

PGM Furnace Design, Construction, Improvement, and Performance Optimisation



Isobel Mc Dougall, Gerrit de Villiers, Hugo Joubert, Burger van Beek, John Davis, and Trevor Goff

Abstract Tenova Pyromet designed, supplied, and commissioned a 12 MVA circular electric furnace for Sibanye-Stillwater (previously Lonmin) in South Africa. The furnace has been operating successfully since its commissioning in 2012. The paper provides an overview of the furnace performance and campaign life history, and explores the innovative design concepts and improvements implemented. Of particular interest is the use of a novel sidewall lining design that utilizes indirect cooling to remove excess heat from the matte/slag tidal zone without the need to use water-cooled copper. Furthermore, the performance of Tenova's Söderberg electrode column designed for base metal applications, limiting water use above the furnace, is discussed. In addition, the joint development and performance of an uncooled cast iron matte taphole faceplate is presented. Potential future design innovations to further improve smelter operating safety are discussed.

Keywords Furnace cooling · Refractory lining · Graphite · Söderberg electrode · Taphole · Cast iron

I. Mc Dougall · G. de Villiers · H. Joubert (✉)
Tenova Pyromet, Midrand Business Park, 563 Old Pretoria Main Road,
Halfway House, Midrand 1685, South Africa
e-mail: hugo.joubert@tenova.com

I. Mc Dougall
e-mail: Isobel.mcdougall@tenova.com

G. de Villiers
e-mail: Gerrit.devilliers@tenova.com

B. van Beek · J. Davis · T. Goff
Sibanye-Stillwater Smelter Marikana SA PGM Operations, Johannesburg, South Africa
e-mail: Burger.VanBeek@sibanyestillwater.com

J. Davis
e-mail: John.Davis@sibanyestillwater.com

T. Goff
e-mail: Trevor.Goff@sibanyestillwater.com

Introduction

The Marikana smelter complex currently consists of five electric smelting furnaces and three Peirce Smith type converters.

In April 2010 Tenova Pyromet was contracted to design and build a new circular 12 MVA primary platinum smelting AC electric furnace (Furnace 2). The furnace replaced the decommissioned rectangular Merensky six-in-line electric smelting furnace. At the time of project initiation in 2010 the smelter complex operated with the primary existing circular 28 MW Furnace 1 as well as the three Pyromet circular 5 MW furnaces (Furnaces 3, 4, & 5). In 2009 management estimated the smelter plant would soon run at full capacity and additional furnace capacity will be required to recover any concentrate stock accumulated during furnace planned and unplanned outages. It was decided that the upgrade and modernisation of the existing six-in-line furnace would not be suited for the high operating temperatures and that a new circular furnace would be better suited to smelting feed blends containing chromite rich UG2 concentrate [1].

Tenova Pyromet was selected to design, supply, construct, and commission the new Furnace 2 following the successful completion of a pre-feasibility study commissioned in 2009. In selecting Tenova Pyromet for the project, the then Lonmin recognised Tenova's experience with circular bath smelting furnaces in the platinum and base metal industries, including the three Pyromet furnaces at the Marikana smelter complex that have been operating for more than 20 years at that time. Tenova Pyromet is part of the Tenova group of companies with its headquarters in Castellanza, Italy. Based in Johannesburg South Africa, Tenova Pyromet is the electric submerged arc furnace centre-of-excellence within the Tenova group, and supplies furnace technology and equipment to clients all around the world. The project was completed within 28 months and the first matte tap took place during July 2012.

This paper provides an overview of the performance and campaign life history of Furnace 2 since its start-up in 2012. Some of the key design concepts and innovations implemented on the furnace during the original project as well as subsequent design improvements are discussed. These include the use of graphite in the critical matte-slag tidal zone lining design and less water cooling above the furnace roof, as well as the successful development and implementation of an uncooled cast iron matte taphole faceplate.

Furnace Operation and Performance

Following the commissioning of Furnace 2 in July 2012 a performance test was successfully conducted, and the Furnace was operated at the design power set point of 10 MW for the duration of the performance test. Subsequently the furnace has been operated between 8 and 9 MW depending on the production throughout requirements and has cumulatively processed over a half million tonnes of concentrate.

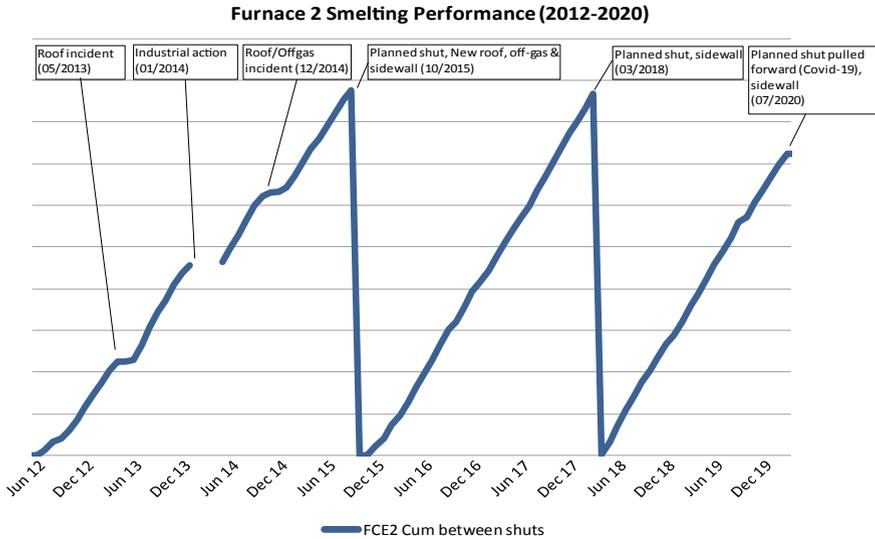


Fig. 1 Furnace 2 cumulative tonnes per sidewall campaign. (Color figure online)

The refractory crucible design performed as per design, and no slag or matte leak occurred during the last eight years of operation. The hearth and skew design performed well with limited hearth ratcheting recorded. The sidewall wear was as expected for a shallow cooled plate cooler sidewall and good structural stability of the sidewall was noticed as the campaigns progressed. The matte tap block design performed well with almost no wear experienced on the matte tap block lintel cooler. The slag tap-block and granulation system performed as per design with no safety-related incidents reported.

In Fig. 1 the cumulative tonnes smelted can be seen for the three sidewall campaigns for Furnace 2.

During the first sidewall campaign off-gas and roof-related problems were experienced, resulting in high freeboard temperatures and off-gas blockages. This was addressed during the first sidewall repair in October 2015 by installing a new roof and off-gas uptake design similar to what is installed at Furnace 1. An additional row of plate lintel coolers was also installed in the freeboard area to assist in supporting the upper sidewall as undercutting is experienced throughout the campaign.

During the second sidewall campaign the addition of lime flux was stopped, and the sidewall monitoring was used to schedule the replacement of the sidewall. The sidewall wear profile was more pronounced compared to the first campaign. From the start of the third sidewall campaign in April 2018 stable Furnace operation was experienced during the campaign. A strategic decision was taken to move the planned sidewall rebuild three months forward due to the lower production volumes experienced as a result of the impact from the Covid-19 pandemic. The sidewall wear profile was similar compared to the first two campaigns although the sidewall

upward tilt was slightly more pronounced. On all three campaigns the matte–slag tidal zone performed well with a 13% wear reduction in wall thickness of the tidal zone area.

Improved Tidal Zone Design

The matte–slag tidal zone is one of the most vulnerable sidewall wear areas for sulphide smelting furnaces. The same is true for primary platinum smelter furnaces such as Sibanye's Furnace 2. The sidewall lining is intermittently exposed to superheated slag and matte. The slag operating temperature varies between 1550 and 1680 °C and has been found to aggressively wear the refractory lining if not adequately cooled [2, 3]. The superheated matte, operated at temperatures above 1500 °C, is similarly chemically aggressive to the refractory. In particular, the matte has a strong tendency to sulphidize mag-chrome ($\text{MgO-Cr}_2\text{O}_3$) refractories [4].

In the past copper plate coolers have been installed intermittently between the bricklayers to improve the campaign of the matte–slag tidal zone refractory lining [2, 5]. The theory is for the copper plate coolers to remove excess heat from the lining and reduce the operating hot face temperature. This in turn will slow the brick-wear and potentially stop wear through the formation of a slag freeze lining. The slag freeze lining will prevent direct contact between the molten slag or matte and the brick hot face, and therefore limit chemical attack. The downside to this solution is the potential contact between matte and the copper plate cooler. This could happen when, usually due to abnormal operating conditions that do occur from time to time, the remaining working lining in front of the copper cooler is worn away and no slag freeze lining is maintained. A copper cooler is likely to rapidly melt or dissolve in contact with the superheated matte, resulting in a containment failure with all the associated safety risks and prematurely ending the lining campaign life.

During the engineering phase for Furnace 2 it was decided to investigate alternative ways to remove excess heat from the matte–slag tidal zone without the use of water-cooled copper cooling elements. Graphite was identified as a potential material to use due to its high thermal conductivity enabling the removal of excess heat from the lining hot face. Furthermore, graphite has been used successfully on the hot face of copper coolers adjacent to the slag bath in other platinum smelting furnaces, showing that it can withstand the attack mechanisms if its operating temperature is kept low enough [6, 7]. Nonetheless, as part of the investigation graphite's resistance to chemical attack by both superheated slag and matte was tested [8]. It was found to provide better resistance to both slag and matte compared to mag-chrome refractory material. Mag-chrome is typically used as the working lining in platinum and other sulphide smelting furnaces.

Following careful consideration of the risk of graphite oxidising in the long term while in contact with the superheated slag, it was decided to focus on graphite as a potential back lining in the matte–slag tidal zone [9]. In the concept mag-chrome is maintained as the working lining with the graphite back lining, replacing the typically

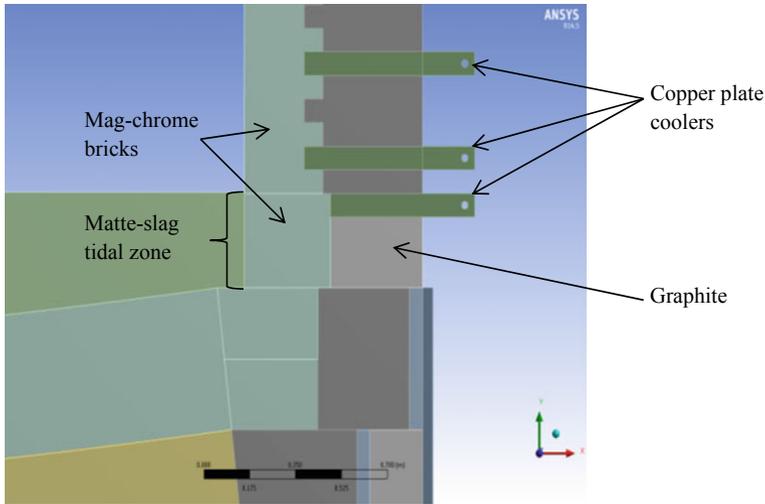


Fig. 2 Matte–slag tidal zone sidewall design concept with a graphite backing lining. (Color figure online)

used alumina-chrome refractory, enabling the more effective removal of excess heat from the working lining. A water-cooled copper plate cooler is placed directly on top of the graphite back lining. The proposed concept tidal zone design is shown in Fig. 2.

Thermal FEA (Finite Element Analysis) modelling was employed to evaluate the concept design compared to typical tidal zone lining design arrangements used in industry [8, 9]. It was compared to a design without any cooling, copper or otherwise, in the tidal zone, as well as an arrangement with a water-cooled copper plate cooler installed one brick above the hearth skewback level, directly extracting heat from the tidal zone. The results indicated that the graphite backing lining enabled the removal of enough excess heat from the working lining to ensure similar working lining temperatures achieved with the use of a copper plate cooler installed one brick above the hearth skewback. The use of the graphite backing lining with the copper plate cooler on top further ensured that the 800 °C isotherm, the temperature at which matte will be completely solid, is kept closer to the hot face of the working lining. In addition, the 450 °C isotherm, above which oxidation of the low porosity graphite material becomes possible, is kept well in front of the graphite hot face. It was concluded that the same benefits to the critical tidal zone working lining can be achieved through the use of a graphite backing lining as compared to the use of direct copper cooling without the downside risk associated with water-cooled copper coming in contact with molten matte. The comparative thermal FEA results, as well as the location of respectively the 450–800 °C isotherms are shown in Fig. 3 for the case with no cooling and the case with the graphite backing lining in the tidal zone.

Based on the results of this investigation, Sibanye-Stillwater and Tenova jointly agreed to implement the use of the graphite backing lining in Furnace 2. The original

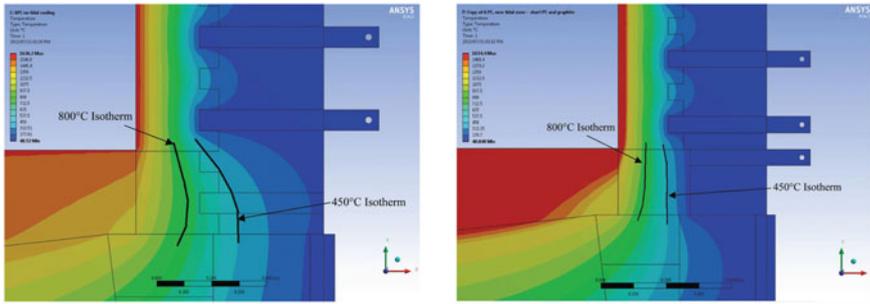


Fig. 3 Comparative thermal FEA results between an uncooled tidal zone and one with the proposed graphite backing lining [9]. (Color figure online)

graphite backing lining has been in operation since the start-up of Furnace 2 in 2011, and was replaced for the first time during the 2020 furnace reline. During the reline in 2018, the sidewall demolition damaged a few of the graphite blocks mechanically. However, no operating process-related wear or oxidation was noted. The machining marks on the blocks were still visible. To do repairs to the upper skewback ring the complete ring of graphite blocks were removed, cleaned, and reinstalled and only the mechanically damaged graphite blocks were replaced. The graphite blocks are shown in Fig. 4 during the 2018 Furnace 2 reline. The same matte–slag tidal zone lining design was installed during the 2020 reline.

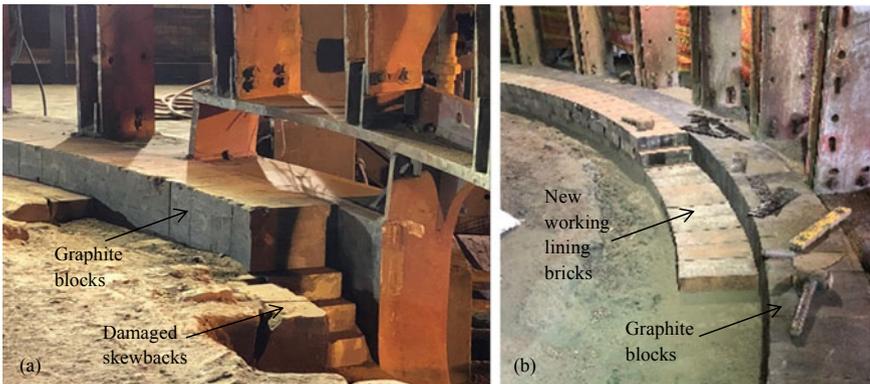


Fig. 4 Photos showing the graphite blocks during the **a** demolition and **b** rebuilding phases of the most recent Furnace 2 reline. (Color figure online)

Moving Towards Waterless Electrodes

The presence of cooling water above a smelting furnace has been a risk many furnace operators had to live with, and still has to live with. Examples of explosions due to water coming into contact with molten metal, matte, or slag are unfortunately numerous [10]. Cooling water is typically used to cool the electrode components, and in some industries the furnace roof, all equipment located directly above the furnace bath. In the platinum industry most furnace roofs are not water-cooled, and consist of refractory bricks supported by an anchoring system, commonly referred to as a hanging brick roof design. However, on all operating platinum furnaces known to the authors water is used to cool the electrode components. This is the case for Söderberg type self-baking electrodes as used on typical platinum smelting furnaces, for example Furnace 2, as well as for prebaked graphite electrodes as used on some smaller and older furnaces, for example Furnaces 3, 4, and 5 at Sibanye-Stillwater's smelter complex at Marikana (originally designed and built by Tenova Pyromet). Explosions due to water leakages on furnace roofs have occurred in the past. For example, a large explosion occurred on a silicon smelting furnace in Norway in 2006 due to water leaking from electrode components [11]. In 2004 Sibanye-Stillwater experienced an explosion in Furnace 1 due to a water leak from a flexible hose that blew off the furnace roof.

Due to the relatively low electrode current densities present in Söderberg electrodes used in the platinum industry, and the base metals industry in general, the electrode casing remains intact for a relatively long distance below the contact shoes and provides structural strength to the electrode. This allows the water-cooled lower electrode components, such as the contact shoes and pressure rings, to be located above the furnace roof. This is in contrast to other industries, such as ferroalloys, where the water-cooled contact shoe and pressure ring arrangement has to be located close to the feed burden in the furnace freeboard to limit the free electrode length. In addition, as the casing remains intact below the contact shoes, sealing directly against the electrode casing at the furnace roof level is possible. There is thus no need for water-cooled heat shields extending through the seal into the furnace freeboard as is the case in most other furnace operations.

Notwithstanding that this arrangement is typical of most base metal furnaces, these furnaces tend to still use extensive water cooling on the lower electrode components, including water-cooled pressure rings, contact shoes, bus tubes, and in some cases water-cooled heat shields. Tenova Pyromet realised this arrangement presented an opportunity to significantly reduce the use of cooling water above the furnace roof for base metal furnaces. Starting with Sibanye-Stillwater's Furnace 2, the water-cooled electrode pressure ring was changed to an uncooled stainless steel design and the water-cooled heat shields were removed. The water-cooled heat shields can be replaced with uncooled dust shields if excessive dust build-up is a concern above the furnace roof. The only water-cooled electrode components remaining above the furnace roof are the contact shoes and the bus tubes supplying electrical current and cooling water to the contact shoes, as well as the pressure below between the

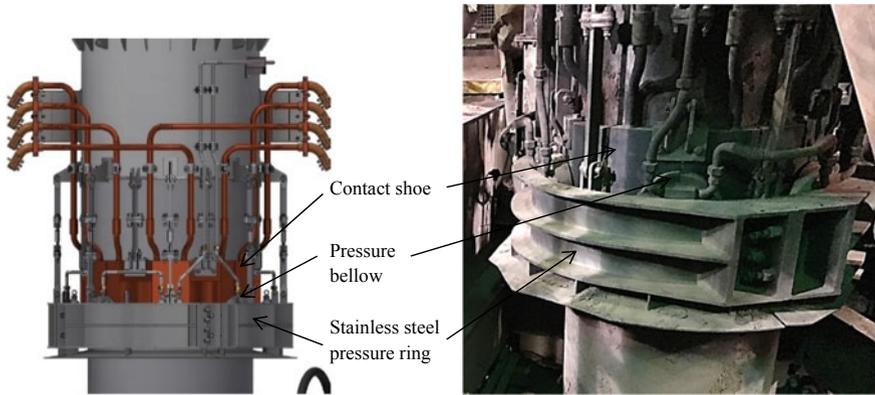


Fig. 5 Furnace uncooled lower Söderberg electrode arrangement and components. (Color figure online)

contact shoes and the pressure ring. A 3D model of the Furnace 2 lower electrode arrangement as well as a photo of the actual installation is shown in Fig. 5. The design of Tenova Pyromet's electrode for base metal furnace applications is discussed in more detail by Bantubanie et al. [12].

The new lower electrode design has been in operation on Furnace 2 since start-up in 2012. The maintenance required on the electrode components has been minimal apart from a single contact shoe that was replaced and inspected during 2015 scheduled reline as a precautionary measure.

Tenova Pyromet subsequently implemented the base metal style lower electrode design on another project with similar success. The design was expanded to include a new innovative, robust, and easy maintainable seal design for sealing directly onto the electrode casing [13]. Work is currently underway to develop a completely waterless electrode for base metal furnaces, removing all cooling water from above the furnace roof.

Matte Taphole Faceplate

Tenova Pyromet's standard matte taphole design consists of water-cooled copper elements split between the inner taphole block, the outer taphole block, and the taphole faceplate. The same design was employed for the original matte tapholes on Furnace 2 as shown in Fig. 6. Both the conical faceplate insert and the taphole blocks are manufactured from magnesite-chrome refractory material.

Based on the positive experience with the cast iron taphole faceplates on the smaller Pyromet furnaces (designed and supplied by Tenova Pyromet in 1989), Sibanye-Stillwater requested Tenova Pyromet to jointly investigate the use of uncooled cast iron faceplates for Furnace 2. The use of uncooled cast iron faceplates

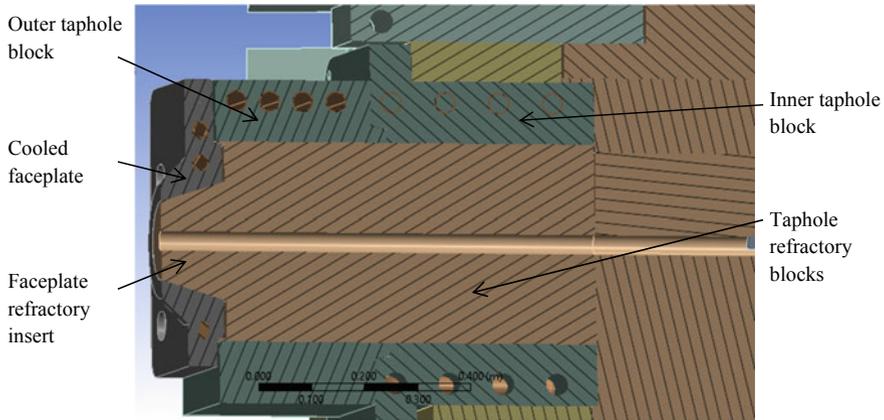


Fig. 6 Model showing section through the Furnace 2 matte taphole. (Color figure online)

assists in the removal of water from close proximity to the molten matte stream and would reduce the safety risk. In addition, the existing water-cooled copper faceplate is physically damaged from time-to-time during tapping operations, and pre-mature cracking of the refractory insert is attributed to overcooling by the faceplate resulting in a high radial temperature gradient across the insert.

Three material options were selected for further investigation: A typical ductile cast iron, a high-temperature Meehanite grade cast iron, and a high-temperature stainless steel casting grade. The three materials are described in Table 1.

Thermal finite element analysis (FEA) was performed to evaluate the different material options. A matte tapping temperature of 1550 °C was assumed in line with normal operating conditions. In the lead up to a taphole repair or a furnace rebrick, the furnace is emptied through one of the matte tapholes. Therefore, another load case considered was the tapping of slag at 1650 °C through the matte taphole. Both steady

Table 1 Alternative faceplate materials investigated [14, 15]

| Material type | Max operating temperature | Material | Main attributes |
|-------------------|---|---|---|
| Ductile cast iron | Up to 500 °C | Nodular graphite, according to DIN EN 1563 Grade EN-GJS-700-2 | Readily available, good machinability. |
| Meehanite HE | Up to approximately 900 °C | Flake graphite, pearlitic | Best for cyclical heating applications, involving thermal shock |
| ASTM A297 HH | Scaling resistance up to 1093 °C Long term strength up to 954 °C | Fe–Cr–Ni alloy. 25% Cr 12% Ni | Excellent resistance to hot sulphur bearing gasses. |

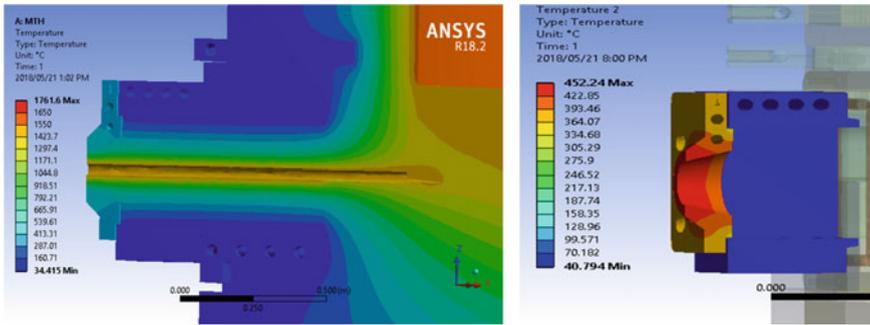


Fig. 7 Steady state temperature plot for uncooled Meehanite HE - Load case no.3. (Color figure online)

state and transient analyses were performed. The steady state analysis, which implies continuous tapping, was performed to represent the worst case. The transient analysis was limited to 1 h, the maximum tap duration for matte on Furnace 2. For comparison, analyses were performed for the current water-cooled copper faceplate design. The main purpose of the FEA modelling was to determine the maximum expected operating temperature for the faceplate. For example, the steady state temperature plot results for the uncooled Meehanite HE grade cast iron as shown in Fig. 7 indicates a maximum faceplate temperature of 452 °C. This represents the worst case for Meehanite HE and is well below the maximum allowable operating temperature of 900 °C as referenced in Table 1.

The maximum faceplate temperature for a number of load cases are listed in Table 2. The maximum temperature for the existing water-cooled copper faceplate remains low, even under steady state conditions. This is positive for the faceplate itself, but results in the expected high radial temperature gradient through the refractory insert (see Fig. 8a). Of the three new materials tested, Meehanite HE has the lowest maximum operating temperature, both under steady state and transient conditions, as well as during slag tapping. Next is ductile cast iron followed by the stainless steel cast material. The maximum faceplate operating temperature tends to be higher relative to a lower material thermal conductivity. Of interest for Meehanite HE the maximum operating temperature is calculated to be 177 °C after 1 h of matte tapping and 315 °C after 3 h of slag tapping, well below the steady state maximum temperature, and significantly lower than the Meehanite HE operating temperature limit. Ductile cast iron operates at temperatures close to its maximum operating limit. From Fig. 8b the maximum radial temperature gradient under steady state conditions for the Meehanite HE faceplate is estimated to be 20 °C/mm compared to 28 °C/mm for the water-cooled copper faceplate. The refractory insert should therefore experience less thermal stress and thermal fatigue when used in combination with the uncooled Meehanite HE faceplate.

It was decided to proceed with Meehanite HE and manufacture two uncooled faceplates for testing on Furnace 2 for the following reasons:

Table 2 Maximum calculated faceplate temperature for selected load cases

| Load case no. | Steady state or transient | Face plate material | Faceplate cooling | Maximum faceplate temperature |
|---------------|---------------------------|--------------------------------|-------------------|-------------------------------|
| 1 | SS | Copper | Yes | 62 °C |
| 3 | SS | Meehanite HE | No | 452 °C |
| 6 | SS | Ductile Cast Iron | No | 498 °C |
| 7 | SS | Ductile Cast Iron slag tapping | No | 512 °C |
| 8 | SS | Meehanite HE slag tapping | No | 464 °C |
| 9 | SS | ASTM A297 HH | No | 542 °C |
| 10 | SS | ASTM A297 HH slag tapping | No | 554 °C |
| 2T | T 1 h | Copper | Yes | 59 °C |
| 3T | T 1 h | Meehanite HE | No | 177 °C |
| 6T | T 1 h | Ductile Cast Iron | No | 222 °C |
| 8T | T 3 h | Meehanite HE slag tapping | No | 315 °C |

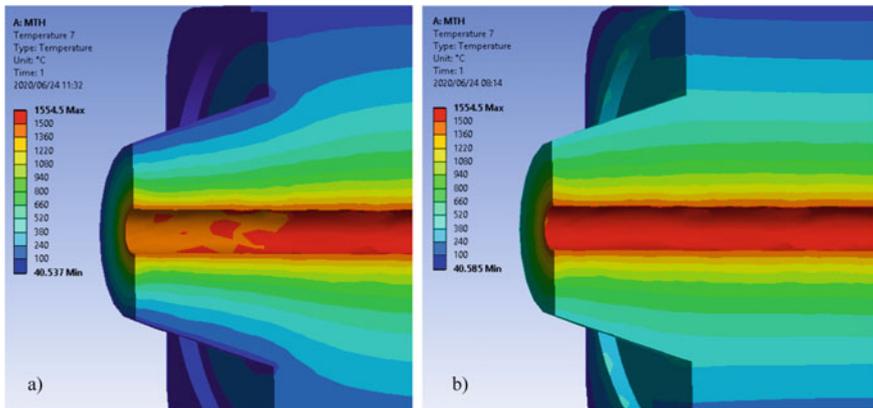


Fig. 8 Temperature gradient through faceplate refractory insert: **a** Water-cooled copper faceplate; **b** Meehanite HE faceplate. (Color figure online)

- Meehanite HE’s calculated maximum operating temperature relative to its allowable maximum operating temperature is significantly lower compared to that for the Ductile Cast Iron. The cost for Meehanite HE is very similar to that for Ductile Cast Iron.



Fig. 9 Cast and machined Meehanite HE faceplates. (Color figure online)

- Meehanite HE's calculated maximum operating temperature relative to its allowable maximum operating temperature is very similar compared to that for the cast stainless steel option. Meehanite HE is less than half the cost of ASTM A297.
- Meehanite HE is less than half the cost of the existing copper faceplate, is anticipated to reduce the thermal stress experienced by the refractory insert, and reduces the overall safety risk associated with water in close proximity to the molten matte.

The first two Meehanite HE faceplates were manufactured in 2018. The cast and machined faceplates are shown in Fig. 9. The first Meehanite HE faceplate was commissioned in December 2018 on one of the matte tapholes and was inspected and replaced in January 2019 due to non-related oxygen lancing damage. Subsequently both matte tapholes were equipped with Meehanite HE faceplates that lasted for 12 months of operation before being replaced. It was decided to continue with the use of the Meehanite HE faceplates on Furnace 2 and subsequently on Furnace 1 as well. To date, the average campaign life for a Meehanite HE faceplate is six months, or the equivalent of approximately 270 matte taps. In most cases the campaign was terminated after a small hairline crack has been noticed at the top of the faceplate. An investigation is currently underway to determine the cause of this crack.

Conclusions

Furnace 2 has been in operation since July 2012 and the refractory crucible design performed very well. Improvements to the roof and off-gas design assisted in achieving uninterrupted sidewall campaigns. Three successful sidewall campaigns have been completed since start-up of the furnace. The tidal zone refractory design, including the graphite back lining, assisted in limiting refractory wear in this critical area of the Furnace. The graphite back lining has been replaced for the first time during the July 2020 furnace reline.

The uncooled pressure ring design on the Furnace 2 electrodes has been performing well with only minor maintenance required since start-up in 2012. Tenova Pyromet has installed the same design on other base metal furnaces with similar success. Future developments include the removal of all cooling water from above the furnace roof.

3D thermal FEA modelling was performed to determine whether the current water-cooled copper matte taphole faceplate could be replaced by an uncooled cast iron faceplate. Results indicated that the maximum temperature after 1 h of matte tapping was well within the limits of operation of grey cast iron, and that the maximum steady state temperature attained by the cast iron was well within the limits of high temperature cast iron material. It was concluded that the water-cooled copper matte taphole faceplate could safely be replaced by an uncooled faceplate made of Meehanite HE grade cast iron. A six-month campaign life has been averaged since its implementation on Furnace 2.

References

1. Eksteen JJ, Van Beek B, Bezuidenhout, GA (2011) Cracking a hard nut: An overview of Lonmin's operations directed at smelting of UG2-rich concentrate blends. Paper presented at Southern African Pyrometallurgy 2011 International Conference, Cradle of Humankind, South Africa, pp 231–251
2. Joubert H, Nourse RB, Masters B, Hundermark R (2005) Copper Cooling Design, Installation and Operational Results for the Slag Cleaning Furnace at Waterval Smelter, Rustenburg Platinum, South Africa. Paper presented at COM2005 44th Conf of Metallurgists, International Symposium on Nickel and Cobalt Production, Calgary, Alberta, Canada, pp 21–25
3. Nelson LR, Geldenhuis JMA, Emery B, de Vries M, Joiner K, Ma T, Sarvinis J, Stober FA, Sullivan R, Voermann N, Walker C, Wasmund BH (2006) Developments in furnace design in conjunction with smelting plants in Africa. In: Jones RT (ed) Presented at Southern African Pyrometallurgy 2006, SAIMM, Johannesburg, 5–8 March 2006
4. Eksteen JJ (2011) A mechanistic model to predict matte temperatures during smelting of ug2-rich blends of platinum group metal concentrates, minerals engineering special issue. In: Processing Nickel Ores and Concentrates, vol 24 (7), pp 675–687
5. Nelson LR, Geldenhuis JMA, Emery B, de Vries M, Joiner K, Ma T, Sarvinis J, Stober FA, Sullivan R, Voermann N, Walker C, Wasmund BH (2006) Developments in furnace design in conjunction with smelting plants in africa. In: Jones RT (ed) Southern African Pyrometallurgy 2006, SAIMM, Johannesburg, pp 5–8
6. Thethwayo BM, Garbers-Craig AM (2012) Corrosion of Copper Coolers in PGM Smelters". Paper presented at the 4th International Platinum Conf, Platinum in Transition "Boom or Bust", SAIMM., 2010
7. Shaw A, De Villiers LPVS, Hundermark RJ, Ndlovu J, Nelson LR, Pieterse B, Sullivan R, Voermann N, Walker C, Stober F, McKenzie AD (2013) Challenges and solutions in PGM furnace operation: high matte temperature and copper cooler corrosion. *J South Afr Inst Min Metall* 113(3):10–25
8. McDougall I, Eksteen JJ (2012) Sidewall Design to Improve Lining Life in a Platinum Smelting Furnace. Paper presented at the TMS 2012 International Smelting Technology Symposium, Orlando Florida, pp 11–15
9. Mc Dougall I (2013) Sidewall design for improved lining life in a PGM smelting furnace. *J Southern Afr Inst Mining Metall* 113:631–636

10. Kennedy MW, Nos P, Bratt M, Weaver M (2013) Alternative coolants and cooling system designs for safer freeze lined furnace operation. Present Ni-Co 2013:299–314
11. Tveit HM, Garcia H, Delbeck AT, Haug B, Saugestad, and Eikeland IJ (2006) Water leakages in ferroalloy and silicon reduction furnaces—experience gained from a severe accident in 2006, presented at the Silicon for the Chemical and Solar Industry IX, Oslo, Norway, pp 1–16
12. Bantubani S, Hansraj R, Arjun S, Mc Dougall I, Joubert H (2019) Electrode and electrode management technology for use on base metal electric furnaces. The 68th Annual Conference of Metallurgists (COM) hosting the 10th International Copper Conference 2019
13. Esterhuizen A, Joubert H, Essack S, Fowler N (2019) Innovative technologies for copper smelting and electric slag cleaning and matte settling furnaces. The 68th Annual Conference of Metallurgists (COM) hosting the 10th International Copper Conference 2019
14. Steel Casting Handbook, Supplement 8-High Alloy Data Sheets-Corrosion Series, Steel Founders' Society of America (2004). <http://www.sfsa.org/sfsa/pubs/hbk/s8.pdf>
15. Meehanite Specification Handbook, Meehanite Worldwide Corporation (2013). <http://www.meehanite.co.uk>. Accessed xxx 2013