Composite Furnace Modules – Application in DC Furnaces for FeNi alloy production

Frik Marx, Mike Shapiro, Nico Fowler

Bateman Engineering Projects
Pyrometallurgical Technologies
Bartlett Road
Boksburg, South Africa

Neil B. Gray

The University of Melbourne
Department of Chemical & Biomolecular Engineering
Parkville, Australia

Isabel Geldenhuys

Mintek
Pyrometallurgy Division
200 Malibongwe Drive
Randburg, South Africa

Keywords: lateritic ore processing, Composite Furnace Modules (CFM), DC-Furnace, FeNi smelting, refractory cooling system

Abstract

The arduous operating conditions in high intensity furnaces require specialised equipment incorporated into the containment vessel to ensure viable, long term operation. This is particularly true for high temperature pyrometallurgical processes where the slag constituents are chemically aggressive to the conventional refractory materials utilised in the sidewall lining. Smelting of nickeliferous lateritic ores in an electric furnace is an example of such a process. These operations typically require high operating temperatures to achieve the production of ferronickel. Composite Furnace Module (CFM) cooling technology was employed to construct the furnace bath sidewall of a pilot DC furnace used during a test campaign at Mintek to demonstrate the smelting of a siliceous lateritic ore to produce FeNi alloy. The structural support and uniform hot face temperature of the CFM system successfully formed and maintained a mechanically competent frozen slag layer on the hot face, thereby achieving negligible wear rates of the refractory material in contact with the process and extending the life expectancy of the furnace lining. The data gathered and experience gained from operating the pilot furnace confirmed that the CFM technology can be successfully employed in a commercial scale, DC FeNi Furnace.

1 Introduction

Composite Furnace Module (CFM) technology was developed in the early 1990's to address the shortcomings of refractory cooling systems. The main aim of the technology is to provide a uniform hot face temperature on the furnace lining, combined with the additional safety aspect of the water passages being far removed from the process interface. This technology has undergone extensive theoretical development and has been successfully tested in various applications and commercially installed in flash furnaces, an electric slag cleaning furnace and an Isasmelt furnace.

The basis of the CFM technology consists of a backing plate from which a number of copper pins extend towards the hot face. A refractory material is cast between the copper pins. The backing plate is water cooled. The distribution of the copper pins between the refractory material reduces variations in the hot face surface temperature distribution.

A large scale smelting campaign was designed and implemented at Mintek to demonstrate the production of FeNi alloy from siliceous nickeliferous lateritic ore in a 2 m ID pilot scale DC electric arc furnace. The chemical composition of the ore smelted is relatively high in silica and therefore falls out of the SiO_2 to MgO range that is normally processed by pyrometallurgical means. CFM technology was selected to construct the lower furnace sidewalls to withstand the aggressive nature of the siliceous slags. This presented a further opportunity to demonstrate the application of CFM technology in high temperature pyrometallurgical processes involving corrosive bath conditions. The results from the test campaign have been described in much detail previously [1], but in general the testwork successfully demonstrated the production of ferronickel alloy and established the grade-recovery relationship for the ore samples tested.

2 Experiment Description

2.1 Objectives

The main objective of the campaign was to demonstrate that a pyrometallurgical method could be successfully applied to smelt these siliceous ores and produce an acceptable Ferronickel alloy. A secondary objective was to simultaneously test the performance of the furnace vessel used during the trial to extrapolate the projected campaign life of a commercial application. Severe lining erosion indicates that the refractory composites used in the construction of the trial furnace would not be suitable for the commercial unit, whilst minimal wear indicates desirable refractory design criteria. The primary and secondary objectives are discussed separately, with the latter forming the focus in this paper.

2.1.1 Overall campaign objectives

The following main campaign objectives were defined:

- Processing of calcined lateritic ore with nickel grades ranging from 0.98 to 1.60 mass% Ni in a DC furnace (approximately 260 t of calcined sample was available for the test campaign).
- Evaluation of the grade-recovery relationship for the ore samples tested, whilst targeting nickel recoveries of 90 %.
- Verify furnace vessel energy and power density levels
- Obtain sufficient data to provide a design base to scale up to a 80 MW furnace

2.1.2 CFM trial objectives

The objectives for the CFM trial, supporting the overall campaign objectives, were defined as follows:

- Provide containment of the molten process bath for the duration of the trial campaign
- Provide sufficient containment of the molten process bath for all planned energy and powerdensities during the trial campaign
- Support the furnace tap holes in order to maintain the integrity of the tap hole areas and also to facilitate efficient tapping operations
- Obtain sufficient data and demonstrate that a CFM installation is capable of containing this specific process over prolonged periods of operation and also to apply this technology in large scale furnaces

2.2 Equipment description

The following schematic describes the overall process flow and equipment associated with the furnace vessel specifically:

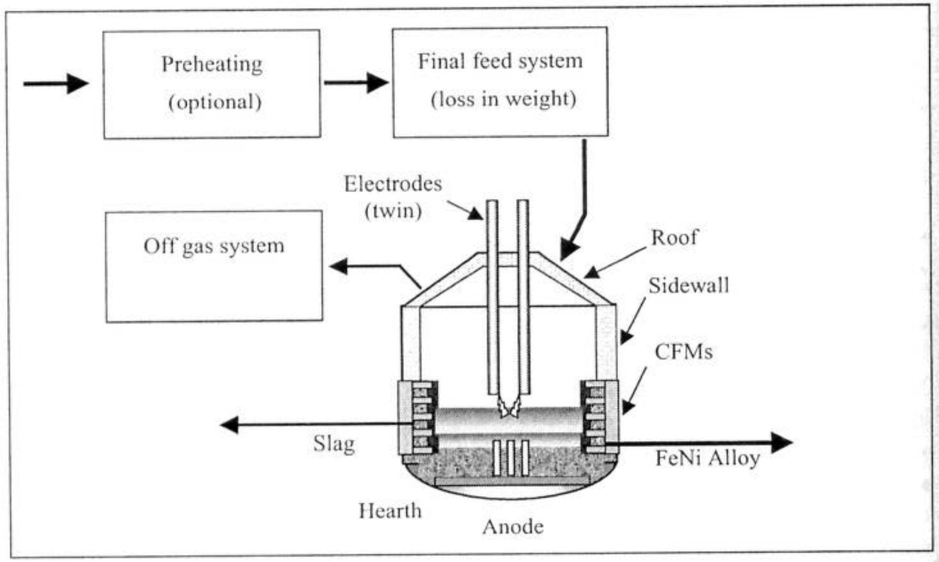

Figure 1: Overall process schematic

The CFM elements were installed in the lower sidewall of the furnace vessel. The purpose of the CFM elements was to provide a long term containment system specifically for the molten slag bath, since the slag produced by this process is extremely corrosive to conventional refractory materials. The CFM elements contain the slag by producing and maintaining a layer of frozen slag on the hot face of the elements.

The lower side wall consisted of a single ring of 6 CFM elements; two fitted with tap hole openings, one for slag employing a copper tap block and one for alloy, using a refractory tap block. The face of each CFM element incorporated two surfaces inclined at 30 degrees relative to one another in plan view. This enabled the circumference to be approximated by 12 surfaces without requiring 12 CFM elements which significantly reduced the complexity of installation, support and water cooling infrastructure. It also indicated the configuration versatility of CFM technology, demonstrating that complex, customised refractory lined surfaces can easily be developed. Each CFM element was also fitted with two internal cast-in water passages. The copper pins on the CFM elements were 70 mm long, alternating with 50 mm long adjacent pins. Thermocouples were installed in the CFM elements at the metal and average slag bath levels.

The CFM system was approximately 2 meters in diameter at the hot face and the elements were 500 mm in overall height. The CFM elements were somewhat imbedded into the hearth (anode) refractory to cover the complete molten bath, including the metal bath. In order to protect the CFM elements from coming into contact with the molten alloy, additional refractory bricks were installed in front of the CFM bottom toe.

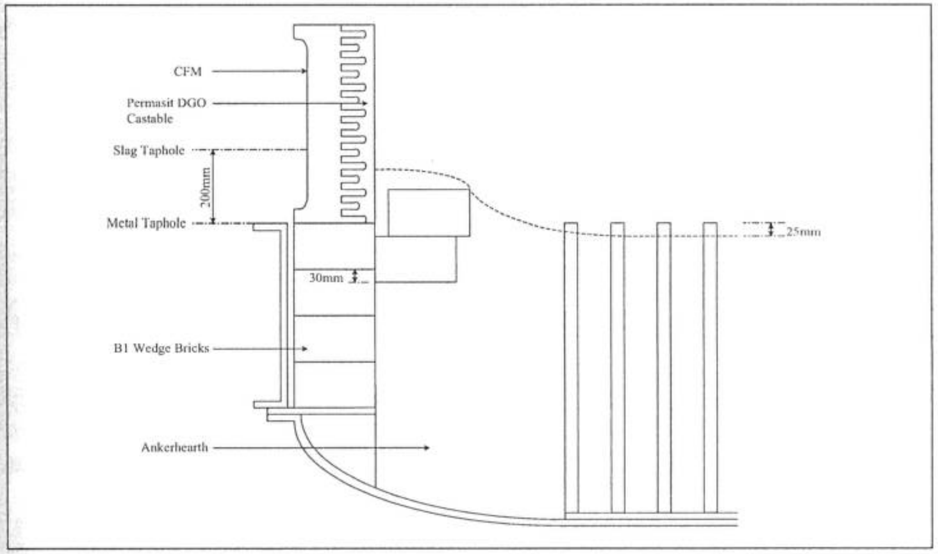

Figure 2: Furnace CFM element installation

2.3 Process operating parameters

During the test campaign, operating parameters were adjusted to achieve the various campaign objectives and numerous distinct operational conditions were achieved. Variables included total power and smelting rate, degree of reduction, flux addition and operating temperature. The following table summarises some of the typical operating parameters to show the range of operating conditions evaluated during the test campaign.

Table 1: Typical operating parameters

Parameter	Value [Average (Range)]	Unit
Feed rate, calcine	1.0 (0.8 to 1.4)	t/h
Operating temperature	1,623 (1,568 – 1,677)	°C
Hearth power flux	445 (375 – 580)	kW/m^2
Operating power	1.4 (1.2 to 1.8)	MW

3 Campaign overview

A total of 193 tons of calcine was fed in 161 batches, during the smelting campaign, which lasted for 19 days after initial start-up. Continuous smelting was achieved for 15 of the 19 days during which 34 metal taps and 160 slag taps were performed. During this campaign, in which 12 tons of FeNi with an average Ni content of 18 % were produced, it was demonstrated that FeNi can be successfully produced with this process and all of the objectives listed in section 2.1.1 were achieved. The following table summarises a simplified overview of the campaign timeline.

Table 2: Campaign Time Line Summary

No.	Duration	Period/event
1	7 days	Furnace warm-up using propane gas, commissioning water-cooling circuits and feed system
2	8 days	Electrical warm-up on 0.5 ton scrap metal, feeding/smelting 15 tons calcine
	2 days	Completed first metal tapping operation, the start of the next period was interrupted due to a slag foaming incident, incurring downtime for cleanup of material (slag) in the feedpipes
4	8 days	Smelting of calcine material – 78 tons thereof
5	2 days	Attempt to feed material through preheating kiln via a dedicated hot feed system. Resultant blockages in the feed system necessitated a switch to a belt feeder system with calcine fed at ambient temperature
6	8 days	Smelting of calcine – 95 tons thereof

Prior to gas warm-up of the furnace vessel, approximately 500 kg of metal were placed in the furnace, consisting mainly of scrap iron. The furnace was then heated by gas for approximately 130 hours, followed by electrical heat-up for a period of 24 hours. At this point, feed was introduced to the furnace, but failure of the feed system resulted in the furnace being switched to idle for a period of time. Manual feed by means of 20 kg buckets was then introduced, while the feed system was modified. The buckets were fed over a period of around 56 hours during which a total of approximately 2 tons of calcine was fed. After this period, the feed system was repaired and automatic loss in weight control feed was employed for the remainder of the campaign.

Early on in the campaign, higher than expected temperatures were recorded on the CFM elements in the areas of the metal level. Three adjacent elements, installed opposite the tapholes, indicated significantly higher temperatures and heat fluxes (instantaneous values in the order of 2 MW/m^2 where recorded in some localised areas) than the remainder of the elements. Analysis of the temperatures and fluxes measured indicated that direct contact between the copper pins of the CFM elements and the metal bath occurred. This suggested high levels of refractory wear during the initial stages, which was confirmed by the refractory constituent pick-up in the slag during the initial batches.

The contact of the metal on the CFM elements required close monitoring of the temperatures on the elements in order to prevent failure and possible water rupture of the elements. These temperatures responded very quickly to changes in both the metal bath depth and power input into the furnace vessel and provided the basis for the furnace operation as discussed in more detail in the following section.

During the initial phases of the campaign, the furnace was operated with a very short arc. The calcine and resultant slag is highly siliceous with high viscosity and electrical resistivity. As a consequence, arc stability was only achieved with relatively short arc lengths despite relatively high voltage requirement. The electrical properties of the slag at the pilot plant scale of operation required a much higher ratio of voltage-to-current to achieve stability than would be the case for an industrial furnace. The operating voltage is required to have the electrode clear of the bath (arc length). A consequence of the higher voltage requirement was that at the power levels required for the pilot plant operation, the electrical operating window was typically constrained by relatively low currents. Resulting poor arc stability frequently restricted attempts to increase the arc length. Ideally, the arc length is utilised to maintain an open pool under the electrode to allow for optimum smelting conditions. In order to operate closer to these ideal conditions (longer arc length) the overall power input was increased to achieve higher current levels, resulting in improved arc stability, but with the consequence of increased intensity. The overall power input increase resulted in high hearth power flux conditions in the furnace, namely in excess of 500 kW/m^2. The high level of energy input, combined with the high level of refractory wear during the initial start-up periods, exposed the CFM elements to very high temperatures and heat loads from early on in the trial campaign.

4 CFM performance

The CFM elements were exposed to two distinct areas of the process, namely the slag bath and the metal bath. The largest exposed area was the slag bath, which is the primary containment zone to resist the corrosive slag. In the slag bath, the recorded temperatures initially increased, after which they stabilised to a large extent for the duration of the campaign. This observation is typically associated with the formation of a frozen layer of slag on the CFM hot face.

The area exposed to the metal bath was identified during the refractory post mortem as the bottom 3 cm to 5 cm of CFM elements. The bottom of the elements were in actual fact exposed to the variation in the level of the slag-metal interface, which implies it came into contact with both slag and metal. The period of exposure depended on the rate of metal production offset by the frequency of metal taps.

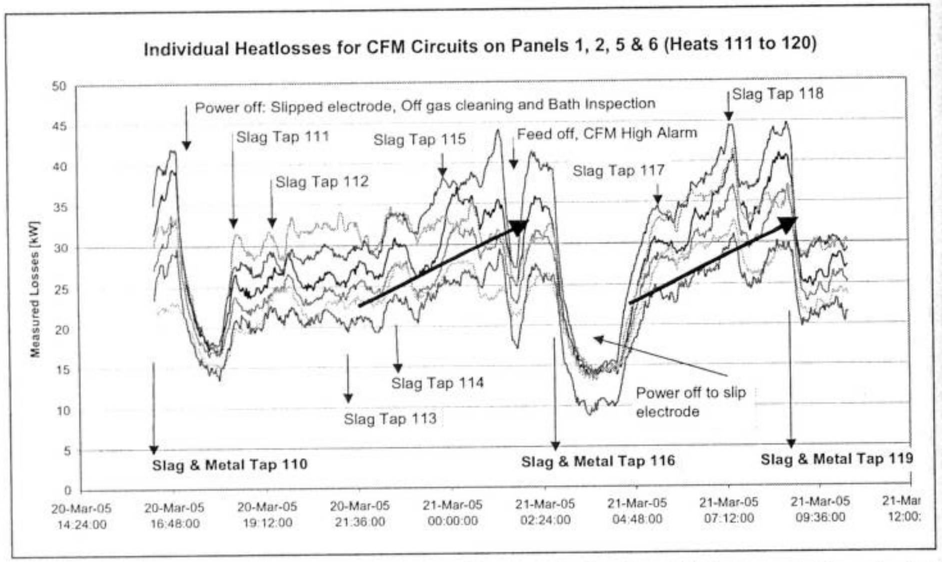

Figure 3: Total heat losses (reporting to cooling water) for four CFM elements for a typical 24 hour period of operation

The historical trend of the heat losses reporting to the CFM elements indicated a very quick response to the operational conditions in the furnace as indicated in figure 3. The largest response was associated with the power input into the furnace and the levels of bath inventory. This implied that there was limited refractory material providing both thermal inertia and conductive resistance between the process and the CFM elements, confirming the observation of refractory loss by dissolution into the slag.

As indicated in figure 3, the heat losses to the CFM elements show a reduction in the order of 10 % after each slag tap. This is explained by the area of the CFM exposed to the slag bath being reduced after each slag tap. Furthermore, the magnitude of the reduction and a small delay in the response from the recorded heat fluxes in the slag bath area suggested that the CFM elements were somewhat isolated from the process in this area, further supporting the conclusion that a layer of frozen slag (freeze lining) formed on the elements. The heat fluxes calculated from the temperature measurements on the CFM pins indicated average values in the order of around 70 kW/m^2. The CFM elements were performing as required in the overall slag bath area

However, the heat loss data indicated a much higher response to the level of metal inventory in the furnace. This was evident from a dramatic reduction in heat losses occurring almost simultaneously with a metal tap. Also, the level of response was more severe for three adjacent elements situated opposite the tap holes, as mentioned in section 3. These elements were also furthest away from the feed port. This observation supported the conclusion that the metal bath was in direct contact with the copper pins on the CFM elements and the heat losses in this area were a direct result of the level of the metal bath in contact with the copper. As metal was tapped and the metal level dropped, the pins previously exposed to metal were then covered with slag and the heat extracted through the copper pins resulted in the slag freezing to the pins, thermally insulating the pins and reducing the heat loss in this area. However, as metal was produced by the process, the metal level rose gradually and melted the slag layer in front of the copper pins, bringing the metal into contact with the pins again. This phenomenon, occurring during the increase in the level of the slag-metal interface, manifested as a continuous rise in heat losses through the CFM elements between metal taps as indicated by the arrows in figure 3.

With a reduction in the energy input to the furnace vessel, the transport mechanisms and particularly the bath stirring velocities were reduced. The convective thermal loads on the CFM elements reduced accordingly. This was particularly observed during the power-off conditions required for performing an electrode slip operation. Sufficient protection of the CFM elements by frozen slag layer in contact with the metal bath area was ultimately achieved by scheduling slag taps, metal taps and power off duration. This enabled sustained metal production between taps, thereby making the trial process operation viable. This operating method provided a mechanism of controlling the temperatures in the CFM elements to complete the trial campaign and beyond.

The taphole designs incorporated in the CFM elements performed as required, with no difficulties of opening and closing the tap holes being reported.

5 Post mortem

After completion of the trial campaign, the furnace vessel was tapped empty and allowed to cool down. A systematic break-out of the furnace lining was performed in order to assess the level and profiles of wear. With regards to the CFM elements the following observations were recorded:

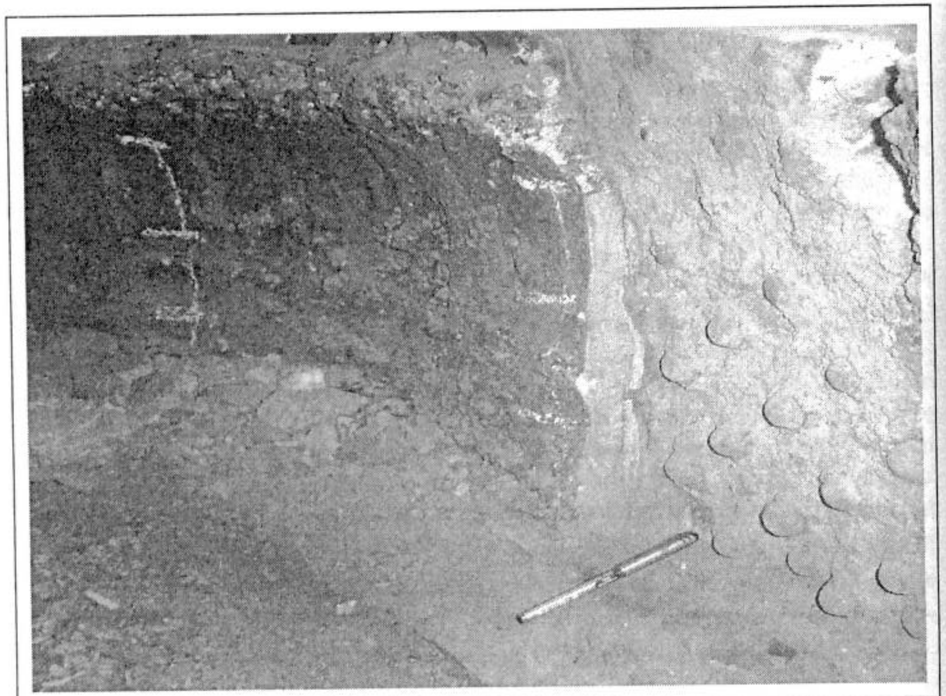

Figure 4: CFM slag layer break-out (undisturbed – left; removed – right)

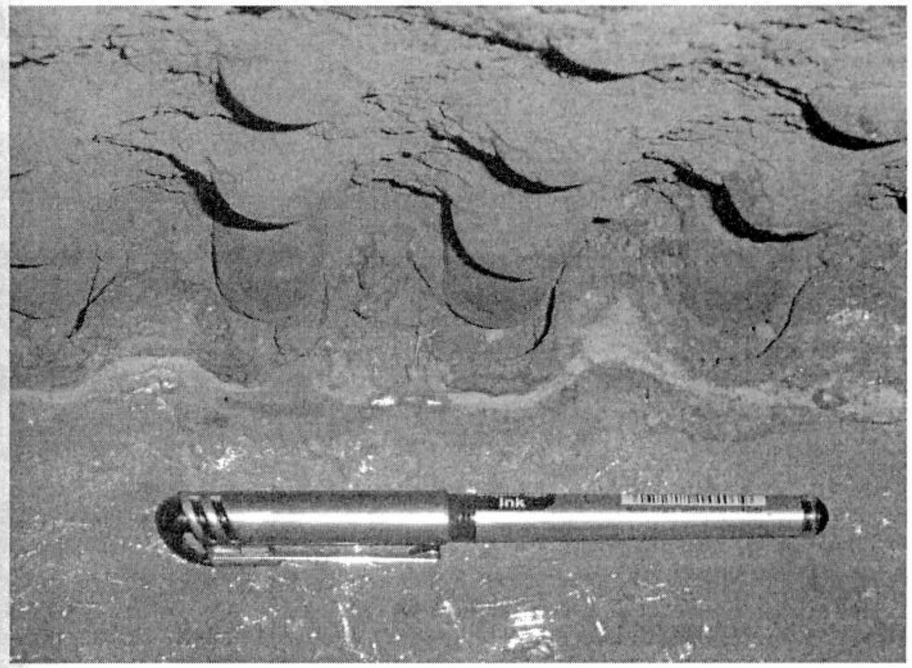

Figure 5: Frozen metal on bottom of CFM element

- A substantial frozen slag layer (freeze lining) was formed in the overall slag bath, averaging a thickness of around 5 cm, but ranging from a few millimetres to almost 20 cm in some areas.
- The refractory in front of the copper pins of the CFM element was worn back, exposing on average around 10 mm of the tip of the long pins to the slag in the overall slag bath area. Most of the short pins in this area were still completely covered by refractory.
- The refractory at the bottom of the CFM elements which came into contact with the metal bath was severely worn compared with the initial condition. The bricks installed in front of the CFM elements were completely worn away.
- Metal came into direct contact with the bottom pins of the CFM elements. This metal appeared to be have been frozen in stages, starting from a very small layer and gradually increasing in size.
- No physical damage to any of the copper pins on the CFM elements was visible.
- The bottom of the CFM elements had not been levelled during the installation. The CFM elements opposite the tapholes were immersed approximately 2 cm deeper than those containing the tapholes. This explains the higher heat flux measured on those elements.

- Further mineralogical evaluation of samples taken from the tips of the copper pins indicated no definite presence of chemical compounds which would be indicative of chemical corrosion of the copper in the long term.

6 Conclusions

The following conclusions regarding the applicability of CFM technology to the production of FeNi alloy in a DC electric arc furnace are drawn, based on observations during the trial campaign:

- CFM technology is capable of sustained operation over the range of hearth power densities tested during the campaign.
- The design of a commercial vessel incorporating CFM technology needs to address the following criteria:
  - The bottom of the CFM elements must not be installed below the bottom of the metal taphole to limit contact with the metal bath in order to prevent continuous metal contact.
  - Special attention is required for the refractory system (composite) on the CFM hot face exposed to the movement of the slag-metal interface
  - Additional heat transfer capacity is required at the bottom of the CFM panel to cope with possible contact with molten metal. This can be achieved by increasing the water flow rate per unit area at the bottom of the CFM, possibly with additional water passages. However, no water passages must be installed below the maximum metal level to prevent a steam explosion in the extreme case of burn through in the metal bath zone.
  - A high level of instrumentation must be installed at the bottom of the CFMs to provide early warning of an incipient failure.
  - The CFMs must be designed for ease of replacement from the outside to ensure short shutdowns capable of significantly extending overall campaign life.
  - Special attention is required for the level tolerances of the hearth skew back bricks to ensure that the CFMs are evenly immersed in the bath
  - Furnace inventory management and control of the slag-metal interface movement plays a key role in determining refractory campaign life.

7 References

[1] Reinecke, I.J. and Lagendijk, H. A twin-cathode DC arc smelting test at Mintek to demonstrate the feasibility of smelting FeNi from calcine prepared from siliceous laterite ores from Kazakhstan for Oriel Resources plc, Infacon XI, 2007, pp. 781–797

[2] Kyllo, A.K, Filzwieser A, Gray N.B.: Composite Furnace Modules – Background and update, EMC 2007, Düsseldorf, Germany, 11-14 June, 2007, p915-926

European Metallurgical Conference

EMC 2009

June 28 - July 1, 2009, Innsbruck, Austria

Global Growth of Nonferrous Metals Production

General Pyrometallurgy / Process Control
Zinc

Volume 3

GDMB