THE EFFECT OF A HIGH SHEAR HYDRODYNAMIC CAVITATION DEVICE ON THE FLOTATION OF A PGM UG2 ORE

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ABSTRACT

Fine valuable particles are often lost to flotation tailings streams due to inefficient collection by air bubbles as well as passivation by oxidation and slimes. With the increased use of ultrafine grinding, and the reprocessing of tailings from PGM operations, this poses a key challenge for efficient recovery. The application of high-shear hydrodynamic cavitation devices (HSCDs) to overcome this problem has already proven to be a considerable success in the industry.

This paper details the results of further investigations that were undertaken at Mintek to better understand the mechanisms involved when preconditioning feed slurries in an HSCD. The so-called Mach reactor consists of a series of venturi's through which the feed slurry is recirculated prior to flotation. By promoting inter-particle attrition and conditions of high shear, it not only enhances cleaning of their surfaces but also the formation of superfine (nano) bubbles which are believed to aid their agglomeration and subsequent collection by micro and macro bubbles. Plant experience has shown that the significant increase in the gas holdup of the pulp as a result of the fine bubbles also alter the hydrodynamics of the pulp phase, leading to improved concentrate grades.

In order to broaden the envelope of understanding with regard to feed grade, rather than tailings material, a Platinum Group Mineral (PGM) run-of-mine UG2 ore from the Bushveld Complex in South Africa was used in this study. The results of a series of batch flotation tests in a 10 L Denver cell are presented, being conducted after the feed has been subjected to different methods of preconditioning. It was demonstrated that the preconditioning significantly improved the flotation kinetics of the PGMs, the optimum being obtained after 20 passes through the reactor. This was accompanied by a much enhanced recovery-mass pull relationship and a significant improvement in the recovery-grade response. Significantly, the selectivity between the PGM and the deleterious chromite (expressed as Cr_2O_3) gangue more than doubled under these conditions.

The continuous supply of a low air flow to the reactor during preconditioning appears to be beneficial, the results being much improved compared to the situation where no air was introduced, and better than the situation where air was introduced only during the last pass prior to flotation. Whilst this could point to a cumulative effect of aeration during conditioning, further tests are required to assess whether this can be ascribed to the higher velocity or turbulence in the reactor under such conditions. The addition of reagents during circulation of the feed through the reactor, in order to preserve as best possible the improved floatability imparted by the reactor, produced the best grade-recovery response. Modelling of the PGM data by means of the modified Kelsall model indicated that both the fast and slow floating rate constants were improved.

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KEYWORDS

High shear, surface cleaning, gas holdup, PGM ores, mechanisms, fine bubbles

INTRODUCTION

It is well known that the recovery of fine and ultrafine particles, typically less than 10 to 20 micron in size, by flotation is a challenge (Yoon et al., 1989; Miettenin et al., 2010). Although these particles are typically well liberated, due to their very low mass and inertia, the collision efficiency with air bubbles is low as a result of the inability of particles to penetrate the liquid streamlines around bubbles. Hence the probability of contact is often regarded as the rate-determining step in flotation of ultrafine particles. This causes significant mass pulls in flotation circuits due to the prolonged flotation time that is required to establish acceptable recoveries.

With the increased need for fine and ultrafine grinding (UFG) of flotation feeds to achieve the required degree of liberation, especially in lower grade or complex ores, this problem is exacerbated (Rule and Anyimadu, 2007). Introducing more power into conventional flotation machines is likely to solve only part of the problem, as conventional mechanisms are effective only to a point in terms of shear and micro-turbulence. Further challenges are posed by the treatment of low-grade or oxidised tailings dump material, where valuables are passivated due to prolonged exposure to the atmosphere or slimes. Over the years, various mitigating strategies have been investigated, including the use of dissolved air flotation (Calgaroto et al., 2014; Martinez-Gomez et al., 2013; Qi and Aldrich, 2002), shear flocculation (Subrahmanyam and Forssberg, 1990), seed or carrier flotation (Tabosa and Rubio, 2010) by spiking the pulp with concentrate so as to promote the formation of larger agglomerates that are easier to recover by air bubbles, sonication to clean particle surfaces (Aldrich and Feng, 1999; Qi and Aldrich, 2002), high intensity conditioning (Bulatovic and Salter, 1989; Tabosa and Rubio, 2010; Chen et al., 1999), and various electrochemical approaches such as changing Eh in order to promote formation of dixanthogen, dissolution of oxidation products by lowering the pH, activation by sulphidisation (Becker et al., 2014) or Cu(II), and the use of alternative collectors to float oxides and hydroxides.

A technology that seems to offer a robust solution in this regard is high-shear hydrodynamic cavitation devices (HSCDs). Typical examples are the Eriez CavTube (Hu et al., 1998; Oliveira et al., 2018) and the Mach reactor (Singh, 2016; Ross et al., 2017). These devices typically consist of one or more venturi aerators in series or a multitude of parallel, restricted apertures in which intimate contact is effected between the fine particles and the very fine bubbles that are formed as a result of the high shear. This results in a hydrodynamic environment in the pulp zone which is quite different to that normally observed with conventionally aerated mechanical flotation cells. The significantly increased gas holdup that develops within the pulp at the high gas fluxes and very fine bubbles are believed to form a sort of 'safety net' in which particles that detach could readily re-attach (Dickinson and Galvin, 2014). An added opportunity offered by these devices is an increased activation of the surfaces of the hydrophobic particles as a result of the intense inter-particle attrition as the slurry stream moves through the successive restrictions under conditions of high turbulence. As will be discussed further below, such a mechanism can be exploited by applying the HSCD as a high-energy attritioner, prior to employing its benefits in micro-bubble generation and improved particle-bubble attachment.

The Mach reactor has already found commercial application in both the gold and platinum industries in South Africa; in the former case for the oxygenation of leach slurries, and in the latter, for improved flotation of tailings material. An earlier paper (Ross et al., 2017) reported the results of an investigation to better understand the various mechanisms that determine the efficiency of the device. Feed samples from various parts of a PGM tailings retreatment plant were preconditioned in the reactor by recirculation for a predetermined number of passes, which demonstrated enhanced kinetics and selectivity of PGM recovery especially during the early stages of flotation. Importantly, the maximum recoveries (R_{max}) of PGMs, as modelled by the modified Kelsall equation, improved dramatically in all cases, suggesting a significant improvement in floatability due to either surface cleaning or additional liberation, or some combination thereof. An interesting observation from this study was the fact that the PGM recovery peaked after a certain number of passes through the reactor, and that this increased along with an increase in the feed grade. This was ascribed to the generation of slimes which gradually would overshadow the effect of surface cleaning through attritioning, adsorbing onto valuable mineral surfaces and rendering them increasingly less hydrophobic.

The current study was aimed at further elucidation of the mechanisms that drive the efficiency of HSCDs. In order to broaden the scope of the test programme and the envelope of application, as well as enhancing the integrity of results that are sometimes compromised as a result of very low tailings assays, a run-of-mine PGM UG2 ore rather than a tailings sample was used for the investigation.

Mechanisms

Relatively little information is currently available in the literature regarding the various mechanisms that affect the efficiency of high shear conditioning devices. However, the preliminary results of earlier work at Mintek on a variety of ores, together with published literature on hydrodynamics and flotation of fines, suggest at least four distinct mechanisms. These mechanisms have been discussed in more detail in an earlier paper (Ross et al., 2017) and thus will be dealt with only briefly below. Each would play a more or less dominant role depending on the particular type of ore and its condition as far as oxidation, slimes and other de-activating species are concerned.

Surface cleaning

Due to the intense turbulent conditions created in the HSCD as the slurry passes through a series of nozzles, a significant degree of inter-particle attrition is taking place. This aids in the removal of oxidised layers and slime coatings from the surface of particles, leading to increased rates of flotation and recovery of valuable minerals. Equally important, it could lead to the removal of hydrophobic species such as talc rimming on gangue minerals, thus decreasing the activation of the gangue when collector is added.

Increased liberation

Due to the intensive attrition, it is likely that successive passes of the slurry through an HSCD would also increase the liberation of valuable particles, such as fine PGMs being associated with chromite particles on grain boundaries, and thus lead to increased valuable mineral recovery. In addition, partly liberated valuable grains could be exposed increasingly as the gangue coatings are being worn away.

Increased gas holdup and bubble flux

The combined effects of a higher gas flow and the formation of micro bubbles when compared to a conventional flotation cell translate into a much increased bubble flux and hence improved flotation kinetics. An added effect is the significant increase in gas holdup in the pulp due to the presence of small bubbles, creating conditions in which entrainment of gangue into the froth is reduced.

Nucleation and agglomeration

HSCDs impart significantly higher shear and energy dissipation rates to the feed compared to conventional flotation cells (Singh, 2016). The design and operating conditions of the reactor promote hydrodynamic cavitation (Sobhy and Tao, 2013; Calgaroto et al., 2015; Oliveira et al., 2017) and the formation of stable, ultrafine (nano) bubbles which nucleate on particle surfaces. This aids the agglomeration of fines and hence their subsequent recovery as effectively larger particles by micro and macro bubbles (Figure 1). Nanobubbles have diameters in the order of 1 micron or less and are thus smaller than the ultrafine particles. Therefore it is suggested that the ultrafine bubbles be introduced to complement, rather than replace, normal sized bubbles (Tao, 2005; Nesset et al., 2006).

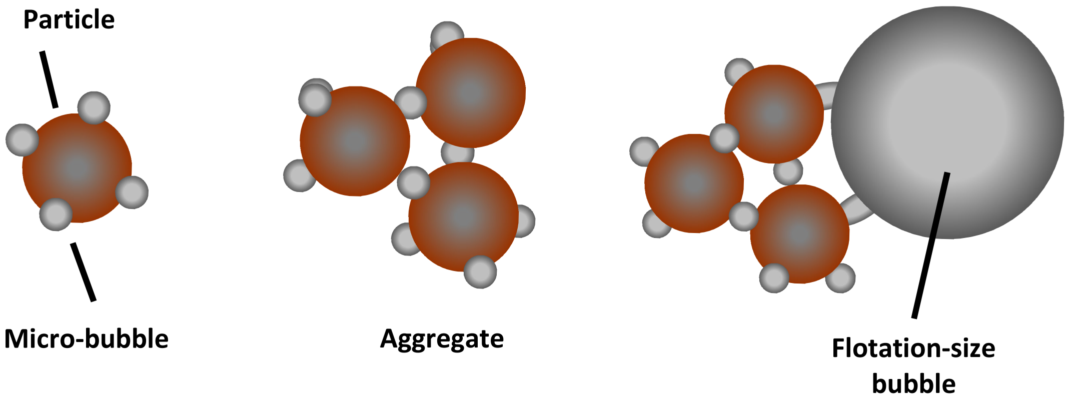

Figure 1 - Mechanism of fine particle aggregation and levitation. Nucleation of nano-bubbles on fine particle surfaces is followed by agglomeration of the hydrophobic fines and subsequent collection by micro and macro bubbles (not to scale).

EXPERIMENTAL

A UG2 run-of-mine PGM chromitite ore from the Bushveld Complex in South Africa was used for the testwork. The main gangue component in the ore is chromite, with lesser amounts of pyroxenite, base metal sulphides occurring in only very low quantities. The ore has an A*b value of 49, which classifies it as medium hard, the Bond ball work index being around 18 kWh/t. The relatively low 4E head grade and Cr_2O_3 values in the feed are ascribed to dilution of the reef with waste during blasting. The PGM deportment in the material is dominated by PtS, PtFe and PtPdS. The presence of alloys like the ferro-platinum is regarded as indicative of a high degree of alteration and remobilization of the PGMs from base metal sulphide minerals into silicate and oxide minerals, and generally viewed as difficult to float.

Table 1 - Chemical composition of the UG2 feed

Pt	Pd	Rh	Au	4E	Cr_2O_3	Cu	Ni	S	Fe	Si
g/t	**g/t**	**g/t**	**g/t**	**g/t**	**%**	**%**	**%**	**%**	**%**	**%**
1.53	0.74	0.18	0.10	2.55	14.6	<0.05	0.1	0.1	10.9	15.4

The experimental rig used for the test work is shown in Figure 2. In each case around 4 kg of an ore that was crushed to -1.7 mm and milled to 75% -75 micron was used as feed. Depending on the nature of the test, the sample was transferred either to the Denver cell directly (for the baseline), or to the feed tank of the rig.

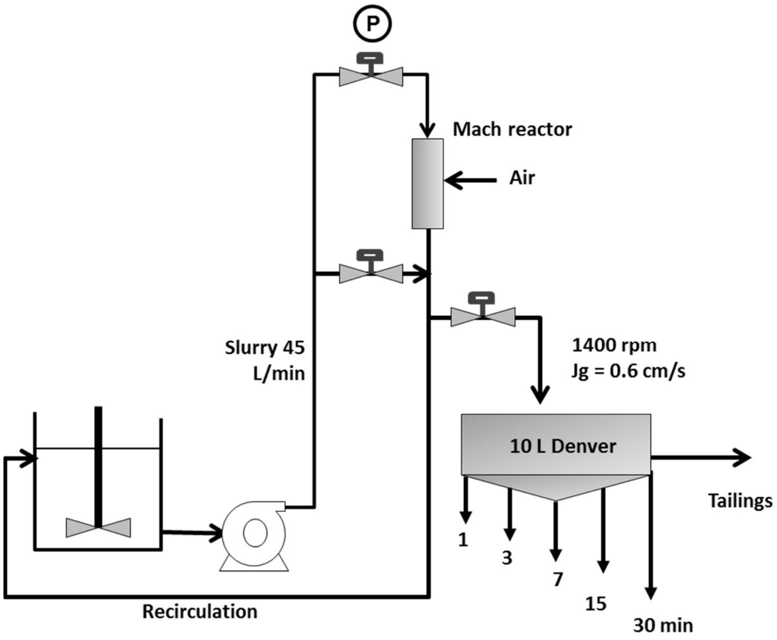

Figure 2 - Experimental rig

Mach reactor

A schematic representation of the Mach reactor is shown in Figure 3. The reactor features four custom-designed nozzles that are connected in series: a medium speed mixing nozzle feeds into two high-speed cavitation nozzles which in turn jet into a collection nozzle at the exit of the reactor. External air is injected under pressure between each nozzle, at around 5 bar. This design maximises cavitation in the high speed nozzles while also providing an environment in the collection nozzle to promote aggregation of hydrophobic fine particles via the proposed bubble bridging aggregation mechanism. The collection nozzle, which incorporates features of a plunging jet, also generates flotation size bubbles which attaches to particle-bubble aggregates to complete the collection process and provide for a higher rate of flotation in a conventional flotation cell (Zhou et al., 1995). In addition, the reduced bubble size translates to a significantly higher bubble flux than in conventional machines, together with higher shear and energy dissipation rates, which should lead to better flotation of fines.

Reasons for selecting this reactor for the test programme included ease of operation and reduced downtime due to blockages and wear, as well as the fact that it could be scaled quite easily and effectively so as to enable investigations at both a laboratory and pilot scale.

Figure 3 - Schematic of Mach reactor (after Singh, 2016)

Test procedure

The range of conditions used in this experimental programme is shown in Table 2. The work entailed firstly a conventional batch rougher rate flotation test performed on the feed sample in a 10L laboratory Denver cell in order to set the baseline (Test 1). Prior to flotation, the slurry was conditioned for 5 minutes ($CuSO_4$ as activator at 40 g/t for 1 minute, SIBX as collector at 150 g/t for 2 minutes, KU433 as depressant at 40 g/t for 1 minute, XP200 frother at 30 g/t for 1 minute) before flotation commenced. The Denver cell was operated at an impeller speed of 1200 rpm and a superficial gas velocity (Jg) of 0.6 cm/s. Concentrates were collected after 1, 3, 7, 15 and 30 minutes of flotation respectively

In a further set of tests (2 to 5), the effect of particle surface cleaning and/or additional liberation was established by preconditioning the feed prior to flotation by circulating it through the Mach reactor for 10, 20, 30 and 40 passes respectively at a slurry flowrate of 45 L/min. Under these conditions, a slight positive air flow was maintained in order to prevent slurry pushing into the air lines. Subsequently, the effect of air supply to the reactor was studied (Test 6) by operating the reactor for the same 20 passes as in test 3, but with no air being supplied. It thus represents purely the effect of additional surface cleaning and perhaps some additional liberation of valuable grains. Whilst the feed tank was kept full so as to prevent air being sucked into the pump, it is however possible that a very minor amount of air could have found its way into the reactor. Following this, test 7 was conducted under the same conditions as test 6, the only exception being that air was supplied to the reactor only during the very last pass. Comparison of these two set of results would therefore highlight the effect of the mode and quantity of air addition on the flotation efficiency.

Finally, in another set of tests (8 and 9), the feed sample was preconditioned with the same reagents and dosage in the reactor rig than Tests 6 and 7, the difference being that, instead of being added in the Denver cell after the mechanical preconditioning, it was added in the rig, starting 5 minutes before completion of the recirculation. The reagent was dosed directly and slowly into the recirculation line so as to promote the best mixing of the reagent with the slurry.

Comparison of these two sets of tests thus provides insight into the mode of reagent dosage and its effect on flotation efficiency. Another key aspect of these tests was the fact that, instead of potentially destroying some of the properties bestowed upon the slurry by the reactor through conditioning in the Denver, the slurry could be floated as soon as it exited the reactor rig. It is for instance believed that the effect of the nano-bubbles would be best demonstrated under these conditions. Although gas holdup in the pulp was not measured during these initial tests, it is believed that it would be higher at the start of the float than was the case when the slurry had first been conditioned with reagents.

Table 2 - Experimental conditions

Test #	**Passes**	**Air to rig**	**Reagent conditioning**
1	0	-	Denver
2	10	Low rate for full duration of recirculation	
3	20		
4	30		
5	40		
6	20	None	
7	20	For 1 pass only before flotation	
8	20	None	Rig
9	20	For 1 pass only before flotation	

RESULTS

Surface cleaning / liberation

Figure 4 shows the results of the first set of tests in which the feed slurry was circulated through the Mach reactor for an increasing number of passes prior to conditioning with reagents and flotation. Test 1 (T1) represents the baseline during which the feed was not passed through the reactor but was transferred directly into the 10L Denver cell. A 3E recovery of 70% was obtained at just more than 10% mass pull, exhibiting a fairly flat grade-recovery response. Comparison of these results with those of tests 2 to 5, where a low supply of air was maintained throughout, indicate that this had a positive effect on recovery, but especially the grade. Similar to the results on UG2 tailings samples reported earlier by Ross et al. (2017), the grade-recovery response improved up to around 30 passes (test 4), after which it seems to flatten out (test 5). Figure 5 shows that this was as a result of a significantly improved recovery-mass pull relationship, the optimum recovery-mass pull relationship being obtained during tests 3 and 4 and presumably because of a significant decrease in the amount of entrained material.

An interesting observation from these tests is the fact that the grade-recovery profiles seemed to shift predominantly with regard to grade (i.e. vertically upwards) rather than with regard to recovery. This was in contrast to results reported earlier using the same reactor to treat rougher, cleaner and recleaner feed samples from a tailings treatment plant (Ross et al., 2017), with head grades ranging from 0.7 to 10.6 g/t. Whilst that particular observation was ascribed to the improved cleaning of particle surfaces, in the current study the particle surfaces would have been reasonably clean as the sample was not aged like in the case of the tailings. Thus it appears that preconditioning through the reactor influences metallurgical behaviour differently depending on the properties of the particles.

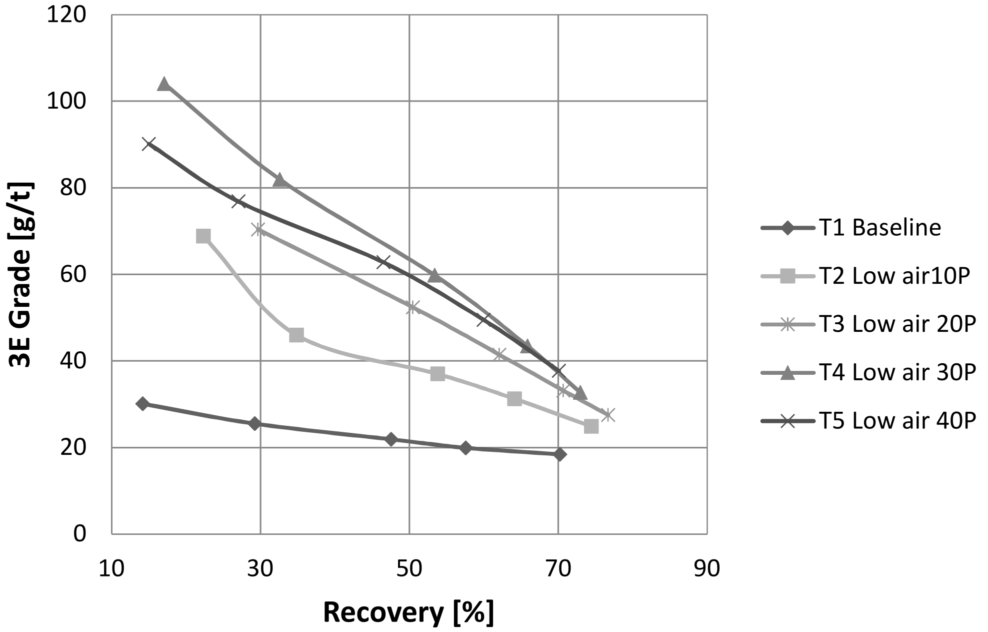

Figure 4 - Grade-recovery relationships for different number of passes

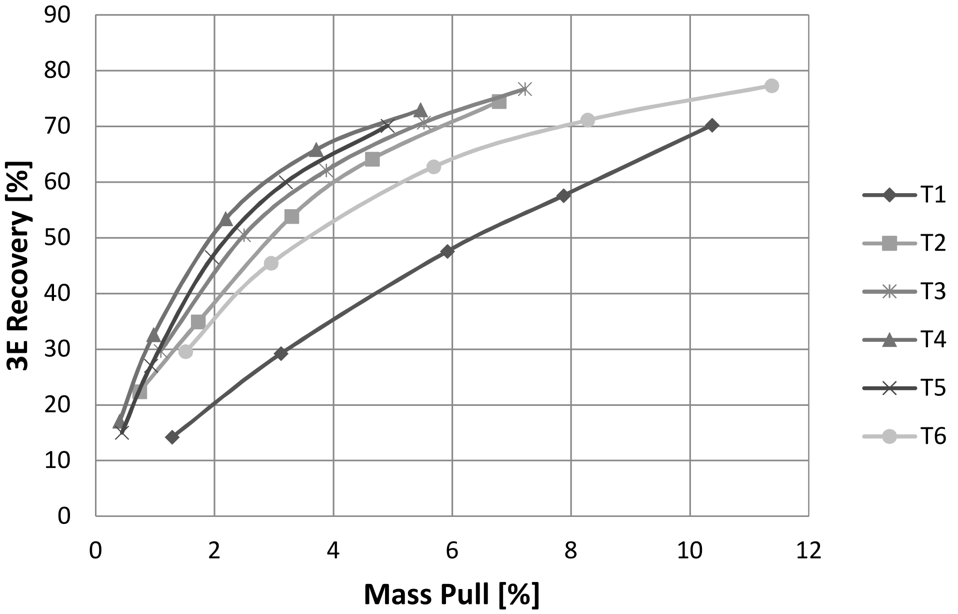

Figure 5 - Recovery – mass pull relationships for the Mach reactor under various conditions

Effect of air

Further insight into the effect of the high-shear environment is provided by analyzing the above results against those of test 6 (Figure 6). Here, the reactor was operated for the same 20 passes than test 3 but with no air supply, and thus represent purely the effect of additional surface cleaning and perhaps some additional liberation of valuable grains. Comparing the results against that of the baseline (Test 1) indicate that it had a slight positive effect in recovery, even though the ore was freshly milled and little additional cleaning would therefore be expected. The recovery-mass pull relationship was also improved, suggesting froth conditions that were more supportive of valuable mineral recovery whilst reducing entrainment. The positive effect of the air supply during preconditioning is evident in comparing the results to that of test 3, which substantially improved the grade-recovery relationship.

By comparison, test 7 (again, 20 passes but with air supplied to the Mach only immediately prior to the slurry being diverted into the Denver cell) produced a better grade-recovery curve than test 6 and was also characterized by an improved recovery-mass pull relationship. This demonstrates that the single pass of aeration, after 20 passes without air and thus at the same cleaning as effected in test 6, had a distinctly positive effect. Whilst still slightly worse than test 3, it should be kept in mind that in all these case the conditioning of the pulp with reagents was performed in the agitated Denver cell only after it was processed in the Mach reactor. Thus, it seems that the effect of aeration in the reactor was carried through to the flotation cell, presumably in the way in which microbubbles on particle surfaces were able to withstand the turbulence in the cell during the 5 minutes of reagent conditioning. Although it was hypothesized that any microbubbles that would have formed on particle surfaces during a pass through the reactor would be destroyed as it encountered the extreme conditions with a following pass, the current results do seem to support some cumulative effect. An alternative perspective on this observation is that the improved performance was simply due to the increased velocity through the Mach reactor with the addition of air, resulting in improved conditions for cavitation and hence flotation. Currently more tests are underway to better understand this mechanism.

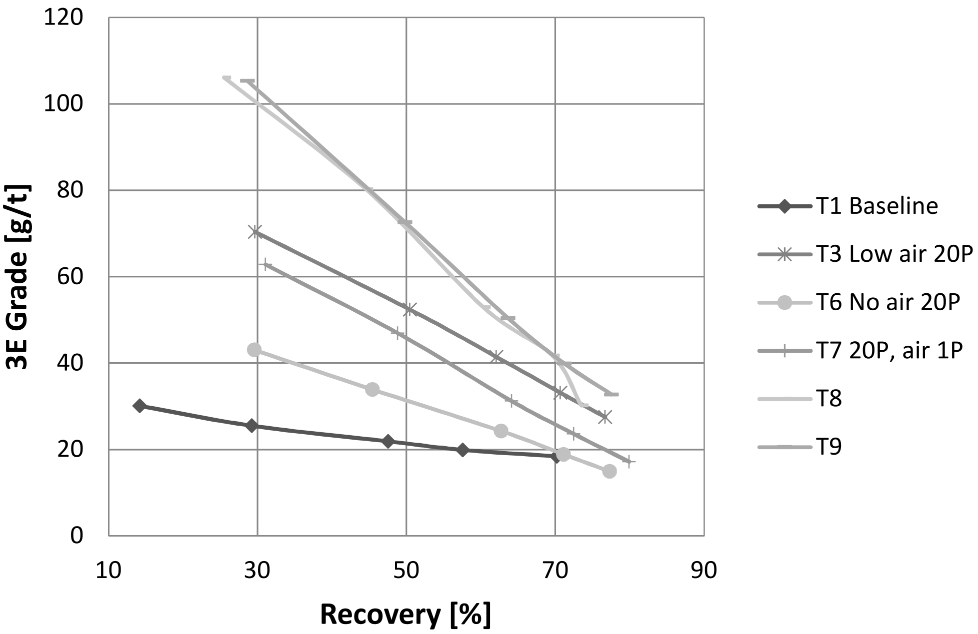

Figure 6 - Effects of the mode of air addition, and reagent conditioning in the reactor rig versus in the Denver cell

Method of reagent conditioning

As mentioned earlier, the potential impact of the conditioning in the Denver on the gas holdup and microbubbles generated by the Mach reactor was studied in one set of tests by performing the conditioning in the rig, thus enabling the float to start immediately afterwards in the Denver cell. These results are shown in Figure 6, tests 8 and 9 being repeats of 6 and 7 respectively, the difference being that in the latter the reagents were introduced in the rig towards the end of the pre-conditioning, rather than afterwards in the Denver cell.

The grade-recovery relationship in this case was clearly superior to the rest of the samples, especially during the first stages of flotation a very much improved concentrate grade being obtained. This supports what was expected, namely that the intense mixing of the slurry during circulation through the reactor, and the better preservation of the conditions created by the Mach, would lead to improved recoveries. Although the difference between the two tests were in this case much less than e.g. in the case of tests 6 and 7, it is interesting to note that the results improved even further on those obtained where air was supplied during recirculation (test 3). These support also the observations from industrial application of the Mach technology where the slurry is floated immediately after conditioning, thus preserving as best possible the improved floatability effected on it by the reactor.

PGM - Chromite selectivity

An important aspect of UG2 flotation, and one that carries severe smelter implications and penalties, is the presence of chromite in the PGM concentrate. The chromite has several negative effects on smelting, including chrome spinels building up in the hearth, thereby reducing capacity, attacking the refractory liners, and impacting on matte fall through formation of a mushy slag layer. The selectivity of PGM vs Cr_2O_3 recovery is therefore key; this aspect is analysed in more detail in Figure 7.

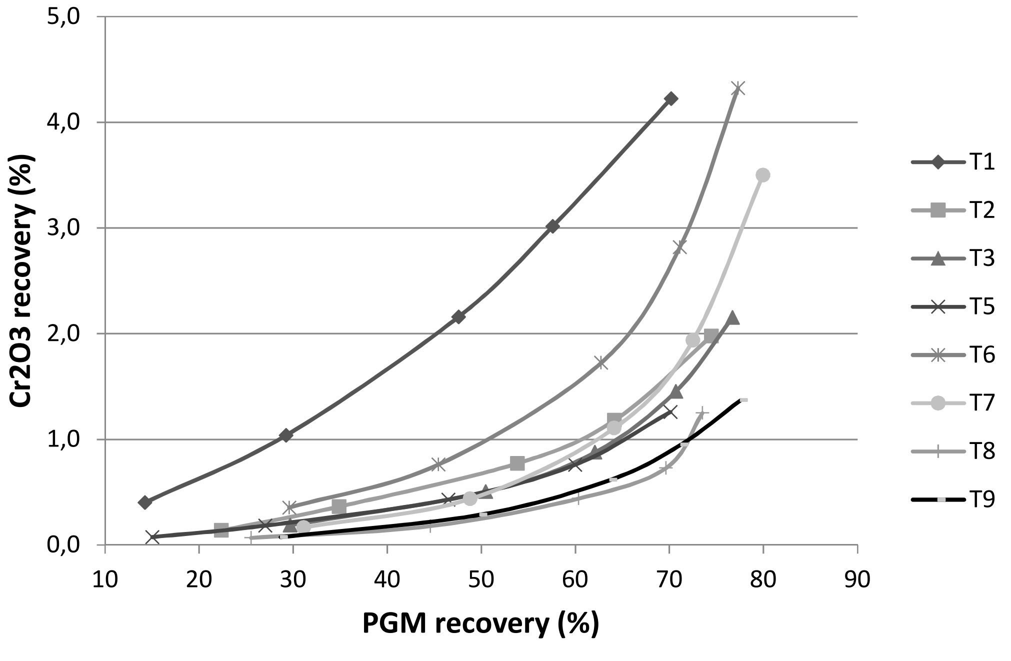

Figure 7 - PGM – Cr2O3 selectivity under various conditions

Compared to the base case, processing of the feed through the Mach reactor has a marked positive influence on the PGM-Cr2O3 selectivity in all cases, effectively doubling it at a PGM recovery of around 70%. An increasing number of passes through the reactor slightly improves the selectivity, the optimum being reached at around 20 passes (Test 3), and being ascribed to increased cleaning of activated chromite surfaces. Surprisingly, the worst selectivity of the Mach-based flotation tests was obtained under conditions of no air supply to the reactor, suggesting that the increased velocity during the other tests played an important part in de-activating the chromite. More work is required to understand why this would be the case. Finally, the impact of the reagent conditioning in the rig, enabling flotation directly after the pre-conditioning, was telling in that it improved also the PGM-Cr2O3 selectivity. This suggests that the recovery of chromite was not increased by the particular conditioning procedure.

Comparison of flotation kinetic parameters

In order to better quantify the effect of various operating conditions on the performance of the ore during flotation, the kinetic data have been fitted by means of the modified Kelsall model. This simplified two-component model describes recovery in terms of the (extrapolated) ultimate recovery Rmax, the fraction of the floatable component which is fast-floating (Qf), a fast-floating rate constant (Kf), and a slow-floating rate constant (Ks). These results are shown in Table 3 for both the valuable fraction (3E, or Pt, Pd and Au) and the total mass. Due to the very small percentage of the valuable fraction and S in the ore, the mass pull was assumed to represent the recovery of gangue.

Table 3 - Modified Kelsall rate parameters fitted to 3E and gangue kinetic data

Test #	**Passes ***	**3E**				**Gangue**				**Relative Grade max**
		Rmax	**Qf**	**Kf**	**Ks**	**Rmax**	**Qf**	**Kf**	**Ks**	
1	0	81.6	0.4	0.42	0.05	13.7	0.28	0.27	0.04	1.00
2	10	76.1	0.25	1.91	0.11	11.8	0.14	0.34	0.02	1.08
3	20	79.1	0.57	0.91	0.09	8.71	0.17	0.73	0.05	1.52
4	30	73.9	0.16	1.49	0.14	7.17	0.04	0.23	0.05	1.73
5	40	72.3	0.13	2.25	0.11	9.37	0.10	0.23	0.02	1.30
6	20	77.6	0.37	1.59	0.14	14.9	0.19	0.33	0.04	0.87
7	20	81.2	0.46	1.21	0.11	14.8	0.07	0.86	0.03	0.92
8	20	73.4	0.35	1.16	0.18	5.82	0.17	0.54	0.01	2.12
9	20	79.1	0.62	0.76	0.10	7.51	0.28	0.26	0.04	1.77

* Refer to Table 2 for the full set of experimental conditions.

The considerable scatter in the 3E results makes their interpretation somewhat troublesome. However, despite the drop in the fitted Rmax compared to the baseline (where the feed was floated without circulation through the reactor) and the erratic values of the fast-floating fraction (Qf), the fast-floating as well as the slow-floating rate constants were enhanced throughout. The equivalent figures for the gangue indicated that for the tests in which a small amount of air was introduced continuously during circulation (i.e. tests 2 to 5), the maximum mass recovery was generally dropping with increased circulation. This is consistent with earlier results on UG2 tailings material (Ross et al., 2017) in which rougher feed, cleaner feed and recleaner feed material was floated, and explains the improved grades that were observed under these conditions. The reason for the increased mass pulls for tests 6 and 7, slightly exceeding that of the baseline, is not known but possibly point to the importance of slurry speed through the Mach reactor also in ensuring deactivation of the gangue. The other interesting aspect to note is the fact that, except for test 9, the fast-floating fraction (Qf) seemed to decrease consistently under these conditions, lending further support to the argument that the conditioning is somehow deactivating the surfaces of naturally flo.

Finally, the extrapolated recoveries of valuable and gangue were used to calculate a final projected grade, relative to that of the baseline. As shown in the rightmost column of Table 3, the most significant enhancement was observed after around 30 passes. Whilst this is not feasible in practice, it should be noted that the test programme was aimed at a better understanding of the mechanisms involved in the reactor with a UG2 ore. The drop in Grade max for tests 6 and 7 compared to the baseline is the result of a poorer final 3E recovery, accompanied by an increase in the mass pull. As mentioned above, at this stage it is believed to have to do with the speed of slurry through the reactor; a following set of tests will be aimed at validating this by reducing the length of the reactor.

CONCLUSIONS

The efficient recovery of platinum group mineral particles, many of them very fine, poses a significant challenge to flotation operations and a range of studies have been undertaken over the years in order to enhance the metallurgical performance of concentrators. Coupled with this is the need to suppress the recovery of chromite into the concentrate, as it has severe implications in downstream smelting operations. This paper described the results of a further test campaign using a high-shear cavitation device (HSCD) to better understand the impact of the various mechanisms that are believed to play a dominant role in the significantly enhanced efficiencies of PGM minerals when compared to conventional flotation. Whilst earlier work focused on the treatment of material from UG2 tailings treatment plants, this current study investigated the effect of the pre-conditioning on a run-of-mine UG2 ore.

The results have shown that preconditioning has a noticeably beneficial effect on the metallurgical performance of the particular ore, improving the grade-recovery as well as the recovery – mass pull relationships. In particular, at similar recoveries, the mass pulls were practically halved, supporting the findings of earlier work on tailings samples. Some interesting new aspects emerged from the current investigation, including the fact that the addition of a constant amount of air during pre-conditioning seems to aid floatability. This is believed to be due to either a cumulative effect of increasing micro-bubbles, or due to the increased speed of the slurry through the reactor under these conditions, enhancing hydrodynamic cavitation. Whilst pre-conditioning in the absence of air to the reactor did improve on the baseline recovery, the results were slightly poorer than with the introduction of air.

From a chromite suppression perspective, the results were also promising in that the PGM – Cr_2O_3 selectivity was much enhanced during all conditions involving the use of the Mach reactor. This seems to be as a result of a reduced water recovery and thus entrainment of Cr_2O_3 into the concentrate, whilst still maintaining a froth that is sufficiently stable for transporting the PGMs into the concentrate. When reagent conditioning was done within the reactor rig and the slurry was floated immediately afterwards in order to preserve as best possible the properties imparted to the slurry by the reactor, the best 3E grade-recovery relationship and selectivity with respect to chromite was obtained. The grade-recovery relationships in the worst case approximated that of the baseline test, and were consistently lower than those obtained when the reagents were added after pre-conditioning in the reactor.

The findings presented here, together with earlier results, provide evidence of the positive impact that the conditions in the Mach reactor have on the recovery of difficult to float PGMs. As expected, the effect was less pronounced for the run-of-mine ore than for oxidised tailings. Contrary to earlier findings on tailings material, where the major shift in improvement was an increase in recovery, in this case the shift was predominantly in terms of grade. Importantly, it also provides new insight into the mechanisms driving the improved performance.

ACKNOWLEDGEMENTS

We gratefully acknowledge permission by Mintek executive management to publish the results of the testwork.

REFERENCES

Aldrich, C., Feng, D., 1999. Effect of ultrasonic preconditioning of pulp on the flotation of sulphide ores. Minerals Engineering, 12 (6), 701-707.

Becker, M., Wiese, J., Ramonotsi, M., 2014. Investigations into the mineralogy and flotation performance of oxidised PGM ore. Minerals Engineering 65, 24–32.

Bulatovic, S.M., Salter, R.S., 1989. High Intensity Conditioning: A New Approach to Improve Flotation of Mineral Slimes. Conference of Metallurgists, Halifax, Canada, pp. 182–197.

Calgaroto, S., Azevedo, A., Rubio, J., 2015. Flotation of quartz particles assisted by nanobubbles. Int. J. Miner. Process. 137, 64–70.

Chen, G., Grano, S., Sobieraj, J., Ralston, J., 1999. The effect of high intensity conditioning on the flotation of a nickel ore. Part 2: Mechanisms. Minerals Engineering, 12 (1), 1359-1373.

Dickinson, J.E., Galvin, K.P., 2014. Fluidized bed desliming in fine particle flotation Part I. Chemical Engineering Science. Volume 108, 28 April 2014, pp. 283–298

Hu, H., Finch, J.A., Zhou, Z., Xu, Z., 1998. Numerical and experimental study of a hydrodynamic cavitation tube. Metallurgical and Materials Transactions B, 29(4), 911–917.

Martínez-Gómez, V., Pérez-Garibay, R., Rubio, J., 2013. Factors involving the solids-carrying flotation capacity of microbubbles. Minerals Engineering 53 (2013) 160–166.

Miettinen, T., Ralston, J., Fornasiero, D., 2010. The limits of fine particle flotation. Minerals Engineering, 23(5), 420-437.

Nesset, J.E., Hernandez-Aguilar, J.R., Acuna, C., Gomez, C.O., Finch, J. A., 2006. Some gas dispersion characteristics of mechanical flotation machines. Minerals Engineering, 19(6), 807–815.

Oliveira, H., Azevedo, A., Rubio, J., 2018. Nanobubbles generation in a high-rate hydrodynamic cavitation tube. Minerals Engineering, 116, 32-34.

Qi, B.C. and Aldrich, C., 2002. Effect of ultrasonic treatment on zinc removal from hydroxide precipitates by dissolved air flotation. Minerals Engineering, 15(12), 1105-1111.

Ross, V., Singh, A., Dlame, M., Pillay, K., 2017. Improved flotation of fine PGM tailings in a high-shear cavitation device. Proceedings of the Flotation 17 conference, Cape Town, South Africa, November.

Rule, C.M. and Anyimadu, A.K., 2007. Flotation cell technology and circuit design - an Anglo Platinum perspective. Journal of the South African Institute of Mining and Metallurgy, 107(10), 615.

Singh, A., 2016. Enhanced flotation of platinum mineral fines through feed cavitation: 'Bringing the mountain to Mohamed'. IMPC 2016: XXVIII International Mineral Processing Congress Proceedings, Quebec City.

Sobhy, A., & Tao, D., 2013. Nanobubble column flotation of fine coal particles and associated fundamentals. International Journal of Mineral Processing, 124, 109-116.

Subrahmanyam, T.V., Forssberg, E.S., 1990. Fine particle processing: shear flocculation and carrier flotation – a review. International Journal of Mineral Processing 30, 265–286.

Tabosa, E., Rubio, J., 2010. Flotation of copper sulphides assisted by high intensity conditioning (HIC) and concentrate recirculation. Minerals Engineering 23, 1198–1206.

Tao, D., 2005. Role of bubble size in flotation of coarse and fine particles – a review. Separation Science and Technology, 39 (4) 741-760.

Yoon, R.H., Luttrell, G.H., Adel, G.T., Mankosa, M.J., 1989. Recent advances in fine coal flotation. Advances in Coal and Mineral Processing Using Flotation, 211–218.

Zhou, Z.A., Xu, Z., Finch, J.A., 1995. Fundamental study of cavitation in flotation. Society for Mining, Metallurgy, and Exploration, Inc., Littleton, CO (United States).