5.0 Electric Arc Furnace Steelmaking

The use of the electric arc furnace for producing steel began early in the 20th century. For many years production was limited to specialty steels supplying niche applications for industry in the United States and the world. Typically in the early years the grades produced were highly alloyed which had very low demands. It was until the 1960's when the "mini-mill" concept revolutionized the steel industry. By the 1960's large quantities of steel scrap began to enter the market through various recycling programs across industry and consumers. This source of iron units was inexpensive and when coupled with a small, low capital steel mill consisting primarily of an electric arc furnace, a continuous caster and a rolling mill prompted the explosion in use of the electric arc furnace for steel production. In the 60's production was limited to low end products such as reinforcing bar and other long products and this growth was primarily at the expense of the open hearth. However through continued EAF process development, improved residual control and the advent of thin slab casting, the EAF process began to be utilized for more critical applications such as bearings and automotive bodies where internal and/or surface quality are extremely important to the end-user markets. During 2015 more than 60% of all steel produced in the United States was produced through the EAF process. This growth has been at the expense of the BOF. Today there are approximately 100 mini-mills in the U.S. capable of producing 60 million or more tons per year.

Figure 5-1 shows some of the technologies that have propelled this growth and indicates the reduction in tap-to-tap times and electrical energy for furnaces equipped with state-of-the-art technology.

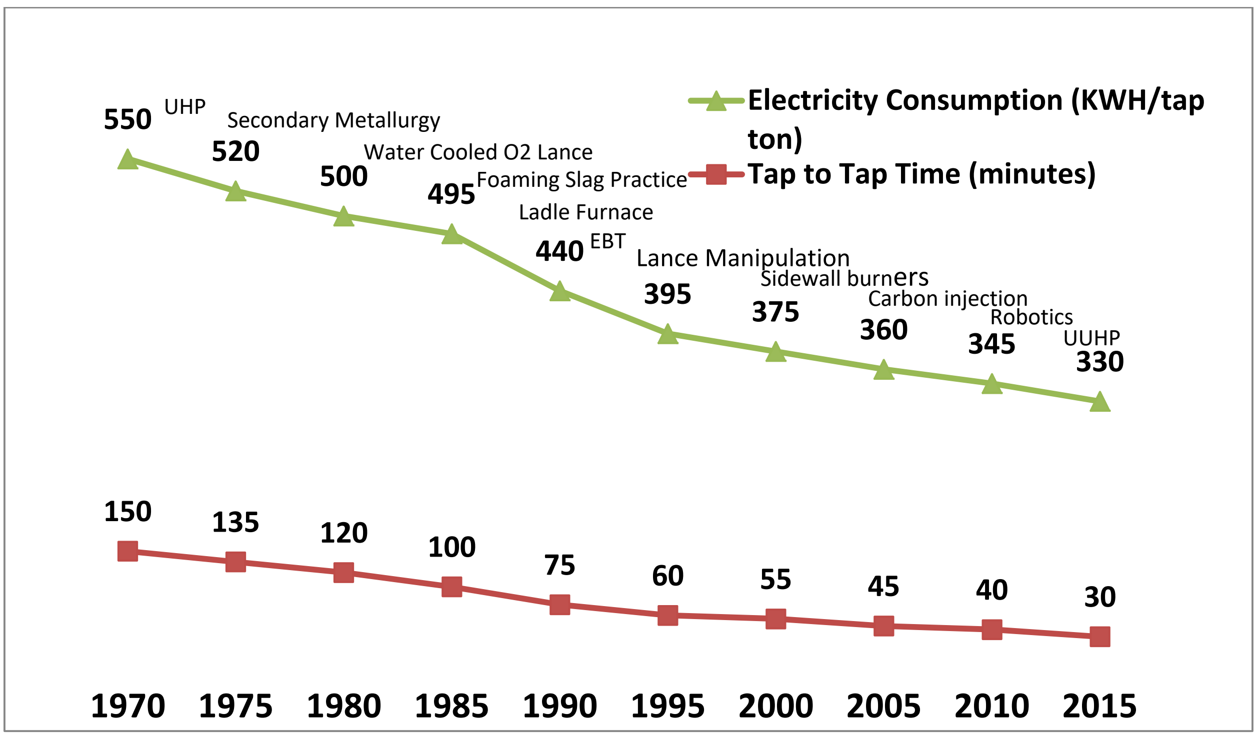

Figure 5-1 EAF Evolution

New technology has vastly increased EAF productivity. Originally, production rates ranged from 10-30 tons/hour and had advanced to furnaces in excess of 100 tons per hour by 2001. Over the last 15 years, technologies such as carbon injection, sidewall burners-injectors, smart furnace technology for controlling arc regulation and ever higher powered transformers (up to 300MVA) have been developed, resulting in furnaces producing in excess of 200 tons per hour. The "mini-mill" has grown from a plant producing 250,000 tons per year to plants producing in excess of 3.5 million tons per year. Once relegated to producing inexpensive concrete reinforcing bar, today mini-mills can produce over 80% of all steel products. Although EAF productivity has significantly increased, steelmakers must still optimize the EAF with their finishing operations so that production rates and sequencing are the same.

The electrical energy used in the EAF process is only about 55% of the total energy input however this will depend on the specific raw materials utilized and the operating practices of each shop. The other 45% comes from chemical energy generated by the exothermic oxidation of carbon and iron and by oxy-fuel or natural gas burners. Schematically, the energy balance for an EAF is shown in Figure 5-2. The tapped steel and slag require a specific amount of energy (approximately 60% of the input), regardless of heat time. Losses to waste gas, cooling water, and radiation, are all generally proportional to heat time (tap to tap time) directly account for the balance. For operations which rely more on chemical energy the percentage of energy lost to off-gasses can be higher. In addition an operations ability to control slag foaming also impacts heat losses to the sidewalls of the furnace if the foam does not contain the arc.

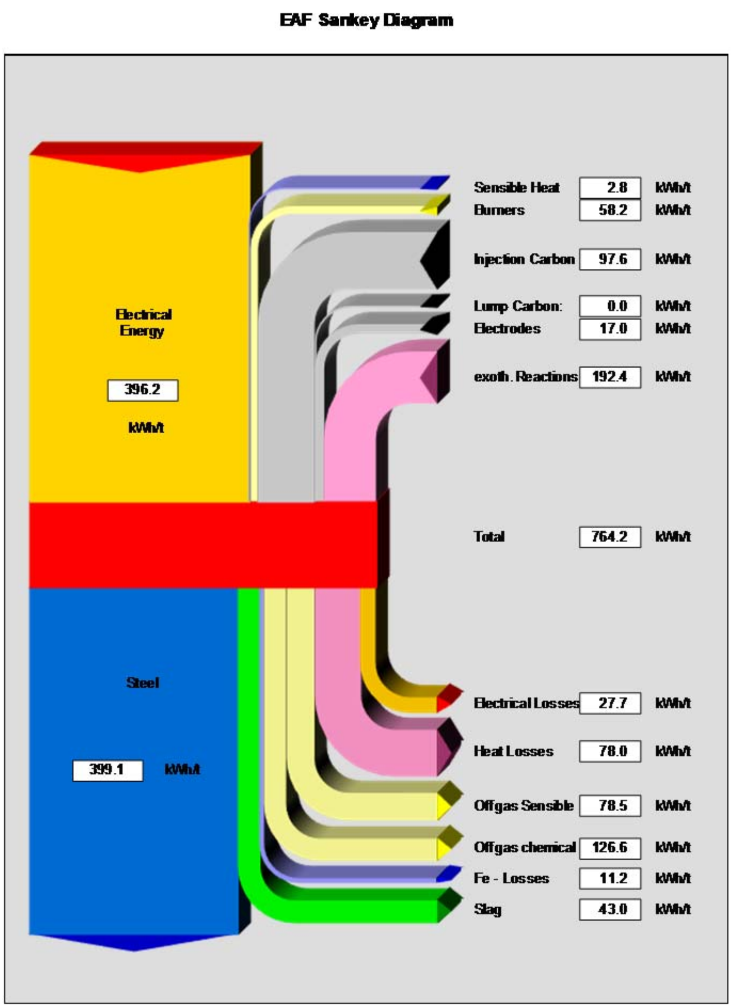

Figure 5-2. EAF Energy Input/Output (Courtesy of SMS group)

There has been a relentless drive to shear minutes from the process by maximizing the rate of energy input when the power is on and to minimize the power-off time. This has led to ongoing developments in the area of minimizing the time between tap and the subsequent power on as well as maximizing the energy input per minute from power on to tap. As a result, the term "Time Utilization" has been coined as a measurement of efficiency of a furnace. Time utilization is the percent of tap-to-tap time when the power is on. In addition, shops have also have spent considerable effort to optimize their ability to maintain a foamy slag including areas such as oxygen lance placement, flow rates, types of carbon additions and timing of carbon additions.

5.1 Raw Materials

Raw materials and operating practices affect EAF efficiency and yield. The traditional EAF charge was 100% cold scrap. Over the last 15 years the use of alternative iron sources such as direct reduced iron (DRI), hot briquetted iron (HBI) and pig iron have grown domestically to more than 5 million tons per year which represents about 10% of all metallics charged into electric arc furnaces. Further use has been constrained by a combination of high cost as compared to scrap and high phosphorous levels inherent in some of these alternate iron sources. .

The iron unit situation is important for several reasons:

- The product mix served by EAFs has moved more towards value-added steels, which are specified with low metallic residuals and low nitrogen levels (automotive flat rolled, cold heading-rolled and wire).

- The availability of scrap needed to meet these requirements is limited to prompt scrap, which is decreasing as more and more near-net-shape metalworking operations appear.

- Yield and energy consumption are both strongly dependent on the quality and physical characteristics of the iron units available.

The following topics are of central importance to raw material issues: supply of manufactured iron unit (which includes DRI, HBI, and pig iron), upgrading of purchased scrap, and the physical nature of purchased scrap. These topics are discussed in more detail below. Melt process yield is an important driver to overall costs. Yield is related to scrap quality and control of the operating practices in each facility. Properly controlling the amount and timing oxygen input along with maintaining a foamy slag which protects the bath from oxidation are important drivers for improving EAF yield.

Trends and Drivers. Manufactured iron unit supply is a major concern. As mills increase their output, demand for prime scrap will begin to outstrip supply. Pig iron is an excellent charge material for an EAF because of its high density, low melting point, carbon contribution ability, and low metallic residuals. However, the availability is low as integrated producers consume nearly all they produce. All alternative iron sources are relatively high in price compared to utilizing conventional scrap charges limiting their use to only grades which require very low residuals in the final products.

Upgrading of purchased scrap has been another way to increase raw material quality by controlling residuals, including sulfur, phosphorous, tin and copper. Several chemical approaches to remove copper that is physically associated with junked cars (shredded scrap, #2 bundles) have been developed. However, physical separation (shaking, magnets) is more practical compared to chemical methods, all of which either create environmental problems (coping with H_2S, chlorine) or require auxiliary operations (molten aluminum bath). In the past 10 years, dirt levels in the scrap have climbed from 0.5 – 1 % to as high as 4 %. As a result, there is an opportunity to utilize mechanical separation to "clean" the scrap resulting in lower operating costs and greater scrap to liquid yield, however, the cost of mechanical separation, thus far, has been an impediment to widespread implementation.

Sizing of scrap is important to maximizing density and minimizing energy losses. Proper scrap sizing limits the number of required recharges, thereby saving energy lost during roof swings, and minimizes refractory damage due to impact of heavy pieces at charge and flare from uneven charges. One of the predominant trends in the last 15 years which impacted the tap to tap times has been a drive to one bucket charge (i.e. no recharges) which eliminates the delay and subsequent heat losses from interrupting melting to open the furnace.

The physical preparation of scrap to provide a physically homogenous charge is important for efficient preheating and fast melting. Manufactured iron units are ideal. DRI and HBI can be feed continuously during the melting operation with feed rates as high as 50KG/MW/min. Charging DRI and HBI through conventional buckets is limited for many shops which do not have the ability to continuous feed. Some of these shops, however, have turned to pig iron which can be charged in a conventional scrap bucket or as hot metal where available. Most recently DRI facilities have developed processes to increase the carbon content and metallization of the product to make it more desirable as a charge material. Also some DRI facilities are directly linked to EAFs so that hot charging of DRI is possible which dramatically decreases the energy required for melting.

One of the limiting factors in EAF productivity is the need to determine the chemistry of the bath prior to tapping the heat. Most shops have incorporated computer modeling which is very reliable for determining many of the elements recovered from a scrap charge. Some work has been undertaken to have real time chemistry measurements available to the operator. This work should continue to be followed. Of particular interest to many steelmakers would be a reliable continuous measurement of temperature and phosphorous. This would be used to further optimize the operation of the EAF resulting in reduced energy consumption and as input information to downstream ladle refining processes.

Almost all EAFs are linked as part of the production process to downstream ladle refining capability prior to the molten metal being poured into a continuous caster. One of the key elements controlled during ladle refining is hydrogen content. For today's ultraclean steels it is important to control hydrogen to very low levels, many times lower than 2 PPM. If the hydrogen content is too high it will result in casting problems or cracking in the final product which ultimately reduces yield and increases cost. The hydrogen level is reduced through exposing the liquid steel to a reduced vacuum level for a period of time. The hydrogen content after this degassing cycle is measured and if the metal's hydrogen content is higher than the specification, the degas cycle is repeated. A method for continually measuring the hydrogen level would minimize the amount of time and energy expended during the degassing cycle.

New and Emerging Technologies. The Iron Dynamics plant, in production since 2001, is based on Rotary Hearth Furnace (RHF) and Submerged Arc Furnace (SAF) technology. It produces liquid pig iron for consumption in an EAF. Other RHF/SAF processes and advanced iron smelting processes are being considered by both EAF and integrated steelmakers to provide needed virgin iron units for their operations. The Paired Straight Hearth Furnace under development by AISI in cooperation with the Department of Energy produces hot pellets for use in EAF and integrated steelmaking. It is described in the Ironmaking chapter. Continued development and installation of these processes will help relieve pressure on future prime scrap supplies and lessen domestic dependence on imported cold pig iron.

5.2 Energy

Productivity is a function of the net rate of energy input and percent of that input utilized for scrap melting. Efforts are ongoing to maximize the energy delivery rate and its effective use to achieve reduced heat times. Electrical energy is dominant on the input side and often cheaper than chemical energy when consumables are considered. Conservation of energy by minimizing heat time is critical because of the large heat loss per minute during the EAF process and significantly increased heat loss during the final stages of heat.

The limitations of the conventional EAF have been identified and are forcing the builders of "greenfield" furnaces and those operating less efficient EAFs to consider new and advanced designs. The new generation of EAFs covers a multitude of configurations. Another key issue in EAF efficiency is the ability to pace and balance EAF production with the other parts of the steelmaking process.

The following topics related to energy are discussed: chemical/electrical energy input ratios, AC/DC power, and energy load.

Trends and Drivers. There is increased emphasis on chemical energy input, which is generally concurrent with electrical energy input and thus supplements it to reduce heat time. The post combustion of CO and H_2 gases leaving the furnace is an important issue. Ideally, the gases should be burned in the furnace with the resulting heat load applied to the slag/metal system. The oxidation of CO while the scrap is still solid and relatively cold provides a better opportunity to capture the heat. The level of CO and H_2 leaving the furnace through the off-gas duct provides some measure of the effectiveness of post combustion and are key process parameters for off-gas analyzing systems with closed loop control of the process and on-line energy balance model for furnace practice optimization.

Direct current (DC) furnaces and the projected savings in electrode consumption reinvigorated the EAF industry. Current carrying capacity depends on electrode diameter, and as furnaces have increased in size (greater than 150 tons), diameter has become a potential limiting factor. Large electrodes (up to 32 inches) sell for a premium which may offset the electrode savings. One solution is dual electrode DC furnaces. Concurrently, high impedance AC furnaces and "jumbo" furnaces (those with tap weights in excess of 200 tons) have also been installed and AC power circuits have been improved to compete with the electrical efficiency of DC power supplies.

Energy load can be reduced by reducing tap temperatures. A 100°F reduction in tap temperature is theoretically equivalent to about 13 kWh/ton. At the front end of the process, preheating of iron units (including scrap, alloys, and fluxes) can reduce energy requirements. This approach has been known for years, but both the economics and logistics defeated the simple approach (for example, heating the scrap in the bucket).

Technological Challenges. Utilization of heat from the waste gas to preheat scrap has been fraught with environmental and other problems, including difficult logistics, damaged buckets, and limited benefits. The typical savings is 25 kWh/ton, which is a poor return on the capital investment of the required equipment. More recently technologies to recover heat from the off-gas for steam and ultimately power generation have been investigated, but the trend is to utilize the Organic Rankine Cycle for this purpose instead of generating steam directly.

Much of the improvement in EAF productivity over the last 15 to 20 years is due to the incorporation of a foamy slag practice. Foamy slag comes from combusting carbon sources with oxygen generating either carbon monoxide or carbon dioxide which foams the slag making materials. The foamy slag increases the heat transfer from the arc to molten bath and protects the sidewalls from the electric arc improving the life of the sidewall refractory. The process is reliant in many cases on a consistent bath level in the furnace, however, due to a number of reasons the level can vary considerably. Too low can reduce furnace efficiency due to poor heat transfer. Too high results in the slag running off the furnace which causes increased sidewall wear thus higher production costs. A method to continually monitor the bath level and slag foaming along with integrating this knowledge into the furnace control technology would improve the reliability of the operation, shorten tap to tap time and reduce energy consumption. The addition of carbon to the slag also creates challenges related to nitrogen control due to much of the carbon consumed being a by-product of the petroleum industry. An improved understanding of the amount of carbon required to generate a foamy slag would reduce the amount of nitrogen in the resulting melt making it easier to produce lower nitrogen steels via the EAF process. A properly controlled foamy slag would also shield the arc from air and reduces the nitrogen pick-up from this source.

New and Emerging Technologies. Continuous scrap feeding systems that eliminate top charging and its energy losses are in regular use and have been proven to increase productivity in terms of MVA per ton of steel produced.

EAFs over the last 15 to 20 years have continually increased the rate of energy input either from electricity or oxygen to higher and higher levels. This has led to increasing safety measures and a resulting drive to move the operators as far away as possible from the EAF while it is melting. This focus has led to increased use of robotics, sensors and modeling of operations. The need, however, continues for further advances in these areas. Many components in an electric arc furnace are water cooled. An undetected water leak can lead damage to the equipment. A reliable method to detect a water leak inside the furnace during operation is highly desirable.

Prior to tapping EAFs into ladles, the ladles are preheated to approximately 2000°F. Historically this has been done with natural gas fired burners which often utilize oxygen enrichment to increase the flame temperature and speed preheating of the ladles. Recently the use of superheated high velocity air has been found to be capable of preheating ladles in half the time while utilizing significantly lower gas consumption. The use of this method is in its infancy however it is showing promise.

5.3 EAF Steelmaking Research and Development Needs and Opportunities

Major research needs in the area of EAF steelmaking include raw material and energy issues.

Raw Materials

R&D opportunities regarding raw materials include needs of characterization and understanding. The heat transfer coefficients for different scrap types and mixes, including hot metal as a charge, need to be determined. Also, methods need to be developed to reduce nitrogen and hydrogen pick-up from carbon sources and ferro alloys added to furnaces and ladles. These and other raw material R&D needs are summarized in the text box.

An understanding must be developed of how preheating feed materials affects the process conditions, for example, the degree of oxidation. Further research is needed on the effects of injecting DRI fines on yield, tap-to-tap time, and final chemistry. Modeling of the EAF process with variable air infiltration, flexible charges, and variable degrees of post-combustion is needed to benchmark the optimum process and potentially improve EAF design. This modeling could also help steelmakers minimize air infiltration to provide for continuous charging of DRI and batch charging.

EAF raw materials research and development needs and opportunities

- Determination of heat transfer coefficients for different scrap types and mixes
- Defined role of section size, melt carbon, time, and temperature in dissolving scrap
- Incorporation of heat transfer coefficients for scrap into an integrated mass and energy balance program
- Optimization of the correct carbon amount to generate a foamy slag resulting in improved nitrogen control
- Reduced nitrogen and hydrogen pick-up from carbon sources and ferro alloys
- EAF modeling to improve continuous charging of DRI and batch charging of scrap and hot metal
- Technique to inject EAF dust so only Zn is recycled
- Relationship between carbon injection rates and techniques

Other alternate carbon sources such as plastics and rubber have had limited usage. Further work on optimizing the timing of these types of alternate carbon additions, impact on slag foaming and addressing environmental concerns with these alternate sources is needed.

Energy

One main area for EAF energy research is artificial intelligence (advanced control systems) in conjunction with increased instrumentation and monitoring of off-gas analysis. The complexity of the EAF process is such that artificial intelligence techniques need to be applied to optimize and control the energy input, especially with the high-voltage, high-impedance UUHP furnaces and chemical energy sources. EAFs have yet to optimize the use of existing solid fuel injection technology. While the simultaneous injection of carbon and oxygen has proven to be beneficial in reducing electrical energy consumption the limitations of implementing this technology is still not well understood. In addition, the physics of oxygen injection into the bath and kinetics of the oxidizing reactions requires further research.

Large quantities of gas are used to preheat ladles and other devices used in EAF steelmaking and throughout the steelmaking process. Additional work is needed to improve the understanding of superheated air along with the potential extension of this process beyond preheating of ladles and tundishes to potentially reheating steel for downstream processing.

Energy research and development needs and opportunities

- Determine limitations of secondary voltages
- Instant steel bath and off-gas chemistry, temperature and volume analysis to enable feedback control
- Improved flicker control
- Artificial intelligence techniques for EAFs
- Solid Fuel Injection
- Maximized Time Utilization

Another EAF development need is the continuation of time utilization improvement. Time utilization maximization is approached in conventional shops by minimization of tapping and turn around procedures, the use of robotic analytical units even on the floor, and disciplined electrode changing practices. The typical power- off time can be as low as 10 minutes. With new furnace designs, time utilization is improved through scrap preparation, increased automation and the use of a high percentage of continuously charged iron units.