 ISBN: 978-1-926872-32-2

EFFECT OF USING DIFFERENT GRINDING MEDIA ON THE FLOTATION PERFORMANCE OF A PLATINUM GROUP ORE

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ABSTRACT

In the present study the effect of using different grinding media, viz, ceramic balls, forged steel balls, 15% Cr steel balls, stainless steel and mixture of stainless steel and 15% Cr steel balls (50:50) on the flotation performance of a Platinum Group Mineral (PGM) UG2 ore was investigated. Test work was conducted using a laboratory scale horizontal tumbling mill and a batch flotation cell. Power draw to achieve a specific P80 was determined for each media type. Changes in flotation behaviour were evaluated in terms of particle size distribution, water recovery, solid recovery and valuable mineral recovery. pH, Eh and DO levels were also measured. Grinding products of five different media produced similar solids and water recovery, which is indicative of the froth characteristics, but the grades and recoveries of PGE and chromite were different. The product obtained when using ceramic media showed the best flotation performance, producing the highest PGE recovery and the lowest Cr2O3 recovery. The products obtained when using stainless steel balls (SS) produced the lowest PGE recovery and highest Cr_2O_3 grade and recovery. The paper proposes possible reasons to explain these observations which may have significant importance for the operation of a PGM concentrator.

Keywords: PGM; Grinding media; Flotation; Chromite.

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INTRODUCTION

The UG2 chromitite ore body is a complex, highly disseminated platinum containing ore from the Bushveld Complex in South Africa, with typical platinum group mineral (PGM) grain sizes below 15 µm. A detailed survey of global platinum group element (PGE) resources in 2010 reported that 70.9% of the world's PGE resources are within the Bushveld Complex, of which UG2 ore contributes about 60% (Mudd, 2012). There are seven Platinum Group Metals in this ore body, i.e. Platinum, Palladium, Rhodium, Gold, Ruthenium, Iridium and Osmium. The first four are the primary metals and head grade is normally defined as the total of these and referred to as 4E. Typically, head grades vary between 2 and 9 g/t (4E-PGE) with the majority between 4 and 5 g/t (Hay & Roy, 2010; Rule & Schouwstra, 2011; Mudd, 2012). UG2 ore contains up to 75% chromite by mass, which is interlocked with silicates, mainly orthopyroxene and plagioclase. The large fraction of chromite in the ore introduces additional challenges in the comminution and flotation circuits as well as in the downstream smelting stage.

The challenge in the comminution of UG2 ore is owing to the higher density of the chromite (SG~ 5) relative to the silicates (SG ~2.6-3) which leads to inefficiencies in classification, causing a high circulating load of fine chromite particles. This leads to the loss of PGMs locked in coarse silicate particles that report to the cyclone overflow, a reduction in the mill's throughput capacity and greater energy consumption due to overgrinding of the chromite (Mainza et al., 2004). The challenge for the flotation circuit is to minimize the chromite recovery in the concentrate because of the problems it causes in the smelter (Hay & Roy 2010). Chromite is dense and naturally hydrophilic, so it is generally recovered to the concentrate through entrainment especially the fine particle sizes (-45 µm).

Recently Khonthu (2012) investigated the flotation behaviour of UG2 ore milled using a laboratory horizontal ball mill and a laboratory scale M4 IsaMill. The IsaMill produced finer PGM ore particles than the ball mill and this resulted in higher Cr2O3 entrainment during flotation. This study also suggested that the different milling procedures may produce particles of different shapes and hence different flotation behavior. The shapes were estimated using apparent viscosity measurements since it has been shown that the apparent viscosity decreases in the order of rods > plates > cubes/grains > spheres for the same phase volume of particles (Barnes, 2000). Solomon (2010) and Chapman (2011) studied the effects of using HPGR and ball milling in treating PGM ores and found that the ball mill product appeared to result in a better flotation response compared to the HPGR.

The present study complements this series of studies and investigates the use of different milling media in the treatment of UG2 ore using a laboratory scale tumbling ball mill. Flotation performance was used essentially as a diagnostic indicator of the effects of using the different media.

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EXPERIMENTAL PROCEDURES

Sample preparation and particle characterisation

The ROM UG2 ore sample was crushed using a cone crusher, and screened to produce ball mill feed with 100% passing 1.7 mm. A 30.5 cm × 30.5 cm laboratory scale cylindrical ball mill was used for the grinding experiments. 4 kg ore was used for grinding and flotation tests. Grinding was performed in the absence of reagents, at 67% solids using respectively; ceramic balls, forged steel balls, 15% Cr steel balls, stainless steel balls and a 50:50 mixture of stainless steel and 15% Cr steel balls. The particle size distributions of the feed and mill product were determined using wet sieving. The grinding time was determined to achieve a d80 = 75 µm. Details of the media used and grinding time required is shown in Table 1.

Table 1 - Details of conditions used in the grinding tests

Media material	Media Volume (ml)	Media size (mm)	Grinding time to obtain d_{80} = 75 µm (min)	Nomenclature
Ceramic	3420	10~30	67	CE
15%Chrome steel	2120	30	53	CS
Forged steel	2120	34	56	FS
Stainless steel	2120	36~42	56.5	SS
Stainless steel + Chrome steel (50:50)	2120	36-42;30	56.5	SS+CS

Apparent viscosities of each sample were determined using an AR 1500 rheometer with a standard 4 panel vane rotor geometry. These tests were carried out using volume percentage solids in the range between 10 and 45% at increments of 5% and were performed on particles which were less than 25 µm in size. The temperature of the instrument was set at 23 °C and the test solutions were prepared using synthetic plant water.

Batch flotation tests

Batch flotation tests were performed on samples prepared using various grinding conditions, at 36% solids, in an 8 L laboratory bottom driven batch flotation cell. In the flotation tests, the impeller speed was set at 1200 rpm and the air flow rate was maintained at 7 L/min throughout the test. Froth height was maintained constant at 2 cm by regular addition of water. 50 g/t sodium isobutyl xanthate (SIBX) was used as a collector and 50 g/t DOW 200 was used as a frother. Four concentrates were collected at 15 second intervals for 2, 4, 6 and 8 minutes, i.e. total flotation time of 20 minutes. Solids and water masses were measured for each concentrate as well as the total mass of water added to maintain constant froth height.

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Solids-water recoveries were used to ascertain the repeatability of the flotation tests and to study the froth properties. The samples generated during the batch flotation tests were analyzed for 4E and chromite. pH, Eh and DO were measured in the flotation cell using 556 Multi-Probe System. The system was calibrated regularly. The measurement was made after the ore had been transferred to the flotation cell and the pulp conditioned for 5 minutes, before any reagents were added. All flotation tests were carried out in triplicate.

RESULTS AND DISCUSSION

Size distribution and power draw of different grinding media

Figure 1 shows the size distribution of the sample after grinding under different conditions. Table 2 shows the proportions of -75 µm, -25 µm and -10 µm fractions obtained when using the different grinding media. It can be seen that using the stainless steel balls (SS), alone or with 15% chrome steel (CS), and ceramic balls (CE) produced slightly greater amounts of fines (-10 µm to -25 µm). Otherwise, overall the differences were not significant.

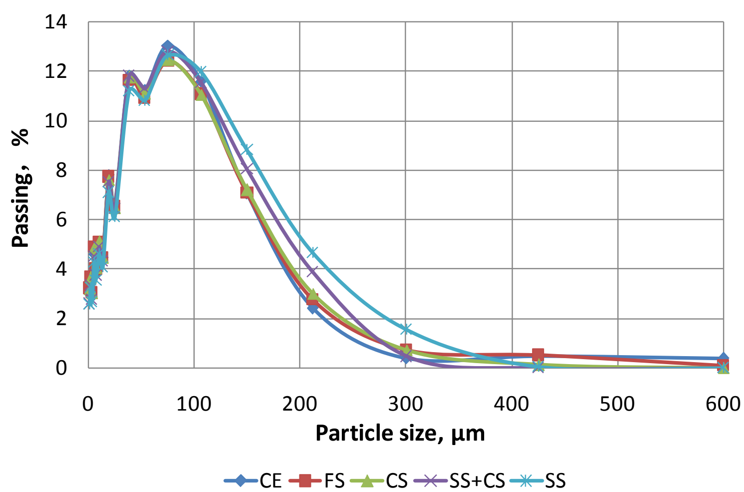

Figure 1 - Particle size distribution of products obtained when using different media

Table 2 - Particle size distribution of samples after milling using different media and specific energy required to achieve a d_{80} of 75µm

Media	-75 µm,%	-25 µm,%	-10 µm,%	%-10 µm in -25 µm	Specific energy, kWh/t
CE	79.78	35.85	22.90	63.90	11.55
FS	80.41	37.32	22.60	60.55	17.58
SS	79.48	38.14	24.79	65.00	19.96
CS	79.52	37.39	22.98	61.47	18.20

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SS+CS	79.34	38.70	25.39	65.61	17.53

The specific energy consumptions based on power draws of the different grinding media are also listed in Table 2. It can be seen that there were significant differences. The ceramic balls (CE) had the lowest specific energy consumption of 11.55 kWh/t to achieve similar particle size distributions compared to using the other media.

DO, Eh and pH

pH, Eh and Do levels and relative viscosities of the different grinding products are shown in Table 3. The pH was natural and always between 8.7 and 8.8. Using stainless steel balls (SS and SS+CS) and ceramic balls (CE) resulted in relatively higher Eh values, viz. 170 mV, 172 mV and 133 mV respectively, which is indicative of a more cathodic environment. The DO levels in the case of SS, SS+CS and CE were 6.4 ppm, 5.9 ppm and 5.9 ppm respectively. The higher Eh values are consistent with higher DO levels because less O_2 is consumed. Oxygen is consumed when it is reduced to OH^- (½ O_2 + H_2O + 2e → $2OH^-$) but that reaction presupposes an equivalent oxidation reaction. In the case of mild or forged steel the oxidation of Fe (s) follows the reaction: Fe_x(s) → $Fe_{(1-x)}$ (s) + Fe^{2+} (aq) + 2e. As expected forged steel balls (FS) and 15% chrome steel balls (CS) produced lower DO and Eh levels, which indicated a more reducing environment. The DO levels when using SS+CS was lower than in the case of SS and this indicated that 15% chrome steel balls were more reducing than stainless steel balls. The apparent viscosity data provides an indication that particles in the samples produced after milling using ceramic media had slightly higher aspect ratios than in the case of the other media. It appeared that the particles produced after using 15% chrome steel may have the lowest aspect ratio.

Table 3 - Eh, pH, DO and relative viscosities of mill product when using different media types

Media	pH	Eh, mV	DO, ppm	Relative viscosity, Pa.s
CE	8.73	133.55	5.9	0.26
CS	8.67	106.5	5	0.12
FS	8.80	106.8	5	0.15
SS	8.70	170.3	6.4	0.22
SS+CS (50:50)	8.68	172.9	5.9	0.23

Flotation performance

Figure 2 shows the solids and water recovery obtained after flotation for grinding products of different media. The solids and water recovery of the five grinding products were almost the same, with solids recovery of 200 g and water recovery of 1600 g.

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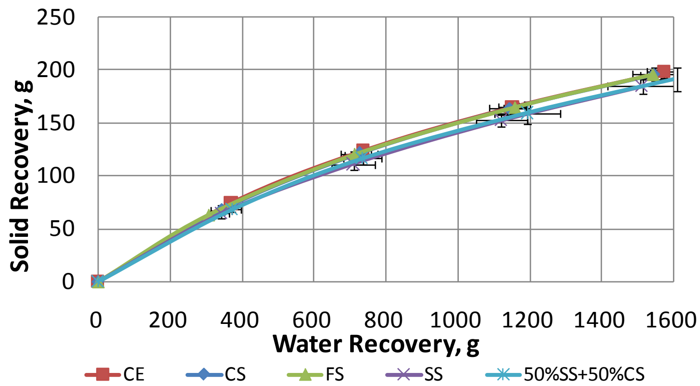

Figure 2 - Solids-water recoveries obtained after the flotation of samples produced using different milling media

The grades and recoveries of Cr_2O_3 and PGE (4E) of the flotation tests with different media products are shown in Table 4.

Table 4 - Flotation results of samples produced using different milling media

Media	Conc. Grade		Recovery, %	
	Cr_2O_3,%	PGE (4E),ppm	Cr_2O_3	PGE (4E)
CE	3.77	58.36	1.22	84.94
CS	3.82	56.91	1.21	83.52
FS	3.98	56.85	1.29	77.99
SS	4.97	55.26	1.55	75.98
SS+CS	4.16	58.03	1.31	78.07

The sample obtained after grinding with ceramic media produced the highest grades and recoveries for the PGEs. This was accompanied by the lowest Cr_2O_3 recovery, viz. 84.94% and 1.22% respectively. On the other hand, the sample obtained after grinding with stainless steel balls (SS) produced the lowest PGE recovery and grade and the highest Cr_2O_3 grade and recovery. Compared to the results of SS, the combined use of stainless balls and 15% chrome balls (SS+CS) produced the best flotation performance, yielding higher PGE recoveries and grades and lower chromite grades and recoveries. All of the results are shown graphically in Figure 3 and Figure 4.

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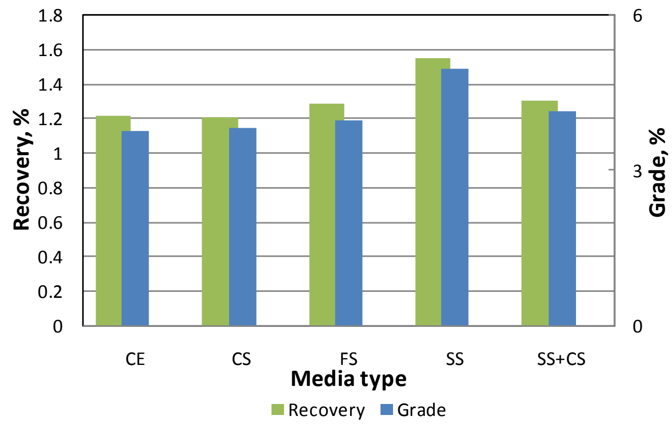

Figure 3 - Cr_2O_3 grade and recovery of different media products

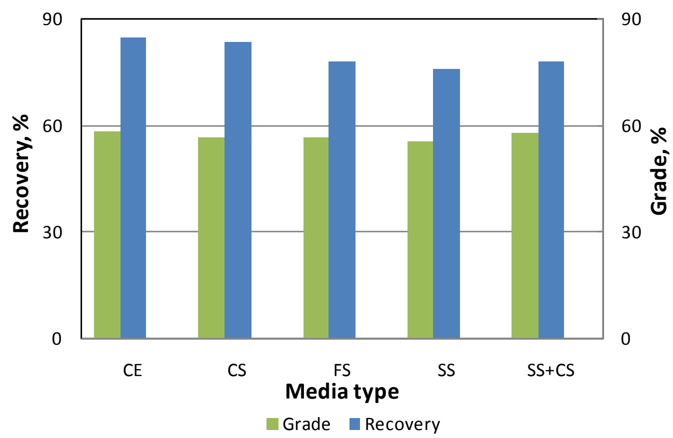

Figure 4 - PGE grade and recovery of different media products

The results in the case of chromite are of particular interest. It is well known that chromite is naturally hydrophilic and its recovery is almost entirely due to entrainment. This recovery would increase as the proportion of fines increases. Due to its high density chromite in the >25 µm fraction seldom reports to the concentrate (Alvarez- Silva, et al, 2014) and hence it would be expected that there would be a good correlation between the amount of chromite in the <25 µm fraction and chromite recovery. The results in Table 2 and Table 4 confirm this since the CE media produced almost the least amount of <10 µm material and the lowest chromite recovery while, for example, the opposite was the case for stainless steel media.

It is interesting to compare specifically the flotation performance when the ore was milled using CE media compared to SS media. As mentioned at the outset flotation was used in this study as a diagnostic indicator of the effects of using different media. In the first instance it is clear that the flotation results showed that higher PGE grades and recoveries were obtained when ceramic balls (CE) were used to grind the ore compared to SS. Moreover lower chromite grades and recoveries were obtained in the former case. In the case of using CE as the grinding media, Table 2 showed that the CE media produced less <10

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µm fraction material than in the case of SS and this fact has been used to explain the chromite flotation results since chromite is recovered through entrainment and hence producing excess fines will result in higher chromite recoveries. Table 3 also showed that when using SS the DO levels and the Eh of the pulp was greater than when using CE media. This implies that there is a greater degree of O_2 reduction and equivalently of oxidation reactions when using CE media. Since the oxidation cannot be ascribed to the media which is inert it implies that the lower DO levels may be indicative of an enhanced oxidation of the xanthate collector to dixanthogen which then increases the hydrophobicity of the PGMs resulting in an increase in recoveries. Since the solids recovered are almost the same in every case the grade differences, which are not very great, are probably simply due to a greater selectivity in terms of recoveries of PGMs at constant gangue recoveries. In addition the higher recoveries of chromite, as in the case of SS media, will further contribute to a decrease in grades. It is also important to note the differences between using forged steel and stainless steel. The forged steel was better with respect to PGE and chromite flotation performance. The lower DO and Eh values in the case of the forged steel are also hence indicative of the possibility that the differences may be due to the electrochemical reactions referred to above thus enhancing the flotation of the PGMs.

Figure 5 shows the particle size distribution of the flotation concentrates obtained after the flotation of ore milled with SS and CE respectively. It can be seen that there was a higher percentage of <10 µm fraction in concentrate in the case of SS milled material. It is thus possible that reduced recovery of PGEs in the case of SS media is due to the greater amount of fines (<10 µm fraction) being present and the problem of fines flotation may become important. However previous studies have shown that it is not problematic to recover PGMs in <10 µm fractions (Corin et al., 2012) and this therefore is probably not a cause of the lower recoveries.

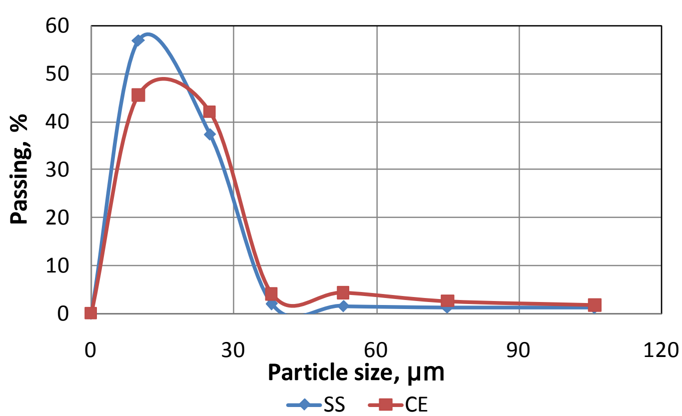

Figure 5 - Particle size distribution of SS and CE floatation concentrates

It has been recently shown that entrainment is a strong function of shape of particles with particles of higher aspect ratio being more readily entrained (O'Connor et al, 2014). It is interesting to note that the particles with the lowest aspect ratio (CS samples) also had the lowest chromite recovery and this may

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suggest that using different media also impacts on particle shape and hence recovery. It is also known that high aspect ratio particles are more amenable to flotation (Vizcarra et al., 2011) and this is consistent with the CE results. However at present these must be regarded as speculative findings.

CONCLUSIONS

This study has investigated the effect of using different milling media on the ultimate flotation performance of a UG2 ore milled in a laboratory tumbling mill. The results showed that the different media required different energy inputs to obtain the same grind. They also resulted in different chemical conditions in the mill product in terms of parameters such as pH, Eh, DO and relative viscosities. Flotation tests were carried out on each mill product in order to investigate whether using different media significantly affected the recoveries and grades of the PGMs and the chromite since these are key factors in the treatment of such ores. Using stainless steel (SS and SS+CS) and ceramic (CE) media resulted in higher Eh and DO values compared to the use of forged steel (FS) and 15% chrome steel (CS). The five different media produced virtually the same solids and water recovery. There were however significant differences in the recoveries and grades of the PGMs (as indicated by PGE assays) and of chromite. Grinding the ore using ceramic media produced the highest PGE recoveries and the lowest Cr_2O_3 recovery while the grades and recoveries after using stainless steel (SS) were the lowest in the case of PGEs and the highest in the case of Cr_2O_3. The possible effect of galvanic interactions on these results has been proposed to contribute to the differences observed. Stainless steel produced higher fines content and this may explain the higher chromite recovery. Using ceramic media also required the least amount of specific energy to achieve a grind of d80 < 75 µm.

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