The effect of hydrodynamic cavitation device on the performance of the Platinum Group Metals flotation

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The benefits of applying hydrodynamic cavitation device (HCD) technology to improve the performance of flotation operations have already been proven through a range of commercial applications and bench testwork. Various mechanisms combine to achieve increased recoveries and grades, including the cleaning of particle surfaces, additional liberation of valuables, and the formation of ultrafine (nano-) bubbles to collect especially the fine and ultrafine valuables. This paper details the results of tests to quantify the impact of the GoldOre Mach reactor on the recovery of the fine (-25 µm) fraction in floating a platinum-bearing ore from the northern limb of the Bushveld Complex in South Africa. To explore the effect of grind in detail, the ore was milled under inert conditions to three P85 product sizes, namely 53, 38, and 25 µm respectively. Subsequently, the feed slurry was conditioned by repeated circulation through a laboratory-scale reactor which was connected to a bottom-driven flotation cell. A suite of reagents that have been established in earlier tests on the same ore was dosed during circulation through the Mach reactor. Results show that for all three grinds, both the kinetics and the recoveries of the -25 µm platinum group metals (PGMs) were enhanced by the physical conditioning in the reactor, and, in alignment with earlier findings on bench and industrial scale, were accompanied by reduced solids and water recoveries. This resulted in improved grades compared to the base case, where no physical pre-conditioning of the feed took place. An unexpected, though consistent, trend was that the mass pull was reduced with increasing fineness of the feed material. The Cu-Ni minerals followed the PGM behaviour, with improved grade-recovery relationships and kinetics being observed under all the experimental conditions.

Keywords: Fine flotation, hydrodynamic cavitation, ultrafine bubbles, PGM flotation

INTRODUCTION

Recent research and operational results have provided more insight and clearly demonstrated the advantages of applying hydrodynamic cavitation device (HCD) technology to the flotation of especially fine and ultrafine valuable minerals. It is well known that the low rates of flotation of these species can be attributed mainly to inefficient particle-bubble collision in conventional flotation machines as the fine particles follow the streamlines of water around the relatively large bubbles in the pulp (Gontijo *et al.*, 2007; Safari *et al.,* 2016; Hoseinian *et al.,* 2019; Hassanzadeh *et al.,* 2022a). In the PGM industry, typical recoveries of the ultrafines range between 40 and 70%. Recovery of platinum group metals (PGMs) is achieved through flotation, which uses the difference in hydrophobicity of minerals in pulp to achieve selective separation (Gaudin, 1932; Wills and Atkinson, 1991; Jameson, 1992; Safari *et al.,* 2017). The slow rates of flotation translate into long residence times, increased mass pulls of concentrate and increased flotation circuit capacity to capture the 'tail' of the so-called 'elephant curve' (Lynch *et al.,* 1981; Hassanzadeh *et al.,* 2022b; Safari *et al.,* 2022).

Nano- and micro-bubbles that can be formed by either hydrodynamic or acoustic cavitation when the local pressure drops below the vapour pressure of the liquid and the saturation pressure of the dissolved air, offer a unique solution and huge potential to the challenge of fines recovery. Instead of the conventional particle-bubble contact mechanism, the ultrafine bubbles nucleate on exposed hydrophobic surfaces and thus act as a very efficient collector (Ahmadi *et al.,* 2014; Calgaroto *et al.,* 2015; Farrokhpay *et al.,* 2020; Zhang *et al.,* 2021; Hassanzadeh *et al.,* 2022c), allowing the fines to agglomerate (Knüpfer *et al.,* 2017) and eventually be recovered by the 'macro' bubbles of a size typically associated with mechanical cells and columns. This mechanism greatly enhances their floatability and can be viewed as 'reverse attachment', as, instead of the conventional situation with the bubble much bigger than the particle that attaches to it; here it is the (nano-sized) bubble that nucleates on the surface of the particle, being much larger than the bubble. Recently, an attachment–detachment kinetic model for flotation was evaluated by Safari *et al.,* (2020) and a good contribution to this 'two-stage attachment model' was made by Mitra *et al.,* (2021), where the mechanism of aggregation was demonstrated by means of high-speed imaging in a laboratory-scale cell, ultrasonic cavitation being used to create the nanobubbles. The bubbles formed by the cavitation resulted in the formation of agglomerates with ballotini particles, the clusters being floated by larger (macro) bubbles. Factors such as the power input and the duration of the pulses were found to be key to controlling the process. In addition to the aggregation, Ross *et al,*. (2018, 2019) have suggested supporting mechanisms that allow for increased flotation efficiencies that are observed with the pre-conditioning of PGM ores in the GoldOre Mach reactor. These include the cleaning of valuable particle surfaces where for instance hydroxide species have precipitated, promoting their floatability, or, in the case of Upper Group 2 Reef (UG2) PGM flotation, removal of talc rims on chromite grains and thereby reducing their floatability. Also, mechanisms such as the dispersion of slimes, allowing better particle-bubble adhesion, are expected to contribute to improving performance. The added liberation of valuables on the grain boundaries with gangue particles, due to the high and repeated inter-particle attrition that takes place in the nozzles of the reactor, was also considered a potential contributor. Support for this hypothesis was found in the increased fineness of a PGM stream after repeated recycling through the reactor. Whilst the benefit of applying hydrodynamic cavitation to the flotation of PGM ores has been demonstrated in increasing final recoveries, kinetics, concentrate grades, and impact of the technology on specifically the recovery of fines and ultrafines has not yet been investigated. The work reported here was therefore aimed at elucidating specifically the behaviour of these fractions in the flotation of PGM ore.

Material, reagents, and methods

Ore

A sample of Platreef ore from the northern limb of the Bushveld Complex in South Africa was used for the testwork; this area represents the 'new frontier' as far as PGM production in the country is concerned. The pyroxenitic host rock consists mainly of enstatite and plagioclase, the 3E+Au head grade totalling 3.6 g/t, with Cu and Ni grades of 0.18 and 0.3% respectively. The ore was crushed and blended, followed by grinding in a Vibramill using inert media to a target P80 of 75 µm, and subsequently to P85 grinds of 53, 38 and 25 µm respectively in an inert vertical stirred laboratory mill. As shown in Table I, in each case more than 80% of the PGMs deported to the -25 µm fraction, as were even higher portions of the Cu and Ni. The data clearly illustrates the challenge associated with having to liberate the valuables at finer sizes, and subsequently having to recover them selectively by flotation.

Table I. Deportment of PGM in size fractions after milling to three different P85

			Grade			Distribution		
P85	**Fraction**	**Mass**	**3E+Au**	**Ni**	**Cu**	**3E+Au**	**Ni**	**Cu**
(µm)	**(µm)**	**(%)**	**(g/t)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**
53	+25	34,2	1,99	0,11	0,05	19,5	12,5	10,5
	-25	65,8	4,27	0,4	0,20	80,5	87,5	89,5
	Total	100,0	3,49	0,30	0,16	100	100	100
38	+25	24,6	1,52	0,11	0,05	10,7	8,8	6,9
	-25	75,4	4,14	0,37	0,20	89,3	91,2	93,1
	Total	100,0	3,50	0,31	0,18	100	100	100
25	+25	14,2	3,11	0,10	0,05	11,7	4,6	4,2
	-25	85,8	3,89	0,34	0,20	88,3	95,4	95,8
	Total	100,0	3,78	0,31	0,17	100	100	100

Equipment

The tests were carried out in the GoldOre laboratory flotation rig (shown in Figure 1), which is equipped with a bottom-driven flotation cell of 6 L capacity and a bench-scale Mach reactor which is connected to the flotation cell through a high-pressure centrifugal pump. Physical pre-conditioning of the ore was achieved by circulation of the slurry through the reactor for a predetermined number of cycles, expressed in terms of the equivalent volume of slurry in the flotation cell.

Figure 1. The laboratory Mach test rig used for the testwork.

Reagents and experimental procedure

The work reported here comprised a series of six tests in which the response of the ore to Mach preconditioning was investigated at each of the three P85 grinds. In each case, Flomin C7160, a dithiophosphate (DTP), was added to the laboratory mill at a dosage of 6.25 g/t. The DTP is largely insoluble in water, hence the approach to add it directly into the mill. This was followed by the addition of Senfroth522 (35 g/t) prior to physical conditioning in the Mach reactor for 5 cycles; no air was introduced to the reactor at this stage. The float commenced with air being introduced to the bench cell as well as to the Mach reactor. The first concentrate was collected after 1 minute with 15 second froth scraping intervals. The pulp was subsequently conditioned by the addition of sodium isopropyl xanthate (SIPX), Aero3477 and Sendep 30E as collector, promoter and depressant respectively at dosages of 75, 75 and 125 g/t for a period of five cycles through the Mach with, again, no air being introduced. The second concentrate was collected after another two minutes of flotation, after which the same reagents were added at dosages of 25, 25, and 63 g/t respectively and conditioned for a further three cycles. Finally, the third, fourth and fifth flotation concentrates were collected after another 4, 8 and 15 minutes respectively, i.e. the total flotation time totalling 30 minutes. In each case, tests were performed in duplicate, with the corresponding concentrate and tailings samples being combined for assay.

Results and discussion

Solids and water recovery

The results of the test campaign are shown in Figures 2 to 6 and Table II respectively. The bottom-driven cell and test rig allowed for very good reproducibility of both solids and water recoveries, a typical example of water recovery being given in Figure 2.

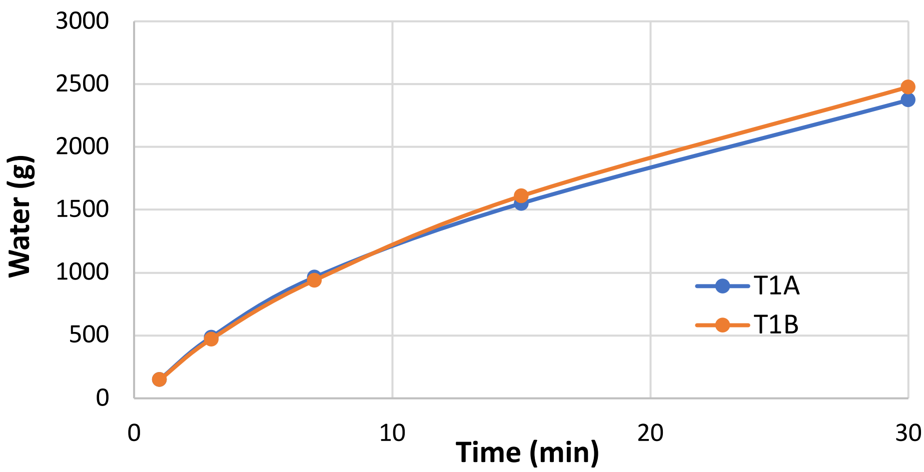


Figure 2. Typical reproducibility of water recoveries in the Mach laboratory rig: P85 of 53 µm.

Figure 3 shows the mass pull behaviour of the -25 µm fraction of the six bench flotation tests. By comparing the results for Tests 1 and 2, those of Tests 3 and 4, and finally Tests 5 and 6, it is evident that the physical pre-conditioning with the Mach reactor produced a consistent reduction in mass pull across all three grinds when compared to the base case of no conditioning, dropping from an average of over 20% after 30 minutes of flotation, to about 16%. These results corroborate with similar earlier work on UG2 PGM ores and can be attributed to a change in froth characteristics, with the water recovery following the mass pull trends, although less pronounced. Reducing the water recovery will decrease entrainment which will lower concentrate dilution by undesirable gangue minerals (Zheng *et al.*, 2006; Hoseinian *et al.*, 2021). Similarly, by comparing the results for the Mach preconditioning only (Tests 2, 4 and 6), it is evident that the mass pull of the -25 µm fraction decreased slightly with an increase in grind, i.e. increased fineness of the feed. This is contrary to typical flotation behaviour where the contribution of entrainment in the finer size fractions often tend to dominate the solids recovery, and can at this point be attributed mainly to changes in froth characteristics brought about by changes in the hydrodynamics and the bubble size distribution in the pulp (Testa *et al.*, 2017; Hoseinian *et al.*, 2020).

Table II. Test conditions at three different P85

Test #	1	2	3	4	5	6
P85 (µm)	53	53	38	38	25	25
Pass #	0	13	0	13	0	13

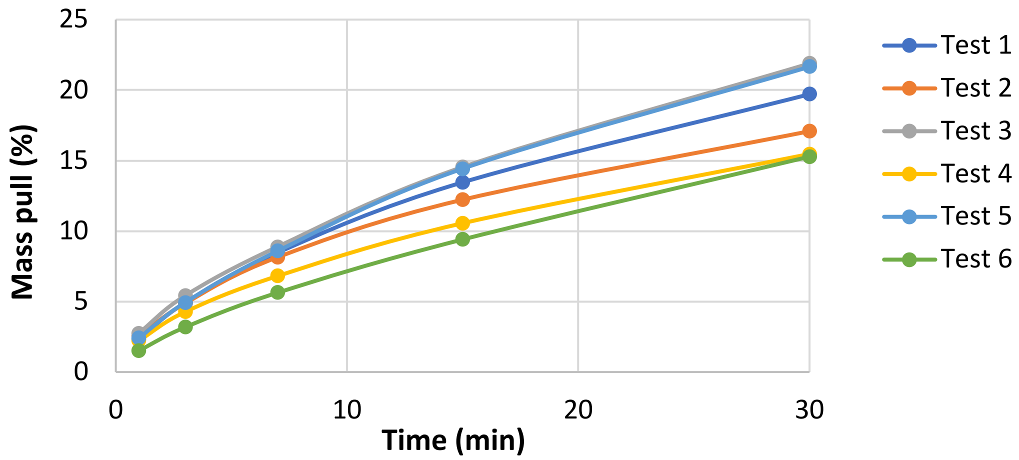


Figure 3. Mass pull for the various tests.

Solids/water ratios

The solids/water ratios of the concentrates for the flotation of the Platreef material mimicked those of earlier tests on UG2 ore and followed a similar trend in all the current tests, *viz.* a steep drop from the first concentrate and flattening out to a ratio that is decreasing only slightly during the latter stages of flotation (Figure 4).

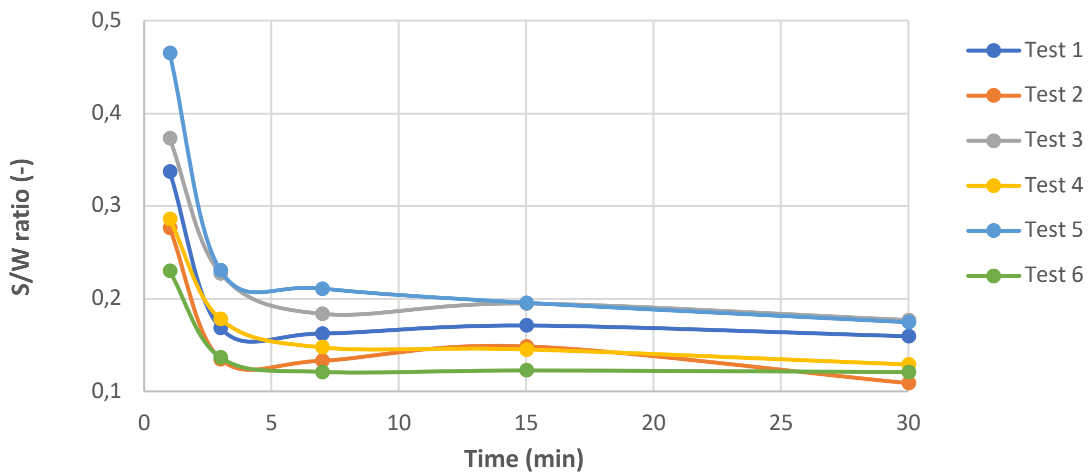
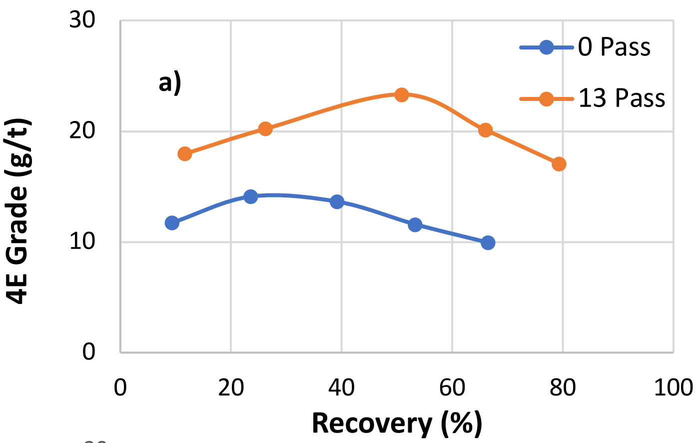


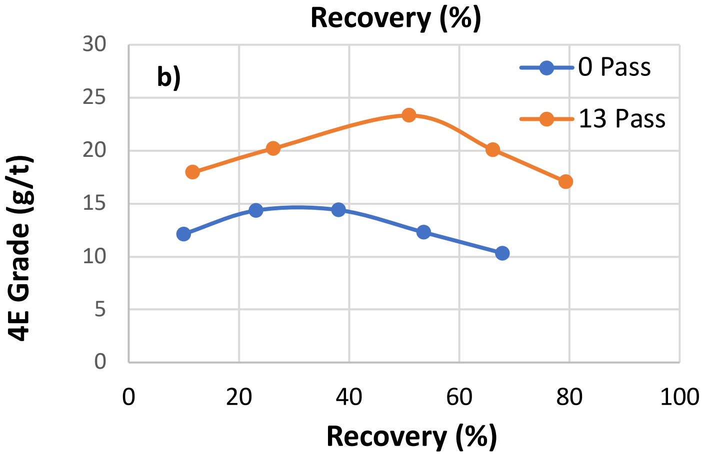
Figure 4. Solid/water ratios for the various test conditions.

Considering the fact that these ratios represent the overall solids and water recoveries, and not that of the -25 µm fraction only, as was to be expected the initial solids/water ratios of the concentrate during the baseline floats increased with increasing fineness of grind. However, of specific note is the fact that the conditioning in the Mach reactor reduced the ratios, i.e., makes for a relatively wetter and mobile froth especially during the early stages of flotation. This points to a reduced level of naturally floatable material and/or entrainment compared to the base case, brought about by the changed hydrodynamics and froth properties. Of further interest is the fact that the difference was amplified the finer the grind became, the highest reduction in the solids/water ratios being achieved at the finest grind (Test 5 vs Test 6). In the flotation of Platreef ores, the relatively high mass pull to final concentrates is a challenge that has yet to be overcome, as this impacts unfavourably on concentrate grades and smelter costs. The results observed for the HCD conditioning are most promising in this regard.

PGM behaviour

The flotation behaviour of the PGMs in the -25 µm fraction is shown in Figures 5 (a–c), demonstrating not only an improvement in the grade-recovery relationship but also an increase in the PGM kinetics and the final recoveries after pre-conditioning in the Mach reactor. The response of the PGMs to the addition of the DTP in the mill, even though at a very modest dosage of 6.2 g/t, is unexpected and not at this point readily explained. The reagent recipe and dosages were carried over from extensive earlier optimisation flotation bench work on the same material, where the ore was milled in a standard laboratory mill with stainless steel media. Whether the fact that, in the current tests, the ore was ground under inert conditions had any impact on the anomalous behaviour, needs further investigation. However in this investigation inert grinding is used often in PGM operations to regrind streams in the cleaner circuit. In each case, the discrete PGM concentrate grades peaked only in the third flotation interval, i.e. between cumulative minutes 3 and 7. A potential pointer to this is the fact that the balance of the SIPX (25 g/t out of the total 100 g/t) was added only after the second flotation interval, suggesting that the collector dosage in the first two intervals may have been insufficient. However, this is contrary to the normal collector requirement for the specific ore and warrants further investigation. In all cases, the recovery kinetics exhibited a very linear response over the last three flotation intervals.





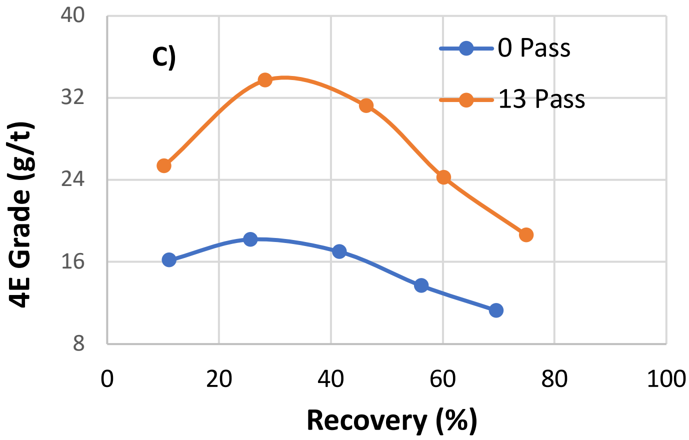


Figure 5. PGM grade-recovery response of the -25 µm fraction after processing in the Mach reactor. Feed P85 of: a) 53 µm, b) 38 µm, c) 25 µm.

The substantial increases in the PGM recoveries after 30 minutes of flotation at all three grinds are in accordance with earlier results on PGM ores and can be attributed mainly to increased floatability that is brought about by cleaning of particle surfaces and the dispersion of slimes. While this effect was believed to be more prominent in the case of coarser particles, it is most encouraging that it seems to be carried through to the fine and ultrafine valuables as well and without the addition of an extra collector. It is also not unlikely that the mechanism of fines agglomeration, rather than individual particle-bubble contact, contributed to the increased recoveries.

Cu kinetics

As shown in Figure 6 for the Cu in the -25 µm fraction, similar trends were observed for the PGMs at all three of the grinds. As summarised in Table I, the Cu head grade in the -25 µm fraction in each case amounted to around 0.2%. The initial upgrading ratio therefore varied from only around 4 (in the case of the P85 of 53 µm) to around 6 for the P85 of 25 µm, which is very much smaller than the normal ratio for this ore. However, even though the grade-recovery behaviour was not as expected, especially since the DTP was added upfront specifically for Cu collection, it is clear that the pre-conditioning of feed material in the Mach reactor managed to improve not only the grade-recovery relationship but overall, also the kinetics and the final recoveries.

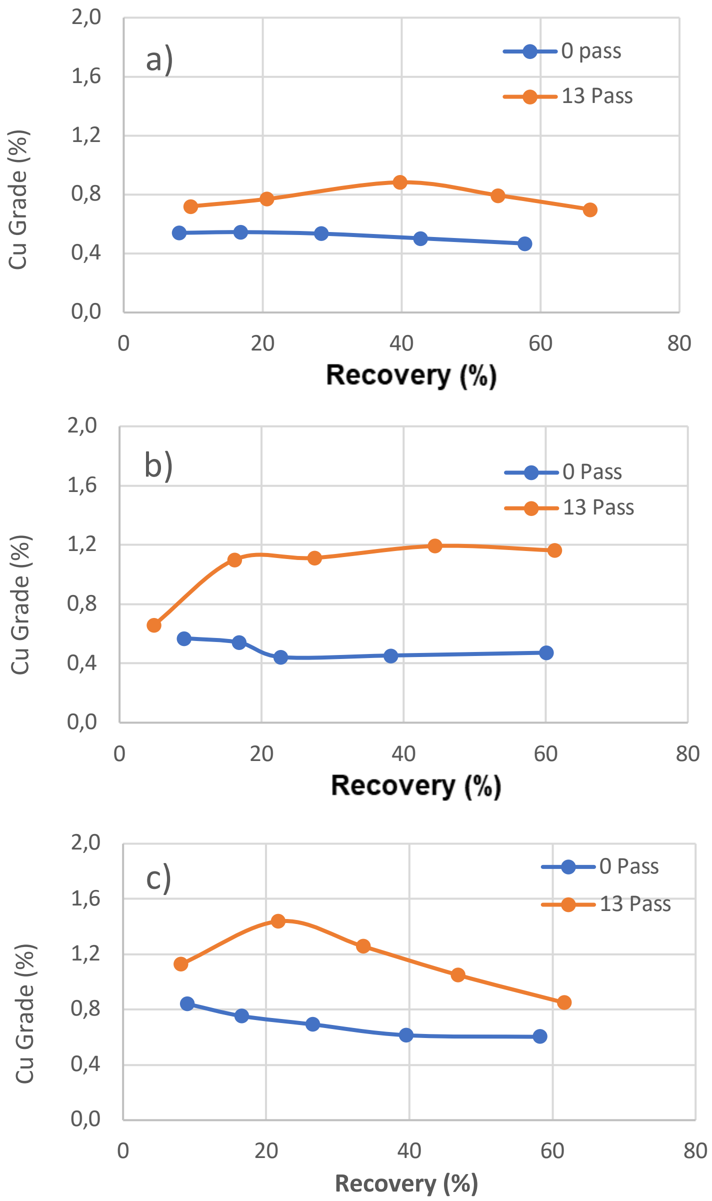


Figure 6. Cu kinetics in the -25 µm fraction for the three grinds. Feed P85 at a) 53 µm, b) 38 µm, c) 25 µm.

The Ni kinetics followed similar trends to both the PGMs and Cu, the concentrate grades nearly doubling after the pre-conditioning, and the kinetics being improved throughout.

CONCLUSION

HCDs have, over the past few years, demonstrated significant benefits in enhancing the kinetics of flotation as well as improving the grade-recovery relationships of a variety of ores. Following on from earlier work on UG2 PGM ores, the focus of the research reported here investigated in more detail the impact of fine bubbles on the fine and ultrafine fractions of these ores. Addition of DTP into the mill, even at low dosages, apparently was responsible for the anomalous flotation behaviour that was observed, when compared to earlier work on the same material.

In spite of the above, the benefit of hydrodynamic cavitation technology on fine and ultrafine PGM recovery was demonstrated clearly. The results indicated that physical pre-conditioning of the flotation feed with the Mach reactor reduced water recoveries as well as the mass pull in the -25 µm fraction, the latter being reduced with increasing fineness of the feed material. Intriguingly, the PGM kinetics as well as recoveries were improved when compared to the base case at all three grinds, leading to improved grade-recovery relationships. The Cu and Ni results followed the same trends as those of the PGMs with improved recovery-grade relationships and kinetics having been observed under the set of experimental conditions.

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