Charging Hot Metal in Electric Arc Furnaces (EAF’s): Reducing Cost Structure and Expanding Grade Horizons

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INTRODUCTION

The latest technology in steel making is to substitute BOF technology with EAF route for steelmaking as raw material flexibility, better quality, higher scrap recycling and increased energy efficiency are realized. With the new advancements in EAF and process technology, in many parts of the world, there is a strong tendency in the mini-mills to improve the quality range to produce flat products that compete strongly with integrated mills.

There are several key opportunities that can be explored by mini-mills and EAF based steel makers to further improve their cost competitiveness, quality and flexibility of operations based on geography, price dynamics and product goals. New charge mix combinations to produce higher quality steels at competitive mini-mill cost structures are possible by converting the conventional EAF operation into a flexible one. Capex and opex lite flexible EAF based mill configurations with optimal combination of scrap, Direct Reduced Iron (DRI), Hot Briquetted Iron (HBI), Hot Metal (HM) can further lower the cost for standard long and flat steels in Asian countries, like India, while enabling the production of higher quality flat steels in North America at mini-mill cost structures. A predictive charge mix model applied to such flexible configurations optimizes production costs taking advantage of the volatility of raw material prices, material compositional constraints and grade goals and can improve profit margins, quality and competitiveness of such hybrid EAF operations substantially.

The current work elucidates a methodology for determining economically attractive and technologically feasible configurations and dynamically computing the associated charge mix model for different price regimes. An integrated approach encompassing mass and energy balance modeling, flexible design, statistical simulation and economic modeling was used to develop the framework for Charge Mix Optimizer. This optimizes the production cost elements taking into account volatility of raw material prices, operational constraints and grade goals. We substantiate the assertions in our framework using comparative analysis that outlines the selection of the most cost-effective option based on charge mix models, capital investment requirements for flexibility, cost of flexibility and key operational parameters based on data from customers in North America and Asia. We further evaluate the techno-economic feasibility of producing higher quality and auto-grade flats using one such flexible design option, which can be attractive for mini-mills.

A FRAMEWORK FOR FLEXIBLE EAF OPERATIONS

The framework for designing and operating a flexible EAF based facility is based around the premise of raw material input flexibility, operating unit flexibility (DR unit, mini-blast furnace based iron making unit, modified EAF with oxy-lancing), dynamic charge mix model for EAF and a techno-economic design and operations model.

Technological developments in EAF have enabled the use of various types of charge mixes such as DRI, HBI, HM, pig iron and scrap. This flexibility of the EAF allows the selection of a charge mix, which can hedge input material volatility and minimize raw material costs and can be optimized for least cost of operations. Successful operations using steel scrap, DRI, HBI, and HM in different proportions, has already been confirmed by a large number of reference installations. The addition of HM into EAF charge is popular in Asia where shortage of scrap and/or electric power is observed and BF is nearby to
Recently, responding to raw material price trends, a growing number of steel plants are using both BOF and EAF steelmaking routes. The EAF can utilize the excess HM produced from blast furnaces or in case when BOF is not functioning. Recent developments prove that EAF with HM charge can operate with very short tap-to-tap times. 

The aforementioned techno-economic model also shows that charge material flexibility, including substantial hot metal charge, in EAFs in North America can enable mini-mills to produce higher quality flats (including EDD, DD, IF, linepipe grades, etc.) at cost structures comparable to all scrap based charge for producing longs and low end flats.

Influence of Raw Material Characteristics on Charge Mix Model and Flexible EAF Design

The various EAF input materials and their effect on EAF design options and operation are discussed below. These characteristics influence the design of flexibility options in the EAF and the charge mix model.

DRI: coal-based and gas-based

DRI production is common in Middle East, US, India, South East Asia and Mexico. While more than 80% of the global DRI plants use natural gas, DRI production in India is primarily coal-based. The composition of coal-based and gas-based DRI is shown in Table I.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Coal-Based DRI</th>
<th>Gas-based DRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon content</td>
<td>%</td>
<td>0.2-0.25</td>
<td>1.2-3.0</td>
</tr>
<tr>
<td>Metallization</td>
<td>%</td>
<td>85-90</td>
<td>85-96.5</td>
</tr>
<tr>
<td>Metallic iron</td>
<td>%</td>
<td>80 to 84</td>
<td>83 to 86</td>
</tr>
<tr>
<td>Carbon</td>
<td>%</td>
<td>0.2 to 0.5</td>
<td>1.2 to 2.5</td>
</tr>
<tr>
<td>Gangue</td>
<td>%</td>
<td>3 to 5</td>
<td>2 to 4</td>
</tr>
<tr>
<td>Fluxes</td>
<td>%</td>
<td>1 to 3</td>
<td>0 to 3</td>
</tr>
<tr>
<td>Sulphur</td>
<td>%</td>
<td>0.02 to 0.03</td>
<td>0.05 to 0.25</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>%</td>
<td>0.04 to 0.07</td>
<td>0.03 to 0.08</td>
</tr>
</tbody>
</table>

Source: DASTUR Global database

There are three main quality aspects of DRI that have largest influence on steelmaking productivity and conversion costs:

a) Gangue in iron ore feed material

DRI contains gangue as its inherent constituent, which cannot be eliminated by reduction process. Presence of gangue constituent in DRI necessitates feeding more lime into the EAF in order to maintain the desired slag chemistry. This results in additional deslagging with substantial heat loss, operational delays, damage to refractory lining, prolonged melting time, higher power consumption etc. Using operational data (average) from various reference plants, the effect of gangue materials on melting power is shown in Figure 1.
Since EAF steelmaking requires a slag with basicity (CaO/SiO₂) > 2.0 for phosphorus removal and 12-14% MgO for protection of refractories, substantial flux additions are required with lower quality ore. Higher acid gangue ore will reduce Fe-yield and increase melting time, energy and electrode consumptions because of additions of nearly twice the volume of lime/dolomite. The extra flux needs to be melted and is lost to the slag phase.

b) Degree of metallization

This is the second most important parameter for EAF steel production - the higher the better. Steel makers aim to produce highly metallized DRI for use in steel plants because of downstream benefits regarding yield, energy, electrode and refractory consumption. The effects of varying degrees of metallization on EAF process parameters are presented in Figures 2(a) – (c).

c) Carbon in DRI

The carbon content in DRI varies from 2.5-3.0% depending on retention time in shaft. Carbon, which is in the form of iron carbide (Fe₃C):

i. Combines with oxygen resulting in the formation of CO. This is an exothermic reaction and helps in slag foaming. A foamy slag prevents the ingress of nitrogen and hydrogen from atmosphere, thereby resulting in a lower dissolved level of these elements.  

ii. Reduces the remaining FeO in DRI

Hot Metal

Considering required productivity, layout considerations and handling facilities, an EAF with hot metal charge in the mix can be designed in a way to have productivity close to a conventional BOF. In order to have high productivity, continuous HM charging in EAF is desirable.
The influence of % HM and EAF geometry (furnace diameter) on productivity, along with oxygen and power consumption is presented in Figure 3. It can be observed from the figure that the best results are usually obtained with ~40-50% hot metal in the total charge. On one hand, hot metal reduces power consumption and tap-to-tap cycle time due to the use of its sensible heat, but on the other hand additional carbon due to hot metal addition increases the carbon removal time thus affecting productivity.

In some situations, productivity requirements might require the modification of the EAF to have the flexibility to work with up to 85% hot metal in the charge mix. The consequence is increase in specific volume of EAF, in order to allow the injection of higher flow rates of oxygen and to improve the decarburization rate, without slopping of steel and slag during the process. It is also possible to have a single bucket operation with ~40% of hot metal in charge mix, which will enhance productivity with reduction of power-off time and energy losses. Characteristics of some reference plants are summarized in Table II.

Table II - Effect of % HM on EAF process parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Plant A</th>
<th>Plant B</th>
<th>Plant C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat size</td>
<td>95t, 80t tapped</td>
<td>175t, 150t tapped</td>
<td>80t, 70t tapped</td>
</tr>
<tr>
<td>Hot metal % (Balance scrap)</td>
<td>34%</td>
<td>40%</td>
<td>53%</td>
</tr>
<tr>
<td>Charging</td>
<td>1 bucket + HM slag door</td>
<td>1 bucket + HM - roof</td>
<td>1 bucket + HM – roof</td>
</tr>
<tr>
<td>Transformer</td>
<td>85 MVA + 20%</td>
<td>125 MVA + 20%</td>
<td>72 MVA</td>
</tr>
<tr>
<td>Shell diameter</td>
<td>6.1 m</td>
<td>7.5 m</td>
<td>5.8 m</td>
</tr>
<tr>
<td>Oxygen lance</td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Coal injection lance</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Burner</td>
<td>7</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Energy cons.</td>
<td>320 kWh/tls</td>
<td>290 kWh/tls</td>
<td>260 kWh/tls</td>
</tr>
<tr>
<td>Oxygen cons.</td>
<td>40 Nm³/tls</td>
<td>38 Nm³/tls</td>
<td>52 Nm³/tls</td>
</tr>
</tbody>
</table>
Scrap

Modern EAFs utilize steel scrap in different ways. Scrap is an energy intensive and valuable commodity and comes primarily from three major sources viz. a) reclaimed or obsolete scrap b) industrial scrap and c) revert or home scrap. The latter two forms of scrap tend to be clean. Scrap reduces the overall environmental footprint of steel making considerably. Variation of a few important EAF with different proportion of scrap is presented in Table III.

Table III – Variation of important EAF parameters with different proportion of scrap

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>85% scrap +15% DRI</th>
<th>70% scrap +30% DRI</th>
<th>100% scrap</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAF metallic yield</td>
<td>%</td>
<td>89</td>
<td>88</td>
<td>91</td>
</tr>
<tr>
<td>Heat Size</td>
<td>Ton</td>
<td>110</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>Productivity</td>
<td>t/h</td>
<td>108</td>
<td>104</td>
<td>110</td>
</tr>
<tr>
<td>Power on time</td>
<td>Min</td>
<td>56</td>
<td>58</td>
<td>55</td>
</tr>
<tr>
<td>T-T, nominal</td>
<td>Min</td>
<td>61</td>
<td>63</td>
<td>60</td>
</tr>
</tbody>
</table>

Source: DASTUR Global database

Lower scrap density has direct impact on electrical energy consumption in EAF steel making due to higher requirement of buckets. Bucket charging (normally 2 in no.) can be replaced with single bucket process and continuous scrap charging. This results in following advantages:

- Possibility of using lighter scrap (reduction in conversion costs).
- Less electrical energy consumption compared to bucket charging process: ~ 30 kWh/t (reduction in conversion costs).
- Higher productivity compared with only bucket process: ~ 20% (reduction in conversion costs).
- Reduced harmonics and reduced flickers compared with more than one-bucket charging process: ~ 20-30%.

Technologies are available for continuous charging of scrap in EAFs utilizing latent and chemical heat from off-gas generated during melting process to preheat scrap prior to its melting in furnace. Comparison between bucket and continuous charging of scrap in EAF is given in Table IV below.

Table IV – Comparison of a typical bucket and Continuous charging of scrap in EAF

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Bucket Charging</th>
<th>Continuous Charging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity (t/h)</td>
<td>108</td>
<td>120</td>
</tr>
<tr>
<td>Tap- to-tap ( min)</td>
<td>65</td>
<td>60</td>
</tr>
<tr>
<td>Power on ( min)</td>
<td>56</td>
<td>51</td>
</tr>
<tr>
<td>Electrical energy ( KWh/tls)</td>
<td>485</td>
<td>450</td>
</tr>
</tbody>
</table>
Dynamic Charge Mix Model

In order to select the best set of operating practices, a holistic approach consisting of a mass and energy balance model along with empirical observations were used to develop the charge mix model. The baseline charge mix model is used to drive the techno-economic model for sizing of the flexible EAF facility and for determination of the target NPV curves for the various design options.

Model development

A charge mix model considering the input material basket of DRI, scrap and hot metal, was developed based on fundamental principles of high temperature chemical reactions, mass and energy transfer. Using such a model allows testing the effects of changing a specific parameter, say temperature/pressure/flow rate/composition, keeping all other process parameters constant. Hence, unlike an actual operation where maximizing productivity is the main goal, the effect of a single operational change on the process can be easily determined using such a model. Although lab-scale tests and/or plant trials are required to validate the model findings, development of the model allows us to narrow down the material options resulting in significant cost advantages.

In the present work, a mass and energy balance model considering conditions of chemical equilibrium has been developed to understand the effect of various input mixes on the process of EAF steelmaking. These balances are based on total mass/energy input and output to the furnace over the entire tap-to-tap cycle.

Both exothermic and endothermic reactions take place in an EAF. While processes such as melting of scrap/DRI/pig iron, flux material, raising their temperature, radiation losses result in energy consumption in the EAF, processes such as electrode oxidation, post-combustion reactions and oxidation of C, Si, Mn, Fe generate energy. Electrical energy from the transformer is utilized to make up the energy deficit. Few important chemical reactions taking place in EAF and their enthalpy (heat of reaction) values are stated in Table V below:

Table V – Chemical reactions taking place in EAF and their corresponding enthalpies (H).[4]

<table>
<thead>
<tr>
<th>Reaction</th>
<th>H (kWh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe + ½O₂ (g) = FeO</td>
<td>-1.275</td>
</tr>
<tr>
<td>Si + O₂ (g) = SiO₂</td>
<td>-9.348</td>
</tr>
<tr>
<td>4A1 + 3O₂ (g) = 2A₁₂O₃</td>
<td>-8.650</td>
</tr>
<tr>
<td>C + ½O₂ (g) = CO (g)</td>
<td>-2.739</td>
</tr>
<tr>
<td>CO(g) + ½O₂ (g) = CO₂ (g)</td>
<td>-2.763</td>
</tr>
<tr>
<td>C + O₂ (g) = CO₂</td>
<td>-9.184</td>
</tr>
<tr>
<td>Mn + ½O₂ (g) = MnO</td>
<td>-2.044</td>
</tr>
<tr>
<td>H₂(g) + ½O₂ (g) = H₂O(g)</td>
<td>-34.614</td>
</tr>
<tr>
<td>CH₄ (g) + 2O₂ (g) = CO₂ (g) + 2H₂O (g)</td>
<td>-13.994</td>
</tr>
</tbody>
</table>
Apart from using these data for calculation, certain empirical equations are also used. For e.g., the energy required to melt 1 kg of Fe is estimated from the following empirical correlation[^4]:

$$\text{Energy required (kWh/kg Fe)} = (2.27 \times 10^{-4} \times T) + 0.0142$$

Mass balance calculations are performed by considering the chemical compositions of input and output material and equating the moles of various elements present in charge mix and products. The scheme of calculation using the mass and energy balance model is schematically represented in Figure 4.

![Figure 4 – Basis of mass and energy balance model.](image)

The model has been fine-tuned and validated by using industrial data from various sources. In order to understand the effect of charge variability on EAF operations, calculations were performed for the case of an EAF reference plant in India. Our model iterations suggest the following six alternatives with different composition of metallic charge mix for the purpose of present analysis:

- Alternative I: 100% Scrap
- Alternative II: 40% Hot metal & 60% scrap
- Alternative III: 70% Scrap & 30% CDRI
- Alternative IV: 80% CDRI & 20% scrap
- Alternative V: 70% HDRI & 30% CDRI
- Alternative VI: 55% HM, 40% CDRI & 5% Scrap

Table VI – Usage Norms Considered for Major Input Materials

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Item</th>
<th>Unit</th>
<th>Alt. I</th>
<th>Alt. II</th>
<th>Alt. III</th>
<th>Alt. IV</th>
<th>Alt. V</th>
<th>Alt. VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Steel Scrap</td>
<td>Kg</td>
<td>1086</td>
<td>655</td>
<td>765</td>
<td>230</td>
<td>-</td>
<td>62</td>
</tr>
<tr>
<td>2.</td>
<td>Hot Metal</td>
<td>Kg</td>
<td>-</td>
<td>435</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>640</td>
</tr>
<tr>
<td>3.</td>
<td>Pig Iron</td>
<td>Kg</td>
<td>-</td>
<td>-</td>
<td>325</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
The model predictions were compared with reference operating data from plants of similar size and practice as shown in Figure 5 (a) – (c). The model found to work accurately with respect to plant operational data.

![Figure 5(a) - Power consumption: model vs. ref. plants](image1)

![Figure 5(b) - Oxygen consumption: model vs. ref. plants](image2)

![Figure 5(c) - Lime consumption: model vs ref. plants](image3)

Source: DASTUR Global database

**TARGET CURVES AND ECONOMIC ASSESSMENT OF EAF DESIGN OPTIONS FOR CHARGE ALTERNATIVES**

To compare the various alternatives of charge mix, discounted cash flow analysis was used for each option to arrive at the expected NPV of producing liquid steel for each alternative for both North America and India. However, given the volatility in raw material prices we used Monte Carlo simulation to generate target curves [5] for each of the alternatives to determine the relative economic attractiveness and the variability of the NPV at different likelihood points. The shape of the target curve provides important insight for the design options.

For the purposes of our analysis, three alternative EAF facility options of 1 mtpa liquid steel producing capacity, which can support all the six alternatives at both the geographies, have been considered:

1. 100 ton Electric Arc Furnace Facility (Supporting Alt-I, III, IV and V)
2. 100 ton Electric Arc Furnace with Oxygen Lancing enhancements + 500 m³ mini-Blast Furnace with Sinter plant (Supporting, Alt-II and VI)
3. 100 ton Electric Arc with Oxygen Lancing enhancements + 500 m³ mini-Blast Furnace (Supporting Alt-II and VI) with 90% pellet charge
In North America, it was assumed that all pellets, DRI/HBI will be sourced from the market and DRI plants or pellet plants were not considered as a part of the design options. In Asia, the installation of a sinter plant was considered, as it is economical due to the price advantage, nature and availabilities of iron ore fines.

Cost of production at the liquid steel level for all the options have been calculated for both North American (representing developed economy) as well for Indian (representing developing economy) scenarios. Iron ore, pellet, scrap, hard coking coal, DRI and pig iron are considered as purchased input metallics as easily available from market. However, hot metal cost has been calculated based on typical charge mix for both the regions i.e. 90% pellet in North American scenario and 75% sinter in Asian scenario. The global trends in raw material price for last 5 years are given below in Figures 6(a) – (f). These figures show the volatility in the prices, and any design option needs to account for these volatilities, which we do through target curve analysis. Cost of HM based on typical charge mix by region is also estimated and shown below in Figure 7. It has been observed that HM cost in India is cheaper than North America by 40 – 80 USD/ton due to lower iron ore/pellet price.

![Graphs showing raw material prices in North America and India](image)

Based on estimated HM cost and purchased input metallics, the time series of the cost of liquid steel under alternative scenarios for North America and India show the variability and is shown in Figure 8(a) and Figure 8(b).
Scrap and Hot Metal Dynamics

Economy of scrap maximization in EAF is driven by the cost differential between scrap and hot metal, as shown in Figure 9. Scrap prices in India is relatively higher due to demand-supply gap. This provides flexibility to Indian or Asian steel plants to use hot metal, DRI and scrap in various proportions in the EAF based on price dynamics, grade constraints, operational economics and operational feasibility. On the other hand, the lower scrap price and higher scrap availability in North America enables EAF based mini-mills in USA to use relatively higher amount of scrap in the charge mix. However, only scrap based operations limits the range of grades that can be produced. Based on the scrap and hot metal spread in North America, combination of scrap, hot metal and metallics can provide a wider range of cost competitive grades through EAF operations in North America.

Target Curves Definition and Flexibility Option Assessment

The uncertainty and volatility in prices and spreads creates the opportunity for a range of economically and technically optimum operation over time, for the alternatives discussed. Monte Carlo simulations were used across the lifecycle of the total cost (cost of capital plus production cost) and generate “target curves” to evaluate the design options for the various alternatives. A target curve is a useful way to present the distribution of possible values associated with each design. It shows the probability that realized NPV of costs will be higher than any specified level or target. It derives directly from the results of the Monte Carlo simulations. Specifically, it shows the range of results reflecting the dispersion in outcomes and the risk of the downside of any specified level (sometimes referred to as the “value at risk”). The 10 percent and 90 percent likelihood markers of the results, also called the $P_{10}$ and $P_{90}$ values, as preferred measures of the range of dispersion because they are statistically more stable than the absolute minimum and maximum values in an uncertain environment. Target Curves were used as a guide to designing flexibility in the EAF that generally looks at cost reduction in two complementary ways a) Reduce downside cost consequences b) Increase upside cost reduction opportunities.
Based on price information for last 5 years, input prices are sampled from the derived price distributions and corresponding steel cost has been estimated using Monte Carlo simulations. The steel cost frequency distribution and spread with 70% confidence level are shown below in Figures 10 (a) and (b). The associated target curves for the six alternatives for India and North America are shown in Figures 11 (a) and (b) respectively.

Figure 10 (a) - Cost spread of liquid steel for alternative options in North America in USD/ton.

Figure 10 (b) - Cost spread of liquid steel for alternative options in India in USD/ton.

Figure 11 (a) – Cumulative NPV of LCC (Life Cycle Costs) distribution for Alternative options in India.

```
Alt - I  Alt - II  Alt - III  Alt - IV  Alt - V  Alt - VI
2.45M  2.445  2.38M
```

```
Alt - I  Alt - II  Alt - III  Alt - IV  Alt - V  Alt - VI
466  478  438  443  438  51
```
The following insights can be derived from the target curves:

(a) *India (representing developing markets)*

1. The expected NPV of costs is lowered and shifts to the right in India with highest cost being for Alt III (70% scrap, 30% DRI) - all sourced metallics EAF operation with no hot metal. The lowest expected cost is Alt VI (55% hot metal, 40% DRI, 5% scrap) which require an addition of a mini-blast furnace and sinter plant.

2. The NPV of cost curves progressively reduce by shifting rightward based on the charge mix and design options – Alt III> Alt-I>Alt IV > Alt V > Alt II > Alt VI.

3. The $P_{10}$ values progressively reduces from about 2.9 BB$ to 2.3 BB$, with a “value at risk” cost spread of 600 MMS. This reduces the elevated cost consequences, increases the expected value of the design by minimizing the downside tail of poor results. They act like insurance or “put” options.

4. Similarly, the upside in the Indian case moves from 2.4 BB$ in costs to 1.9 BB$ in reduced cost of operations at the extreme upper $P_{90}$ level and are acting like “call options” in the project.

5. The $P_{10}$ to $P_{90}$ spread is about 400 MMS in the case of all alternatives in the Indian case.

(b) *North America (representing developed markets)*

1. In the North American case, Alt-I (all scrap charge) and Alt –II (40% hot metal, 60% scrap) are similar, and are also the lowest cost NPV curves with similar expected NPVs of total costs at about 2.36 BB$.

2. The North American $P_{10}$ values in Alt-I reduces from about 2.9 BB$ to 2.7 BB$ in Alt – II, with a “value at risk” spread of 200 MMS. Alt-II thus provides the lowest likelihood of elevated cost consequences compared to all other alternatives, by minimizing the downside tail.
3. However, in the North American case the P_{10} to P_{90} spread at 700 MM$ for Alt-II (scrap + hot metal) is substantially lower than 1000 MM$ spread for Alt-I (scrap) only operation. Steepening of the curve in Alt-II is indication of lower variation in operational costs than Alt-I of scrap only operation.

4. Shallower NPV target curve in North America results in higher P_{10} to P_{90} spread at about and overall average of 800 MM$ and indicates more uncertainty compared to the same alternatives in India. Having metallics and hot metal flexibility creates opportunities to take advantage of raw material volatility and spreads for short-term cost minimization by using a mix of scrap, hot metal and metallics.

Scrap – Hot Metal Spread and Liquid Steel Cost

Additionally, the price difference between scrap and hot metal (scrap price – hot metal price) is also plotted with the normalized cost of liquid steel (using Alt-I as the base line) for alternative charge mixes. The sample includes input costs as prevalent during last 5 years and same has been shown in the Figures 12 (a) and (b). These scatter plots also show that combination of scrap or metallic with hot metal (Alt-II) shows a more predictable and downward bias and equivalency on cost of steel produced compared to the spread and scrap only charge in North America. In India or Asia on the other hand, a combination of metallic and hot metal (Alt VI) is more likely to be competitiveness compared to scrap only charge.

The model considers both capital and production costs and implies that from the perspectives of total cost of operations, risk management and the ability to produce higher quality of steel in EAFs, scrap, along with hot metal provides an attractive alternative in the North American steel mills. Considering the quality requirement for value-added product and higher end flats and the limitation of Alt-I, Alt-II could be a more profitable and competitive option in North America.
POSSIBILITY OF PRODUCING HIGH QUALITY FLATS IN NORTH AMERICAN MINI MILLS USING A MINI BLAST FURNACE (ALT-II - 40% Hot metal & 60% scrap)

(a) Conventional

(b) Proposed

The product basket of conventional oxygen steelmaking and electric steelmaking processes is schematically shown in Figure 13 (a). Historically, the electric steelmaking process has been used for manufacturing long products. Since the major charge material of EAF steelmaking is scrap, the process always ends up with higher amounts of residual or tramp elements such as Cu, Sn, Sb, Zn, etc. in comparison to oxygen steelmaking. The dissolved nitrogen content of steel produced by EAFs is also relatively higher due to: (a) high nitrogen content in scrap, coke, coal carrier gas, etc. and (b) absorption from atmosphere during arcing. Subsequently usage of the EAF route for production of high quality flat products, which permit presence of extremely low levels of tramp elements, has been very challenging in the past. However, as the current analysis suggests, the usage of an optimal charge mix can address these challenges to create higher-grade steels at cost structures similar to scrap based mini-mills. This can result in a wider spectrum of products via the EAF route, as shown schematically in Figure 13 (b).

Table VII- Maximum allowable limit of tramp elements for different steel grades.\(^6\)

<table>
<thead>
<tr>
<th>Tramp element</th>
<th>Maximum allowable limit, in wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD</td>
<td></td>
</tr>
<tr>
<td>EDD</td>
<td></td>
</tr>
<tr>
<td>IF/ULC</td>
<td></td>
</tr>
<tr>
<td>Commercial</td>
<td></td>
</tr>
<tr>
<td>Wire rod</td>
<td></td>
</tr>
<tr>
<td>Special Bar quality</td>
<td></td>
</tr>
</tbody>
</table>
Since usage of Alt-II (40% HM and 60% scrap) is quite comparable to Alt-I (100% scrap) from an economic standpoint under North American scenario, the feasibility of using the former charge mix for development of high quality flat products such as DD, EDD, IF, etc. has been analyzed. Addition of HM to the charge mix can lead to the following advantages:

(a) Decrease in total amount of tramp elements due to a dilution effect
(b) Increased levels of dissolved carbon leading to increased slag foaming and carbon boil. This subsequently leads to flat arcing, thereby lowering the power consumption.
(c) Reduced levels of dissolved nitrogen leading to decrease in formation of harmful nitride inclusions, which can greatly reduce defects in the final product.

The maximum allowable levels of residual/tramp elements in different steel grades are shown in Table VII. The variation of total tramp elements with varying charge mix compositions is depicted in Figure 14. Two frequently used scrap mixes in EAFs were analyzed as depicted in Figure 14:

(a) Scrap Mix 1: 85% Reclaimed/Obsolete + 12% Revert/Home + 3% Industrial/Process
(b) Scrap Mix 2: 75% Reclaimed/Obsolete + 20% Revert/Home + 5% Industrial/Process

Attainment of tolerable limits of tramp elements in higher quality grades becomes easier with increase in %HM in the charge mix, as shown in Figure 14. When Alt-II (40% HM and 60% scrap) is used, almost all the grades considered can be produced. While production of IF grades with 40% HM might necessitate slight modification of the charge mix by addition of DRI/HBI when the hot metal percentage is limited to 40%, it can be easily produced by using a combination of 50% hot metal and 50% scrap.
CONCLUSION

Charge mix in EAF which includes hot metal as a component of the charge, can alter the cost and quality dynamics of steel production in developing countries like India, as well as in developed countries in North America. It has been shown that how various combinations of metallics and hot metal can lead to optimal operations with favorable cost and quality impacts. In particular, the total imputed cost of operation i.e. including both incremental capital and production costs, was modeled using the charge mix model as a basis to determine the various flexibility options available for EAF based plants. The dynamics of these flexible operation alternatives in a volatile raw material pricing environment was then simulated to determine the target curves so as to determine the cost and performance options.

In many parts of the world, and South East Asia in particular, EAF based steelmakers have been increasing the percentage of higher quality steel grades produced in their portfolio. Additionally, volatility in scrap price and higher electricity costs has pressured steelmakers to look for new ways to control lifecycle costs. One strategy that has seen some success has been utilization of alternative feed stocks including hot metal into EAF. This is helpful in two ways. First, in the production of cleaner steels by lowering the level of tramp elements. Second, by providing an additional lever to control raw material and power costs amidst the volatility of the iron ore and scrap spread to make production more competitive. It is hoped that many more such options can be analyzed and evaluated, and ultimately successfully implemented alongside mini-mills in South East Asia, using this framework.

REFERENCES