"Corrosion control may be a potential measure in decreasing grinding media consumption."

Corrosion of Grinding Media

by

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ABSTRACT

An experimental technique in resolving wet grinding media wear into its mechanical and corrosive wear component is presented. The results of the tests indicated that wet grinding media wear is approximately 46 percent mechanical wear and 54 percent corrosive wear.

INTRODUCTION

The natural occurrence of most mineral ores is in a finely disseminated state and is intimately associated with gangue minerals. This necessitates that the various minerals be broken apart or liberated before they can be recovered in separate products. The mineral liberation step is accomplished by size reduction or comminution.

Crushing is the coarse phase of comminution. It is usually performed on dry ore. Run of mine ore materials as large as six feet in diameter can be reduced to one-eighth of an inch through a series of crushing stages designated as primary, secondary, and tertiary crushing, in the sequence of decreasing material feed size. The preferred size reduction ratio for the different stages ranges from 8:1 to 4:1. Further size reduction of the relatively coarse crusher products is performed by grinding.

Tumbling mills are used for grinding in approximately all concentrating and leaching plants and in many plants processing non-metallic minerals. Tumbling mills consist of shells rotating on a horizontal axis, partly filled with loose hard bodies or grinding media which grind the ore in the mills. Grinding media may either be steel balls, rods, pebbles, or coarse materials of the ore itself. Ore materials charged to the mills are usually in the size range of one-half to three-fourths of an inch and the size of discharge may be almost anything desired. Tumbling mill operation may be performed either wet or dry, the former used in most mineral processing plants and the latter common in cement and chemical plants.

Comminution is frequently the area of maximum usage of power and wear resistant materials in mineral beneficiation. The bulk of the operating cost of comminution is largely due to the inefficiency of the grinding operation. Orr(1) estimated that only one to two percent of the energy consumed during grinding is used for the creation of new surfaces. The rest of the energy input is converted to heat and wasted. Grinding inefficiency naturally results to greater wear of shell liners and grinding media.

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The magnitude of the energy consumed by grinding was estimated in a paper on energy expenditures in various copper producing processes by the University of Utah(2) in 1980. It showed that grinding operation accounts for 60 percent of the total energy consumption to produce copper concentrate and 27 percent of the total energy consumption to produce cathode copper.

Relative power consumption and metal wear in comminuting soft and hard ores having bond work indices of 7 KWH/ton and 17 KWH/ton respectively was published by Digre(3) in 1980. Feed materials 80 percent passing 150 mm (6") were crushed and ground to 80 percent passing 0.06 mm. The percentage of the total power consumption for crushing, grinding, and auxiliary operations were 6.2, 84.2, and 9.6 for soft ore and 6.4, 86.2, and 6.9 for hard ore respectively. The percentage of total metal wear of crusher liners, metal liners, and grinding media (rods and balls) were 1.0, 5.39, and 93.61 for soft ore and 1.22, 5.43, and 93.35 for hard ore respectively. Power consumption and metal wear accounted for 47.3 and 52.7 percent for soft ore and 31.34 and 68.66 percent for hard ore respectively of the total operating cost. Data on actual ball mill operations from a 1934 U.S. Bureau of Mines report presented by Gaudin(4) showed that power cost ranged from 25 to 50 percent and supply costs from 31 to 57 percent of the total operating cost. Taggart(5) stated that on average ore, power consumption is from 40 to 60 percent of total operating cost, labor from 5 to 10 percent, and steel the balance. On hard ores, steel may comprise 50 to 60 percent of the total cost.

The depletion of high grade ore reserves will further increase the cost of comminution as more tonnages of low grade ore materials which require finer liberation sizes will have to be milled per weight of metal to be extracted. Because of the large magnitude of power and grinding media requirements of grinding operations, any measure that could reduce either or both of the requirements even by a small increment could have a considerable impact on the operating cost. This would be welcomed by existing operations and would possibly make the exploitation of certain ore bodies economically feasible. Since media wear in wet grinding is a joint effect of abrasion and corrosion on newly generated metallic surfaces, corrosion control may be a potential measure in reducing the cost of comminution.

The problem in controlling the corrosion of grinding media in this study was approached by resolving wet grinding media wear into its mechanical and corrosive wear components and then using corrosion inhibitors to reduce the magnitude of the corrosive wear component. The experimental technique in determining the wear components is presented below while the results of the corrosion inhibitor tests will be presented in the forthcoming issue.

EXPERIMENTAL METHOD

Materials and Equipment

The sulfide ore used for the study was provided by Philex Mining Company. The ore was obtained from the ball mill feed materials of the company's milling operations in Benguet. Approximately 800 kilograms of -1.5 inches ore sample were crushed to -1/4 inch using the laboratory cone crusher and rolls for primary and secondary crushing respectively. The crushed ore was thoroughly mixed and riffled to obtain 1.928 kilogram-samples for batch grinding tests. Specific gravity of the -1/4 inch material was determined to be 2.7 by volume displacement method.

The test balls used to monitor media wear in grinding were M-25 Armco Marsteel grinding balls. The test balls were identified from the rest of the ball charge used in grinding by filing a V-shaped notch approximately 3/8 inch long and 1/8 inch deep on the surface of the balls. The test balls were conditioned by wet grinding several batches of ore materials to remove scales and surface imperfections. Conditioned test balls were then washed, dried, and stored in a dessicator.

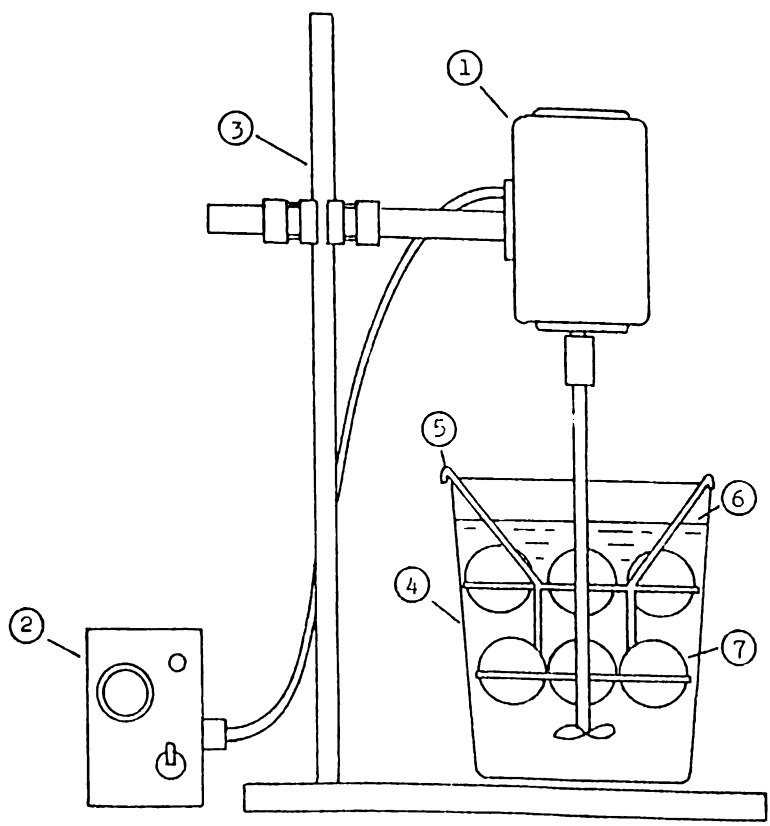
The tumbling mill used for media wear determination was a Denver Laboratory rod mill with a wave type liner. It was driven by a one horsepower motor and was operated at 87 percent of the critical speed. Steel balls weighing 12.18 kgs. with diameters ranging from 3/4 to 2 inches replace steel rods for grinding media.

The slurries in the experimental runs for static corrosive wear determination were agitated by GK Heller Corporation Laboratory Stirrers model GT 21-18 with GT 21 motor controllers. The stirrers were operated at 5,500 rpm.

The Mettler H-10 W analytical balance was used for weighing the test balls. Weights were recorded to the nearest tenth of a milligram. Dissolved oxygen and pH of pulps and solutions were measured using the YSI 51 A Dissolved Oxygen Meter and Photovolt pH Meter 112 respectively. The screen series and screen shaker used were Endecotts Ltd. Laboratory Sieves and Tyler Portable Sieve Shaker respectively.

Experimental Procedure

The retention time required to grind batch samples of sulfide ore materials to 60 percent passing 200 mesh was obtained by wet and dry grinding tests. Grinding media wear was monitored by weight loss measurements of test balls included in the mill charge. Wet grinding media wear was determined for the mesh of grind and was resolved into its mechanical and corrosive wear components by dry grinding and static corrosion tests respectively. The set up for the latter test is shown in Figure 1. The results obtained from Factorial Experiments(6, 7) were subjected to variance analysis at a 95 percent level of confidence. Figures 2 and 3 show the flow diagram of the experimental runs.



1. stirrer, 2 stirrer motor controller, 3. iron stand,
4. beaker, 5. test ball holder, 6. slurry, 7. test ball

Figure 1. Experimental Set-Up for Static Corrosion Test

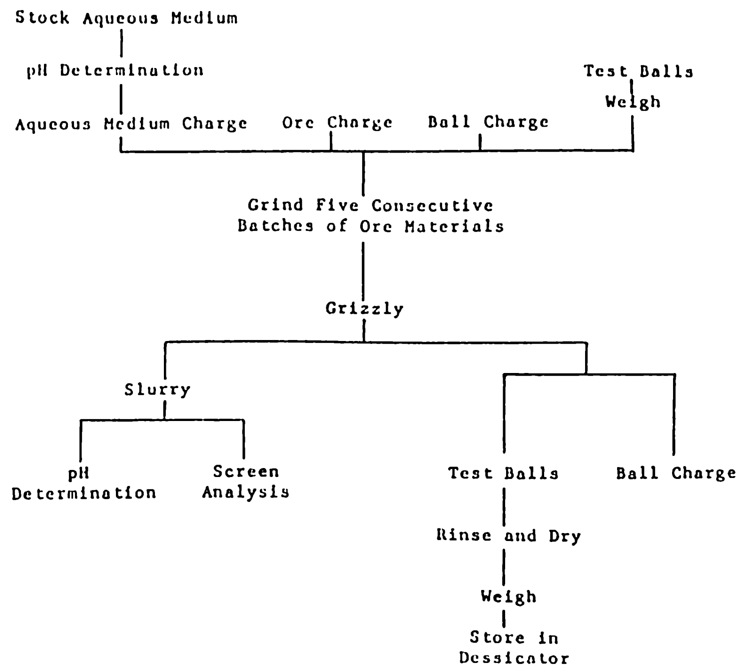


Figure 2. Flowsheet for Batch Wet Grinding Tests

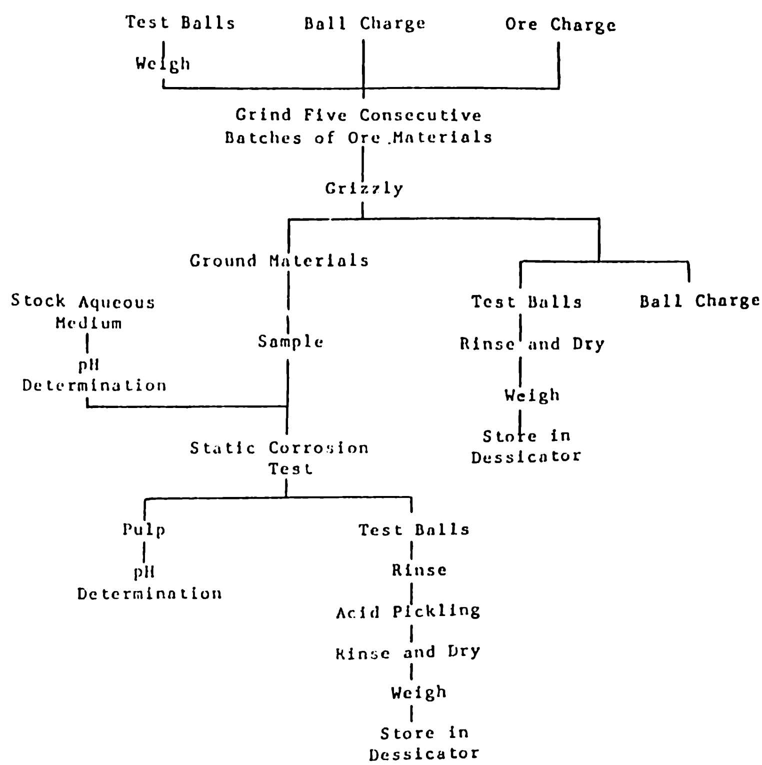


Figure 3. Flowsheet for Batch Dry Grinding and Static Corrosion Tests

RESULTS AND DISCUSSION

Ore Grindability Tests

Batch wet and dry grinding tests were performed to determine the time required to reduce the -1/4 inch ore materials to 60 percent passing 200 mesh. The mesh of grind arbitrarily chosen was intermediate between coarse and fine grinding operations performed by Philippine mining companies on sulfide ores. Coarse grinding is exemplified by a mesh of grind of 50 percent passing 200 mesh used by Marcopper Mining Company in its copper flotation mills in Marinduque(8). Fine grinding on the other hand is exemplified by the operations of Surigao Consolidated Mining Company in Surigao del Norte where a mesh of grind of 80 percent passing 200 mesh is required to leach the gold and silver values from the sulfide minerals(9).

The batch wet grinding tests were conducted at 60 percent solids and at grinding times of 20, 25, and 30 minutes. The mill charge consisting of 1.928 kgs. ore materials, 12.180 kgs. steel balls, and 1.286 liters of tap water occupied approximately 40 percent of the mill volume. After each test, the mill charge was dumped into a bucket with a grizzly cover to separate the ball charge from the slurry. A slurry sample was obtained, filtered, and dried for screen analysis. Screen analysis was performed for a period of ten minutes on 200 gram-samples of ground materials.

The screen analysis of the -1/4 inch ore materials and the wet ground materials in terms of percent cumulative retained are shown in Table 1. The percent cumulative retained on a 200 mesh screen is plotted against grinding time in Figure 4 from which the grinding time of 22.7 minutes for a mesh of grind of 60 percent passing 200 mesh is obtained.

Batch dry grinding tests were conducted using a similar procedure as applied in wet grinding, with the tap water excluded from the charge. The grinding times of 22.7, 30, 35, and 40 minutes were used in the tests. The screen analysis of the ground materials in terms of percent cumulative retained is shown in Table 2. The corresponding plot of the percent cumulative retained on a 200 mesh screen against grinding time is presented in Figure 5 from which the grinding time of 34 minutes for a mesh of grind of 60 percent passing 200 mesh is obtained.

Ball Wear in Wet Grinding

Wet grinding experimental runs were performed to determine the extent of ball wear in grinding the -1/4 inch ore materials to 60 percent passing 200 mesh. The weight loss incurred by five test balls included in the mill charge after grinding five consecutive batches of ore materials to the required mesh of grind was the measure used for media wear determinations. The number of batches ground in an experimental run was established through exploratory runs which indicated that using such a procedure results to a measurable weight loss of the test balls. After each run, the test balls were washed, dried, and stored in a dessicator for a minimum of one hour prior to weight measurements. Media wear was expressed in terms of milligrams weight loss per gram ball to normalize weight differences between test balls.

The operating design of the laboratory tumbling mill used in the experiment requires the charge to be sealed in the shell by two end covers during grinding. Since the presence of end covers might lower the oxygen level in the pulp during grinding, it is possible that the rate of corrosion could be significantly decreased. This possibility was investigated by conducting a factorial experiment using the variables method of grinding and grinding time. The levels used for the method of grinding were close and open end grinding. The latter level was accomplished by fabricating a discharge end cover with a one inch diameter hole at its center. The levels used for the factor grinding time were 22.7 and 32.7 minutes. The results of the experiment are presented in Table 3 and the analysis of variance performed on the data is summarized in Table 4. The increase in ball wear as a result of the increase in grinding time as expected was found to be significant. Grinding method

Table 1. Screen Analysis Results of the Ground Products Obtained from Wet Grinding Tests

	Percent Weight Cumulative Retained Grinding Time, Minutes			
Mesh No.	0	20	25	30
10	56.55	–		
20	72.85	0.10		
30	76.00	0.25	–	
40	70.70	0.45	0.10	–
50	82.10	1.80	0.60	0.15
60	83.35	4.05	1.15	0.30
70	84.45	7.25	2.70	0.90
80	85.40	11.85	5.35	2.45
100	86.70	17.90	9.65	5.30
200	90.50	45.30	38.20	32.45
–200	100.00	100.00	100.00	100.00

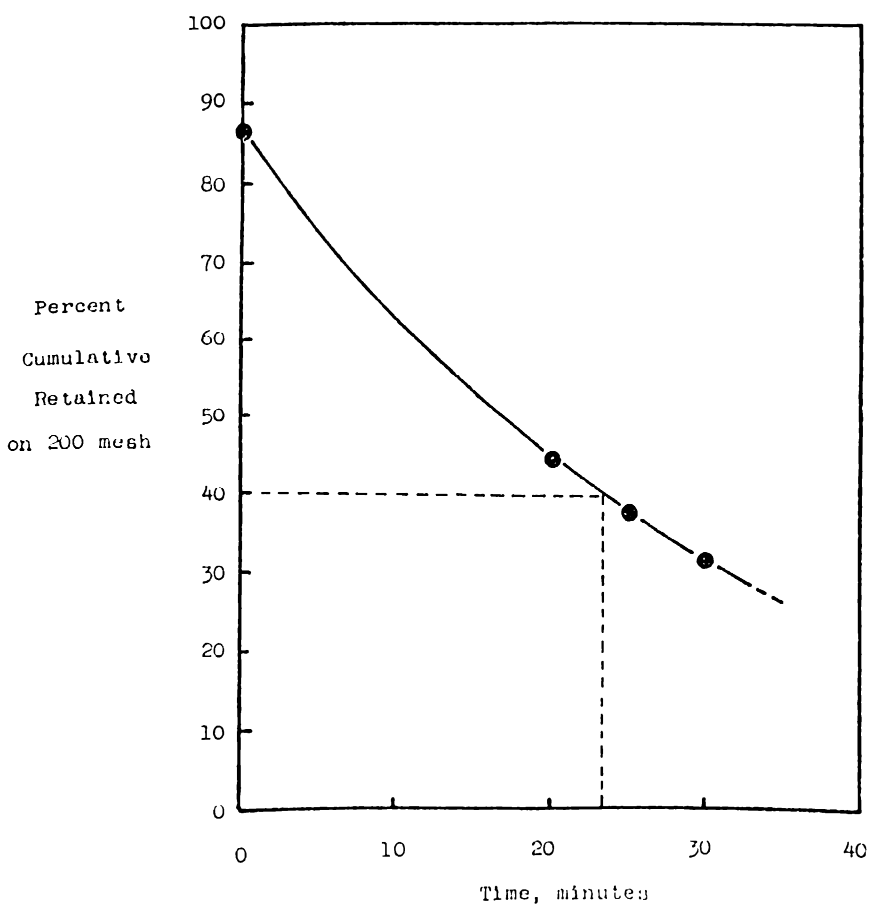


Figure 4. Wet Grinding Time Determination for a Mesh of Grind of 60 percent Passing 200 Mesh

Table 2. Screen Analysis Results of the Ground Products Obtained from Dry Grinding Tests

	Percent Weight Cumulative Retained Grinding Time, Minutes			
Mesh No.	22.42	30	35	40
10				
20		–		
30	–	0.05	–	–
40	2.35	0.25	0.20	0.10
50	8.50	1.40	1.10	0.70
60	13.68	4.70	3.20	2.75
70	18.36	8.25	6.20	5.00
80	23.55	14.80	11.90	10.10
100	28.55	20.20	16.70	15.10
200	49.45	44.30	39.70	39.75
–200	100.00	100.00	100.00	100.00

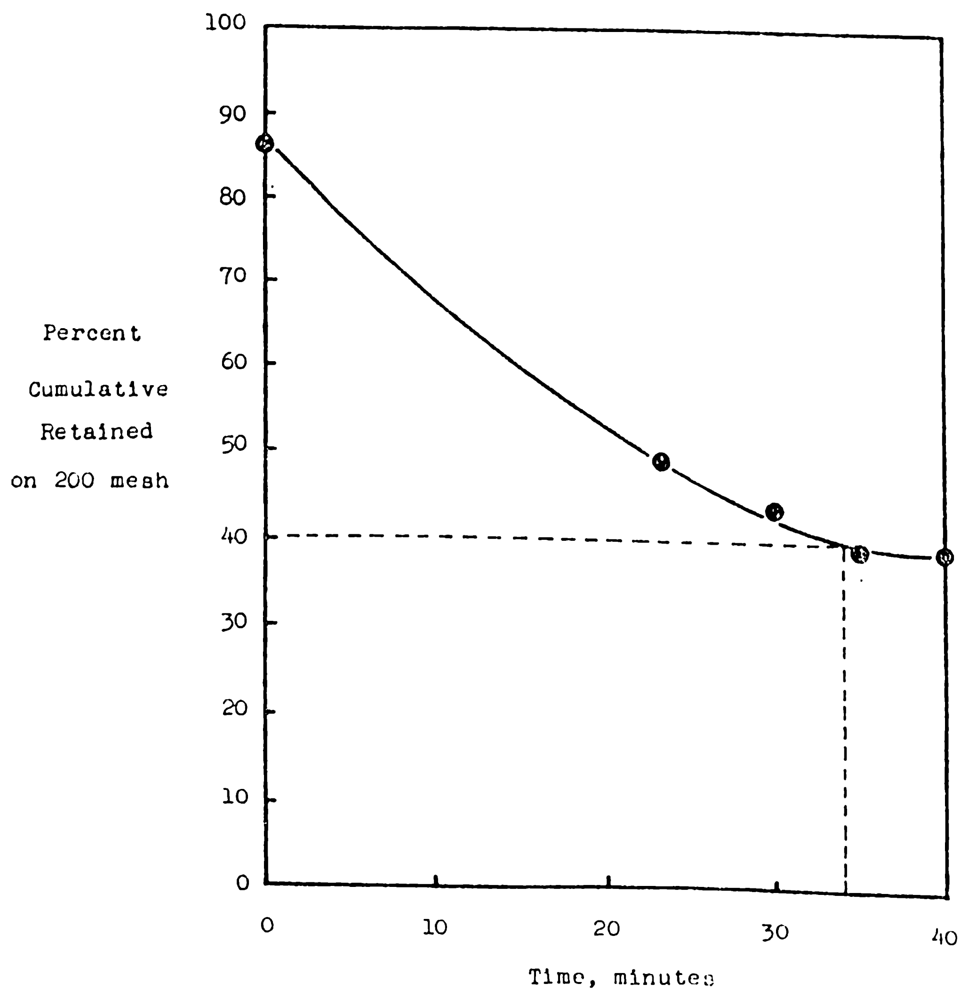


Figure 5. Dry Grinding Time Determination for a Mesh of Grind of 60 percent Passing 200 Mesh

Table 3. Results* of the Factorial Experiment on Grinding Method and Grinding Time

Grinding Time, mins.	Grinding Method	
	Open End	Close End
22.7	1.389	1.321
	1.312	1.215
32.7	1.683	1.632
	1.512	1.481

*mg loss/gm ball

Table 4. Analysis of Variance for the Data in Table 3

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Computed f	$F_{0.95}$
Grinding Time	0.1433	1	0.1433	16.6628	7.71
Grinding Method	0.0076	1	0.0076	0.8837	7.71
Interaction	0.0009	1	0.0009	0.1046	7.71
Error	0.0344	4	0.0086		
Total	0.1862	7			

and the two-factor interaction on the other hand produced no significant effect on ball wear. This means that the difference between the dissolved oxygen levels during open and close end grinding may not have been appreciable to affect the rate of corrosion. This was later verified when a dissolved oxygen meter became available for laboratory use. Experimental runs were performed to obtain the profile of dissolved oxygen and temperature of the slurry during close and open end grinding. The dissolved oxygen and temperature levels of the tap water to be used for grinding were measured and were considered as the initial levels of the slurry. The measurements made are presented in Table 5 and the plot of dissolved oxygen and temperature against time is presented in Figures 6 and 7. It is seen that the data for both methods of grinding were practically the same. Pulps at 30 percent solids when not aerated in the agitator tanks of the cyanidation circuit of Surigao Consolidated Mining Company usually have dissolved oxygen levels from 0.7 to 1.0 ppm(9). The temperature increase of the slurry from 27°C to 41°C was normal because slurries flowing out of grinding mills in actual operations are usually warmer than the inflowing water by as much as 10° to 20°C(5). The initial and final pH of the pulp in the grinding tests averaged 7.25 and 6.40 respectively.

Linearity of Wear Rate

Since there was no statistically significant difference between close end and open end grinding, the experimental runs performed could be considered as replications of each other. A third data point using the same sets of balls for the grinding time of 22.7 minutes was obtained for both grinding methods to determine the linearity of ball wear with respect to the time exposed in grinding. This will indicate whether or not the hardness of the test balls varies significantly as they are continually used in the tests. The data obtained together with the previous data of close end and open end grinding are presented in Table 6. Note that the grinding time tabulated for an experimental run is equivalent to the total number of minutes for grinding five batches of ore materials to the mesh of grind. The sum of the ball wear for each grinding method at time increments of 113.5 minutes obtained for regression analysis are presented in Table 7. The regression line obtained for ball wear is:

$$y = 0.3349 + 0.0113x,$$

where

y = ball wear in mg loss/gm ball

x = grinding time in minutes

Table 5. Dissolved Oxygen and Temperature Levels of the Slurry during Wet Grinding

Time, mins.	Grinding Method: Open End — Dissolved Oxygen, ppm	Open End — Slurry Temp., °C	Close End — Dissolved Oxygen, ppm	Close End — Slurry Temp., °C
0	8.8	27	8.8	27
10.0	0.9	35	0.8	35
22.7	0.8	37	0.9	38
32.7	0.9	41	0.9	41

Table 6. Data for the Determination of the Linearity of Ball Wear Rate in Wet Grinding

	Grinding Method	
	Open End	Close End
Test Run	Ball Wear*	Ball Wear*
1	1.389	1.321
2	1.312	1.215
3	1.251	1.202

*mg loss/gm ball

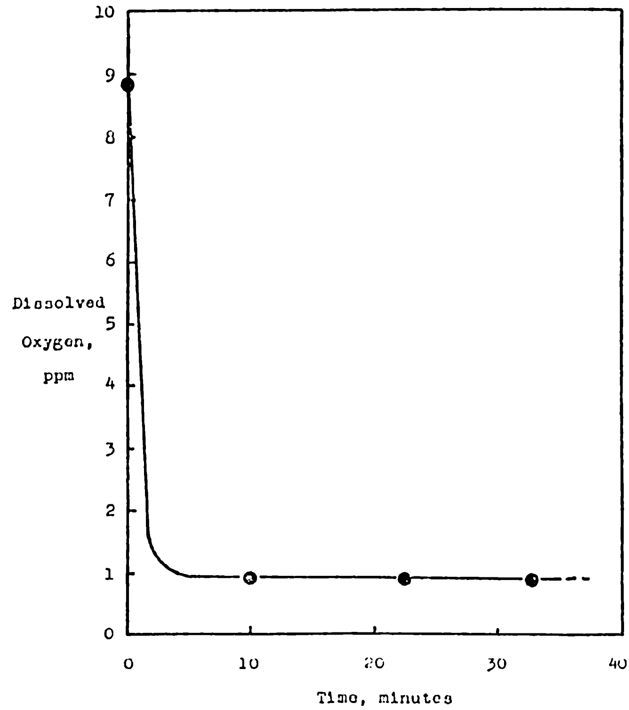


Figure 6 . Dissolved Oxygen Profile of the Slurry for Close and Open End Grinding Method

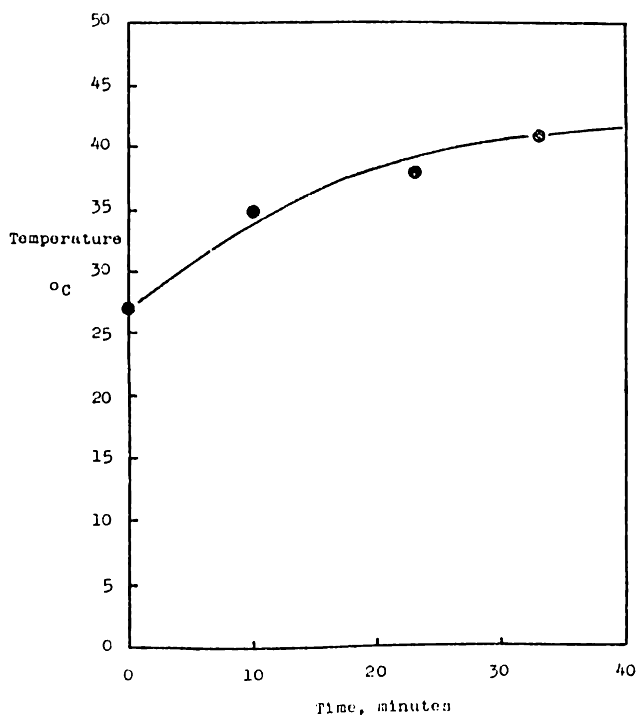


Figure 7. Temperature Profile of the Slurry for Close and Open End Grinding Method

A test of significance performed on the regression line indicated that the regression is significant and that the lack of fit is insignificant. This means that the ball wear is linear with grinding time. The analysis of variance is summarized in Table 8 and the plot of ball wear against grinding time with the corresponding regression line is shown in Figure 8.

The average media wear for the close end and open end grinding methods were 1.246 and 1.317 mgs. loss/gm ball respectively. Assuming that the properties of the test balls were not significantly different from the ball charge, the ball consumption in grinding the -1/4 inch ore materials to 60 percent passing 200 mesh is approximately 1.7 kgs. steel balls per metric ton ore. This is well within the wear range of 0.38 to 2.25 kgs. steel balls per metric ton ore given by Taggart(5) for forged steel balls in primary service. The ball consumption of the ore may be considerably lower in actual operations since ball to ball contact is lessened by circulating loads of the ball mills.

Mechanical Wear Determination

Dry grinding tests were conducted to estimate the contribution of abrasive or mechanical wear to the total media wear in wet grinding. The mechanical wear was likewise determined by test ball weight measurements after grinding five consecutive batches of ore materials. The grinding

Table 7. Cumulative Wet Grinding Media Wear

Total Batch Grinding Time, mins.	Ball Wear, mg loss/gm ball
0.0	0.000
	0.000
113.5	1.389
	1.321
227.0	2.701
	2.536
340.5	3.952
	3.738

Table 8. Analysis of Variance for the Data in Table 7

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Computed f	$F_{0.95}$
Regression	16.3818	1	16.3818	1687.3186	7.71
Error					
Lack of Fit	0.0086	2	0.0043	0.4428	6.94
Pure Error	0.0388	4	0.0097		
Total	16.4293	7			

time used was 22.7 minutes per batch of ore materials in order to expose the test balls to the same span of time in which the test balls used in wet grinding media wear determination were washed and dried after each run, and stored in a dessicator for a minimum of one hour prior to weight measurements. Dry grinding tests were also conducted to determine the dry grinding media wear for the mesh of grind of 60 percent passing 200 mesh. The grinding time used per batch of ore materials was 34 minutes. The results of the wear tests are presented in Table 9.

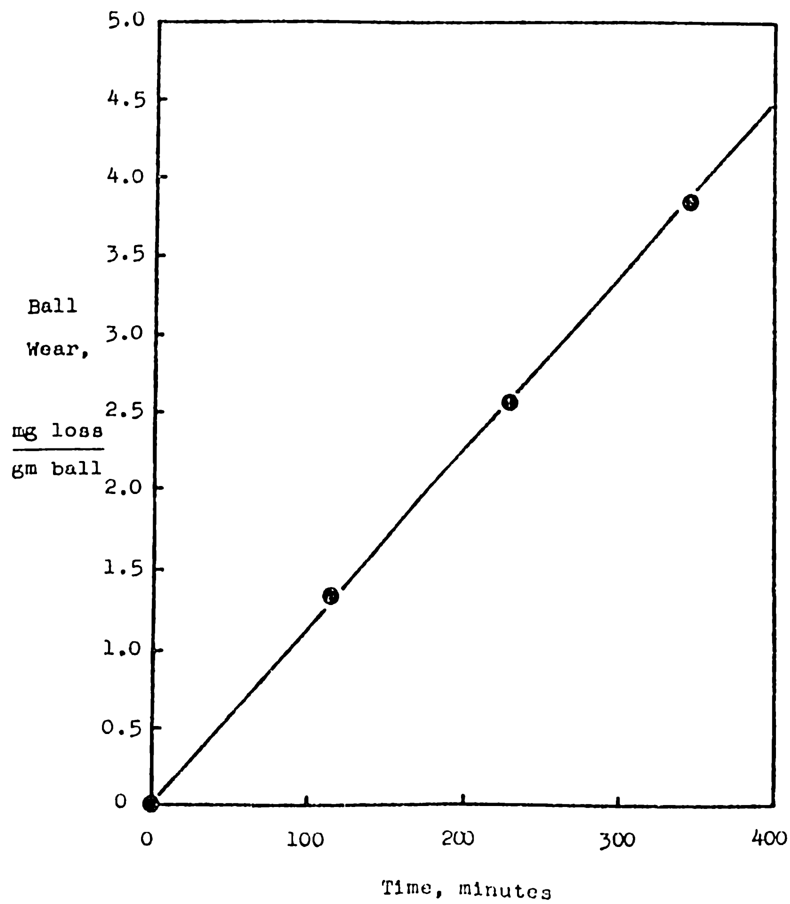


Figure 8. Linearity of the Wear Rate of Grinding Media during Wet Grinding

Table 9. Mechanical Wear Determination

Batch Grinding Time, mins.	Test Run	Ball Wear*	Ball Wear Average
22.7	1	0.587	0.592
	2	0.596	
34.0	1	0.819	0.789
	2	0.759	

*mg loss/gm ball

The average mechanical wear component obtained was 0.592 mg loss/gm ball which is 46.16 percent that of the wet grinding media wear. Data on screen analysis presented in Table 2 shows that only 55.55 percent of the ore material in ground to minus 200 mesh for a 22.7 minute dry grinding time. This observation demonstrates that the work done on the ore material is lesser in dry grinding when all other things are considered equal. The difference in comminution efficiency lies in the degree of cushioning provided by the ground materials in dry and wet grinding. Cushioning(5) consists of the readjustment of the mass ground materials in such a manner as to distribute the forces of impact over the large interfacial contact within the mass and to dissipate it in friction and local fine pulverization without any breaking commensurate to the energy expended. The aqueous medium used in wet grinding lessens the internal friction between the particles of ground materials by its lubricating effect. Consequently, the amount of energy that should have been lost to friction is used for doing comminution. The total effect is the reduction in the degree of cushioning, making wet grinding more efficient than dry grinding.

The average dry grinding media wear obtained for the mesh of grind of 60 percent passing 200 mesh was 0.789 mg loss/gm ball which is 61.52 percent that of the wet grinding media wear. The reduction of ball wear shows that corrosion is effectively minimized by dry grinding. This is, however, coupled with an increase in power requirements. The increase in the retention time to attain the mesh of grind from 22.7 minutes in wet grinding to 34 minutes in dry grinding indicates that the power consumption for dry grinding is about 1.5 times that in wet grinding. The range of power consumption for dry grinding given by Taggart(5) is from 1.1 to 1.7 times that of wet grinding.

Corrosive Wear Determination

Static corrosion tests were performed to estimate the contribution of corrosive wear to the total media wear in wet grinding. Corrosive wear was determined by measuring the weight loss incurred by test balls after immersion in an agitated pulp for 113.5 minutes, the equivalent time used in grinding five batches of ore materials to the required mesh of grind. The corrosive wear for the immersion times of 170.25 and 227 minutes were also measured to determine the linearity of the corrosion rate. The pulp was prepared by mixing 771 grams of dry ground ore materials and 514 mls of tap water in a one liter capacity beaker. The resulting pulp composition and volume were 60 percent solids and 800 mls, respectively. Initial runs indicated that the use of five test balls results to a problem in the reproducibility of data owing to the smaller magnitude of wear incurred by the test balls. The problem was solved by increasing the number of test balls to twelve. Corrosion products adhering on the test balls after a run were removed by pickling with 200 ml of a 25 percent hydrochloric acid solution for one minute. The test balls were immediately washed after pickling, dried, and stored in a dessicator prior to weight measurements. The corrosive wear resulting from acid pickling was measured and deducted from the total wear of the test balls to obtain the actual corrosive wear incurred in a test run. The results of the static corrosion tests are presented in Table 10. The initial and final pH of the slurries of the tests averaged 7.70 and 7.40, respectively.

The average corrosive wear component obtained was 0.170 mg loss/gm ball which is only 13.25 percent that of the wet grinding media wear. The regression analysis performed on the results of the static corrosion tests yielded the equation:

$$Y = 0.0117 + 0.0012X,$$

where

y = ball wear in mg loss/gm ball

x = corrosion time in minutes

A test of significance performed on the regression equation showed that the equation is significant and that the lack of fit is insignificant. This means that the rate of corrosion was still constant within the span of time used in the tests and also implies that the layer of corrosion products adhering on the test balls does not have a deterrent effect on the corrosion rate. Visual observations made on the test balls after the tests were in agreement with the finding. Thin films of corrosion products were found to cover approximately 70 to 90 percent of the test balls' surfaces, leaving 10 to 30 percent of the test balls' surfaces exposed for further corrosive attack. The summary of the test of significance is presented in Table 11, and the plot of corrosive wear against grinding time with the corresponding regression line is shown in Figure 9.

Media Wear Accounting

The results of the ball wear determination tests are summarized in Table 12. The ball wear balance performed on the data showed that 40.56 percent of the total wet grinding media wear remained unaccounted after adding the mechanical and corrosive wear components together. The unaccounted wear is probably due to the removal of the interaction between abrasion and corrosion that results from the tumbling action of the grinding media in the ball mill when media wear was resolved into its components. A similar observation was made by El Raghy et al.(10) from the tests they performed on the effect of temperatures on the abrasive wear resistance of chro-

Table 10. Results of Static Corrosion Tests

Corrosion Time, mins.	Corrosive Wear, mg loss/gm ball
0.00	0.000
	0.000
113.50	0.156
	0.184
170.25	0.249
	0.208
227.00	0.286
	0.262

Table 11. Analysis of Variance for the Data in Table 10

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Computed f	$F_{0.95}$
Regression	0.0844	1	0.0844	222.3738	7.71
Error					
Lack of Fit	0.0017	2	0.0008	2.1838	6.94
Pure Error	0.0015	4	0.0004		
Total	0.0876	7			

mium cast steel balls. Part of their test consisted of the determination of ball wear by weight loss measurements during wet and dry grinding of sand and during the exposure of the steel balls to water corrosion for the same period of times. They found out that the sum of the ball wear obtained in dry grinding and corrosive wear to be lower than that of the ball wear in wet grinding by an average of 39 percent.

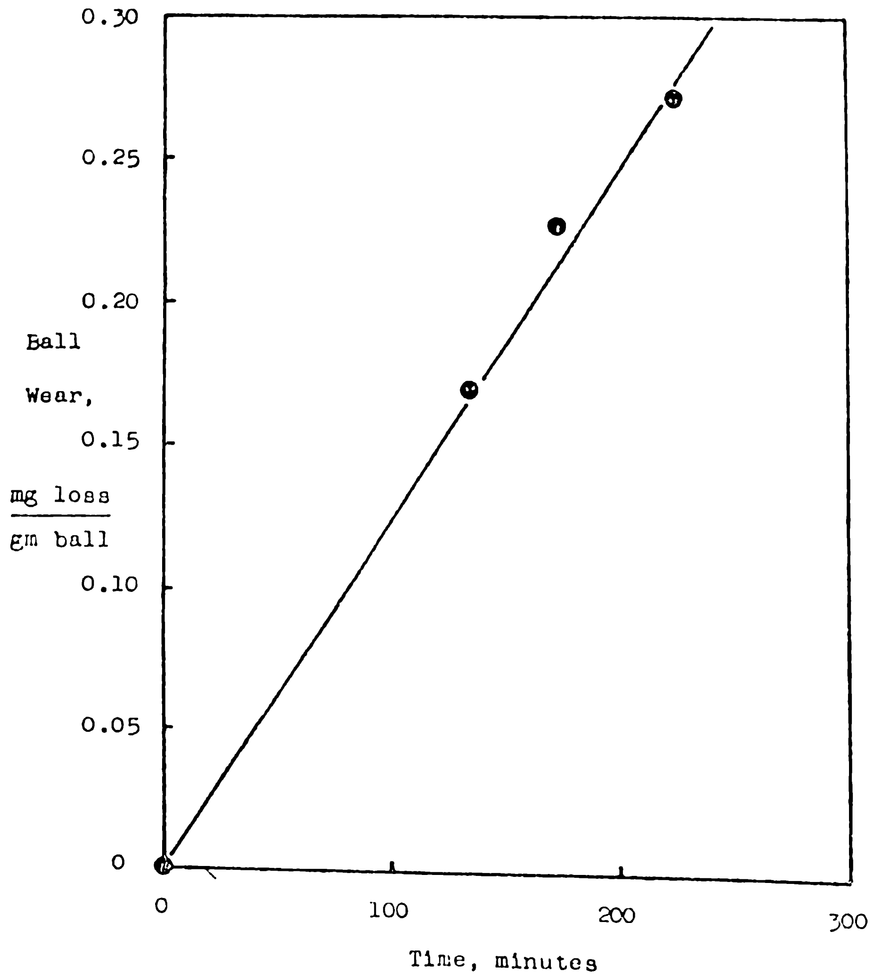


Figure 9. Linearity of the Wear Rate of Static Corrosion

Table 12. Summary of Ball Wear Determination

Ball Wear Component	Ball Wear*	Percent of Total Wear
Mechanical Wear	0.592	46.18
Corrosive Wear	0.170	13.26
Unaccounted Wear	0.520	40.56
Total	1.282	100.00

*mg loss/gm ball

A proof of the existence of the interaction between abrasion and corrosion in the ball mill was presented in another study made by El Raghy et al.(11) on the abrasion-corrosion process of low alloy steel in aqueous solutions of sodium chloride. Their experimental set-up consisted of a steel specimen submerged in an aerated one percent sodium chloride solution and a silicon carbide disc for specimen abrasion. The currents generated by the corrosion of the steel specimen were measured by a Wenking Potentiostat when the system was static, when the silicon carbide disc was rotated three millimeters above the steel specimen, and when the steel specimen was abraded by the silicon carbide disc. The anodic current densities obtained in the second and third conditions were respectively four and eight times greater than that obtained in the static system. This showed that the rate of corrosion is substantially increased by the continuous removal of the corrosion products and is even greater in magnitude when fresh metal surfaces are continuously generated by abrasion. Thus, the unaccounted wear must be added to the corrosive wear component. This will resolve the wet grinding media wear into 46 percent mechanical wear and 54 percent corrosive wear.

CONCLUSION

The mechanical and corrosive wear components of wet grinding media wear are approximately 46 and 54 percent respectively. The magnitude of the corrosive wear component shows that it is a major cause of grinding media wear, making corrosion control a potential measure in decreasing grinding media consumption.

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REFERENCES

(1) ORR, C. Jr., *Particulate Technology,* Macmillan Pub. Co., Inc., New York, 1966, pp. 47-49.

(2) UNIVERSITY OF UTAH, "An Assessment of Energy Expenditures in Various Copper Producing Processes," Utah, 1980, 21 pp.

(3) DIGRE, M., "Energy Accounting in Hard-Rock Comminution," Trondheim, Norway, March 1980, 7 pp. Mimeographed.

(4) GAUDIN, A.M., *Principles of Mineral Dressing,* McGraw-Hill Pub. Co., Ltd., New York, 1939, p. 114.

(5) TAGGART, A.F., *Handbook of Mineral Dressing,* John Wiley and Sons, Inc., New York, 1945, pp. 5.36–5.40, 6.1–6.15.

(6) WALPOLE, R.E., and MYERS, R.H., *Probability and Statistics for Engineers and Scientists,* The Macmillan Company, New York, 1972.

(7) COCHRAN, W.G. and COX, G.M., *Experimental Designs,* John Wiley and Sons Inc., New York, 1957.

(8) WONG, A.R.G., Former Metallurgical Engineer-In-Charge of the Metallurgical Laboratory Section of Marcopper Mining Company, 1980-1983, Interview, March 1985.

(9) DEL ROSARIO, A.F. Jr., Former Sr. Metallurgist of Surigao Consolidated Mining Company, 1982-1983, Personal Observation.

(10) EL-RAGHY, S.M., EL-KOUSSY, R., and EL-MEHAIRY, A.E., "Effect of Heat Treatment Conditions and Compositions on the Wear Resistance of Some Chromium Steels," *Tribology International,* December 1981, pp. 323-328.

(11) EL-RAGHY, S.M., ABD-EL-KADER, H., and ABOU-EL-HASSAN, M.E., "Electrochemistry of Abrasion-Corrosion of Low Alloy Steel in 1% NaCl Solution," *Corrosion,* February 1984, p. 60.