Developments in Electric Arc Furnace Steelmaking

Dr Geoffrey Brooks
Department of Materials Science Engineering
McMaster University
Hamilton, Ontario, Canada L8S 4L7
brooksg@mcmail.mcmaster.ca

ABSTRACT

In recent years, the growth of EAF steelmaking and the corresponding push for improved productivity and lower energy usage, has seen a blurring of the boundary between oxygen and electric steelmaking and a departure from the pure batch processing operating philosophy associated with early EAF steelmaking. These developments include hot heel operation, continuous feeding, oxygen injection, preheating and post combustion. This paper provides an overview of developments in EAF steelmaking in the last twenty years, critically evaluates the current state of the technology and discusses the future of EAF steelmaking.
INTRODUCTION

Electric Arc Furnace (EAF) Steelmaking technology became 100 hundred years old in the year 2000. Though De Laval had patented an electric furnace for melting and refining iron in 1892 and Heroult had demonstrated electric arc melting of ferro-alloys between 1888 and 1892, the first industrial EAF steelmaking operations only came into operation in 1900 (1). Development was rapid and there was a ten fold increase in production from 1910 to 1920, with over 500,000 tonnes being produced in 1920 (1), though this still only represented a very small proportion of the world’s steel production at the time.

Initially, EAF steelmaking was developed for producing special grades of steels using solid forms of feed such as scrap and ferro-alloys. Solid material were firstly melted through direct arc melting, refined through the addition of the appropriate fluxes and tapped for further processing. Until only twenty years ago tap to tap times over three hours were common and power usage was often well over 600 kWh/t (2), nearly twice the thermodynamic requirement. For much of this century EAF steelmaking was viewed as an expensive and slow process only suitable for high value steels.

Since the 1960s the technology has undergone rapid development moving from a “boutique” technology to the second largest steelmaking technology behind Basic Oxygen Furnace (BOF) steelmaking. This rapid rise in EAF production and technology reflects several major inter-related trends, some of which are:

1. The demise of the Open Hearth (OH) process as a competitive steelmaking process.

2. The desire to move away from the large capital and operating costs associated with large scale integrated steelmaking towards smaller, less capital intensive operations.

3. A very rapid improvement in electrical technology, lowering the costs of large scale electrical equipment but also allowing greatly improved control of electrical devices.

4. The ready availability of scrap in many countries combined with a strong social pressure towards recycling of metals.

5. The increasing availability of alternate iron sources, especially from developing countries.

6. A great improvement in EAF operation, control, efficiency and product quality.
EAF steel production now represents over 30% of the world's steel production and is expected to keep rising as a proportion of the world's steel for some time (3). EAF steelmaking is no longer limited to specialty steels and has largely replaced other forms of steelmaking in the production of long products and is making rapid advances into the production of high quality flat products. In the USA alone over 40 new EAF's have been installed during the 1990s and recent developments in thin strip casting are expected to accelerate this trend towards EAF steelmaking (4). John Stubbles stated in a 1995 review of the North American Steel Industry:

"The old steel industry died in 1989 when Nucor Corporation commissioned a thin slab continuous caster at Crawfordsville in rural Indiana. Overnight, this evolution from thick slab casting caused a revolution within the industry. The so-called "minimills" finally had penetrated the one market that was considered to be the unassailable domain of the major integrated companies - flat rolled sheet (5)"

Canadian steelmakers have played a significant role in this shift to EAF steelmaking. Based on 1999 figures (6), 41.5% of the steel produced from Canada was from the EAF route, this compares to 12.8% in Russia, 22.4% in the United Kingdom, 41.9% in Taiwan, 46.2% in the United States and 71.9% in Spain. The EAF production of the world's 20 largest steelmaking countries is summarised in Table I. Canada is ranked 8th of the twenty largest steelmaking countries in terms of proportion of total steel production made from the EAF route.

The growth in EAF production for the world has been rapid during the 90s and Table II summarizes the growth associated with the twenty largest steelmaking countries. An audit of North American EAF steelmaking facilities published in May 2000 identified 26 operating EAFs in Canada with a combined nominal capacity of 10.2 MT (6). Ten new furnaces have been installed since 1980, the nominal production from these new furnaces accounts for well over 50% of total EAF steelmaking capacity.

**ADVANCES IN EAF STEELMAKING**

This shift towards EAF steelmaking has been accompanied by technical advances that have allowed large decreases in power requirements and increased productivity. Some of the major technical advances during the last twenty years include:

1. Foamy Slag Practice - a foaming slag is used to "bury" the arc and reduce refractory damage and heat loss from the arc region.

2. Hot Heel Operation - molten steel is left in the bottom of the furnace to assist in the melting of fresh solid feed entering the furnace. Processes such as the CONSTEEL process utilise a permanent hot heel into which scrap is fed into continuously (7).
Table 1 - Electric Arc Furnace Production of the Twenty Largest Steel Producing Countries in 1999 (6)

<table>
<thead>
<tr>
<th>Country</th>
<th>Steel Production (kT)</th>
<th>% EAF Route (Ranking)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>123,700</td>
<td>15.8 (17)</td>
</tr>
<tr>
<td>United States</td>
<td>97,284</td>
<td>46.2 (5)</td>
</tr>
<tr>
<td>Japan</td>
<td>94,195</td>
<td>30.5 (13)</td>
</tr>
<tr>
<td>Russia</td>
<td>51,510</td>
<td>12.8 (19)</td>
</tr>
<tr>
<td>Germany</td>
<td>42,062</td>
<td>29.2 (14)</td>
</tr>
<tr>
<td>South Korea</td>
<td>41,042</td>
<td>41.6 (7)</td>
</tr>
<tr>
<td>Ukraine</td>
<td>27,453</td>
<td>4.4 (20)</td>
</tr>
<tr>
<td>Brazil</td>
<td>24,996</td>
<td>21.9 (16)</td>
</tr>
<tr>
<td>Italy</td>
<td>24,409</td>
<td>57.8 (4)</td>
</tr>
<tr>
<td>India</td>
<td>24,300</td>
<td>32.1 (12)</td>
</tr>
<tr>
<td>France</td>
<td>20,210</td>
<td>37.6 (9)</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>16,284</td>
<td>22.4 (15)</td>
</tr>
<tr>
<td>Canada</td>
<td>16,235</td>
<td>41.5 (8)</td>
</tr>
<tr>
<td>Taiwan</td>
<td>15,380</td>
<td>41.9 (6)</td>
</tr>
<tr>
<td>Mexico</td>
<td>15,307</td>
<td>65.0 (2)</td>
</tr>
<tr>
<td>Spain</td>
<td>14,920</td>
<td>71.9 (1)</td>
</tr>
<tr>
<td>Turkey</td>
<td>14,313</td>
<td>64.1 (3)</td>
</tr>
<tr>
<td>Belgium</td>
<td>10,930</td>
<td>17.8 (16)</td>
</tr>
<tr>
<td>Poland</td>
<td>8,847</td>
<td>34.1 (10)</td>
</tr>
<tr>
<td>Australia</td>
<td>8,170</td>
<td>15.5 (18)</td>
</tr>
<tr>
<td>World</td>
<td>785,534</td>
<td>33.5 (11)</td>
</tr>
</tbody>
</table>
## INNOVATIVE TECHNOLOGIES FOR STEEL AND OTHER MATERIALS

### Table II - Electric Arc Furnace Production of the Twenty Largest Steel Producing Countries 1989/1999 (6)

<table>
<thead>
<tr>
<th>Country</th>
<th>EAF Production 1989 (kT)</th>
<th>EAF Production 1999 (kT)</th>
<th>Increase kT</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>N.A</td>
<td>19,600</td>
<td></td>
</tr>
<tr>
<td>United States</td>
<td>31,400</td>
<td>44,919</td>
<td>+10,519</td>
</tr>
<tr>
<td>Japan</td>
<td>33,035</td>
<td>28,743</td>
<td>-4,292</td>
</tr>
<tr>
<td>Russia</td>
<td>N.A</td>
<td>6,603</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>9,515</td>
<td>12,267</td>
<td>+2,752</td>
</tr>
<tr>
<td>South Korea</td>
<td>15,421</td>
<td>17,073</td>
<td>+1,652</td>
</tr>
<tr>
<td>Ukraine</td>
<td>N.A</td>
<td>1,213</td>
<td></td>
</tr>
<tr>
<td>Brazil</td>
<td>5,679</td>
<td>5,475</td>
<td>-204</td>
</tr>
<tr>
<td>Italy</td>
<td>14,002</td>
<td>14,406</td>
<td>+404</td>
</tr>
<tr>
<td>India</td>
<td>3,824</td>
<td>3,400</td>
<td>-424</td>
</tr>
<tr>
<td>France</td>
<td>5,330</td>
<td>7,600</td>
<td>+1,270</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>5,113</td>
<td>3,650</td>
<td>-1,463</td>
</tr>
<tr>
<td>Canada</td>
<td>4,724</td>
<td>6,731</td>
<td>+2,007</td>
</tr>
<tr>
<td>Taiwan</td>
<td>2,556</td>
<td>6,440</td>
<td>+3,884</td>
</tr>
<tr>
<td>Mexico</td>
<td>4,043</td>
<td>9,950</td>
<td>+5,907</td>
</tr>
<tr>
<td>Spain</td>
<td>7,180</td>
<td>10,728</td>
<td>+3,548</td>
</tr>
<tr>
<td>Turkey</td>
<td>4,635</td>
<td>9,171</td>
<td>+4,536</td>
</tr>
<tr>
<td>Belgium</td>
<td>988</td>
<td>1,950</td>
<td>+962</td>
</tr>
<tr>
<td>Poland</td>
<td>2,264</td>
<td>3,017</td>
<td>+753</td>
</tr>
<tr>
<td>Australia</td>
<td>464</td>
<td>1,270</td>
<td>+806</td>
</tr>
<tr>
<td>World</td>
<td>183,747 (not including China)</td>
<td>262,776 ( +79,029)</td>
<td></td>
</tr>
</tbody>
</table>
3. Post Combustion - CO generated during decarburisation is burnt through oxygen injection from lances inside the furnace; the energy liberated either heating the bath directly or preheating the incoming feed material.

4. Oxy-fuel Burners - auxiliary burners have been introduced to improve melting rates and to provide more even heat distribution throughout the furnace.

5. Preheating of Scrap - a number scrap preheating systems utilising the heat associated with off gases have been developed, some based on batch bucket systems and others on continuous shaft systems.

6. Furnace Electrics - large improvements in control and energy efficiency have been accompanied the development of powers supplies with higher operating voltages.

Table III provides a summary of estimated electrical energy savings associated with these different technologies applied to EAF Steelmaking plants in the USA in 1994. These savings need to be compared with an average power consumption of 480kWh/t for EAF steelmaking in the USA in 1994 (3). It should be noted that electrical energy only accounts for approximately 60% of a typical EAF’s total energy supply, the remainder is from heat associated with chemical reactions in the furnace (8). The figures in Table III only reflect the electrical component of the total energy equation, which will be very specific to the particular furnace feed and operation mode, but are still useful in identifying general patterns of energy consumption.

These results identify that improved management, maintenance and control systems have been widely accepted in the industry and have resulted in large overall savings: these measures (1, 2, 12 and 13) accounting for a potential 26% reduction in power requirements compared to the average power consumption. Advances in transformers and power supplies (measures 3 and 8) account for another potential 22% reduction compared to the average, though the use of DC furnaces was not yet widespread and the potential saving accredited to DC furnaces may be overly optimistic.

Improved furnace design through the use of elongated bottom tapping accounted for only a potential 3% saving compared to the average but was widespread (>50%). The use of gas burners during melt down and increased use of gas injection for stirring and slag foaming (measures 4, 5 and 6) accounts for another potential 16% reduction but were still not widespread in 1994. Preheating the feed materials with post combusted off gases clearly offered substantial saving, up to 25% reduction on the average power consumption, though only a few EAF shops had installed this technology by 1994. This potential saving associated with preheating is consistent with the thermodynamic analysis of Brooks et al. (9).

A statistical comparison of a number EAF plants from 1990 to 1999 by the IISI recognised an average decrease in electrical consumption by 13% to 392 kWh/t and an

<table>
<thead>
<tr>
<th>Technology Measure</th>
<th>Electricity Savings (kWh/t)</th>
<th>Share of Production Measure Applied (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Improved Process Control</td>
<td>30</td>
<td>90</td>
</tr>
<tr>
<td>2. Flue Gas Monitoring and Control</td>
<td>14</td>
<td>50</td>
</tr>
<tr>
<td>3. UHP Transformers - improved efficiency</td>
<td>17</td>
<td>40</td>
</tr>
<tr>
<td>4. Bottom Stirring and Gas Injection</td>
<td>19</td>
<td>11</td>
</tr>
<tr>
<td>5. Foamy Slag Practice</td>
<td>19</td>
<td>35</td>
</tr>
<tr>
<td>6. Oxy-fuel burners</td>
<td>39</td>
<td>25</td>
</tr>
<tr>
<td>7. Eccentric Bottom Tapping</td>
<td>14</td>
<td>52</td>
</tr>
<tr>
<td>8. DC Arc Furnace</td>
<td>89</td>
<td>5</td>
</tr>
<tr>
<td>9. Scrap Preheating - Tunnel (CONSTEEL)</td>
<td>61</td>
<td>20</td>
</tr>
<tr>
<td>10. Scrap Preheating with Post Combustion (Fuchs)</td>
<td>119</td>
<td>20</td>
</tr>
<tr>
<td>11. Twin Shell DC with Scrap Preheating</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>12. Preventive Maintenance</td>
<td>67</td>
<td>100</td>
</tr>
<tr>
<td>13. Energy monitoring and management system</td>
<td>17</td>
<td>100</td>
</tr>
</tbody>
</table>
INNOVATIVE TECHNOLOGIES FOR STEEL AND OTHER MATERIALS

increase furnace productivity by 54% to 94 t/h. (10) This study accredited the improvements in electrical energy consumption to shorter tap to tap time, higher total oxygen input and lower tap temperatures.

FUTURE DIRECTIONS IN EAF STEELMAKING

The author expects the efficient utilisation of chemical energy to be one of the main drivers in the technology over the two decades. The main sources of chemical energy in an EAF are:

1) oxidation of carbon from the molten steel or from solid carbon injected into furnace, this can be expressed in the following two reactions:

\[ C (s) + \frac{1}{2}O_2 (g) = CO (g) \]  \hspace{1cm} (1)

\[ C + \frac{1}{2}O_2 (g) = CO (g) \]  \hspace{1cm} (2)

where _ indicates dissolved in steel

2) oxidation of Fe to FeO through injection of oxygen into the molten steel or semi-molten scrap heap,

\[ Fe + \frac{1}{2}O_2 (g) = (FeO) \]  \hspace{1cm} (3)

FeO also reacts with carbon dissolved in the steel, as per

\[ (FeO) + C = CO (g) + Fe \]  \hspace{1cm} (4)

the balance between reaction 3 and 4 is set by well known thermodynamic relationships, though excess FeO, that is above that expected for equilibrium with the carbon content of the steel, can occur in EAFs when oxygen injection is used because the kinetics of reaction 4 tend to be slow because of poor contact between the slag and metal phases.

3) combustion of hydrocarbons (e.g. natural gas combustion)

\[ CH_4 (g) + 3/2O_2 (g) = CO (g) + 2H_2O (g) \]  \hspace{1cm} (5)

4) post combustion of CO

\[ CO (g) + \frac{1}{2}O_2 (g) = CO_2 (g) \]  \hspace{1cm} (6)
It is also thermodynamically possible for $\text{CO}_2$ to revert to CO through contact with either solid carbon or carbon dissolved in Fe, as per:

$$\text{CO}_2 (g) + C = 2\text{CO} (g) \quad (7)$$

$$\text{CO}_2 (g) + C(s) = 2\text{CO} (g) \quad (8)$$

The heat generated from reactions 2 and 3 are readily utilised in providing heat to the metal and slag because the energy is released close to these materials. Jepson (11) estimates from industrial data that in EAFs close to 100% of energy associated with iron oxidation (Reaction 3) is actually transferred to the bath. The utilization of heat from reactions 1 and 5 is a function of burner design and furnace configuration. The heat from burners is more readily transferred to the melt when the burners directly impinge onto the charge during melt down. Jepson (11) estimates that currently burner heat transfer efficiency lowers from 70% during early melting to only 25% in flat bath mode.

The heat released from post combustion is also hard to fully utilise in either heating the bath or unmelted feed material because (i) the reactants and products associated with the reaction are highly mobile making it difficult to capture the heat in any specific zone of the furnace and (ii) the hot gases from the reaction will tend to rise upwards towards a path of least resistance which is not necessarily optimum for transferring heat to where it is required. Jepson (11) estimated that the heat transfer efficiency of post combustion systems to be no more than 50%. Over the last decade, a number of different approaches have emerged in trying to utilise the heat released from post combustion, they are:

1) Injection of oxygen low in the molten slag bath to promote post combustion in the slag layer. The success of this approach also relies on good contact between the metal and slag otherwise the heat generated will be "wasted" in heating the slag and gases directly above the bath. Of course, good contact between metal and slag through splashing is also likely to lead to oxidation of iron and possibly the decomposition of the CO$_2$ (Reactions 7 and 8).

2) Post combustion in the gas space above the bath and around the scrap stacked in the furnace. The success of this approach is reliant on ensuring good contact between the hot gases and the scrap and avoiding short circuiting of hot gases through to the exhaust system.

3) Post combustion of the gases leaving the furnace and use of the that energy and the sensible heat of the gases to preheat feed materials in a separate preheating unit. Both tunnel kiln and shaft preheating units have used this approach (8).

From this analysis, it would appear that the efficient use of energy released from oxidation of carbon and iron, post combustion and burning of hydrocarbons can only be
achieved through both heat transfer to the bath and the solid feed materials. In essence, efficient post combustion is closely coupled to efficient preheating. Thus, the design issue of promoting efficient heat exchange between hot gases and solid scrap and/or DRI is central to the efficient use of post combustion energy. The author expects that this coupling of post combustion with preheating technology will become a major focus of research and technological development over the next decade. Issues of specific interest are:

(a) What is the effect of scrap sizing and shape on preheating efficiency?
(b) What is the optimum arrangement for transferring heat from post combusted gases to the feed materials?
(c) How much post combustion should be carried out in the furnace compared to post combusting externally in a separate preheating unit?
(d) What is the effect of preheating scrap and/or DRI on melting times?

EAF steelmaking was originally conceived as electrical scrap melting process. Their shape and basic configuration is based around optimising the melting rate of scrap through direct exposure to the arc. This operating configuration results in significantly more power being utilised during the melt down compared to later stages of a typical operating cycle. High power inputs, in turn, promote greater heat loss through the walls and roof of the furnace. The change in power input also causes thermal cycling of the refractories which accelerates their degradation.

Since the arc is used to directly melt iron units, it is only in later stages of the melt down period that the thermal mass of the molten material assists in the melting process. Feeding iron units into a permanent molten bath, effectively replacing the arc as the direct means of melting, would allow utilisation of the thermal mass of the bath and should result in greater productivity and lower heat loss. It would also make it possible for permanent foamy slag operation to be established. For these reasons, the author expects continuous feeding into large hot heels to become common operating practice during the first part of next century, resulting in more consistent power operation and higher efficiencies. This approach is already evident in the CONSTEEL process (7) and the proposed ECOARC process (12).

The shift towards continuous feeding and flat bath operation points towards a move away from a batch processing philosophy. The domination of the batch processing route in EAF steelmaking technology distinguishes it from almost every other major chemical/mineral process. The advantages of continuous processes over batch processing in terms of energy efficiencies and refining capability are well known and are not controversial. The overall direction of development during this century for processes producing glass, cement, ceramics, alumina, aluminium, copper, and lead, is towards
continuous processing at the expense of batch processing. In part, the resistance to this change in EAF steelmaking reflects the perception that continuous steelmaking would be too difficult to operate but also the attractiveness of the current technologies in terms of adaptability and operating simplicity.

The concept of continuous electric steelmaking is not new as the work by H.K Worner and others in the 1960s established that highly refined steel could be produced continuously using a combination of electrical and chemical energy \((13,14)\). Recent studies of continuous systems indicate that high productivity is also achievable in a continuous EAF steelmaking and worthy of further development \((15,16)\)

**CONCLUSIONS**

EAF steelmaking is continuing to evolve as a major technology. The increasing use of chemical energy in the melting of iron feedstocks and desire to reduce the loss of energy is expected to drive the direction of development into the 21st Century. Dramatic changes to furnace design and operation can be expected.

**ACKNOWLEDGEMENTS**

The author is grateful for the insights shared during discussions with Professor Worner, Professor Irons and Professor Coley.

**REFERENCES**

92 INNOVATIVE TECHNOLOGIES FOR STEEL AND OTHER MATERIALS


