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VALIDATION OF A CLOSED CIRCUIT BALL MILL MODEL

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Abstract

Minerals processing engineers and grinding experts agree that classification efficiency and circulating load both have a major effect on the efficiency of closed circuit ball mills. However, the effect of each is difficult to quantify in practice as these two parameters are usually interrelated. Experimental work was undertaken by Metso Process Technology and Innovation (PTI) to better understand this relationship. The data obtained was compared to a simplified relationship for closed circuit grinding performance model, developed by Magdalinovic in 1991, to quantify the effect of classification efficiency and circulating load on the capacity of the circuit. The data also allowed an initial assessment of the model's accuracy to be evaluated.

Key words: *ball mill; circulating load; classification; efficiency; model.*

1. Introduction

Closed ball mill – cyclone circuits are industry standard and it is recognised that classification efficiency and circulating load both have a major effect on the efficiency of closed circuit grinding. The individual effect of circulating load and classification efficiency is difficult to quantify in practice as these two parameters are inherently interrelated. Even though mill capacity increases with circulating load, an optimum circulating load of 250% was established [4] due to limitations in cyclone classification efficiency.

The effect of circulating load on grinding capacity has long been understood. In a report published in 1925 [4], Edward W. Davis, first demonstrated the fundamental relationship between the new feed rate and the circulating load in a closed grinding circuit. His original graph of the relationship (Figure 1) has been reproduced with various modifications in many publications. According to this well-known relationship, the grinding capacity of a given mill is doubled by including a closed circuit classifier producing a 200% circulating load. Similarly, by increasing the circulating load to 500% the capacity factor increases to 2.3.

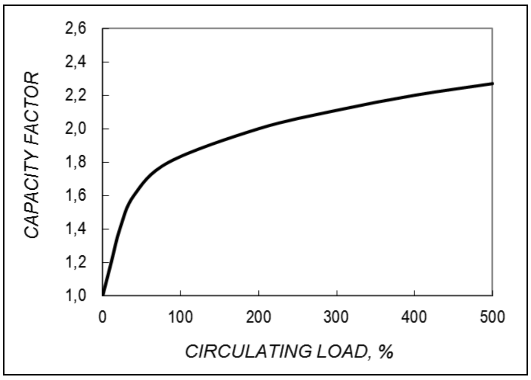

Figure 1. Effect of circulating load on mill capacity [5]

Research into the subject of classification efficiency effect on grinding circuit capacity was carried out by Finnish researchers Hukki, Allenius and Heinonen, [8, 9] using a

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laboratory scale test set-up similar to the one used by Davis. The main difference in their test procedure was that classification efficiency (defined as recovery of final product in the classifier fine stream) was varied, while in Davis' tests, classification efficiency remained constant. Figure 2 summarises the test results and shows that classification efficiency limits the throughput benefits of circulating load.

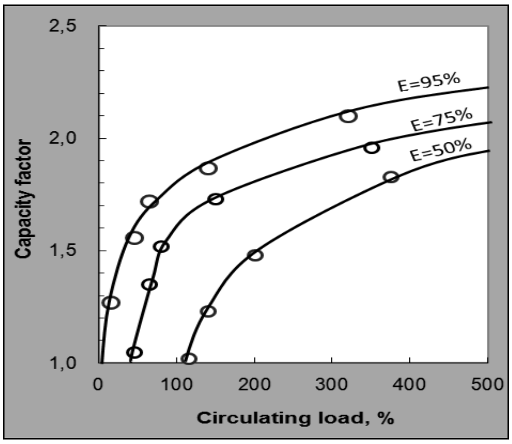

Figure 2. Effect of circulating load and classification efficiency on milling circuit capacity [10]

2. Mathematical model

The grinding kinetics in the ball mill follows first order grinding law which states that the rate of production of fines (D) is equivalent to the rate of disappearance of coarse material (R) which is proportional to the amount of coarse material in the mill. The first order grinding law is described by following equation:

$$\frac{dD}{dt} = \frac{dR}{dt} = -kR \tag{1}$$

Where:

R – amount of coarse material
D – amount of fine material
t – grinding time

For a closed circuit milling flowsheet, as represented in Figure 3, mill capacity (Q) can be related to the circulating load (C) and classification efficiency (E). Assuming that the amount of coarse material in the mill from the feed and to the discharge follows the first order grinding law, then the average amount of coarse material in the mill can be calculated as an arithmetic mean of the content in the feed and product. Based on this, for a simplified case where the feed consists of only coarse material, Magdalinovic [11] developed a model (Eq. 2) for a closed grinding circuit relative capacity at different circulating loads and classification efficiencies.

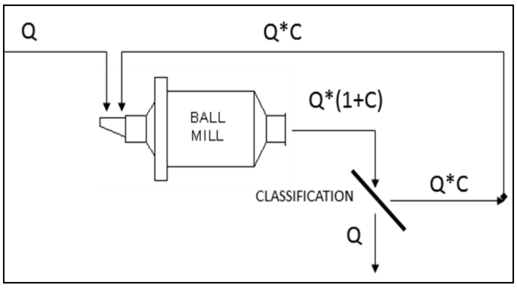

Figure 3. Closed circuit milling flowsheet

$$K_Q = \frac{Q_2}{Q_1} = \frac{(1+C_1)\left(1.5 + C_2 - \frac{1}{E_2}\right)}{(1+C_2)\left(1.5 + C_1 - \frac{1}{E_1}\right)} \tag{2}$$

Where:

K_Q – relative capacity of the milling circuit (fraction)

Q_1, Q_2 – milling circuit capacity under different circulating load and classification efficiency

C – Circulating load (fraction)

E – Classification efficiency (fraction)

The content of fines (product size material) in the circuit feed has a direct effect on circuit capacity. It is therefore expected that the accuracy of the above relative capacity model (Eq. 2) would be affected in some degree by the fines content. The model may be more suitable for harder ores than for the softer ones in cases where the proportion of fines in the feed is higher.

When comparing the model to the values produced by Davis, it is found that the model does not predict an accurate relative throughput when the open circuit baseline is used (C1 = 0, E1 = 1). Davis' data infers a relative throughput of 2.3 against the open circuit at 500% circulating load where the model only predicts an increase in relative throughput to 1.83. When the bond baseline (C1 = 2.5, E1 = 100) is considered, Davis' data reports an increase in relative throughput from 2.1 to 2.32 between circulating loads of 250% and 500%, which is a relative increase of 1.1. The model predicts an increase of 1.07 for these same values. Hence it can be seen that, by comparing modelled values to literature sources, the model provides more accurate predictions when using conventional circulating load conditions as a baseline.

3. Experimental investigation

A number of ball mill grinding tests were conducted by Metso PTI to evaluate the effect of circulating load and classification efficiency on milling performance. This testwork aimed to provide data to compare to the model discussed previously. The procedure followed in this investigation was a deviation of the standard locked cycle Bond Ball Mill Work Index Test (BMWI), where the circulating load and the classification efficiency were systematically changed to determine their relationship on milling performance. The tests were completed in a Labtech Essa laboratory mill that was 200mm in diameter and 250mm long. The mill was operated at 75RPM with an ore mass of 1kg. The ball charge in the mill comprised of three ball sizes and the mass distribution of the size fractions are detailed in Table 1.

Table 1. Ball Charge Mass Distribution

Diameter (mm)	Mass	
	Grams	%
40	3 973	36.14
28	3 117	28.35
18	3 904	35.51
Total	**10 994**	**100.0**

Three test campaigns were completed. The first test was conducted using river sands at a target undersize of 150µm (river sands US150), the second using Cannington silver ore at a target undersize of 150µm (Cannington US150) and the third using Cannington silver ore at a target undersize of 300µm (Cannington US300). The size distributions of feed material for the river sands and Cannington ore can be seen in Figures 4. This figure also shows the percentages of feed material which will directly pass the final cut size for the river sands US150, Cannington US150 and Cannington US300. These values were 1.0%, 11.7% and 21.0% respectively.

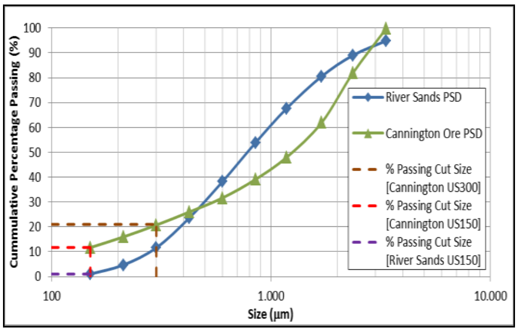

Figure 4. Particle Size Distributions of Feed Materials

Total of 19 tests were conducted under a number of circulating load and classification efficiency conditions. The results from the tests are summarized in Tables 2, 3 and 4.

The relative throughput for each test was determined from the baseline value of a circulating load of 250% and classification efficiency of 50%.

Table 2. River sands: undersize 150 μm

Target Conditions (CL-Eff)	Classification Efficiency (%)	Actual Circulating Load (%)	Throughput (g/rev)	Relative Throughput
250-50	50	243	0.48	100.00
250-75	75	236	0.60	126.0
250-100	100	249	0.60	125.2
600-50	50	578	0.57	120.5
600-100	100	577	0.68	143.7
Open Grind	100	0	0.31	65.1

Table 3. Cannington ore: undersize 150 μm

Target Conditions (CL-Eff)	Classification Efficiency (%)	Actual Circulating Load (%)	Throughput (g/rev)	Relative Throughput
50-100	100	49	0.67	103.9
100-75	75	100	0.63	95.5
250-50	50	245	0.66	100.005
250-100	100	240	0.96	145.5
600-50	50	570	0.88	133.6
Open Grind	100	0	0.23	34.8

Table 4. Cannington ore: undersize 300 μm

Target Conditions (CL-Eff)	Classification Efficiency (%)	Actual Circulating Load (%)	Throughput (g/rev)	Relative Throughput
50-100	100	49	1.27	103.2
100-75	75	96	1.18	95.9
150-75	75	149	1.51	122.4
250-50	50	246	1.23	100.0
250-100	100	243	1.62	131.7
600-50	50	583	1.52	123.6
Open Grind	100	0	0.63	50.9

The open grind tests were carried out until less than 1% of material remained on the test sieve. The experimental results in Table 2 showed that a circulating load of 600% with 100% classification efficiency had the greatest relative throughput. The second best throughput was achieved by using Bonds' conditions of a circulating load of 250% and classification efficiency of 100%. The extremely low throughput obtained from an open circuit configuration could also be seen from the data.

An interesting result from the experiment showed that the throughput of the circuit with a circulating load of 50% and classification efficiency of 100% was similar to the throughput obtained with a circulating load of 250% and classification efficiency of 50%. This data infers that if a processing plant is having classification difficulties due to the mass flow through the classifiers, whether they are cyclones or screens, increasing the classification efficiency and decreasing the circulating load may be a viable option to improve plant performance.

To further investigate these changes in throughput, size distributions for the Cannington undersize 150μm trials were compiled (Figure 5).

Figure 5 showed that each trial produced various size distributions. The open grind produced the finest grind and the Bond test conditions (CL250 E100) produced the coarsest. When comparing CL250 E50 and CL600 E50 it is seen that as circulating load increases and classification efficiency remains constant, the amount of fines in the mill product decreases. When comparing CL250 E50 and CL250 E100 a similar relationship is found, which is increasing classification efficiency at a constant circulating load also reduces fines in the mill product.

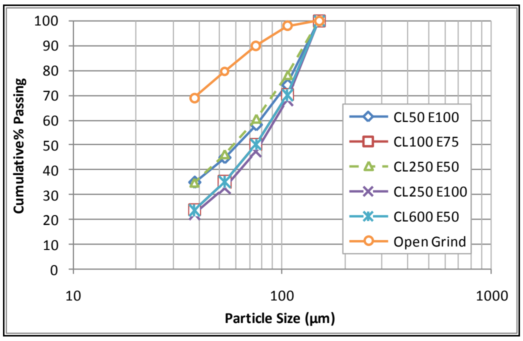

Figure 5. Cumulative size distributions for Cannington US150 trials

Figure 6 was produced to compare the throughput of each trial to the content of minus 38μm material in the product.

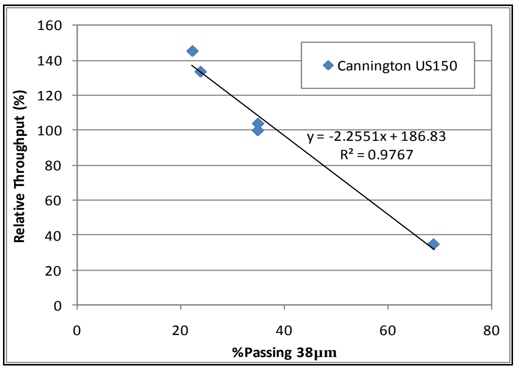

Figure 6. Effect of fines in product on relative throughput (Cannington US150**)**

A linear relationship between relative throughput and content of minus 38μm material in the product can be observed. This relationship reveals a valuable inference, that is increasing the amount minus 38μm material in the product of the ball mill, reduces the throughput of the circuit. It was previously established that changing circulating load and classification conditions changes the amount of fines in the mill product and it is this change in the content of minus 38μm material in the mill that is responsible for the change in relative throughput.

4. Model validation

The validity of the model was determined by comparing the predicted results against the experimental data. The baseline used for the model was a circulating load of 250% and a classification efficiency of 50%. This efficiency was chosen as an industrial practice average. Figures 7 and 8 compare the experimental data to predicted model values.

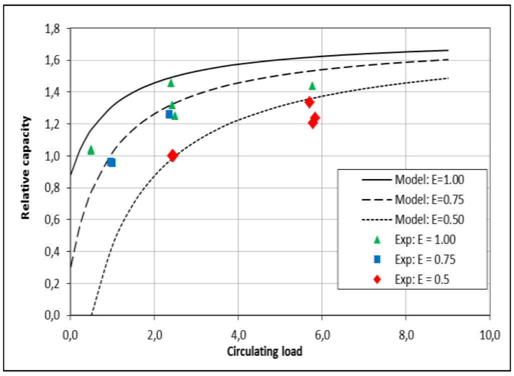

Figure 7. Effect of circulating load and classification efficiency (E) on milling circuit capacity – simplified model (Equation 2) vs. Metso PTI data

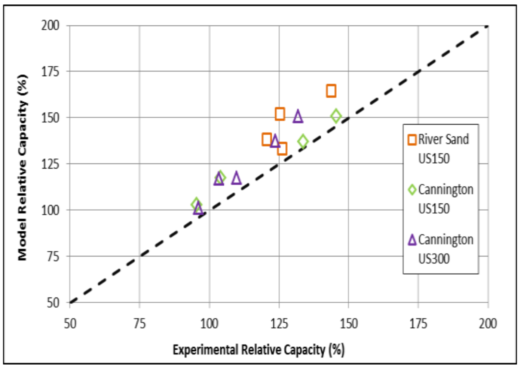

Figure 8. Relative capacity comparison: experimental versus model

Table 5 investigates the individual effect of circulating load and classification efficiency on the model projections by comparing data with classification efficiencies of 100% against each other and circulating load target of 600% against each other.

The agreement between the model and data is generally good although Figure 7 and 8 both show differences between the model predictions and experimental values. Table 5 shows that for this data, it is not clear whether the error in the modelling predictions is from circulating load or classification efficiency. It is likely to be caused by both factors however this cannot be validated without additional data points.

As discussed previously, it is suspected that feed ore size distribution had a significant effect on the results of the testwork. The river sand feed had almost no distribution in the final product size (<150μm) fraction and the 80% passing size was around 1.7mm, while Cannington ore had a more significant amount of fines and a coarser 80% passing size of approximately 2.4mm.

Due to the absence of finial product in the feed, the model predictions for tests conducted with river sand should be the best, while in fact they appear to be the worst.

Table 5. Relative capacity comparisons at consistent classification efficiencies and circulating loads

Data Source	Classification Efficiency (%)	Actual Circulating Load (%)	Relative Capacity (%)		
			Experimental	Model	Error%
River Sands	**100**	249	125.2	152.3	21.6
River Sand	**100**	577	143.7	164.6	14.5
Cannington US150	**100**	49	103.9	117.5	13.1
Cannington US 150	**100**	240	145.4	150.9	3.7
Cannington US300	**100**	49	115.3	117.3	13.6
Cannington US300	**100**	243	131.7	150.8	14.5
River Sands	50	**578**	120.5	138.4	14.8
River Sands	100	**577**	143.7	164.6	14.5
Cannington US150	50	**570**	133.6	137.3	2.7
Cannington US300	50	**583**	123.6	137.8	11.5

What is most important is that the model “follows” the effect of circulating load and classification efficiency.

It may be used to assess if it is more efficient to run mill with high circulating load and low classification efficiency (ball mill + hydrocyclones) or low circulating load and high classification efficiency (ball mill + screens).

5. Conclusion

The capacity of a closed circuit ball mill increases with circulating load. Classification efficiency controls the magnitude of this increase. A simple mathematical model for the closed circuit relative grinding capacity as a function of circulating load and classify-cation efficiency developed by Magdalinovic [11], was compared to the experimental data obtained from the laboratory closed circuit grinding tests with different materials. The average error of the modelled predictions was 11% from the experimental values and this was taken to be a reasonable agreement between model and data. The model generally over-predicts the experimental results. The material specific properties, size distribution and hardness, as well as milling conditions affect the mill capacity and therefore the accuracy of the model is limited. Experi-mental data showed a linear decrease in circuit throughput as the percentage of fines in the mill product increased. This change in fines was attributed to the change in circulating load and classification efficiency conditions. Work is under way to further validate and improve the model.

6. Acknowledgement

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