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Consumable unit cost versus metallurgical performance: the impact of grinding media on grinding chemistry and PGM recovery

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The mining industry is notorious for its 'boom/bust' cycle. The dramatic swings in commodity prices, and therefore the economic viability of mining companies, can have a devastating impact on employee and shareholder confidence alike. However, the impact is not limited to the mining company. Suppliers, support companies, and other entities can all be affected either directly or indirectly.

While it is practically impossible to insulate a mining company against variations in commodity prices, as can be attested to during the recent global financial crisis (GFC), a greater understanding of the process can minimise metal loses. For example, the mining of ore containing significantly higher levels of penalty elements will potentially reduce the value of the concentrate produced as the smelter applies treatment penalties when the maximum allowable limit is exceeded.

Work completed at laboratory, pilot-plant and industrial level has indicated that the grinding media has a significant impact on the grinding chemistry, which in turn affects the recovery of both the valuable and gangue minerals in UG2 ores. The paper briefly presents these results before completing an economic evaluation of the two conditions. This economic analysis indicated that whereas the unit cost of an inert grinding media is significantly higher than a more reactive alloy, the application of this media type has significant ramifications in term of lost revenue (i.e. lower metal recoveries and higher gangue mineral (chromite) grades in concentrate).

Finally, the paper provides the reader with a methodology that can be used to evaluate changes to this process to assess the metallurgical and economic impact.

The PGM extraction cycle

A cynical view of the world would suggest that many fully integrated mining, concentrating and smelting operations (such as the major PGM producers in South Africa) do not completely understand the reliance of the earlier stages of the operation on subsequent processing. In effect, there is a tendency to treat each stage of the extraction process as a separate business unit, with only limited consideration for the overall outcomes for the whole business. While this is a gross simplification, the general observation appears to be true, but is not unique to PGM mining operations. The author has noted similar dilemmas within lead/zinc and copper operations within Australia, and other parts of the world. Mine to mill programmes have tried to break down these barriers, with limited success.

The traditional processing route (Jones, 2005; Coetzee, 2006; Barnes and Newall, 2006) for PGM ores sees the mined ore ground to approximately 80 per cent passing 75 microns, and the sulphides recovered by flotation. The sulphide concentrate undergo smelting and converting to produce a PGM-rich copper/nickel matte. The matte is treated hydrometallurgically to extract the base metals from the precious metals. The precious metals are then refined to separate the individual metals (platinum, palladium, rhodium, ruthenium, iridium, osmium and gold).

It is immediately apparent that each unit process with in this process route will have an impact on the subsequent steps further downstream. For example, if the mining methods employed do not minimize dilution, not only are the feed grades to the concentrator reduced, but higher levels of deleterious gangue minerals enter the concentrator and can severely affect flotation performance through reduced selectivity for the valuable minerals. Higher recoveries of gangue minerals to final concentrate will then cause problems during the smelting and converting phase of the extraction process. This will ultimately lead to a reduction in smelting efficiency (lower recovery) and increased energy consumption, neither of which is desirable.

Historically, the Merensky and Platreef ore were the main sources of PGM in the South African Bushveld Complex. These ores can contain up to 3 per cent base metal sulphide minerals (chalcopyrite, pentlandite and pyrrhotite), and are found in a silicate matrix. The PGMs occur either within the sulphide grains or at the sulphide-gangue grain boundaries (Jones, 2005).

However, as reserves of Merensky and Platreef ore diminish, the UG2 ores have gained in significance. Unfortunately, while the UG2 ores tend to have higher PGM grades than the Merensky and Platreef deposits, the sulphide feed grades are considerably lower, and the chromite content is markedly increased (Jones, 2005).

Broadly, the higher chromite feed grades in UG2 ores result in higher chromite grades in the final concentrate which reports to the smelter. Elevated chromite grades are problematic during smelting.

In an ideal world, during the smelting process, the concentrate is mixed with fluxes and introduced to the smelter. A fully molten bath consisting of the sulphide matte, containing the PGMs pools at the bottom of the hearth, and is covered by a slag phase which contains the gangue species, and a minimum amount of PGMs. The PGM-rich sulphide matte is tapped from the furnace and sent to the converter, and the slag is tapped, granulated, ground and the entrained PGM/sulphide minerals recovered by flotation. The flotation concentrate is returned to the smelter, and the tailing to waste dumps.

Magnetite and chromite have high density, high melting points, low solubility in silicate slags, are partially soluble in the matte, and have high viscosity. When either is present in significant quantities in the concentrate feeding the smelter, a chromite (or magnetite) intermediate zone (spinel) forms at the slag-matte interface. The higher viscosity of the spinel layer prevents matte draining from the slag thereby enriching the slag with PGM and sulphides. The higher density of the chromite spinel, which is only partially liquid at normal operating temperatures (1 350ºC), slowly settles to the bottom of the furnace, reducing the working volume of the hearth. Invariably, smelting UG2 concentrates involves operating the smelter at higher temperatures (up to 1 600ºC), and the energy required is substantially higher.

Flotation of UG2 ores

While the author is not an authority within the field of pyrometallurgical processing, it is apparent that improving concentrate quality may have significant ramifications on the subsequent downstream processing operations. Ultimately, reducing the amount of chromite in the final concentrate of UG2 ores, while maintaining (or improving the recovery), will lead to significant improvements in smelter efficiency in terms of metallurgy, energy usage and the associated economics of the process.

The electrochemistry of the flotation system

The literature tells us that there are electrochemical interactions between forged steel grinding media and sulphide minerals which can have a deleterious effect on the separation process (for example, Rey and Formanek, 1960; Rao *et al.*, 1976; Adam *et al.*, 1984; Iwasaki *et al.*, 1983; Natarajan and Iwasaki, 1984; Kocabag and Smith, 1985; Yelloji Rao and Natarajan, 1989(a); Yelloji Rao and Natarajan, 1989(b); Cheng *et al.*, 1993; Forssberg *et al.*, 1993; Yuan *et al.*, 1996; Greet and Steinier, 2004; Huang and Grano, 2006(a); Huang and Grano, 2006(b); Grano, 2009).

Broadly, these studies indicate that most sulphide minerals are more noble than the grinding media used during comminution, therefore a galvanic couple between the media and the sulphide mineral(s) exists, and the following reactions apply:

Cathode (sulphide mineral):

$$½O_2 + H_2O + 2e^- \rightarrow 2OH^- \quad [1]$$

Anode (grinding media):

$$Fe \rightarrow Fe^{2+} + 2e^- \quad [2]$$

In a real ore system the galvanic cells are complex because the sulphide mineral can act as either an anode or cathode depending on its contact with other sulphide minerals, media and reagents. Sufficed to say a galvanic couple between the grinding media and the sulphide mineral(s) exists, which increases the corrosion rate of the forged steel media. The corrosion products of the grinding media, iron oxy-hydroxide species, invariably precipitate on to the surfaces of the sulphide minerals, thereby affecting their floatability (Johnson, 2002).

One method of preventing the contamination of the sulphide surfaces and improving metallurgical performance is to substitute inert grinding media into the system. As ceramic grinding media is unsuitable in many applications and stainless steel grinding media cost prohibitive, high chrome white iron is a viable alternative to forged steel media. High chrome grinding media is generally superior to forged steel media in terms of abrasive and corrosive wear. Of particular importance to the flotation process is high chrome media's better corrosion resistance, where the surface of the ball oxidizes rapidly to form a passive chromium oxide surface layer which acts as a barrier to further electron transfer, significantly reducing the generation of deleterious corrosion products.

However, the application of more electrochemically inert grinding media to 'real' ore systems at an industrial level to improve metallurgical performance has not gained universal acceptance. Even when it does become the 'industry standard', for example the PGM mining industry in South Africa, when events like the global financial crisis occur the status quo is challenged based on unit cost of the raw material as mining companies pursue cost reduction strategies to maintain their financial viability.

The metallurgical impact of using an inert grinding media on the flotation of UG2 ores

Laboratory study

Greet (2008) presented a laboratory study completed on UG2 ore. The data in Table 1 indicate that changing the grinding media from forged steel to high chrome produced an increase in the Eh to more oxidizing pulp potentials by greater than 200 mV. The EDTA extractable iron data suggest that there was a marked decrease in EDTA extractable iron as the chrome content of the grinding media increased. This indicated that the corrosion of the grinding media decreased with chrome content, and essentially means that for the high chrome alloys there was less iron hydroxide species derived from the grinding media.

Figure 1 indicates that the high chrome grinding media produced a higher PGM recovery at a constant PGM concentrate grade, or a higher PGM concentrate grade for a given PGM recovery. The improvement in PGM concentrate grade can be attributed to improved selectivity for PGM against non-sulphide gangue. Further, the PGM flotation rate was improved when high chrome grinding media was used. In these tests the alloy giving the best metallurgical performance was 15 per cent chrome.

Pilot-plant study

Work completed at pilot-plant scale (Greet *et al.*, 2010a) clearly demonstrated that there were significant differences in the Eh of the primary ball mill discharge between grinding media types. The primary ball mill discharge when grinding with forged media generally had very reducing pulp potentials at around -300 mV, which were approximately 200 mV lower than the averaged high chrome values. These highly negative values would be due

Table I
Magotteaux Mill® discharge pulp chemistry for tests completed on a UG2 ore prepared using forged, 12, 15, 21, and 30 per cent chrome grinding media (Greet, 2008)

Media	Pulp chemistry			
	pH	Eh, mV (SHE)	DO, ppm	EDTA Fe, %
Forged steel	9.16	-211	0.16	0.290
12% Cr	9.36	11	0.20	0.034
15% Cr	9.06	16	0.07	0.021
21% Cr	9.47	86	0.04	0.020
30% Cr	9.42	52	0.02	0.014

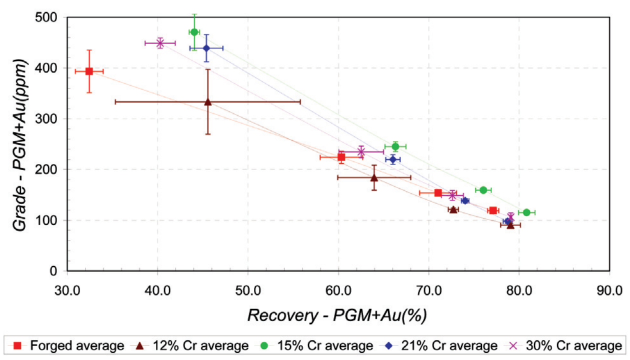

Figure 1. PGM+Au grade-recovery curves for laboratory rougher flotation tests completed on UG2 ore ground with forged, 12, 15, 21, and 30 per cent chrome grinding media (Greet, 2008)

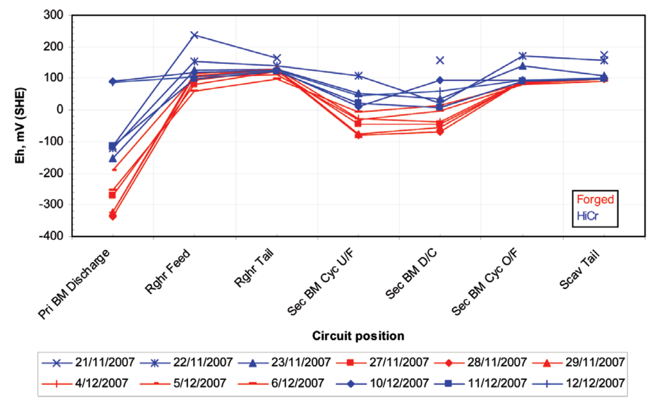

Figure 2. The Eh profile through the pilot plant comparing primary grinding with forged steel and high chrome grinding media in the primary ball mill (Greet *et al*., 2010a)

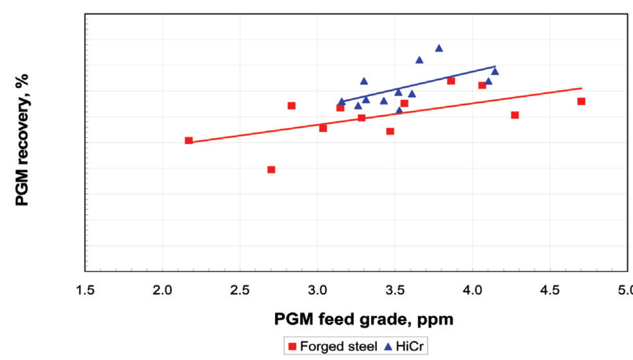

Figure 3. Overall PGM recovery and PGM feed grade for the pilot plant flotation circuit comparing primary grinding with forged steel and high chrome grinding media in the primary ball mill (Greet *et al.*, 2010a)

to forged grinding media corrosion reactions. Further, the higher pulp potentials for the high chrome campaigns were observed across the entire circuit (Figure 2). That is, even after the pulp was ground using high chrome media in the secondary ball mill the Eh of the pulps initially ground using forged steel in the primary ball mill remained lower throughout secondary milling and flotation. This is a clear indicator that the use of high chrome media in the secondary milling circuit does not completely undo the damage to the pulp chemistry that is created when grinding with forged steel in the primary ball mill.

When forged steel grinding media were employed during primary grinding, the percentage of EDTA extractable iron was significantly higher throughout the circuit when compared with the high chrome case. This suggested that forged steel grinding media corrosion products generated during primary grinding continued to have an influence on the pulp chemistry in the secondary grinding circuit and scavenger flotation.

Metallurgically, grinding with high chrome grinding media produced a significantly better PGM recovery compare to the forged steel case (Figure 3). That is, the high chrome alloy resulted in an average increase in PGM recovery of 5.5 ± 0.4 per cent, with greater than 99 per cent confidence. The combined rougher/scavenger PGM concentrate grade was statistically the same for both grinding media types. Similarly, there was no statistical difference in the chromite grade of the final concentrate, although there are indications that employing high chrome grinding media in the primary ball mill may result in lower chromite grades in the rougher/scavenger concentrate. More data is required to confirm this possibility.

Plant study

The Two Rivers concentrator started operations in August 2006, treating UG2 ore in a conventional MF2 configuration. At start-up high chrome grinding media were employed in both the primary and secondary ball mills. Due to supply issues the plant converted to forged steel grinding media in the primary ball mill at the end of May 2007. The primary ball mill conversion from high chrome to forged steel grinding media took the top-up route, whereby the high chrome grinding media was gradually replaced by forged steel. The purge period was estimated to have taken about three months.

With the conversion to forged steel it was noted that the metallurgical performance of the plant had deteriorated. Completing a student t-test on the before (high chrome) and after (forged steel) data indicated that the change from high chrome grinding media to a forged steel alloy had the following impact on overall plant metallurgy:

- The average PGM recovery was reduced by 2.61 ± 1.33

per cent, with greater than 99 per cent confidence

- The average PGM concentrate grade deteriorated by 36.5 ± 14.7 ppm, with greater than 99 per cent confidence
- The chromite grade in the final concentrate increased by 1.76 ± 0.10 per cent, with greater than 99 per cent confidence.

Analysis using other statistical methods (ANOVA and comparison of regression lines (Napier-Munn, 2005)) revealed similar changes in metallurgical performance.

In early 2009 it was decided to convert the primary ball mill back to high chrome grinding media in order to improve metallurgical performance. Analysis of the plant data (Greet *et al.*, 2010b) for the conversion from forged steel back to high chrome grinding media indicated improvements in metallurgical performance of a similar magnitude to those listed above.

Discussion

Laboratory, pilot-plant and industrial studies have all indicated that changing from an electrochemically reactive grinding media (forged steel) to an inert grinding media can have a positive impact on the flotation behaviour of the PGMs. That is, it is possible to improve the PGM concentrate grade, PGM recovery and rejection of chromite. While improvements in PGM concentrate grade and recovery affect the bottom line of the concentrator directly, the rejection of chromite has a positive effect on the downstream processing of the concentrate in terms of smelter efficiency and energy utilization.

However, this aspect of grinding chemistry is seldom taken into account.

Most grinding media trials consider only wear and the unit cost of the grinding media. To conduct a full economic evaluation of the benefits of inert grinding media, it is imperative that the following factors be taken into account:

- Media consumption (wear): employing high chrome grinding media should see a reduction in media consumption. However, the reduction in media consumption may not be sufficient to offset the increased cost per tonne of media purchased.
- Reagent consumption: shifting to a more chemically inert grinding media should product cleaner particle surfaces, which in turn should require less reagent for flotation. Observations in several base metal sulphide operations indicate that it may be possible to reduce collector consumption by about 30 per cent.
- Metallurgical performance: this is generally restricted to improvements in valuable mineral concentrate and recovery. However, this analysis should not be restricted to the primary mineral of interest (in this case PGMs), but should also take into account the flotation behaviour of secondary minerals such as chalcopyrite and pentlandite. Further, an evaluation of the concentrate quality and its impact on the smelter should also be executed. In this case, it is know that UG2 ores contain significant levels of chromite, and that chromite can have a deleterious impact on the operation of the smelter. If, by changing the chemistry of the system one can reject a gangue species that causes significant problems during smelting, this information should be included in the economic analysis.

It is the author's experience that in many instances reductions in media and reagent consumption will overcome the higher unit price of inert grinding media. Improvements in metallurgical performance are usually considerably greater than the added cost of the new media.

Experimental design

Testing an alternative grinding media in the plant is not a trivial exercise, and the experimental design needs careful consideration. In the first instance, it is necessary to complete appropriate laboratory test work to identify which high chrome alloy produces the optimum pulp chemistry and flotation response for the ore under investigation. The procedure employed is discussed elsewhere (Greet and Steinier, 2004). Once an alloy has been identified, it is wise to complete confirmation tests in order to gain confidence in the results. Simultaneously to conducting the laboratory tests, a marked ball test should also be conducted to determine the potential wear benefit.

Once the alloy has been identified, and it has been agreed to move to plant trial, it is wise to agree to a test protocol that will allow for the trial to be evaluated. To do this a plant monitoring programme should consist of:

- Determination of pulp chemistry (pH, Eh, dissolved oxygen, temperature, oxygen demand, and EDTA extractable iron) through the circuit while the plant is operating with forged steel, during the purge period and for three months after the mill was converted to high chrome grinding media
- Complete rougher rate flotation tests on the conditioned feed to the primary and secondary roughers
- Collect the metallurgical and reagent data for the duration of the trial so that a statistical analysis can be completed comparing the plant performance when operated with the two different media types.

The data collected can then be analysed using a number of statistical methods: the Student t-test, comparison of regression lines, and multiple variable regression analysis (Napier-Munn, 2005)), to reveal if changes can be observed in the plant.

Importantly, the methodology for collecting data, the data to be used in the analysis, the statistical methods to be employed, and the expected outcomes (criteria for success) should be agreed to prior to the start of the trial. This last point can present significant challenges to both the mining company and the supplier alike.

Conclusions

A holistic approach to improving concentrator performance should be adopted, which not only takes into account ways of improving cost and metallurgical performance, but also examines the impact of concentrate quality on smelter efficiency.

Within the processing of UG2 ores, chromite offers significant challenges particularly in smelting. Laboratory, pilot-plant and plant trials on UG2 ores have indicated that it may be possible to increase PGM concentrate grade and recovery, as well as reject chromite when using an inert grinding media rather than forged steel. These improvements should be included in any economic evaluation of grinding media rather than just media wear and unit cost.

In evaluating grinding media for a particular system, it is important to complete the right laboratory test programme to identify the optimum alloy to give the right pulp chemistry and metallurgical benefit. Also, conducting a marked ball test allows an evaluation of the wear benefits possible.

Plant trials should be structured in such a way that they allow a meaningful analysis of the data collected.

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