained FeO dictated thermodynamically by the carbon level in the metal at tap. In this case, there are unduly high slag volumes due to reliance on cheap but high gangue ores to produce the DRI as mandated by management. Thus, aiming for lower slag volume is out of scope, as it is important to maintain a sufficient basicity and.
adequate MgO levels to avoid erosion of the furnace refractories, etc.

From a thermodynamic point of view, low yields are the result of an imbalance between oxygen and carbon in the system. In fact, there is also a kinetic aspect that plays a significant role as well. This is because the EAF is not nearly well mixed as, say, the basic oxygen furnace (BOF). As a result there can be global and local departures from equilibrium. Since the slag and metal are not well mixed, the slag, for example, can be excessively oxidizing relative to the metal, yet the metal tap remains at the aim ppm oxygen. In consideration of this phenomenon, the focus will be on the lancing practice and any role it might have in generating excess levels of FeO.

The present paper explores not only the benefits of a tighter control of the lancing practice near the end of the heat to avoid overoxidizing the slag, but also any benefits of delaying initiation of lancing early in the heat. These two practices can lead to lowering slag FeO levels for an essentially fixed slag volume without an adverse effect on ability to achieve the desired ppm oxygen and power-on-time.

Additionally, the benefits are also reported of a further reduction of FeO from the residual slag in the system by making use of the time gap in between heats (where, for example, the slag pot is changed out) and the relatively large hot heel.

Together, the practices of recycling DRI of a subpar pellet size, more optimized lancing practice and further reduction of FeO in the residual slag after tap have resulted in a combined substantial improvement in furnace yield.

**Yield Loss Occurring During Melting**

As stated earlier, it is important that the carbon and oxygen flows in the furnace be in balance. It can be shown from thermodynamic calculations of the FeO-O-C equilibrium for a given slag basicity and temperature that the slag has an FeO composition that is dictated by the aim ppm O if the system is in complete equilibrium. For example, for the ratio CaO/SiO₂ in the slag taken at 1.5, at 1,600°C and for an aim of 1,300 ppm O, the slag FeO is about 20%.

It is of interest for this paper to examine the actual slag %FeO relative to this level during the progress of the heat. This calculation shows the gap from the equilibrium value to widen during melting, thus a deterioration of yield had the gap remained constant. At the start of the heat, the residual slag in the hot heel is about 26% FeO, which is a gap of some 6% from the equilibrium value as a result of the practice to add coke in the pre-melting stage. Given a reasonable maximum heel size of, say, 50,000 kg/heat, of which 40% is slag, then about 5,200 kg FeO is in the furnace at the start of the subsequent heat. Since the equilibrium value is about 20% FeO, the gap at the start of the heat is some 6% FeO, or a maximum potential yield differential of about 0.4%.

The slag volume then increases during the heat as DRI and fluxes are added. If the DRI is particularly high in acidic gangue (Al₂O₃ and SiO₂), the slag volume will reach as high as 300 to 400 kg/ton, or as high as 66,000 to 88,000 kg/heat. At the end of the heat, the slag typically reaches about 35% FeO. This represents a widening of the gap (with respect to the equilibrium value) to about 15% FeO. Taking a slag volume of 350 kg/ton, this represents a maximum differential in yield of more than 4% relative to equilibrium conditions! The difference in potential yields from the beginning of the heat to the end of the heat represents a substantial deterioration of yield during melting. This depends on not only increasing slag %FeO but also the very large slag volume generated during the heat. It is clear that, while there is a significant improvement in yield from the pre-melting stage practice, the bigger potential payback is improvement from preventing increases in slag %FeO during melting in the first place. In this case, this is especially glaring, given the unduly high slag volume.

**Role of Kinetics and Excessive FeO Levels During EAF Melting**

In a previous paper, the authors revealed a key mechanism for the production of excessive FeO in the all-DRI-fed EAF, namely the role of the rate of mass transfer of carbon in the bath during decarburization. This includes not just the mass transfer coefficient, but also the driving force due to carbon dissolved in the bath relative to the equilibrium level. Essentially, when the mass transfer of carbon is limited compared to the lancing rate, the incoming oxygen finds a home oxidizing iron instead. This phenomenon can be particularly important near the end of the heat, when the driving force for mass transfer of carbon can be at its lowest when carbon levels are at their lowest point in the heat. Here it is easy to overblow the heat and produce excessive FeO by this mechanism.

But, this same mechanism can be a factor early in the heat as well, now possibly from a slower rate of dissolution and transfer of carbon due to lower temperatures. Early in the heat, bath temperatures are at their lowest, so perhaps access of the bath to carbon locked in the DRI can be limited, resulting in a lower driving force for diffusion of carbon. Also, the mass transfer coefficient may be lower as well due to less mixing if the DRI is not reacting as vigorously early in the heat. It is recognized that the complete kinetic picture is much more complicated, where interfacial areas, reaction rate coefficients and other
driving forces (i.e., for the oxidation of iron) can also come into play, and where no one mechanism may be rate controlling (i.e., mixed control). However, if decarburization is rate controlling early in the heat, then, if lancing is initiated too early and at too high a rate, excess generation of FeO will be the result. The authors believe this is the basis for any benefit from optimizing lancing at this stage and helps to explain the results now reported. On the basis of numerous plant trials, oxygen lancing is delayed for 8 to 10 minutes, during which time the PTI injector is employed in burner mode.

Optimizing the Reduction of Residual FeO in the Pre-Melting Stage

A practice has been developed that profits from a time gap between heats and the relatively large hot heel. This time gap is the result of having to empty the slag pot often due to excessive slag volume from the high gangue ore for the DRI. It is estimated that some 40% of the hot heel is residual slag containing FeO from the previous heat. Also, since the level of the bath is at its lowest at this stage in between heats, there is little slag-off with concomitant potential loss of iron units with slag over the breast either as FeO contained in the slag or as DRI fines suspended in the slag due to its subordinate size.

At this pre-melting stage, 1,000 kg coke briquettes of agglomerated DRI fines that were screened in the feed of previous heats and additional DRI pellets are charged. These additions to the hot heel are illustrated schematically in Fig. 1.

Numerous plant trials have been conducted to study the effectiveness of various parameters — among them, the amount and characteristics of the carbon added, the amount and carbon level of any DRI added, and the residence time available for this stage, as well as %FeO from the previous heat. Both coke and anthracite were used as the carbonaceous materials. For this, it was found that higher fixed carbon resulted in a faster and more effective reduction of FeO during this stage.

The addition of coke together with DRI and its timing seem to be the most important process variables. DRI is needed along with the coke additions, initially, to help ingest the lighter coke pieces into the hot heel, and soon after, on reaction of the DRI, to provide agitation. The amount of coke (and DRI) charged mildly benefits the overall reduction of FeO, but the residence time during this stage has a profound effect. The effects of these two factors are shown in Figs. 2 and 3.

With regard to amount added, this can be tied to %FeO in the hot heel from the previous heat, but it was found that excessively large amounts of coke and DRI added as needed for slags very high in FeO unduly lowers bath temperature, suppressing kinetics of reduction for this stage as
a whole. An amount of 1,000 kg of coke provides the best results (see Table 1).

The slag at tap is about 32% FeO. With this pre-melting practice, this drops to about 26% FeO. This drop, for a hot heel size of 50,000 kg/heat (at 40% slag), represents a yield savings of 0.64%.

A secondary benefit of the addition of coke at this stage is foaming of the slag as FeO is reduced. If prolonged into the start of the heat, any foam can help protect the lining at the start of arcing. It has been found that a coke nugget size of about 2 inches is optimum. Since the slag in the hot heel is very high in %SiO₂ (i.e., fluxes are not added until the heat commences), the reduction rate is compromised, as silica is surface-active. This phenomenon, however, is actually beneficial in prolonging the reduction reaction, although at a lower rate, and thus lower, although still effective, foam height. Table 1 shows the benefits after the coke addition for %FeO reduction.

The high gangue (unreducible oxides) contained in the iron ore (>6.5%) of which the acid compounds are exceedingly high (SiO₂ + Al₂O₃ > 5.0%) is one of the most unfavorable conditions to be faced while maintaining an acceptable metallic yield. Silica is a surface-active oxide in steelmaking slag, and the physical meaning of this property is that the concentration of this oxide migrates to the slag-gas interface from the bulk slag. The degree of “poisoning” (i.e., adsorption) of silica on the gas-slag interface is intensified as the slag becomes more acidic, rendering lesser interfacial area for reduction of FeO from the slag. Table 2 provides a snapshot of the range of percent of total gangue in the DRI currently consumed.

### Table 1

**EAF Slag Compositions Mid-Way and at Meltdown for a Set of Heats**

<table>
<thead>
<tr>
<th>EAF and heat</th>
<th>EAF slags</th>
<th>Addition</th>
<th>Basicity</th>
<th>Charge</th>
<th>Steel sample</th>
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<tr>
<td>EAF Heat ID</td>
<td>FeO</td>
<td>SiO₂</td>
<td>CaO</td>
<td>MgO</td>
<td>Al₂O₃</td>
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<tr>
<td>EAF3 30187 Melt-down</td>
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<td>8.43</td>
<td>4.51</td>
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<td>34.25</td>
<td>10.20</td>
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<tr>
<td>EAF3 30188 Melt-down</td>
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<td>16.96</td>
<td>31.23</td>
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<td>4.53</td>
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<tr>
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<tr>
<td>EAF3 40125 Melt-down</td>
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<td>29.42</td>
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<td>4.70</td>
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<tr>
<td>EAF4 40126 Melt-down</td>
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<td>18.54</td>
<td>31.31</td>
<td>7.92</td>
<td>4.76</td>
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<tr>
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<td>EAF4 40128 Early sample</td>
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<td>22.68</td>
<td>34.42</td>
<td>11.98</td>
<td>5.86</td>
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### Table 2

**DRI Total Gangue**

<table>
<thead>
<tr>
<th>SíO₂</th>
<th>CaO</th>
<th>MgO</th>
<th>Al₂O₃</th>
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<td>4.30</td>
<td>1.04</td>
<td>0.60</td>
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<tr>
<td>3.91</td>
<td>1.30</td>
<td>0.69</td>
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<td>6.78</td>
</tr>
</tbody>
</table>
Results

Figs. 4 and 5 show substantial progress with final slag %FeO and aim ppm oxygen at tap. The initial target was to decrease the %FeO from 33. The results obtained below in Fig. 4 show an average of 30.6% FeO, which means a net improvement of 2.4%.

Similar improvement is evident as a decrease of oxygen ppm in the steel at meltdown. The initial target was to decrease the oxygen concentration below 900 ppm. The results shown below indicate an average of 860 ppm oxygen was achieved. This means a net improvement of 38 ppm of oxygen.

It must also be mentioned that, concurrent with the above period, there has been good DRI quality in terms of percent metallization and percent contained carbon at the EAF weighing feeders, as shown in Figs. 6 and 7.

Summary and Conclusions

Control of oxygen lancing is critical to avoiding iron yield losses in the all-DRI-fed EAF. This is particularly important early as well as late in the heat. In addition, reduction of residual slag FeO in the hot heel in between heats contributes to yield improvement as well.

It has been found that delaying initiation of lancing by some 8 to 10 minutes results in improvements in yield. This is possibly related to a lack of carbon buildup early in the heat when the melt is cold, in which case, oxygen from the lance finds a home in oxidizing iron instead of decarburization.

Coke addition at the beginning of melting is mandatory, as this decreases the %FeO levels and gives important carbon units to the bath, ultimately generating less corrosive slags.

At the end of the heat, just before tap, a tight control of the lancing practice is necessary to avoid over-oxidizing the slag. This may be, again, related to the mass transfer of carbon versus oxygen, as, at this stage, the driving force for diffusion is again lower, now due to low carbon levels as required to make grade at the end of the heat.

Control of %C (2.4–2.8%) and metallization degree (94%) in the DRI consumed is also very important for the overall lowering of %FeO generated in the EAF slag.

In addition to avoiding excess oxidation of iron during melting, the time gap between heats and the relatively large hot heel size are leveraged to further reduce FeO in the residual slag with the addition of coke nuggets as well as some DRI. This step not only contributes iron units to the overall yield, but also produces foam that can persist into the early stages of arcing, thereby helping to protect the lining early in the heat. The key process parameter for optimal reduction of FeO in this stage is sufficient residence time of the coke and DRI additions.
**References**


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