Cooling innovation in practice: A case study on composite copper-graphite cooler performance before and after a PGM furnace partial sidewall rebuild

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Abstract

Sibanye-Stillwater recently completed a partial sidewall rebuild on Furnace 1 at its Marikana smelter complex. The project involved matte taphole maintenance, which required the removal and subsequent replacement of 18 composite copper-graphite coolers and a section of the lower refractory sidewall. These composite copper-graphite coolers are a newly developed cooling design by Tenova Pyromet, and this rebuild project provided valuable insight into the performance of the composite coolers. The novel composite cooler design was implemented to serve as a safeguard against localised wear and corrosion in the furnace sidewall, particularly at the slag-concentrate interface, where chloride-accelerated sulphidation has been identified as a dominant degradation mechanism affecting the copper cooling elements. The composite cooler design is unique in that all the exposed sides of the water-cooled copper elements are fully encapsulated in graphite, which protects the copper from corrosive sulphur- and chlorine-bearing gases and condensates. This sidewall cooling system was designed to improve corrosion resistance, stabilise freeze lining formation, and extend the campaign life of the furnace sidewall. The partial sidewall rebuild was executed during a planned maintenance shutdown with the main objective of replacing the matte taphole lintel bricks. This paper serves as a case study that compares and evaluates the operational performance of the composite coolers before and after the rebuild. The installation method is discussed to highlight the approach taken to ensure a sound installation while minimising downtime, as well as to present some lessons learned in the process.

Keywords

composite coolers, furnace rebuild, freeze lining, PGM smelting

Introduction

The smelting of platinum group metals (PGM) presents unique challenges in furnace containment and sidewall longevity due to the aggressive chemical and thermal environment within the furnace crucible. To withstand this aggressive environment and to extend the operational lifetime of the PGM furnace, an innovative crucible design was implemented in 2022 for Furnace 1 at Sibanye–Stillwater's Marikana smelter complex. Sibanye–Stillwater's Marikana smelter complex, operational since 1971, comprises of five circular electric smelting furnaces, with Furnaces 1 and 2 being the primary furnaces and Furnaces 3 to 5 being used on a standby basis. All of these furnaces are used to process a blend of Upper Group 2 (UG2) and Merensky PGM-based floatation concentrates, together with some internal recycle streams (Eksteen et al., 2011).

In March 2021, Tenova Pyromet was awarded the contract to upgrade Furnace 1, with the main objective being to improve the overall long-term availability of the furnace. The design intent was to increase the furnace sidewall campaign life from 30 months to 48 months and the hearth campaign life to 12 years. The main changes to the existing design included increasing the furnace diameter, raising the matte tapholes above the skew-back brick level, and introducing a novel sidewall cooling system. As part of the novel sidewall cooling system, water-cooled copper-graphite composite coolers were utilised in the new furnace sidewall design. These copper-graphite composite coolers are unique in that they address some of the most common sidewall wear mechanisms experienced at PGM furnaces. The furnace upgrade project execution started in May 2022, and the first matte was tapped from the furnace in September 2022. The design and changes implemented, as part of the furnace upgrade project, are discussed in detail by Joubert et al. (2024a, 2024b).

Cooling innovation in practice: A case study on composite copper-graphite cooler performance

In January 2025, during a planned maintenance shutdown, Sibanye–Stillwater undertook a partial sidewall rebuild focused on matte taphole lintel replacement. This shutdown provided a unique opportunity to assess the performance of the composite copper–graphite coolers after 29 months of operation. The present paper builds on the foundational work presented by Joubert et al. (2024a) and aims to evaluate the operational effectiveness of the composite cooler system before and after the planned rebuild. It documents the installation methodology, observes wear profiles, and sets out the lessons learned to inform future furnace maintenance and design strategies.

Technical background

The operational environment within platinum group metal (PGM) smelting furnaces is characterised by extreme thermal loads and chemically aggressive conditions, particularly at the slag-concentrate interface (Shaw et al., 2013). This zone is notorious for rapid degradation of furnace sidewall copper cooling elements, primarily through chloride-accelerated sulphidation. Chloride-accelerated sulphidation is believed to be the prevalent copper corrosion mechanism at the slag-concentrate interface, due to the presence of labile sulphur and chlorine-bearing species in the uncalcined feed concentrates (Hoff, Rossouw, 2006; Marx et al., 2007; Shaw et al., 2013; Thethwayo, Garbers-Craig, 2010). This results in the localised attack of exposed copper surfaces, leading to thinning, pitting, and eventual failure of cooling elements, an example of which can be seen in Figure 1.

As mentioned in the introduction, one of the main design improvements during the Furnace 1 upgrade at Sibanye-Stillwater, was to implement a novel sidewall cooling design. This sidewall cooling design includes the use of innovative water-cooled copper-graphite composite coolers. This composite cooler design aims to extend the operational lifetime of the furnace sidewall by mitigating the impact of chloride-accelerated sulphidation and enabling sufficient heat to be extracted to ensure a stable slag freeze-lining formation. The graphite-copper composite cooler designed by Tenova Pyromet limits the opportunity for the mentioned chloride-accelerated sulphidation to take place by encapsulating the water-cooled copper elements in graphite. This design ensures that no part of the copper is directly exposed to furnace gases or condensates, thereby eliminating the primary pathway for sulphidation. Graphite has been shown to provide good protection against sulphidation corrosion (Joubert, 2008; Shaw et al., 2013), while providing the required thermal conductivity to maintain a freeze-lining (Mc Dougall, 2013). The high thermal conductivity of graphite ensures that cooling efficiency is maintained, while its chemical stability prevents degradation under prolonged exposure to the slag. This design combination, as shown in Figure 2, allows for a slag-zone cooler assembly with an operational lifetime estimated to exceed 4 years, governed by the operational stability of the furnace.

Figure 1—Examples of localised attack on exposed copper surfaces

Figure 2—Copper-graphite composite cooler assembly (Joubert et al., 2024a)

The Tenova Pyromet copper-graphite composite cooler solves the slag-zone chemical and thermal wear problem, but high wear rates are still estimated for the matte-slag tidal zone. At this interface, the working lining is subjected to chemical attack from both the matte and slag, and is exposed to superheated matte, which can be in excess of 600°C above the matte liquidus temperature. Having superheated matte present in this area increases the risk of boiling liquid expanding vapour explosions (BLEVEs) if it comes in contact with water-cooled copper components, which can cause catastrophic equipment damage and compromise the furnace lining integrity. Due to this safety risk, no water cooling is applied in this matte-slag tidal zone or in the matte zone.

To increase the operational lifetime of the lower sidewall in the matte-slag tidal zone, a lower sidewall design was developed that makes use of a graphite back lining, together with forced draft air cooling on the shell (Mc Dougall, 2013). This allows excess heat to be extracted from this critical zone, with the help of the highly conductive graphite back lining. Graphite is wear-resistant when exposed to matte and slag at elevated temperatures, making it suitable to be used in the refractory sidewall. A thermal finite element analysis (FEA) was used during the design phase to estimate the maximum wear profile before stabilisation, the results of which more details can be found in Joubert et al. (2024b). The FEA model was used to estimate that the working lining will wear back, leaving approximately 200 mm of working lining brick before stabilising. At this thickness, the graphite brick removes sufficient heat to slow down the wear rate, stabilising this critical zone. An example of the FEA-predicted wear profile is shown in Figure 3(a), in comparison to the actual wear profile, Figure 3 (b), observed during the sidewall rebuild project in January 2025. These figures highlight that the FEA accurately predicted the extent of the anticipated wear, and confirm that the graphite back lining brick provides sufficient cooling to stabilise the wear rate in this critical zone.

In Figure 3(a), the maximum matte and matte taphole levels are indicated, showing that the matte tapholes are positioned in this high-wear zone. Even though the sidewall wear stabilizes, as anticipated by the FEA modelling, the matte taphole areas (more specifically the matte taphole lintels) experience higher wear rates due to the increased activity in these areas during tapping operations. This was anticipated, and even though the rest of the furnace sidewall was designed for a 48-month campaign, the modular composite cooler design allows for a partial sidewall rebuild of the matte taphole areas, which was originally planned for every 24 months (Joubert et al., 2024b). Due to stable operation and good operating temperatures, this hot partial sidewall rebuild was executed in January 2025, 29 months after initial start-up. Even though the main intention of the partial sidewall rebuild was to replace the matte taphole lintels, it also afforded the opportunity to evaluate how well the copper-graphite composite coolers performed after 29 months in operation, as well as to inspect the matte-slag

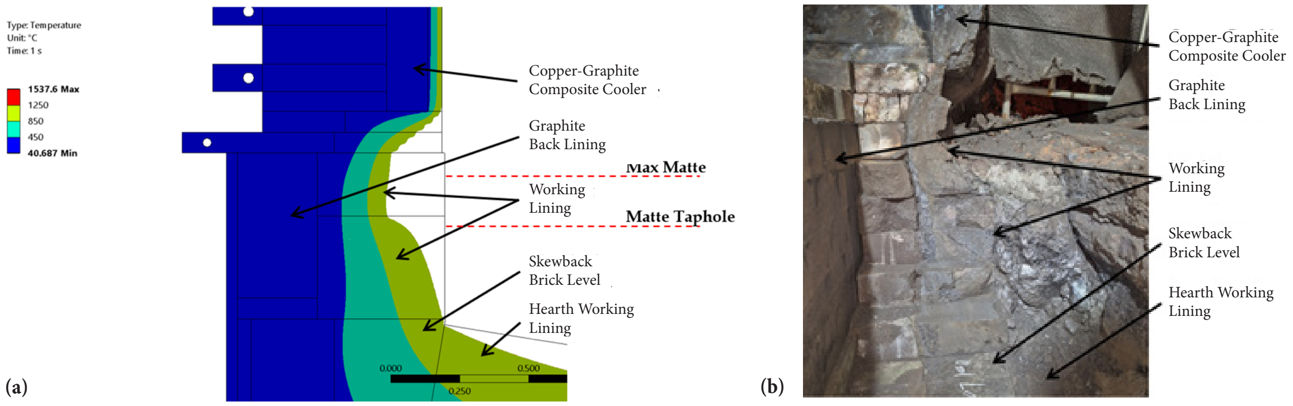

Figure 3—Matte-slag tidal zone (a) FEA estimate, and (b) wear profile observed during partial sidewall rebuild

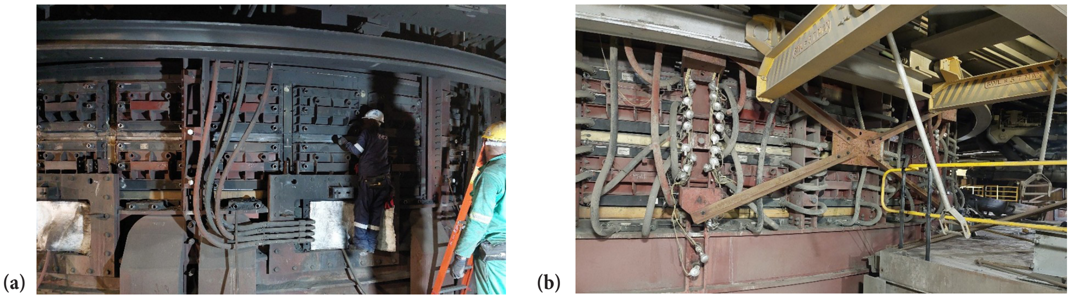

Figure 4—Furnace showing (a) isolated composite coolers above matte tapholes, and (b) the installed temporary cross-brace

tidal zone. In the next section, an overview of the process followed during the hot repair and the steps taken to get the furnace back into production following a month of idling will be discussed.

Hot partial sidewall rebuild methodology

The initial design of the furnace upgrade in 2022, was done with this hot partial sidewall rebuild in mind and done in such a way as to ensure efficient removal of the composite coolers to get to the lower refractory sidewall and matte taphole lintels (Joubert et al., 2024b). As discussed by Joubert et al. (2024b), the matte tapholes were raised above the skewbrick level, ensuring less thermal movement in this critical area. Not only was this one of the main benefits of this design decision, but it also resulted in some material lock-up below the matte taphole level, which ensured much more stable hearth temperatures during the hot partial sidewall rebuild process. The thermal mass below the matte taphole level ensured stable temperatures in the hearth during the power-down periods, limiting thermal ratcheting of the hearth. During the rebuild project, the power was cycled on and off to maintain a molten pool below the electrodes and to maintain the hearth temperatures. This not only ensured that start-up would be easier, due to the maintained electrode contact, but it also reduced the impact the partial sidewall rebuild would have on the hearth operational lifetime.

Preparation

The partial rebuild project was started with a well-established project plan, as required for any well-executed project. Excellent work from the Sibanye-Stillwater Project Team ensured that all contractors were brought up to speed on the exact scope of work before any work on the furnace was started. The project and operational teams ensured that all required spare parts were on site and accounted for before any demolition work started. A list of equipment to be reused was prepared to ensure special care was taken when removing and storing this equipment and parts for later use. A custom-designed, rail-mounted composite cooler installation device was tested and commissioned before the furnace was powered down to ensure this system was functioning as intended and that the refractory contractor was familiar with its operation. With all the preparation work completed and a finalised plan in place, the furnace was drained on 3 January 2025, and the 3-day cool-down period commenced.

Partial sidewall demolition

On 7 January 2025, the furnace was handed over to the refractory contractor, and demolition started. For the partial rebuild, only 18 composite coolers needed to be removed to gain access to the three matte taphole lintels and lower sidewall refractory. The cooling water lines for the 18 composite coolers were isolated and flushed, after which all cooling water flexibles and instrumentation were removed, as shown in Figure 4(a). In parallel with this activity, two temporary cross-braces were installed on the furnace ladder columns, as shown in Figure 4(b), to provide the required lateral stabilisation to the rest of the furnace sidewall while the repair was underway. With the furnace sidewall stabilised, the Tenova Pyromet patented external containment system (De Villiers et al., 2020) could be disengaged to allow the required space to extract the composite coolers from the furnace sidewall. More details on the external containment system can be found in Joubert et al. (2024b).

The last step before the composite coolers could be removed was to open the space above the upper row of coolers. This was achieved by jacking up the freeboard assembly, using hydraulic jacks, and removing the two tapered brick rows in between the coolers and the furnace freeboard structure. Finally, it was time to remove the first composite cooler. On 10 January 2025, the first cooler was successfully removed from the furnace sidewall using the custom hydraulic removal/installation device, developed specifically for this activity. Due to the design of the composite coolers and very tight joints between the coolers, which did not allow any slag penetration, the composite cooler came out easily with a simple tug by the installation device. The removed composite cooler can be seen in Figure 5(a), still mounted to the installation device. Interesting to note is the slag freeze-lining that remained intact as the composite cooler was removed, suggesting a strong freeze-lining, as shown in Figure 5(b). The groove pattern from the composite cooler's hot-face was visible on the back of the slag freeze-lining, indicating that the freeze-lining was securely keyed to the composite cooler hot-face. By observing this stable freeze-lining, it was evident that the Sibanye-Stillwater Operational Team performs an excellent job of maintaining the slag operational levels in the furnace as well as a stable process chemistry. More detail on the condition of the removed composite coolers to follow in the next section. The lower row of composite coolers required more pulling force to be removed due to a larger surface area being in contact with the slag freeze-lining, but the same procedure was followed.

With all 18 composite coolers removed, full access to the lower sidewall and matte taphole lintel areas was now possible. The initial procedure only required the matte taphole lintel bricks to be removed and replaced, but considering that this was the first time this partial sidewall rebuild was done, it was decided to go down to skewbrick level to inspect the condition of this area as well. Eight additional brick rows were removed to get to the skewback brick level, as shown in Figure 6, and were completed by 18 January 2025. At this level, it was clear that the skewback bricks and hearth working bricks were still in good condition. It was also found that the graphite backlining was in good condition, and that there was no reason for replacing these blocks; therefore, the existing bricks were reused. One observation made at this level was the radial crack through the skewback brick row. A similar crack was observed during Furnace 2 rebuilds at Sibanye-Stillwater, and it is believed to coincide with the matte solidus isotherm in this area. The FEA modelling predicts that the matte solidus isotherm passes through the skewback bricks at this position, likely resulting in a substantial thermal and mechanical stress in the bricks, which could have caused the crack-line. From past experiences, it has been found that this crack is not of concern and does not compromise the hearth integrity. The uniform position of the crack in the skewback brick indicates uniform heating and expansion in the hearth, which speaks to a uniform hearth temperature distribution. If the crack is kept clean, it is anticipated to close up once the hearth reaches operational temperatures.

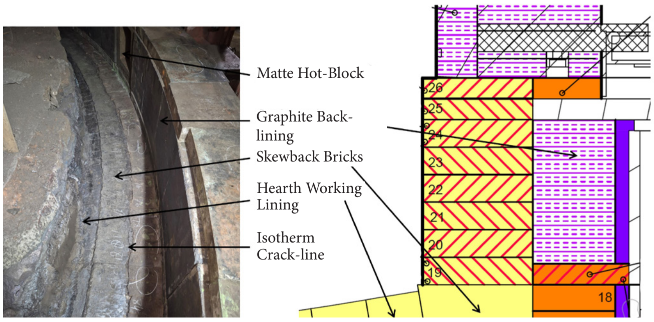

Figure 6—Sidewall refractory cleaned up to the skewback brick level

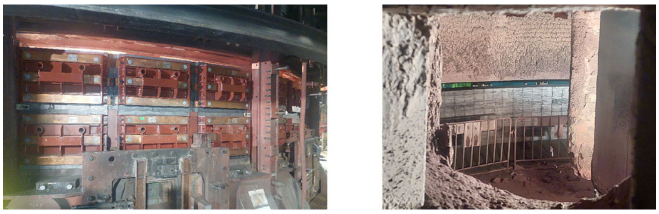

Figure 7—Reinstalled copper-graphite composite coolers from (a) the outside, and (b) from inside through the furnace freeboard inspection port

Installation and commissioning

Once all the demolition work had been done, the required refractory inspections were completed – all of which were satisfactory. The next phase was to reinstall the required refractory in the lower sidewall as well as the composite coolers on the slag sidewall. The reverse order of the demolition sequence was followed, starting by rebuilding the lower sidewall refractory and matte taphole lintels, followed by the composite coolers and the remainder of the sidewall equipment and instrumentation. By 27 January 2025, the lower sidewall refractory installation was completed, slowed by some delays experienced at the matte taphole lintel installation. All 18 new composite coolers were reinstalled, and by 29 January 2025, the slag sidewall was completed and furnace freeboard and roof lowered, as shown in Figure 7. On 31 January 2025, the furnace started heating up again, with all sidewall equipment and instrumentation reinstalled.

Lessons learned and future considerations

Considering that this was the first attempt at a hot partial sidewall rebuild at Sibanye-Stillwater's Furnace 1, it was expected that there would be some lessons learned, and future improvements required. The first lesson learned, and improvement required was implemented during the project, which was to add hydraulic

Figure 5—Composite cooler removal process showing (a) the composite cooler removed using the hydraulic installation device, and (b) showing the slag freeze-lining on the furnace hot-face

tilting to the installation device. Initially, the tilting was done with a mechanical screw jack to avoid the need for a second hydraulic power pack, but the not-so-subtle handling by the installation team resulted in a breakage at the screw jack. It was decided to add a hydraulic jack to the installation device, which allowed for a more robust installation device, but it required a second power pack to be in operation. The second lesson learned was to be aware of the very tight clearances around the furnace on the matte floor side. Due to space constraints, the installation device had to operate within tight tolerances, which did cause some initial problems once the installation device was loaded with a composite cooler. This was also addressed during the project itself, and after all the pinch points were addressed, the installation device operated as intended.

Due to the well-established freeze-lining and good adhesion to the composite coolers, more force had to be applied to the lower composite coolers to break them free from the freeze-lining, while avoiding damage to the cooler itself. Initially, it was attempted to be done with the installation device, but it was later found to be safer and easier to use the lifting lugs on the composite coolers to first break the cooler loose using rigging equipment, and then only use the installation device for removal and repositioning of the composite coolers.

Considering that this was the first attempt at a hot partial sidewall rebuild, it had been decided before the rebuild project was initiated to replace all 18 coolers with new composite coolers, rather than trying to reinstall the existing composite coolers. This was decided as it was not yet clear in what condition the composite coolers would be after being removed from the furnace. Pending inspections on the removed composite coolers, it appears likely that in the future the undamaged coolers will be reinstalled, further reducing the cost of the rebuild project. A future consideration is to establish a failure criterion for chips and wear to the graphite hot face, which will determine whether the composite cooler is to be reinstalled or replaced.

Operational performance

The furnace upgrade project was done with this hot partial sidewall rebuild project in mind, as mentioned before, which dictated and motivated some of the design choices. One that had already been mentioned was the material lock-up in the hearth, together with the furnace power-pulsing, which was aimed at keeping the hearth temperatures stable during the partial sidewall rebuild. By controlling the hearth temperature, less thermal movement is expected, which in turn reduces the risk of ratcheting of the hearth – all of which contribute to the health and operational lifetime of the hearth. Figure 8 illustrates how stable the hearth temperatures were maintained during the hot partial sidewall rebuild. In this figure, it can be observed that during the January 2025 rebuild, the centre long thermocouple (at hearth permanent lining) only decreased by approximately 50°C from the operational temperatures, using December 2024 as a comparison. The centre short (at infill lining level) remained more stable and recorded a temperature decrease in the range of 20°C, which highlights the stability in temperature of the lower hearth refractory. Electrode 3 was positioned towards the matte taphole side, and for the duration of the rebuild, the electrode was raised, and no power input took place – this was done to ensure the safety of the rebuild team. As a result, it can be observed that the upper hearth temperatures in this area decreased more than at the centre of the furnace. In contrast to these results, Electrode 1 (positioned towards the slag tapholes) was powered during the rebuild project to limit the heat losses from the hearth. It is shown that the hearth was back at operational temperatures approximately 20 days after the furnace heat-up was started. These figures highlight the success of the design intent and will positively contribute to achieving the target hearth campaign life of 12 years.

As mentioned before, the partial sidewall rebuild project offered an opportunity to not only physically inspect the composite coolers after just over half of the required operational lifetime, but also allowed for an opportunity to compare the operational temperature data to a newly installed composite cooler. Having replaced the lower refractory sidewall below the new composite coolers is likely to influence the temperature data, but it will provide good insight into how well the composite coolers performed over the 29-month operational period.

In Figure 9(a) to (d), the physical appearance of a typical cooler before installation, and after 29 months of operation is compared. Based on initial visual inspections, the composite coolers seem to be in very good condition, with little to no wear of the graphite hot face. Even though the stable freeze-lining layer, as shown in Figure 5, remained intact when the composite cooler was removed, the visual inspection of the composite coolers indicated that the hot-face grooves in the graphite worked as intended. It provided sufficient surface contact to stabilise the freeze-lining interface and ensure good adhesion to the composite coolers. Some wear and rounding of the graphite at the lower composite cooler's bottom edges were noticed, as shown in Figure 10(b). This is the edge closest to the dynamic matte-slag tidal zone, and with no deep cooling below this point, it is to be expected. This area is exposed to larger temperature gradients, higher heat loads, and does not

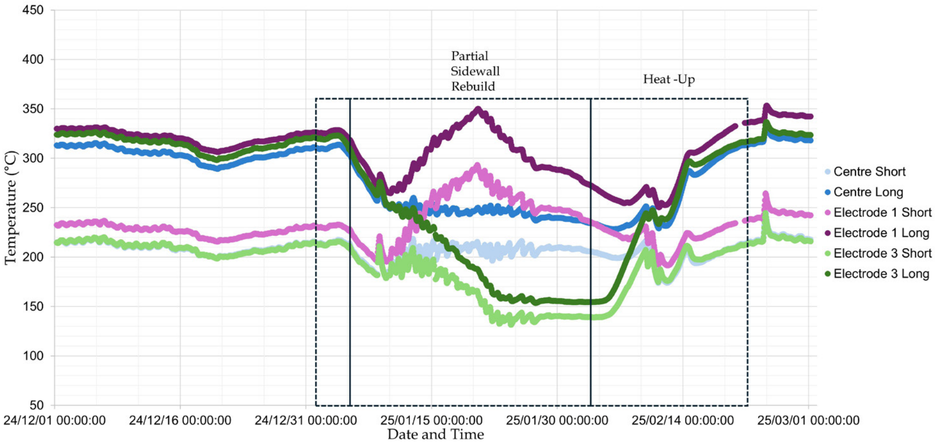

Figure 8—Furnace 1 hearth temperatures before and after the partial sidewall rebuild

experience the additional cooling from below, as is the case with the upper row of coolers. The likely reason for this wear profile on the lower composite coolers is demonstrated in Figure 3 and was expected based on the FEA work completed during the design phase of the upgrade project in 2021. Figure 10(a) shows that the side surface of the composite cooler appears to be untouched, with the surface still showing the shiny machining surface of the graphite. This observation speaks to good contact between the individual composite coolers, which ensured no penetration of any process material. It also speaks to the fabrication tolerances of these composite coolers, which allowed for the good interface contact to be maintained.

Preliminary visual inspections indicate that the removed composite coolers are still in perfect operating condition. The removed composite coolers have been sent for disassembly and internal inspections to confirm no internal or external defects. Pending these inspections, it appears likely that in the future the undamaged coolers will be reinstalled, further reducing the cost of the rebuild project. A future consideration is to establish a failure criterion for chips and wear to the graphite hot face, which will determine whether the composite cooler is to be reinstalled or replaced. The physical appearance of all the coolers seemed to be well within the expected condition after 29 months of operations, and in some instances, better than expected. When observing the temperature trends on the composite coolers from December 2022 to March 2025, a similar observation can be made regarding the thermal performance of the composite coolers. In Figure 11, the historic temperature trends of the bottom copper cooling element in the lower composite cooler are plotted. In Figure 11(a), the 50th percentile temperatures are plotted, and in Figure 11(b), the 99th percentile temperatures for the respective period are indicated. It is not a true representation to average the temperatures across all composite coolers, due to the dynamic nature inside the furnace as a result of tapping and electrode operations, but to generalise, an average temperature increase of 3.8°C/year is recorded across the bottom coolers. The top row of coolers records an average increase of around 1.2°C/year. The likely reason for the difference in temperature increase is the same as the proposed reason for the increased wear on the lower edge of the bottom composite cooler, that is, larger temperature gradients and heat load on the bottom composite cooler. The higher heat load and larger temperature gradient are a result of the wear profile in the matte-slag tidal zone and the cooling arrangement below the bottom composite cooler.

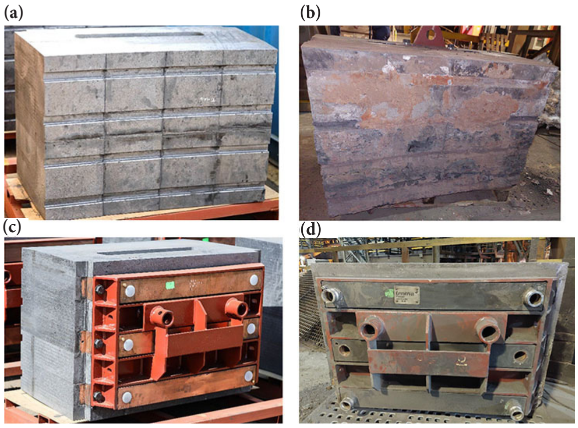

Figure 9—Physical appearance of the copper-graphite composite cooler: (a) front view of a new unit, (b) front view after 29 months of operation, (c) rear view of a new unit, and (d) rear view after 29 months of operation

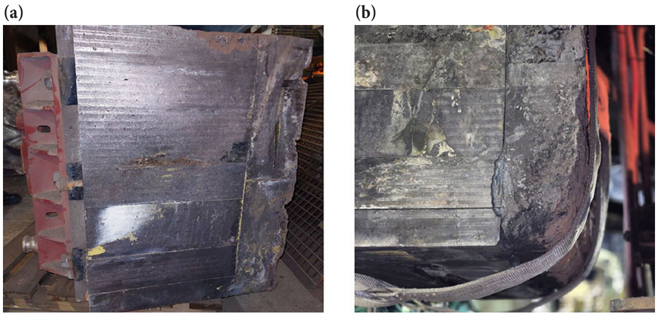

Figure 10—Copper-graphite composite cooler typical wear profile for (a) the top row of coolers, and (b) the bottom row of coolers

As shown in Figure 11, there is no significant temperature change from before the partial sidewall rebuild to after the rebuild, which highlights that the removed composite coolers were still well within the required operating conditions and could be reinstalled in the future. Note that only the composite coolers from 225° to 315° were replaced in January 2025, and a likely thermocouple installation error caused the low temperatures recorded at 270°.

By observing the temperature trends for the lower sidewall refractory in Figure 12 (focusing on the 225° to 315° window replaced during the partial sidewall rebuild), a clear impact of the rebuild is noticeable. It can be seen that, for the section of lower

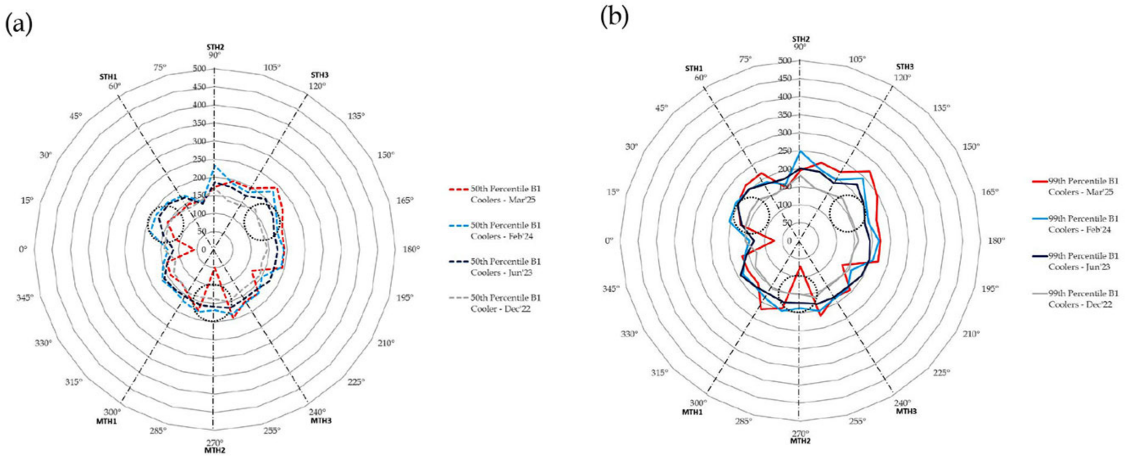

Figure 11—Historic temperature trends on the bottom composite cooler with (a) showing the 50th percentile temperatures, and (b) the 99th percentile temperatures for the specified period

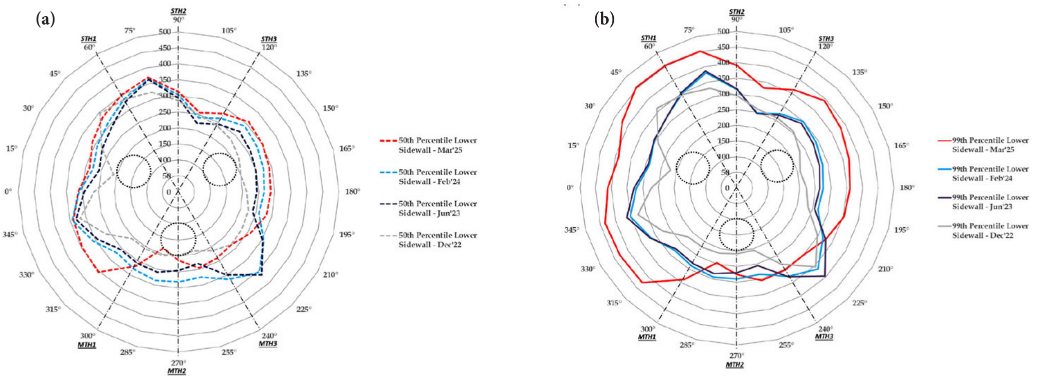

Figure 12—Historic temperature trends on the lower sidewall refractory with (a) showing the 50th percentile temperatures and (b) the 99th percentile temperatures, for the specified period

sidewall that was replaced, the average temperature is lower than that of the same area for the year before, and in some instances, close to the original installation trends from December 2022. An incremental increase in the lower sidewall temperatures, as illustrated in Figure 12(a), was expected due to the wear profile in the matte-slag tidal zone, and on average, increased 23.4°C/year. Interestingly, the mean temperature increase illustrated in Figure 12(a) speaks to incremental increase and wear expected in the lower sidewall. However, in Figure 12(b), a sharp increase for March 2025 is noticed when the 99th percentile temperatures are compared, likely as a result of a single upset event. Based on the site data, these high temperatures are restricted to a single day, after which the temperature returned to the expected range.

Conclusion

The implementation of Tenova Pyromet's copper–graphite composite coolers in Furnace 1 at Sibanye–Stillwater's Marikana smelter has demonstrated stable operational temperatures and good corrosion resistance, positively contributing to the overall furnace sidewall longevity. After 29 months of operation, the copper-graphite composite coolers displayed minimal wear, validating the design intent and confirming the effectiveness of graphite encapsulation in mitigating chloride-accelerated sulphidation of the copper cooling elements.

The successful execution of the hot partial sidewall rebuild highlighted the robustness of the furnace sidewall design and validated the initial design intent of the Furnace 1 upgrade in 2022. Temperature trends and wear profiles aligned closely with FEA predictions, reinforcing the reliability of the design methodology. The preliminary wear and temperature results, and the success of the hot partial sidewall rebuild, indicate that the design sidewall lifetime of 48 months is achievable.

Lessons learned during the rebuild, such as improvements to the installation device and composite cooler handling procedures, will inform future maintenance strategies and potentially reduce rebuild costs through the reuse of undamaged composite coolers. The findings of this case study support the continued use of the copper-graphite composite cooler technology in PGM furnace applications and provide a valuable reference for future furnace upgrade projects.

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