Physicochem. Probl. Miner. Process. 51(1), 2015, 115−126

Physicochemical Problems of Mineral Processing

www.minproc.pwr.wroc.pl/journal/

ISSN 1643-1049 (print)
ISSN 2084-4735 (online)

Received July 21, 2014; reviewed; accepted August 1, 2014

THE USE OF CONTINUOUS CENTRIFUGAL GRAVITY CONCENTRATION IN GRINDING CIRCUIT. MODIFIED APPROACH FOR IMPROVED METALLURGICAL PERFORMANCE AND REDUCED GRINDING REQUIREMENTS

N. Emre ALTUN[*], Givemore SAKUHUNI[**], Bern KLEIN[**]

[*] Middle East Technical University, Mining Engineering Department, Ankara, Turkey; ealtun@metu.edu.tr
[**] University of British Columbia, NBK Institute of Mining Eng., Vancouver, BC, Canada

Abstract: The use of centrifugal gravity concentration in the closed-grinding circuit of a gold-containing massive sulphide ore was tested on classifier underflow and overflow. A continuous Knelson CVD6 was retrofitted to the hydrocyclone underflow for recovery of Au and Pb at a coarser feed size. The objective of treatment of overflow was recovering unliberated Au prior to flotation. The tests were performed in actual operating conditions at Nyrstar's Myra Falls Mine. The results of the tests on the cyclone underflow revealed that both liberated and unliberated Au and Pb were recovered by the Centrifugal Variable Discharge (CVD) concentrator. Concentrate grades <60g/Mg Au were attainable at a more than 20% recovery. This application also allowed early and increased Pb recovery before it became gravity unrecoverable by over-grinding. Other benefits included capturing middlings for regrinding as well as potential coarser grinding and increase in mill throughput. A coarse grind also corresponds to a reduction in deformation of Au-particles, and is beneficial for increased Au recovery in downstream processing. Treatment of cyclone overflow by the CVD also provided favourable results. The outcomes included capturing unliberated gold prior to flotation and potentially reducing pumping requirements and reagent consumption. A comparison of the metallurgical performances showed that CVD application on classifier underflow was more effective. The CVD was capable of recovering unliberated gold in sulphides and performed better at a coarser particle size. Therefore, when used with the grinding circuit, a coarser grind can be applied and the CVD could be used to reject gangue at a coarser size.

Keywords: *centrifugal gravity concentrator, grinding, classification, liberation*

Introduction

By the introduction of centrifugal gravity concentrators, the conventional gravity concentration in mineral processing has moved one step further. The centrifugal type concentrators, particularly the continuous types have the distinction of recovering

http://dx.doi.org/10.5277/ppmp150111

targeted values from the undesired fractions at relatively low specific gravity difference conditions on accounts of the sophisticated separation mechanism depending on centrifugal, gravitational effects as well as effective utilization of air and water. In addition, compared to conventional gravity concentration, separation at finer sizes is possible with these concentrators due to high centrifugal acceleration that the particles are subject to in these units. As a result, continuous centrifugal concentrators produced by leading manufacturers such as Knelson, Falcon, Kelsey, Mozley have found increasing application in mineral processing industry, particularly in the processing of precious metals in the last three decades. In addition to the effective use and growing reputation of these units in typical processing flowsheets, such as in the processing of gold, various applications were reported to be effective. These include talc rejection from iron oxides, separation of siliceous gangue from metallic minerals, concentration of base metals and even coal preparation (Lambert et al., 1999; Byron and Roberts, 2004; McLeavy et al., 2001; Honaker et al., 1996). All these results point to a significant opportunity about the use of these units and increased effort should be dedicated to explore potential areas and new ways for the utilization of these devices. Recent research by Klein et al. (2010) on hybrid flotation-gravity circuits tested potential application of the centrifugal gravity concentration using a Knelson CVD unit, to scavenge unliberated gold in sulphides from final tailings. The basis for this application is reduced flotation performance for sizes generally below 10 micrometer and above 100 micrometers. The Centrifugal Variable Discharge (CVD) concentrator was capable of recovering coarse middlings that were normally non-recoverable or poorly recoverable by flotation. The hybrid use of CVD and flotation enabled a coarser grind size providing a preferred size distribution for flotation and thereby increasing the mill throughput.

In this study, the use of continuous centrifugal gravity concentration was assessed for the treatment of the underflow and overflow streams of a classifier operating in the closed-grinding circuit of Nyrstar's Myra Falls concentrator that processes a polymetallic massive sulphide ore with significant gold content mainly by flotation. The objectives of this novel installation on the existing flowsheet were exploring the opportunity of reducing metal losses, seeking the possibility of a coarser grind size, increasing the effectiveness of gold recovery and overcoming some critical mineralogical and morphological obstacles imposed due to the grinding conditions in the mill.

Materials and methods

Figure 1 illustrates the simplified flowsheet of Nyrstar's Myra Falls Operation at Vancouver Island, BC, Canada. A full scale continuous Knelson CVD6 (Centrifugal Variable Discharge) concentrator was retrofitted during normal operation of the concentrator for the treatment of underflow and overflow streams of the cyclone classifier working in conjunction with the ball mill. These configurations are shown in Fig. 2.

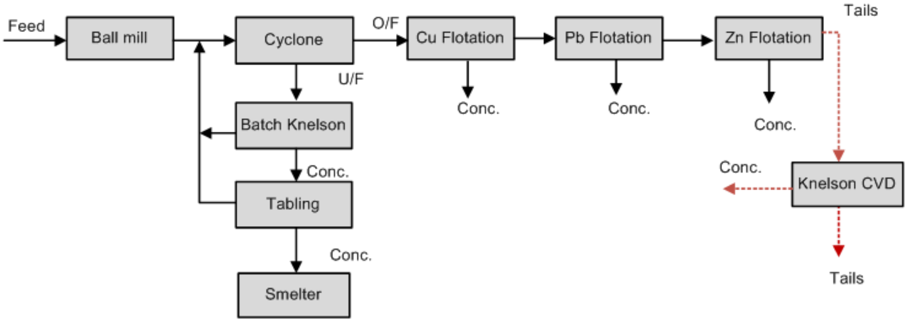

Fig. 1. Simplified flowsheet of Myra Falls concentrator

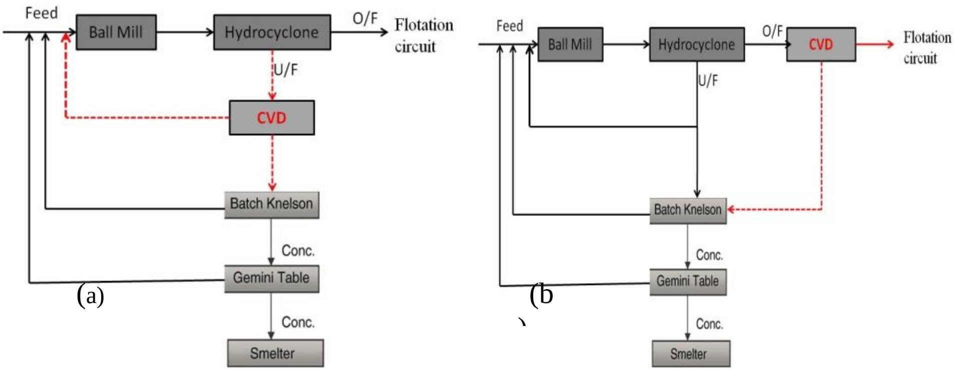

Fig. 2. Treatment of (a) classifier underflow (b) classifier overflow streams, by the CVD

Table 1. CVD machine parameters for tests on classifier underflow and overflow

Test No	Tests on Classifier Underflow			Tests on Classifier Overflow		
	PVO (s)	PVC (s)	G Force	PVO (s)	PVC (s)	*G* Force
1	0.2	5	30	0.18	5	30
2	0.2	30	30	0.18	20	30
3	0.3	5	30	0.32	5	30
4	0.3	30	30	0.32	20	30
5	0.25	15	60	0.32	20	30
6	0.2	5	90	0.18	5	90
7	0.3	5	90	0.18	20	90
8	0.3	30	90	0.32	5	90
9	0.25	15	60	0.32	20	90
10	0.2	30	60	0.25	10	60
11	0.25	30	60	0.2	12	60

The two configurations were assessed by varying main operating parameters, i.e. the pinch valve open time (PVO, seconds), pinch valve closed time (PVC, seconds) and *G* force of CVD, as presented in Table 1, and collecting cross cut samples from the feed and CVD concentrates. To evaluate the effect of operating variables on the metallurgical outcomes, the non-machine variables, i.e. feed pulp density, feed rate and ore specific variables were kept constant. Fluidisation flow rate and feed rate were maintained at 30.3 dm^3/min and at 1 Mg per hour, respectively and continuously monitored. The samples were collected, weighed, filtered and dried. Representative sub-samples were obtained by riffling for chemical analysis and size-assays. Size-assays were obtained by ICP at Myra Falls' facilities.

Results and discussion

Mineralogical studies

The feed to the mill comes from three sources which are mainly polymetallic massive sulphides: the Lynx-Myra-Price system averaging 15% pyrite, the HW system with 75% pyrite; and the Battle- Gap system, a massive sulphide with comparatively higher sphalerite, tennantite/bornite and variable amounts of pyrite. In the ore, the principal gold carrier is electrum with 22 to 30% silver and with a grain size of 2–50 μm. The finer fractions of electrum are enclosed in tetrahedrite and tennantite which are associated with sphalerite and pyrite. Gold was also observed associated with bornite and as intergrown with galena and chalcocite. In order to identify the gangue minerals the flotation tails was analysed using XRD analysis with Rietveld. Main accessory minerals were quartz, pyrite and muscovite (Table 2).

Figure 3 is a typical optical view of gravity gold concentrate. It shows flattened, tarnished gold particles and composite particles which could be the source of gold losses from the batch Knelson and flotation circuit. The presence of flattened gold was attributed to the deformation during grinding and regrinding where coating of gold particles with iron fines is also likely to occur. The difficulty of recovering flattened and/or coated gold particles in flotation circuits even at high collector dosages was explained by Bulatovic (1997). In addition, rod-shaped and rolled gold entities were observed. This is also an evidence of high residence time in the grinding circuit. The tarnished particle surfaces was attributed to the high silver content of the ore since electrum is known to tarnish in the presence of sulphide ions where a 1-2 μm thick silver sulphide layer is formed. The effective density of the electrum particles is less than that of native gold and when further deformed due to prolonged grinding, the electrum particles become less susceptible to gravitational recovery. When tarnished electrum particles also become less hydrophilic, making their recovery during flotation difficult.

Table 2. XRD results of flotation tails

Mineral	%
Quartz	41.5
Pyrite	23.5
Muscovite	22.7
Clinochlore	2.5
Carbonates	2.5
Barite	2.3
Others	5.0

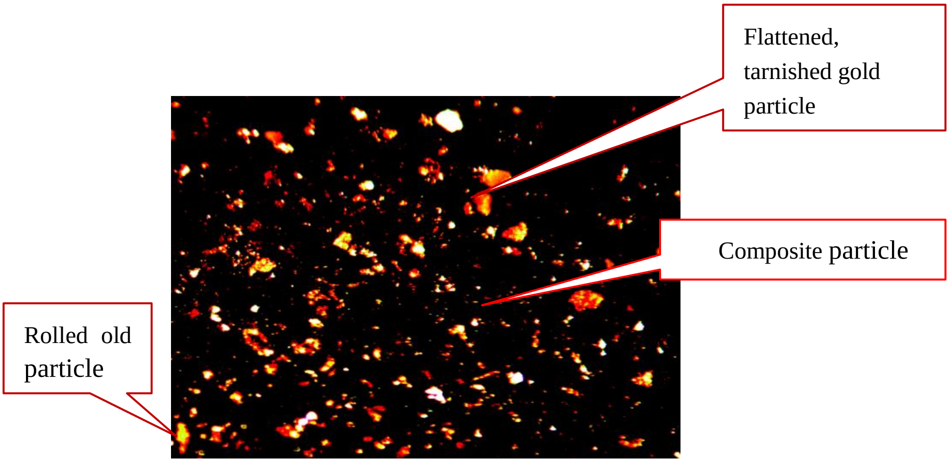

Fig. 3. Typical forms of Au particles and Au bearing entities in the gravity concentrate

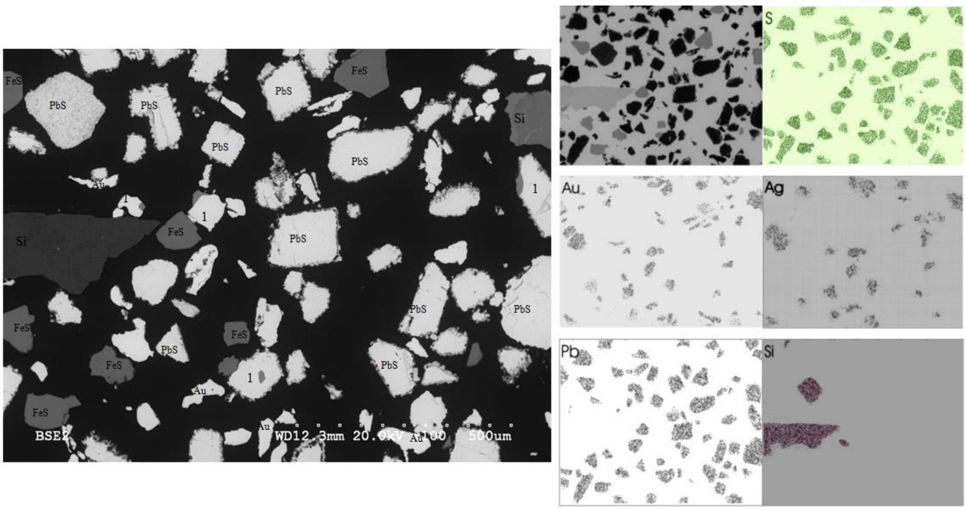

Fig. 4. SEM micrograph and EDX mapping of gravity concentrate: electrum (labeled as Au), galena, pyrite, gangue grains (labeled as Si) and electrum and sulphide composites

The SEM work showed that gold existed mainly in two forms, as liberated electrum grains and as unliberated associations with base metal sulphides. This could be seen in the EDX mapping, particularly by an examination of the prints of Au, Ag and Pb and S (Fig. 4). Au particles or Au bearing composites in elongated (rod like) form were again observed probably due to overgrinding and could be the source of Au losses in flotation, as mentioned. It should also be noted that galena is the main constituent in the gravity concentrate from the classifier underflow as galena particles were still coarse enough to be recoverable by gravity.

CVD installation on classifier underflow stream

The main objective of installing a Knelson CVD on the classifier underflow was to investigate the possibility of treating a coarser feed. In other words, by this application, the recovery of free gold, gold bearing entities and galena at a coarser feed size was targeted. To evaluate this opportunity, the metal content of the underflow stream were assessed in terms of weight and grade distributions of Au and Pb with respect to size fractions (Fig. 5). Fig. 5a illustrates that almost half of the feed is coarser than 150 μm. This coarser fraction in the classifier underflow included a significant amount of metal values, approximately 29% of Pb and 35% Au in the feed. The +150 μm fraction along with –150+75 μm fraction corresponds to around 80% of the total feed weight, 60 % of Pb and more than 55% of Au. The –75+38 μm fraction is distinguished with high Au and Pb grades as compared to other fractions (Fig. 5b). The high Pb and Au grade in the -38 μm fraction should also be noted. The association of Au and Pb with other metals were also investigated and used to assess the liberation mode and componential form of minerals in the classifier underflow as shown in Fig. 6. The close association between gold and silver was verified (Fig. 6a) implying the presence of Au in electrum form. The correlations of Au, Ag and Pb grades in Figs. 6b and 6c demonstrate the strong association of Pb, Au and Ag. In accordance with the mineralogical analysis, significant association of electrum with galena could be suggested. Almost no association between Au, Cu and Zn was observed. Some part of the electrum and galena could be associated with pyrite, as implied by Fig. 6d.

In view of the mineralogical data and these results, it was understood that electrum remains mostly unliberated after grinding. Also, being associated and/or intergrown with galena, a potential existed for the recovery of the unliberated electrum by the CVD. This would provide an opportunity for recycling back these values to grinding for further liberation prior to final upgrading by the batch Knelson concentrator. The CVD was retrofitted to the original flowsheet as shown in the configuration in Fig. 2a to treat the cyclone underflow. By this application it was expected that only the fully liberated gold and galena entities report to the batch Knelson unit. The tailings of the CVD, batch Knelson and Gemini Table were fed back to the grinding circuit to ascertain further liberation of metal values.

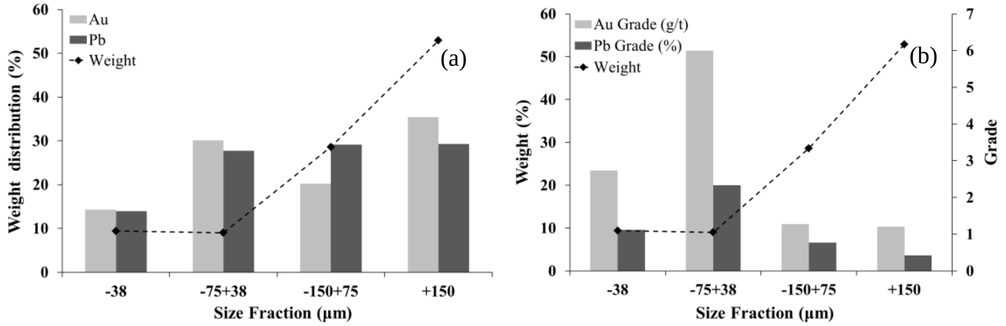

Fig. 5. Distribution of (a) Au and Pb weight, (b) Au and Pb grade, vs particle size in the cyclone underflow

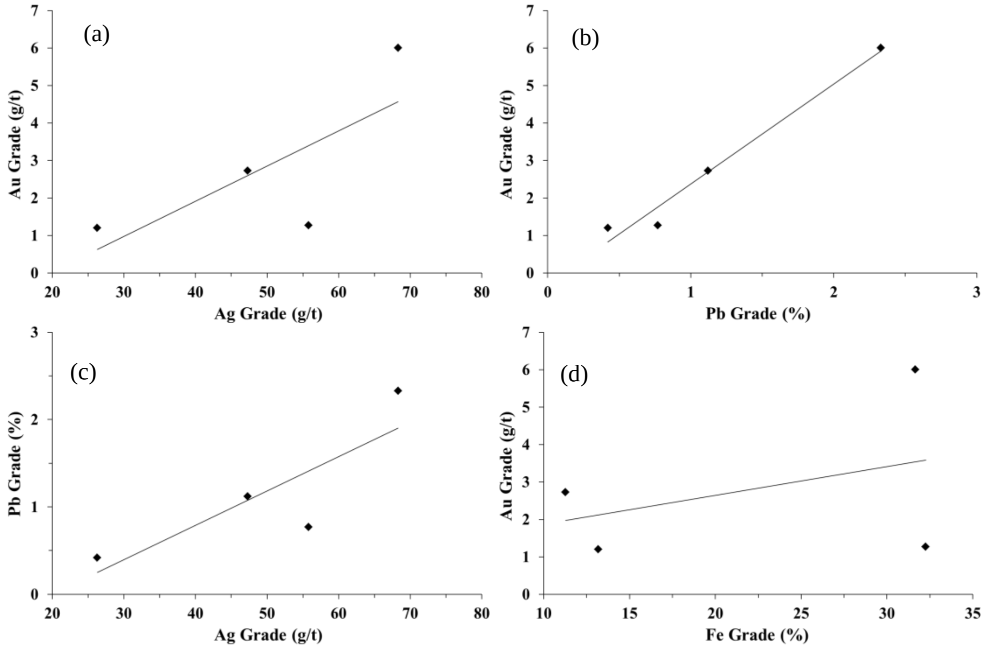

Fig. 6. (a) Au vs. Ag, (b) Au vs. Pb, (c) Pb vs. Ag, (d) Au vs. Fe grades in the underflow

The anticipated benefits from such an application included increase in galena recovery before it was rendered gravity unrecoverable due to over-grinding and setting a coarser grind size from the ball mill to achieve a more favourable size distribution for flotation as described by Klein et al. (2010) and thereby increasing the mill throughput and reducing grinding energy requirements. An increase in recovery, due to a decrease in overgrinding and fines generation as well as capture of middlings, was also expected. The benefit of a coarser grind on gold recovery both by gravity concentration and flotation also includes a reduction in the deformation of gold particles (Bulatovic, 1997). Retrofitting the CVD this way will enable treatment of the whole stream. It has been proved using modelling by Grewal and Fullam (2004) that there is no recovery benefit for gravity treatment of more than 30% of circulating load using the batch unit. Thus, the benefit of capturing liberated and partly liberated gold early by an additional CVD unit becomes obvious. The results are shown in Table 3.

Table 3. Summary of results of treatment of cyclone underflow by the CVD unit

Test	Mass Pull %	Grade					Recovery, %				
		Au g/Mg	Ag g/Mg	Cu %	Pb %	Zn %	Au	Ag	Cu	Pb	Zn
1	12.6	54.1	287.2	1.6	6.6	10.2	41.7	22.0	16.2	34.8	12.7
2	2.5	77.0	315.4	1.6	9.1	9.9	11.4	5.1	3.1	12.7	2.8
3	38.9	30.7	222.7	1.6	4.3	10.5	75.5	53.6	47.4	65.9	42.5
4	6.7	64.9	306.5	1.4	8.4	9.4	25.3	12.8	6.5	22.8	5.8
5	16.4	49.2	260.7	1.5	5.4	10.3	45.9	28.0	18.1	40.2	17.7
6	48.9	24.3	210.3	1.6	4.1	10.3	76.2	62.0	54.7	79.3	52.3
7	60.1	24.3	202.6	1.4	3.3	10.7	85.8	73.0	66.4	81.2	67.4
8	11.6	59.9	245.4	1.4	5.2	10.7	22.1	16.7	11.9	22.1	12.3
9	18.7	44.1	250.5	1.5	6.4	9.8	46.4	28.2	20.9	43.9	17.8
10	3.7	60.2	237.2	1.4	5.4	10.1	14.2	5.9	3.7	13.4	3.7
11	8.6	61.2	263.5	1.3	5.9	10.8	45.1	16.6	7.9	29.4	9.3

The typical grade of Au in the cyclone underflow is 16 g/Mg. By the treatment of this stream, concentrates with Au grades above 60 g/Mg at recoveries above 25% were achieved (Table 3). Obtaining a product with 77 g/Mg Au at 11.4% recovery at a very low mass pull of 2.5% was possible. At this test, Pb and Ag grades were also high, but their recoveries remained relatively limited due to a mass pull of 2.5%. An Au grade of 61.2 g/Mg at 45.1% recovery and 8.6% mass pull obtained at Test 11 was distinctive. At this test acceptable Pb grade and recovery values were also attained. Tests that yielded higher mass pulls generally provided better Au, Pb and Ag recoveries at acceptable metal grades, as seen in Tests 3, 6 and 7.

Figure 7 summarizes the metallurgical performance of the application for Au and Pb. The curves show good metallurgical response for both electrum and galena. Overall, it could be deduced that capturing liberated gold, silver and lead by using a batch machine to treat the CVD product will result in significant reductions in grinding energy requirements, increased recovery of gold due to reduced over grinding, particle deformation and tarnishing during grinding. This application provides the flexibility to target a high mass yield-high metal recovery or a low mass yield-high metal grade operation. The balance between metal price and grinding costs will be the basis for choosing between early gangue rejection or high upgrading options with the CVD where a coarser grind will be viable for both options.

CVD installation on classifier overflow stream

The motivation of installing a CVD concentrator on the cyclone overflow was the recovery of unliberated gold in the flotation feed since such entities are difficult to be effectively recovered by flotation, causing reduced metallurgical performance. This application was preferred over scavenging flotation tailings because it would also decrease the consumption of flotation reagents, pumping requirements and costs. For preliminary assessment of this potential, the classifier overflow was characterized and the results are shown in Fig.8. More than 50% of the feed was finer than 38 μm. This fine fraction was highly loaded with metal values with around 65% of Au and more than 70% of Pb by weight. Generally, the metal content increased with decrease in particle size (Fig. 8a) in contrast with the classifier underflow where Au and Pb were more evenly distributed (Fig. 5a). Also, Au and Pb grades apparently increased with increasing fineness, particularly in the -75+38 μm and -38 μm fractions (Fig.8b). Considering higher Au and Pb grades in the fines of both classifier overflow (Fig. 8b) and underflow (Fig. 5b), it is evident that the batch Knelson unit in the original flowsheet recovered coarse gold or gold bearing entities, leaving the gold bearing fine entities to flotation. Hence it was necessary to verify if the gold was sufficiently liberated to ascertain why it escapes the batch Knelson and account as losses. Fig. 9 shows typical metal associations in the overflow to assess the degree of liberation.

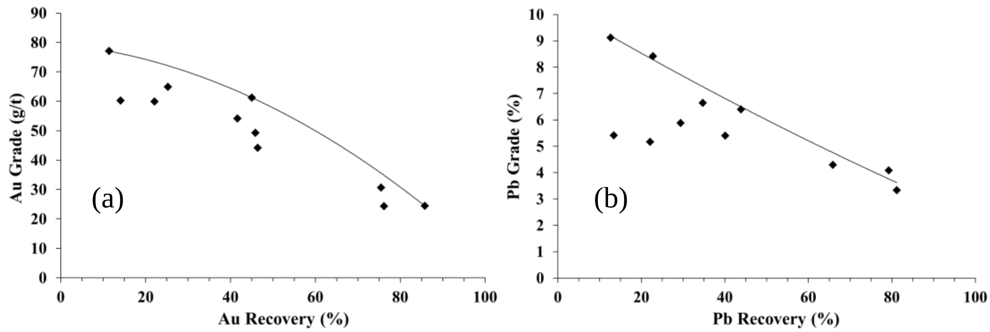

Fig. 7. Recovery vs grade for (a) Au, and (b) Pb for CVD application on classifier underflow

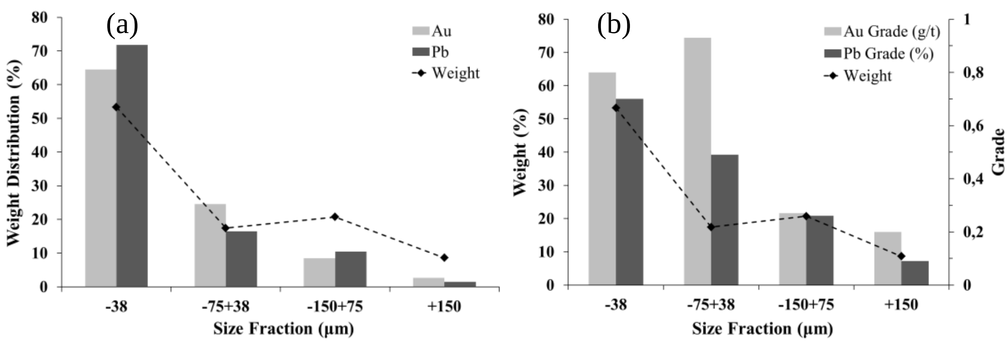

Fig. 8. Distribution of (a) Au and Pb weight (b) Au and Pb grade, vs. particle size in the cyclone overflow

In the overflow, Au and Ag are closely associated and gold mainly occurs as electrum (Fig. 9a). The strong correlations between Au and Pb (Fig. 9b) as well as Au and Fe (Fig. 9d) show that gold in the form of electrum occurred in association with galena and pyrite. The Au-Zn correlation should also be noted (Fig. 9d). This implies that besides being associated with galena and pyrite, electrum was found attached to sphalarite in the classifier overflow. This is a mineralogical distinction of classifier overflow as compared to the underflow stream. The grade correlations suggested that despite P_{80} of 75 µm for classifier overflow in the plant, most of the electrum remained unliberated. In this application the concentrate from the CVD unit is fed to the batch Knelson (Fig. 2b) so that unliberated gold is captured before reporting to flotation. This would provide a reduction in Au losses during flotation and improvement in plant performance as described by Klein et al. (2010) as well as the benefit of reduced pumping requirements and reagent consumption. The results of the test set are presented in Table 4. The results showed that for this application acceptable metallurgical performance for Au and Pb were obtained at relatively high mass pulls. For instance, in Test 8 around 1/3 of Au was recovered at a mass pull of 28.2 %. For all tests Pb grades hardly exceeded 2% at generally low recoveries. Fig. 10 summarizes the metallurgical performance for Au and Pb. Au curve showed a degree of inhibition at higher mass yields. This was attributed to presence of fine unliberated gold in this stream. Pb curve did not show inhibition probably due to better liberation.

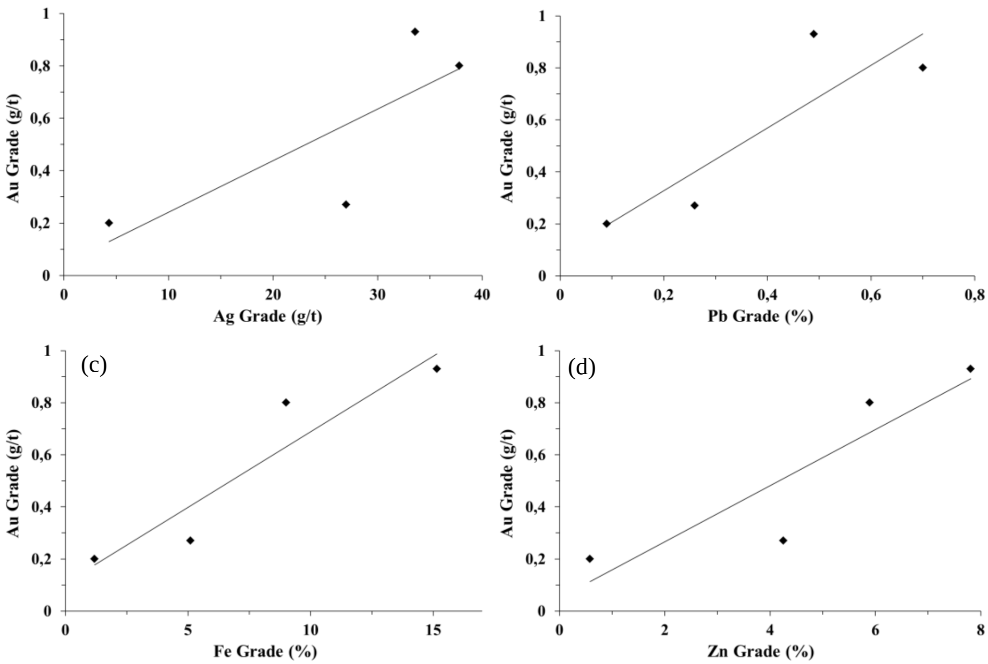

Fig. 9. (a) Au vs Ag, (b) Au vs Pb, (c) Au vs Fe and (d) Au vs Zn grades in the overflow

Table 4. Summary of results of treatment of cyclone overflow by the CVD unit

Test	Mass Pull %	Grade					Recovery, %				
		Au g/t	Ag g/t	Cu %	Pb %	Zn %	Au	Ag	Cu	Pb	Zn
1	0.8	10.9	42.6	1.3	0.8	12.2	4.0	1.7	1.0	1.3	0.9
2	0.2	14.9	46.3	1.1	2.1	8.1	1.2	0.4	0.2	0.8	0.1
3	20.8	2.9	18.2	1.1	0.6	10.8	24.9	18.4	20.6	22.9	19.8
4	7.3	3.7	22.8	1.3	0.8	12.0	12.6	7.4	7.9	11.8	7.5
5	5.6	5.2	28.6	1.4	0.9	12.7	14.2	8.1	6.7	10.1	6.3
6	3.0	3.1	21.5	1.4	1.7	11.7	4.3	3.4	3.6	9.6	3.0
7	0.9	9.2	33.2	1.3	2.2	10.6	4.0	1.4	1.0	4.1	0.8
8	28.2	3.1	21.6	1.2	0.6	11.0	37.3	31.0	29.6	33.7	27.2
9	13.1	7.7	33.8	1.3	1.0	11.2	32.6	21.3	14.7	22.0	12.4
10	7.6	5.3	29.3	1.3	0.8	12.6	18.8	10.6	9.1	14.7	10.3
11	1.4	10.5	36.6	1.5	1.3	12.3	6.2	2.3	1.7	3.7	1.7

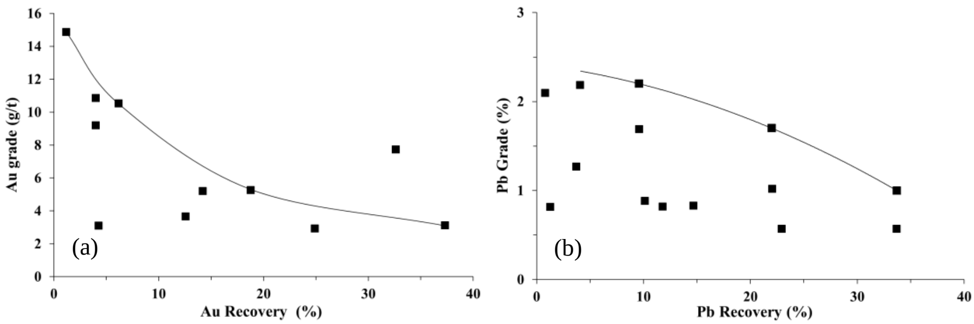

Fig. 10. Recovery vs grade for (a) Au and (b) Pb for CVD application on overflow

Conclusions

CVD application on the classifier underflow provided better performance as compared to the application on the classifier overflow. This implies that CVD6 was capable of recovering unliberated gold associated to metal sulphides and performed better at a coarser particle size. This provides the opportunity for the implication of a coarser grind size and early rejection of barren gangue. Associated outcomes include the reduction of grinding costs, grinding energy consumption, increase in the capacity and performance of downstream processes, achieving better liberation or targeted entities and reduction of metal losses.

Acknowledgement

The authors gratefully acknowledge the support of FLSmidth, Knelson and Nyrstar, Myra Falls to this work.

References

BULATOVIC, S.M., 1997. '*Flotation behaviour of gold during processing of porphyry copper-gold ores and refractory gold-bearing sulphides*, Minerals Engineering, 10, pp. 895-908.

BYRON, R., ROBERTS, K., 2004. *Flotation improvements in the Luzenac Pehhorwood talc concentrator*, Proceedings 36th Annual Meeting of the Canadian Mineral Processors, Ottawa, Canada, pp. 177–188

GREWAL, I., FULLAM, M., 2004. *Gravity Circuit Optimisation via Mathematical Modelling by Particle Size Classes*, Technical Notes, Knelson Gravity Solutions.

HONAKER, R.Q., WNAG, D., HO, K., 1996. *Application of the Falcon Concentrator for Fine Coal Cleaning*, Min**e**rals Engineering, 11 (12), pp. 1191-1199

KLEIN, B., ALTUN, N.E., GHAFFARI, H., MCLEAVY, M., 2010. *A hybrid flotation-gravity circuit for improved metal recovery*, International Journal of Mineral Processing, 3-4, pp. 159-165.

LAMBERT, M., KLEIN, B, GREWAL, I., MCLEAVY, M., 1999. *Preliminary Studies with a New Continuous Centrifugal Concentrator*, Presentation at BC and Yukon CMP Annual Meeting.

MCLEAVY, M., KLEIN, B., GREWAL, I., 2001. *Knelson continuous variable discharge concentrator: Analysis of Operating Variables*, International Heavy Minerals Conferences, Fremantle, Australia, pp. 119-125.