AISTech 2023 — Proceedings of the Iron & Steel Technology Conference
8–11 May 2023, Detroit, Mich., USA
DOI: 10.33313/387/026

Applications of Advanced Smelting Furnace Technology for Sustainable Steelmaking

Kyle Chomyn[1], Sa Ge[1], Terry Koehler[1], Christopher Walker[1]

[1]Hatch Ltd
2800 Speakman Drive Mississauga, Ontario, Canada, L5K 2R7
Phone: 1 905 855 7600
Email: kyle.chomyn@hatch.com

ABSTRACT

The future of steelmaking requires new technologies to achieve significant reduction of greenhouse gas emissions. This paper describes the implementation of electric smelting furnaces (ESFs) to improve process yield and efficiency with lower grade ores. The ESF efficiently converts DRI into pig-iron, for use in the steelshop. ESF technology has 65+ years of development in iron, ferro-nickel, and non-ferrous applications. The furnace crucible design uses an integrated approach considering thermal, refractory selection, cooling, and steel / structural design. This integrated approach has led to the development of a number of key design features that have been proven in many reference applications. Electric smelting furnace technology can be applied to various flowsheets including integrated BF-BOF operators, DRI-EAF and scrap-EAF mini-mills. This facilitates the shift to green steelmaking by using existing facilities and pellet supply chains, as well as providing higher yields and reduced lifecycle costs.

Keywords: CRISP, Decarbonization, DRI Melter, Electric Smelting Furnace, Green Steel, Low Nitrogen, Low Carbon Steelmaking, Reducing Electric Furnace, Sustainable Steelmaking

INTRODUCTION

Steel is and will continue to be an essential commodity that drives the development of global infrastructure; however, the industry is also one of the highest CO_2 emitters globally. Direct emissions from the iron and steel industry are approximately 2.6 Gt-CO_2 per year and account for about 7% of the global total [1]. This increases to 3.7 Gt-CO_2 per year or 10% of the global total when accounting for indirect emissions with the use of off-gas [2]. Decarbonization of the steel industry is critical to meet global climate change goals; the steel industry must decrease its average CO_2 intensity by 60% from 1.4 to 0.6 t-CO_2/t-crude-steel to meet the 2050 Sustainable Development Scenario (SDS) of limiting the rise in global temperature to 1.5°C [2].

Today, the steel industry primarily consists of two process routes: the direct reduced iron (DRI) and/or scrap to electric arc furnace (EAF) mini-mill route, and the blast furnace (BF) to basic oxygen furnace (BOF) integrated route. The BF-BOF route is currently the most widely used with a global production share of 71% [1]. However, the BF-BOF route is also the most energy and emission intense route, as shown in Table 1. Particularly in North America, EAFs have become increasingly popular in part due to the wide availability of scrap. Although EAFs can be operated solely on scrap, the use of Virgin Iron Units (VIU) such as DRI is required, particularly for higher quality products. Carbon in DRI offers benefits such as chemical energy supply and slag foaming in the EAF [3].

The BF-BOF route is inherently dependent on carbon based raw materials, therefore BF-BOF steelmakers must prioritize reducing their Scope 1 emissions. Since the BF-BOF process route does not rely heavily on grid electricity, the opportunities to reduce Scope 2 emissions intensities are less than electrical furnace-based process routes. Regions with availability of green power represent an opportunity for EAF steelmakers to reduce their Scope 2 emissions and offer a path to net zero.

Table 1. Process Route Scope 1 and 2 Emissions Intensities [2] and Energy Consumptions [4]

Process Route	Scope 1+2 Emissions [t-CO_2/t-steel]	Energy [GJ/t-steel]
BF → BOF	2.2	21.4-22.7
NG-DRI → EAF	1.4	17.1-21.8
Scrap → EAF	0.3	2.1-5.2

Global DRI production has increased from 72 Mtpa in 2010 to 114 Mtpa in 2021 [5]. Production is expected to further increase to 272 Mtpa by 2050, of which >50% of the increase would be attributed to carbon-free, hydrogen-based process route, assuming the cost of green hydrogen decreases [6]. North American steelmakers have been steadily transitioning from the integrated BF-BOF route to the DRI/Scrap-EAF mini-mill route over the past few decades and have significantly lowered the energy consumption requirements and CO_2 emission intensity for the industry. Many North American and European integrated steelmaking companies have announced plans to switch to a DRI-EAF based flowsheet to reduce CO_2 emissions.

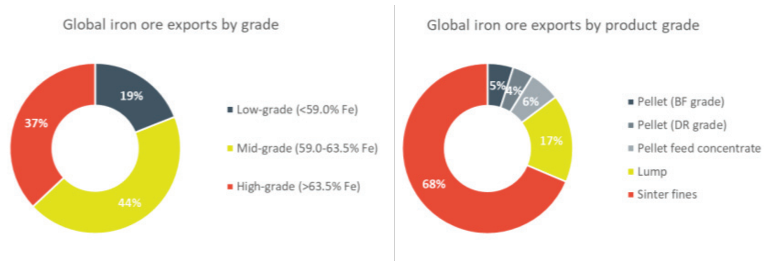

Figure 1. Breakdown of global merchant iron ore export by Fe grade (L) and product grade (R) [7]

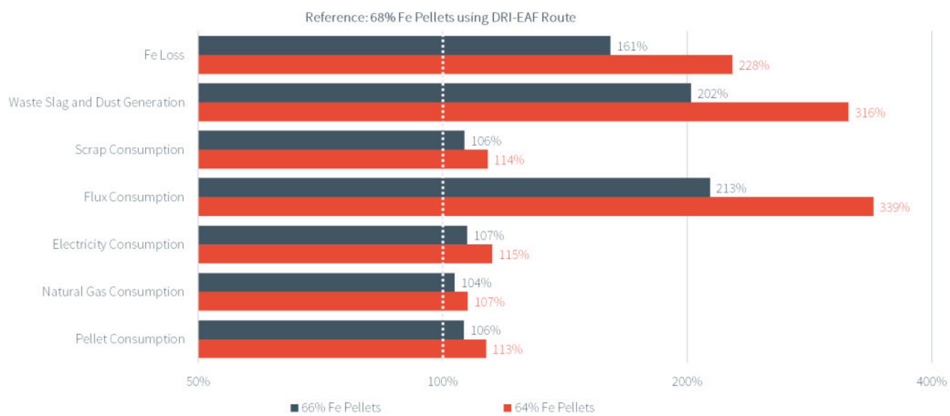

Figure 2. Impact of Feed Grade on DRI-EAF Operating Efficiency

DRI-EAF steelmaking is expected to have a significant place in the future of steelmaking. However, the current trend towards DRI-EAF presents several notable challenges which will limit the ability to increase global steel production using this method:

- Limited availability of DR-grade pellets. Currently only ~10% of iron ore exports are DR-grade pellets or pellet feed concentrate (see Figure 1). Using BF-grade pellets and lump ore in the DRI-EAF process leads to higher gangue DRI and significant impact to EAF efficiency due to slag volume, yield losses, higher fines, etc. The estimated efficiency impacts are shown in Figure 2. Although the availability of DR-grade pellets is expected to increase with demand, the cost is expected to increase substantially.
- Moving from NG- to H_2-DRI process to get to net zero emission, will force conventional EAFs to use carbon-free DRI. This fundamentally changes how existing EAFs operate and significantly impacts their efficiency, availability, and quality unless significant modifications are made.
- The inability of EAF to produce certain high-margin steel currently produced by the BF/BOF such as low nitrogen steel for automotive sheets.
- The inability of EAF to effectively process iron-bearing wastes generated within the plant, such as mill scales, dusts, and slag reverts. In an integrated mill these can be easily recycled in the sinter plant to recover iron.
- Complete departure from conventional steelmaking operations, which creates risks due to changing operations, maintenance, and management approach.

ELECTRIC SMELTING FURNACE SOLUTION

Effective gangue rejection is the main technical challenge for the use of high gangue DRI in the DRI-EAF process. Minimal gangue rejection takes place before BF-grade pellets and lump ore are fed to the DR process. The DR shaft furnace is unable to reject gangue, so most of the gangue would be fed to the EAF. While the EAF is an effective process vessel for scrap-based steelmaking, its efficiency, yield, and productivity are severely impacted by high gangue / slag volume, making the conventional DRI-EAF route unsuitable for high gangue iron ore. Although further upstream beneficiation is a possibility, it tends to create yield losses and additional costs, making it impractical in many cases. In contrast, the BF is extremely effective in processing high gangue iron ore, but with the fatal flaw of requiring coke / coal as the reductant and energy source; however, the BF offers valuable inspiration for a solution to this problem.

The top half of the BF (above the cohesive zone) resembles the shaft DR furnace both in geometry and function. Iron ore descends and is heated and reduced in solid state by ascending gases (CO and H_2). This hot, partially reduced solid continues to descend and is melted, reduced, and carburized by coke in the bottom half of the BF (particularly around the hearth) to produce molten pig iron and slag. These are then separated after tapping to produce a clean, carbon-bearing hot metal ready for steelmaking. While the shaft DR furnace is an ideal replacement for the top half of the BF, a suitable conceptual replacement for the BF bottom half is key to provide a viable route, and must meet the following criteria:

- Does not rely heavily on carbon for melting energy, i.e., be electrical
- Can reduce FeO in the DRI with a lower slag wt% FeO, i.e., strong reducing atmosphere
- Effectively handle large slag volume, i.e., high Fe yield and easy slag tapping
- Direct coupling with DR furnace, i.e., high availability and continuous operation
- Produce a sufficiently carburized hot metal for BOF downstream
- High availability and does not significantly disrupt existing operations
- Effectively process the fines / waste / reverts from all areas of the plant

The electric smelting furnace (ESF) commonly used in non-ferrous, ferroalloy, and ironmaking (including ilmenite / vanadium-titanium magnetite) applications satisfies the above criteria and is uniquely suitable for this application.

DEVELOPMENT OF THE ESF PROCESS FOR IRON & STEEL

ESFs have been extensively used for metallurgical operations since the early 20th century, and are widely applied for non-ferrous, slag cleaning, and certain ironmaking processes (vanadium-titanium-magnetite and ilmenite ores). Hatch has been designing and optimizing ESFs in both non-ferrous and ironmaking applications for over 65 years.

ESFs are typically large, continuously operated, stationary (non-tilting) furnaces with fixed roofs, and permanent refractory linings. Larger furnaces typically use Soderberg electrodes due to the currently available size and resultant current limits in pre-baked electrodes, but pre-baked electrodes can also be used for lower power applications.

ESF technology is uniquely suited to fulfilling the requirements described above, and in combination with an upstream DRI process the function of a modern blast furnace can be replaced. The upstream DRI process can be a DRI shaft furnace, or other DRI technologies such as those using fluid bed reactors. This combination of DRI + ESF allows for continued use of existing steelmaking facilities and avoids the challenges associated with future DRI + EAF steelmaking.

Hatch has developed the CRISP+ furnace technology considering experience in:

- Ironmaking applications, i.e., ilmenite (iron sands) smelting furnaces with power up to 80 MW; references provide key insights on crucible and taphole design
- Ferronickel (FeNi) smelting, including many of the world's largest references with circular furnaces up to ~90MW and rectangular furnaces up to ~100MW; these furnaces are the largest ESFs with similar feed rates to what is required in iron and steelmaking applications, and hot transfer of pre-reduced feeds at >850°C
- New process and pilot plant development, including 15+ years of CRISP direct steelmaking development and piloting, conversion of Highveld electric iron furnaces to partially open bath operation, and development of the shielded arc smelting process for FeNi [8], [9], [10].

PROCESS ADVANTAGES OF DRI-ESF PROCESS USING CRISP+

Advantages of the DRI + ESF + BOF process using CRISP+ relative to DRI-EAF:

- Efficient processing of high-gangue DRI, producing higher yields and enabling use of non-DR grade pellets / lump iron ore
- CRISP+ slag similar to BF-slag, meets specifications for sale to cement industry
- CRISP+ ESF can be fed with pellet and lump-based DRI by operating in partially-open bath (POB) mode, and can also operate in other modes (e.g., open bath).
- Reverts such as high FeO slag from the BOF, LMF, or EAF can be fed back into the smelting furnace
- Continuous and stable operation provides a steady power draw, reducing the strain on the power grid
- The large surface area of the furnace allows for significant active inventory of hot metal in the furnace, allowing for very high availability of hot metal delivery to the meltshop, even during most unplanned downtimes

- Long campaign life of 15-20 years, comparable to a blast furnace
- Stationary, sealed furnace design, which minimizes air ingress to provide a rich-CO off-gas and reduces nitrogen pickup to avoid issues with certain grades of steel
- Ability to effectively process large quantities of fines into the ESF
- Stable tapping operations including the possibility of continuous tapping

Advantages of the DRI + ESF process using CRISP+ relative to existing BF-BOF:

- Coal-based energy from the blast furnace is replaced with natural gas or hydrogen for the DRI plant, and electrical energy in the CRISP+ furnace, resulting in significant reduction in CO_2 emissions
- Higher operational flexibility; productivity of a multi-DRI, multi-ESF complex can be quickly ramped up or down

The ESF technology is well proven at equivalent power and size in other metallurgical applications; the equipment is technically ready for immediate implementation, including proven hot feed technology at equivalent throughputs to take full advantage of the sensible heat energy from the HDRI. This furnace provides a technologically ready, proven solution for the coming years as steelmakers transition to natural gas based DRI processes. In the future when DRI processes switch to primarily H_2-DRI, a CRISP+ furnace can be modified to a CRISP steelmaking furnace to directly produce steel.

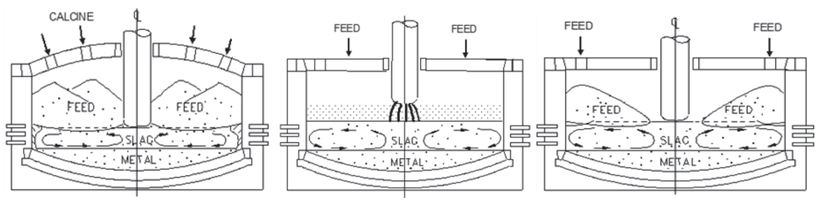

Figure 3. Covered Bath (L), Open Bath (C) and Partially Open Bath (R) for Brush Arc Operation.

The CRISP+ furnace runs in a brush arc mode of operation when using pellet / lump DRI as the main feed, as shown in Figure 3 (R). The key advantage of the brush arc operation is an increase in the operating circuit resistance which increases power delivery intensity. By operating the electrode without immersion, the path length between the electrode and conductive metal bath is maximized, providing a higher resistance. This brush arc operation allows for high power while avoiding excessive current, providing improved operational flexibility, increasing power for a given electrode size, and reducing the operating costs. The advantage of brush arc operation was shown in a previous conversion by Hatch from a submerged arc furnace to brush arc operation at Highveld Steel [11].

A partially open bath mode of operation provides the advantage of significantly reduced heat losses compared to an open bath. A covered bath is not possible in this case as the feed is electrically conductive and would short-circuit the electrodes.

The CRISP+ furnace can also operate in the fully open bath mode of operation when using fine DRI (e.g., those from a fluid bed DR process), as shown in Figure 3 (C).

Where practical, a CRISP+ ESF operating in ironmaking mode can be directly coupled to a downstream BOF or EAF steelshop, in many cases allowing for continued of existing assets and operator experience. Where this is not practical or not desirable the hot metal tapped from the ESF can be granulated or pig cast for later use or shipment to other sites.

COMPARISON OF CRISP+ WITH TYPICAL DRI-EAF PROCESS

A comparison of the OPEX of a DRI-EAF plant to a DRI-ESF-BOF plant shows that for high grade ores/pellets, at current prices, the DRI-EAF process has an advantage. However, for lower grade ores, and considering potential fluctuations in the price of higher-grade ore/pellets, the DRI-ESF-BOF process has key advantages.

- Significantly lower loss of iron through the process
- Lower slag / dust generation; slag generated is saleable to cement industry
- Flexibility on scrap consumption
- Slightly higher flux consumption due to tuning the slag properties for sale
- Only electrical energy used in the ESF, thus reducing Scope 1 emissions
- 5% higher yield, thus 5% lower pellet consumption, reducing raw materials cost

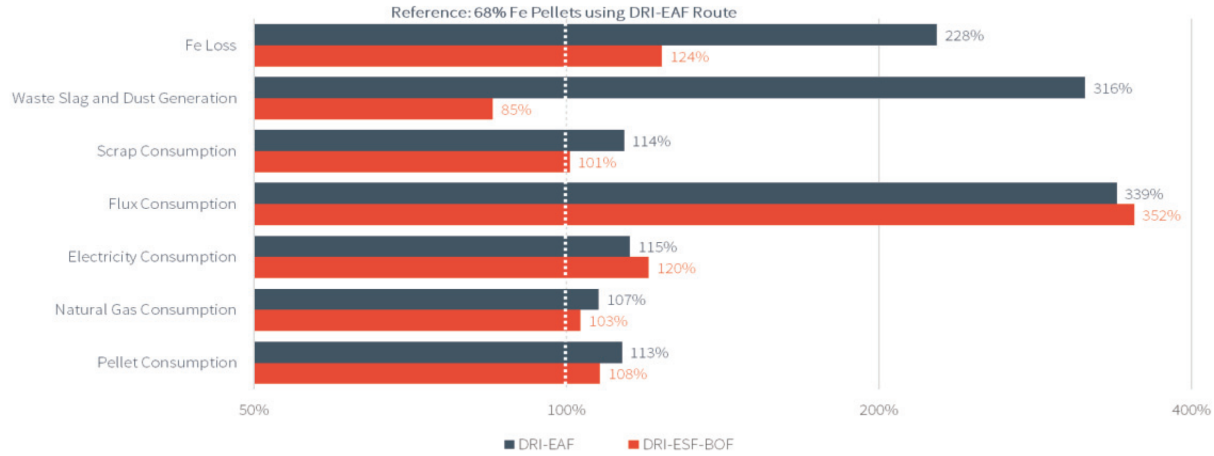

Figure 4. Comparison of OPEX between DRI-EAF and DRI-ESF-BOF Processes with 64%Fe Ore.

TECHNOLOGY READINESS CONSIDERATIONS

CRISP+ technology is ready for immediate implementation in integrated iron and steelmaking operations. Although Hatch has supplied many of the world's largest ESFs, both circular and rectangular, this assessment was not limited to Hatch installations, rather it is indicative of what ESF technology has achieved in general.

In the first generation of ironmaking ESFs it is recommended to maintain equipment parameters within proven benchmarks. This will minimize any risk of technology scale-up in parallel to developing a flowsheet that is new to the steelmaking industry. As the industry develops, it will likely be possible to push beyond past benchmarks.

It is expected ESFs will be paired with the largest DRI plants. Therefore, indicative values are based on producing 2.5 Mtpa of hot metal from HDRI. Depending on DRI grade and revert consumption, this can be achieved with either two 85-95 MW rectangular 6-in-line furnaces or three 60-70 MW circular 3-in-delta furnaces. Larger rectangular 6-in-line units can also be used to maximize economies of scale when matching with multiple DRI plants; for example, three 6-in-line ESFs can be matched to two 2.5 Mtpa DRI plants.

Proven Furnace Power

To achieve the best economy of scale, using fewer larger / higher powered furnaces is desirable. This will tend to result in the lowest CAPEX and OPEX for the plant. In assessing the readiness of electric furnace technology, a key parameter is the scale of the operation in both physical size in plant area of the furnace (hearth area) and active power input (i.e., MW) as well as their ratio, hearth power density (kW/m2).

Power density is a critical benchmark parameter for operations. All things equal, higher power density results in higher metal temperature, higher crucible heat losses and potential for wear (if not properly cooled), higher freeboard gas velocities and potential for dust carryover and higher bath level rise rates (and/or less practical working slag and metal inventory) which impacts tapping logistics.

The "High Intensity Zone" is only practically achievable for two distinct types of operations, which are not applicable for this ironmaking application.

Considering the above, the practical proven limits are ~85 MW for a circular furnace and ~110 MW for a rectangular furnace. A small increase in the length and width of a rectangular furnace could be implemented to increase total power with minimal technical risk, as furnace stability is not tied to these dimensions. However, for a circular furnace this would require either increasing the hearth power density or increasing the diameter, both of which introduce some risks.

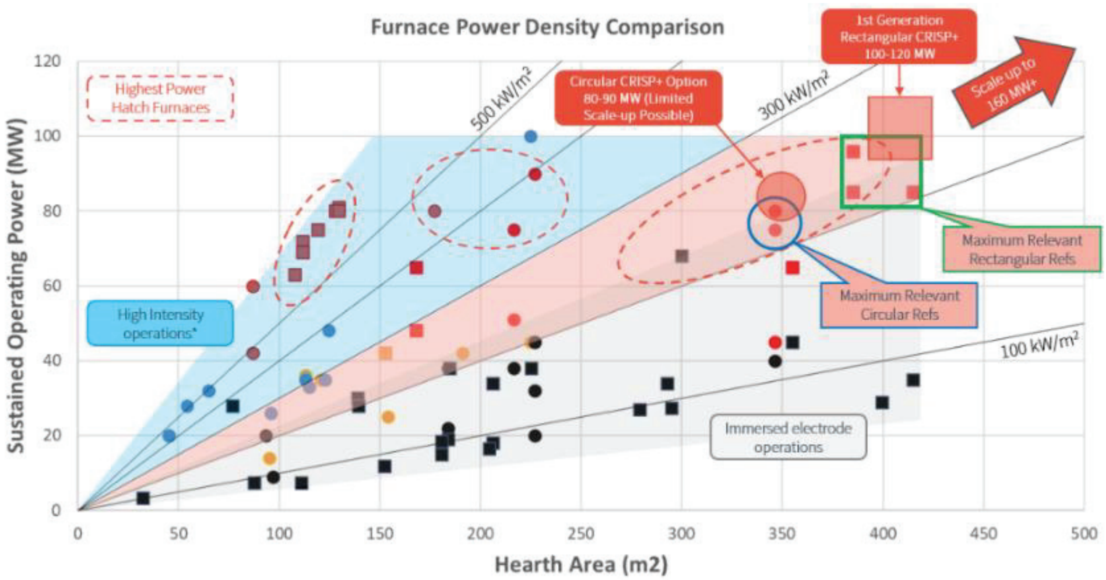

Figure 5. Furnace Power and Size Benchmarks (○= Circular Furnaces, □ = Rectangular Furnaces).

Electrode Configuration and Sizing

Electrode sizing is another important consideration in the furnace. It is expected that Soderberg electrodes will be used in these ESF applications. Soderberg electrodes provide significantly lower operating cost when compared to pre-baked electrodes. In addition, the largest proven Soderberg electrodes are significantly larger than the largest pre-baked electrodes, allowing the furnaces to achieve higher power when limited by electrode current density. During the operation, paste is added to the top of the Soderberg electrode, which is then baked by the current and radiative heat off the process. This is effectively a parallel process that occurs during operations. Although there is no specific limit for the maximum diameter possible for Soderberg electrode, use of larger electrodes adds risk that the paste will not bake properly, particularly in the core of the electrode, potentially causing electrode breaks.

Large circular ESFs use a 3-in-Delta electrode arrangement, while large rectangular furnaces use a 6-in-line arrangement. Having twice as many electrodes means a rectangular furnace requires a much lower power per electrode compared to a circular furnace. In addition, the 6-in-line arrangement results in a moderately higher electrode resistance, reducing the current required to generate the same power.

The majority of ESF operations use ≤1.8 m electrodes, with one known operating furnace using 2.0 m electrodes and another one at 2.1 m. Use of larger (unproven) electrode sizes would introduce a risk of improper baking and electrode failures during operation. As a result, circular furnaces are limited to ~80-85 MW, whereas a rectangular furnace, based solely on electrode size constraint, can achieve powers of 160-180+ MW. The 6-in-line rectangular furnaces, constrained by power densities, can achieve 100-120+ MW of power with a common electrode size of 1.6-1.8 m. Despite rectangular furnaces having more electrodes, the use of smaller electrodes provides a CAPEX and OPEX advantage.

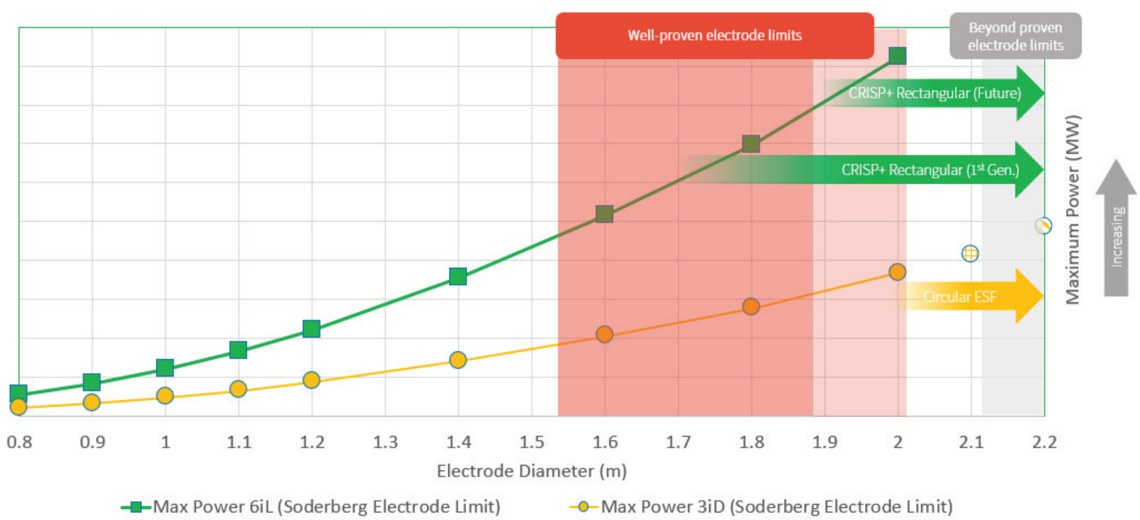

Figure 6. Relationship between Electrode Size and Power Limit.

Other Key Considerations

- *Potential for Hydrogen-DRI Application*. The CRISP+ process is designed with the use of low/zero-carbon DRI (both as pellets of fines) in mind, considering the advent hydrogen-DRI technologies. Various steelmaking options are available ranging from carburization with biocarbon in the ESF followed by BOF, to direct steelmaking in the ESF. The technical readiness limitation mainly lies in equipment to perform the process, rather than the process itself.
- *Campaign Life and Binding System*. the active binding system in a rectangular furnace can provide a longer campaign life compared to circular furnaces. A rectangular furnace campaign will last 15-20 years. Even new operators of rectangular furnaces typically achieve >15 years of campaign.
- *Hot metal chemistry*. ESF hot metal has higher %Si than BF hot metal (e.g., 0.6-0.7% vs 0.4-0.6%). Higher %Si could provide more chemical energy in the BOF to melt scrap and compensates for lower %C in ESF hot metal but would require process adjustment and optmization of the steelmaking operation.

KEY FURNACE DESIGN FEATURES

The design of the furnace crucible requires integrating the thermal, structural, and material properties of the refractory, cooling, and steel components into a single system for effective containment of the hot metal and slag. Each of these systems significantly impacts the others; therefore, Hatch completes the detailed design of all these component systems in-house, to ensure the overall performance is optimized. This includes:

- Selection of materials with high resistance to chemical attack from slag, metal, dust, and off gas
- Robust Cooling Systems in the hearth, walls, and roof
- Tight dimensional tolerance in the brickwork to prevent bridging of bricks and subsequent gap formation as well as ensuring the hearth brick hot taper is always positive after thermal expansion.
- Active binding system with sufficient loads to adjust for expansion and contraction due to thermal cycling
- Optimization of the lining system using advanced modeling methods, as discussed in other papers [12], [13]
- Diligent quality monitoring by trained Hatch experts during fabrication and installation of the crucible system (refractory, coolers, steel, and binding system)

Advantages of the Hatch approach have been shown in past redesigns / rebuilds of furnaces originally constructed by others [14].

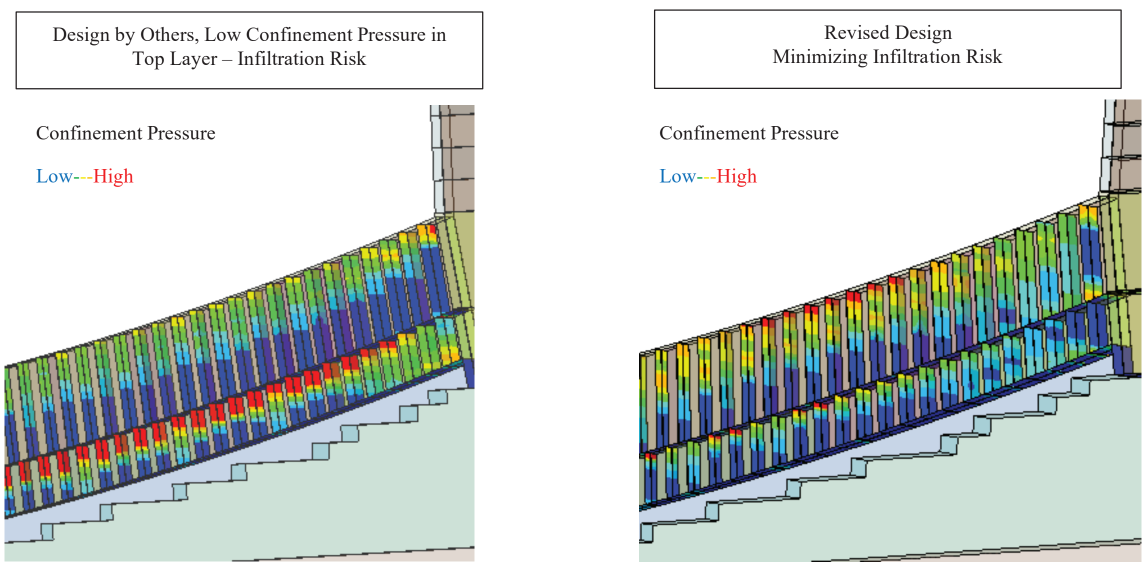

Figure 7. Specialized Refractory Design Optimization using Advanced Tools.

Active Binding System

Much like in a blast furnace, hearth degradation in an ESF is what typically defines the campaign life between major rebuilds. In a large circular furnace, a fixed shell is used with vertical binding system applied at the sidewall. Refractory expansion papering is selected such that the refractory expands into the shell and creates a target confining pressure. During contraction of the refractory due to process changes or extended shutdowns, the confining pressure is lost; this results in metal infiltration between bricks, which causes damage and subsequent over-expansion of the refractory system on the next heat-up. Over time, this causes deformation of the shell and eventually instability of the refractory system.

Rectangular 6-in-line furnace designs include a three dimensional (longitudinal, transverse, and vertical) active binding system to put confining pressure on the refractory system, which helps to prevent metal ingress through joints and extends the campaign life of the furnace. This system consists of adjustable springs and tie-rods, somewhat like what is found in a coke oven battery. During normal operations, these systems rarely require any adjustment; significant adjustments are usually only required during complete cool-down and re-start of the furnace for an extended shut. Sensors are installed to monitor the binding force and spring lengths to identify the need for adjustments, if any. As refractory expands and contracts, this active binding system follows the refractory to ensure joints are kept tight and metal infiltration is minimized. The result is that rectangular furnace designs with appropriately designed active binding system tend to have a longer campaign life when compared to circular furnaces. This is particularly important for new operators that may have more frequent thermal cycles within the furnace.

In both rectangular and circular furnaces, Hatch uses an active binding hold-down system for the walls to ensure tight contact between wall bricks and minimize ingress.

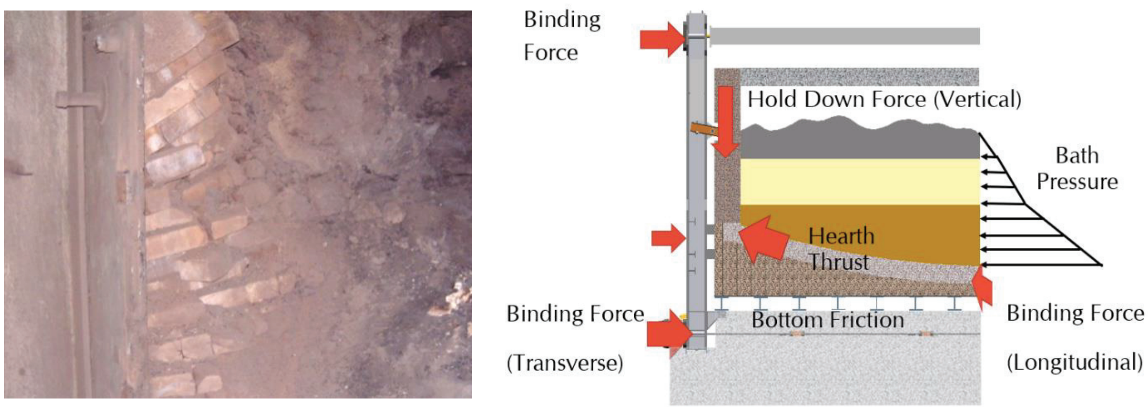

Figure 8. Wall Infiltration Without Bindings (Left) and Load Distribution from Rectangular Furnace Bindings (Right).

Robust Copper Cooler Design

Hatch has developed robust copper cooler designs to ensure the lining is protected in even the highest heat flux zones. In general, the most severe conditions are in the metal / slag interface zone. The interface zone is the most challenging area since it is exposed to both hot metal and slag due to hot metal level changes. In the slag zone high intensity copper plate coolers or waffle coolers are used. These coolers create a slag freeze lining at a point deep in the wall whereby wall structural integrity is not compromised. Waffle coolers have been seen to survive for extended periods even after the protective refractory lining is completely lost, as they provide sufficient cooling capacity to freeze slag on contact. The hold-down system in the furnace walls ensures there is always good contact between the refractory above and below the coolers, to prevent any gap formation and ensure cooling of the brickwork is maximized.

Air-Fin Cooling

Smelting furnaces are often designed with water film cooling in the moderate heat flux areas such as the lower wall (hot metal zone). This introduces the risk that water can infiltrate through the shell and cause hydration (loss of structural integrity) to the refractory, eventually leading to failure. In addition, in the event of a hot metal leak there is a significant risk of steam explosions leading to catastrophic damage. In general, hot metal leaks create larger risk compared to slag leaks due to the high heat capacity and operating superheat.

To mitigate these issues with water cooling in the metal zone, Hatch has developed a proprietary air fin cooling design. The design uses copper fins and forced-air convection. This technology provides comparable heat removal performance to water spray cooling, without any of the risks. As an added benefit, water use is reduced.

Tapping Arrangement

Electric smelting furnaces include dedicated slag and hot metal tapholes located at different elevations in the furnace. This eliminates the need for separation of the slag and hot metal post tapping like in a blast furnace. A typical arrangement would include tapping slag and metal on opposites sides of the furnace, to minimize entrainment and allow separation of the “dry” (hot metal) and “wet” areas (slag tapping, often to water granulation).

Tapping is significantly different in an ESF when compared to a blast furnace. Since the ESF is not internally pressurized like a blast furnace is, the tapping process is relatively more controlled (i.e. less violent taphole opening). However, the life of an ESF taphole is typically significantly shorter than in a blast furnace. Blast furnace tapholes can be “healed” by the mud during closure because the mud pushes against the coke bed (deadman) and creates a mushroom-shaped mass that protects the region. In ESFs, which don’t have any deadman, the excess mud tends to float away into the process. In addition to losing the healing potential, this often results in a plug of frozen metal or slag at the hot face of the taphole. Even when using an automated drill, this requires more frequent oxygen lancing to open the back of the channel when compared to a blast furnace; lancing can also lead to taphole damage. Since the taphole opening process is more controlled, oxygen lancing does not introduce the same risks as in a blast furnace.

In a rectangular 6-in-line arrangement, the long sides of the furnace provide an opportunity to put in many hot metal and/or slag tapholes while maintaining a compact casthouse layout. Having additional tapholes adds relatively little cost and provides an opportunity to extend the time between major taphole repairs, allowing for higher smelter availability.

Tapholes can be designed with and without high-intensity active cooling, including fully water-cooled copper tapblocks.

CONCLUSIONS

Hatch CRISP+ ESF technology provides a commercial-ready solution to help address the significant challenge of decarbonization in the steelmaking industry. In particular, the technology provides significant advantages compared to DRI-EAF when processing lower grade ores or when low-nitrogen steels are required. Rectangular and circular CRISP+ electric smelting furnace technology has been developed over 65+ years and is proven at the required scale in other industries. Key furnace design features include an active binding system for long campaign life, advanced cooling through robust copper coolers and air-fin technology to improve performance and safety, and multiple tapholes to extend the life between major repairs. Smelting furnace technology will continue to advance as it is adopted for steelmaking applications.

REFERENCES

[1] World Steel Association, *Steel's Contribution To A Low Carbon Future and Climate Resilient Societies,* Brussels, Belgium: World Steel Association, 2020.

[2] International Energy Agency, IEA, "Iron and Steel Technology Roadmap," IEA Publications, France, 2020.

[3] International Iron Metallics Association, "Use of Direct Reduced Iron (DRI) in the Electric Arc Furnace (EAF)," 2018. [Online]. Available: https://www.metallics.org/. [Accessed 2022].

[4] World Steel Association AISBL, "Steel Statistics," World Steel Association AISBL, 2021. [Online]. Available: https://worldsteel.org/steel-by-topic/statistics/annual-production-steel-data/P1_crude_steel_total_pub/CHN/IND. [Accessed 2022].

[5] World Steel Association, "Direct reduced iron production 2017 to 2021," 2022. [Online]. Available: https://worldsteel.org/steel-topics/statistics/world-steel-in-figures/. [Accessed 2022].

[6] P. Marcus and J. Villa, "Strategic Insights From World Steel Dynamics," *Iron & Steel Technology,* no. February 2021, pp. 18-19, 2021.

[7] Fastmarkets, "Fastmarkets Understanding The High-Grade Iron Ore Market Fastmarkets," Fastmarkets, 2021.

[8] N. Johannes, W. S. Steinberg and W. Geyser, "The history and development of the pyrometallurgical processes at Evraz Highveld Steel and Vanadium," in *Southern African Institute of Mining and Metallurgy*, Johannesburg, 2011.

[9] B. Marshall, J. Els, N. W. Voermann, K. Sutherland, C. Walker, J. Geldenhuis and B. O. Wasmund, "Conversion to partially open bath smelting on highveld ironmaking furnaces," in *EMC*, 2007.

[10] T. Koehler, K. Wallace, F. Wheeler, F. Atkinson, Y. Gordon, D. Rudge and T. Ma, "Operational Benefit and Design Considerations for a Stationary Electric Furnace for Continuous Steelmaking," in *2010 AISTech Conference Proceedings*, Pittsburgh, 2010.

[11] C. Walker, K. Sutherland, B. Marshall, J. Geldenhuis, J. Els, N. Voermann and B. Wasmund, "Conversion to Partially Open Bath Smelting on Highveld Ironmaking Furnaces," in *EMC*, 2007.

[12] K. Chomyn, C. V. d. Woude, H. Ghorbani, P. Zangeneh, R. Veenstra and C. Walker, "Thermal-Mechanical FEA Modeling of Furnace Hearth Refractory for Design and Campaign Life Improvement," in *COM*, 2016.

[13] M. Maleki, K. Chomyn and H. Ghorbani, "Temperature Fluctuation Impact on Structural Behaviour of Blast Furnace Hearth Refractory System," in *ESTAD*, 2017.

[14] S. Southall, R. Damasceno, A. Zemanek, A. Griebeler, G. Stevens, B. Emery and J. Janzen, "Rapid Redesign and Restart of the Vale Onca Puma Nickel Smelter," in *The Fourteenth International Ferroalloys Congress*, 2015.

