

Theories of ball wear and the results of a marked-ball test in ball milling

by L. A. VERMEULEN*, Ph.D., M.Sc., M.S.A.I.P., F.S.A.I.M.M.,
D. D. HOWAT*, Ph.D., F.I.M., F.S.A.I.M.M., and
C. L. M. GOUGH†, M.S.A.I.M.M.

SYNOPSIS

Formulae expressing the dependence of the mass of a grinding ball on the amount of material milled by a ball mill are derived. It is shown that, with the aid of these formulae, it is relatively simple for the results of a marked-ball test to be analysed and for the relative performance and cost-effectiveness of the various types of ball under test to be evaluated. Predictions based on theory and the results obtained in a marked-ball test in a ball mill are compared in detail and shown to be in close agreement.

The difficulties associated with marked-ball tests are considered, and an explanation for the decrease in the calculated consumption of the balls, which follows naturally from the theory, is presented. The marked-ball anomaly is explained, and it is demonstrated that the ball consumption in a ball mill can be predicted with fair accuracy from the results of a marked-ball test.

SAMEVATTING

Formules wat die afhanklikheid uitdruk van die massa van 'n maalbal op die hoeveelheid materiaal wat deur 'n balmeule gemaal word, word afgelei. Daar word aangetoon dat, met behulp van hierdie formules, dit betreklik maklik is om die resultate van 'n gemerkte-baltoets te analiseer en die relatiewe werkverrigting en bestedings-geregverdigheid van die verskillende tipes balle wat getoets word te evalueer. Voorspellings wat op teorie gegrond is en die resultate verkry uit 'n gemerkte-baltoets in 'n balmeule word in besonderhede vergelyk en toon 'n groot ooreenkoms. Die probleme verbonde aan gemerkte-baltoetse word oorweeg, en 'n verduideliking vir die afname in die berekende verbruik van die balle, wat vanselfsprekend uit die teorie volg, word aangebied. Die gemerkte-bal anomalie word uiteengesit, en dit word gedemonstreer dat die balverbruik in 'n balmeule met redelike akkuraatheid uit die resultate van 'n gemerkte-baltoets voorspel kan word.

Introduction

The consumption of balls in the fine grinding of ores is a major item in the costs of milling operations. A wide variety of grinding balls are available from various manufacturers, but one experiences substantial difficulties in selecting the ball that will be most cost-effective for grinding a particular ore under particular milling conditions.

Plant tests involving the gradual introduction of a full charge of balls of a new type are long and expensive. An attractive alternative is a test in which several types of balls carrying distinguishing marks (e.g. fine holes) are introduced simultaneously into a mill and are removed for examination at intervals. However, the validity of the results obtained by the latter procedure (referred to as a marked-ball test) has frequently been disputed.

In a closely monitored test conducted at the Markikana Mine of Western Platinum Limited¹, six grades of marked balls, one set of which was identical to the 'background' charge of balls, were introduced simultaneously into a mill. This paper analyses and discusses the results of this test.

Evaluation of Grinding Balls

The conventional procedure employed in ball mills illustrates the scale and cost of a test aimed at measuring the durability and cost-effectiveness of a particular type of ball. In this procedure, the entire charge of a mill is

gradually replaced by an alternative type of ball. The replacement is done gradually because it is considered desirable for the graded size distribution of the balls within the mill to be preserved. The technique used is as follows. The addition of the 'old' type of ball is discontinued, and the largest (top) size of the alternative type of ball is added at the rate required to maintain the charge at the desired level.

If M is the total mass of the charge within a mill and dM/dt is the rate at which the balls are consumed, the time constant (as it refers to ball consumption) of a mill is

$$\theta = - \frac{Mt}{dM/dt} \quad \dots \dots \dots (1)$$

In large mills such as those used on South African gold and platinum mines, the ball charge can vary from 20 t to more than 40 t, and the time constants can range from a few weeks to several months. After the old type of ball has been consumed, a period of at least a few time constants is required before the new rate of addition can be established with certainty. In view of the large masses of grinding media and the long time constants involved, it is not surprising that these experiments are costly and time-consuming.

In milling practice, it is usual for ball consumption to be considered with reference to the mass of material milled, T . In terms of T , the ball consumption in kilograms per ton milled becomes

$$\frac{dM}{dT} = \frac{dM/dt}{dT/dt} \quad \dots \dots \dots (2)$$

A 'tonnage constant' for the mill, τ_m , can be defined as follows:

*Council for Mineral Technology (Mintek), Private Bag X3015, Randburg, 2125 Transvaal.

†Formerly Western Platinum Limited, Marikana, 0284 Transvaal. Now retired.

©The South African Institute of Mining and Metallurgy, 1983. SA ISSN 0038 — 223X/\$3.00 + 0.00

$$\tau_m = -\frac{M}{dM/dT} \quad (3)$$

(Because dM/dt is negative, τ_m is positive, i.e. the mass of the charge decreases with increasing tons milled.)

The relation between τ_m and θ is

$$\tau_m = \theta \frac{dT}{dt} \quad (4)$$

where dT/dt is the mass of material milled per unit of time; τ_m is measured in tons or kilotons.

The cost-effectiveness of balls is measured by the use of an index, E , given by

$$E = C \left| \frac{dM}{dT} \right| \quad (5)$$

where C is the cost per ton of balls to the mine. The more cost-effective the balls, the smaller is E .

Because of the large financial benefits that can be secured if the most cost-effective balls are used, it is always desirable that a variety of balls should be evaluated. Clearly, several years of labour and many hundreds of tons of balls would be required before the conventional procedure could show which of the ball types available would be most cost-effective in the conditions pertaining to any given milling installation.

Norman and Loeb² have pointed out that the relative merits of several types of ball can be determined simultaneously in a marked-ball test. The use of such a test could therefore result in a saving of several years of labour and several hundreds of tons of steel, but it is well known that many mill operators regard the results of marked-ball tests with some reservations.

Certain difficulties are associated with the interpretation of the results of marked-ball tests. These difficulties are as follows:

- (i) ball consumption decreases systematically with time (or mass of material milled) in a manner suggesting that equilibrium has not been reached, and
- (ii) marked balls that are of the same type as the 'background' of balls within the mill appear to be more durable than the background balls — an effect referred to as the *marked-ball anomaly*.

The results of a marked-ball test are of interest in relation to theories of ball wear. The work done at Western Platinum Limited¹ shows that, with the aid of a theory of ball wear, it is easy for one to analyse the results of a marked-ball test, to explain the dependence of ball consumption on the tonnage milled, to understand the marked-ball anomaly, and to formulate an index that describes the most cost-effective ball.

Theories of Ball Wear

The volume and surface theories of ball wear were proposed by Davis³ and Prentice⁴ respectively. Their discussions relate mainly to the size distribution of balls within a mill. The theories predict markedly different distributions of ball size. According to the volume theory the size frequency distribution is hyperbolic, whereas according to the surface theory it is flat, i.e. if the size range is divided into a number of equal intervals, the same number of balls is found in every interval.

In a marked-ball test, equal numbers of balls of each of the various types under consideration are introduced simultaneously into a ball mill, and their masses are monitored as a function of the amount of material milled. Therefore, one has to consider the kinetics of ball wear rather than the size distribution of the balls. In the following sections we establish explicit relations for $m(T)$, i.e. the mass of a ball as a function of the tons milled, since these are the quantities that are measured in a marked-ball test.

The Volume Theory

The volume theory postulates that the rate of ball wear is proportional to the mass (or volume) of a ball. It has its origin in the idea that the majority of comminution events occur in the 'toe' of the charge, where impactive events predominate. In these events, the work done by a ball in stressing ore particles is thought to be proportional to the kinetic energy that cataracting and cascading balls receive from the rotary action of the mill, and therefore to the mass or volume of a ball. Davis³ has advanced evidence in support of this theory.

If $-dm/dT$ is proportional to m , where T is the amount of material milled (in tons or kilotons), we can write

$$-\frac{dm}{dT} = \frac{m}{\tau} \quad (6)$$

where the proportionality constant, τ , will be called the 'tonnage constant' of a ball; τ is measured in the same units as T .

From equation (6),

$$m(T) = m_0 \exp(-T/\tau) \quad (7)$$

where m_0 is the original mass of a ball. It can be seen from equation (7) that, after τ tons of material have been milled, the mass of a ball will be reduced by a factor of e^{-1} (e being the 'base' of natural logarithms), so that $m(\tau) = m_0 e^{-1}$ (approximately 37 per cent of m_0). Also, if m_1 and m_2 are the respective ball masses before and after T_0 tons of material have been milled, then τ , the tonnage constant, is given by

$$\tau = \frac{T_0}{\ln(m_1/m_2)}$$

The Surface Theory

The surface theory has its origin in the idea that the vast majority of comminution events are due to three-body abrasive grinding of the particles of ore by the balls, and therefore suggests that the rate of wear is proportional to the surface area of a ball. Norman and Loeb², Prentice⁴, and several other authors, have advanced evidence in support of this theory.

If m is the mass of a ball, its surface area is proportional to $m^{2/3}$. If the wear rate is proportional to the surface area, we can write

$$-\frac{dm}{dT} = b m^{2/3} \quad (8)$$

where b is a constant.

From equation (8), we obtain

$$m^{1/3} = m_0^{1/3} - 1/3 b T \quad (9)$$

or

$$m(T) = (m_0^{1/3} - 1/3 b T)^3 \quad (10)$$

Equations (9) and (10) can be valid only if the shapes of the balls remain constant (i.e. spherical) and are valid only when

$$T < \frac{3m_o^{1/3}}{b}$$

In this paper, the constant b is referred to as the surface-wear constant.

Methods of Analysis

Obvious methods for the analysis of the results of a marked-ball test are suggested by equations (7) and (9). From equation (7),

$$\ln m = \ln m_o - T/\tau,$$

i.e. the $\ln$ (ball mass) varies linearly with the mass of material milled, and the tonnage constant of the ball is simply the reciprocal of the slope of the graph. On the other hand, equation (9) shows that the cube root of the ball mass varies linearly with the mass of material milled. The slope of this graph is equal to the surface-wear constant.

Results of the Marked-ball Test

In the marked-ball test mentioned earlier, which was conducted in the course of a full-scale test at Western Platinum Limited¹, the entire charge of the No. 3 A-stream ball mill was replaced with balls from the Fonderies Magotteaux in Belgium. The mill is an 8ft by

TABLE I
SUMMARY OF THE RESULTS OF A MARKED-BALL TEST CONDUCTED AT WESTERN PLATINUM LIMITED¹

1	2	3	4	5	6	7	8	9
Ball grade	Date	Control no.	Mass of ball* g	Cumulative loss in mass of ball g	Equivalent loss in mass of ball on 22 t t	Mass of ore milled t	Cumulative mass of ore milled t	Calculated ball consumption kg/t
1	6.7.81	Original mass	850,8	—				
	9.8.81	1	734	116,8	3,02	21 151	21 151	0,143
	7.9.81	2	619	231,8	5,99	18 169	39 320	0,152
	12.10.81	3	537	313,8	8,11	22 458	61 778	0,131
	9.11.81	4	480	370,8	9,59	18 092	79 870	0,120
	21.12.81	5	384	466,8	12,07	27 319	107 189	0,113
	15.2.82	6	253	597,8	15,46	33 837	141 026	0,110
2	6.7.81	Original mass	910,7	—				
	9.8.81	1	770	140,7	3,40	21 151	21 151	0,161
	7.9.81	2	657	253,7	6,13	18 169	39 320	0,156
	12.10.81	3	556	354,7	8,57	22 458	61 778	0,139
	9.11.81	4	486	424,7	10,23	18 092	79 870	0,128
	21.12.81	5	392	518,7	12,53	27 319	107 189	0,117
	15.2.82	6	288	622,7	15,04	33 837	141 026	0,107
3	6.7.81	Original mass	873,7	—				
	9.8.81	1	742	131,7	3,32	21 151	21 151	0,157
	7.9.81	2	642	231,7	5,83	18 169	39 320	0,148
	12.10.81	3	545	328,7	8,28	22 458	61 778	0,134
	9.11.81	4	475	398,7	10,04	18 092	79 870	0,126
	21.12.81	5	373	500,7	12,61	27 319	107 189	0,117
	15.2.82	6	278	595,7	15,00	33 837	141 026	0,106
4	6.7.81	Original mass	842,7	—				
	9.8.81	1	792	50,7	1,32	21 151	21 151	0,062
	7.9.81	2	751	91,7	2,39	18 169	39 320	0,061
	12.10.81	3	712	130,7	3,41	22 458	61 778	0,055
	9.11.81	4	686	156,7	4,09	18 092	79 870	0,051
	21.12.81	5	643	199,7	5,21	27 319	107 189	0,049
	15.2.82	6	577	265,7	6,94	33 837	141 026	0,049
	16.8.82	7	419	427,7	11,06	108 405	249 431	0,044
5	6.7.81	Original mass	763,7	—				
	9.8.81	1	693	70,7	2,04	21 151	21 151	0,096
	7.9.81	2	644	119,7	3,45	18 169	39 320	0,087
	12.10.81	3	580	183,7	5,29	22 458	61 178	0,086
	9.11.81	4	543	220,7	6,36	18 092	79 870	0,080
	21.12.81	5	476	287,7	8,29	27 319	107 189	0,077
	15.2.82	6	386	377,7	10,88	33 837	141 026	0,077
6	6.7.81	Original mass	760,6	—				
	9.8.81	1	713	47,6	1,38	21 151	21 151	0,065
	7.9.81	2	689	71,6	2,07	18 169	39 320	0,053
	12.10.81	3	655	105,6	3,05	22 458	61 173	0,050
	9.11.81	4	629	132,6	3,84	18 092	79 870	0,048
	21.12.81	5	592	168,6	4,88	27 319	107 189	0,046
	15.2.82	6	536	224,6	6,50	33 837	141 026	0,046
	16.8.82	7	421	339,6	9,83	108 405	249 431	0,039

*Average of a sample of nominally 10 balls withdrawn from the mill

8ft rubber-lined ball mill running at 85 per cent of the critical speed with a ball charge of 22 t. The daily throughput is about 650 t of ore from the Merensky Reef. Six grades of Magotteaux balls were tested simultaneously. One of the grades, namely grade 4, was identical to the background of balls within the mill. The mill was recharged once a fortnight with 60 mm balls to restore the level of the charge to the bottom of the inlet trunnion, and the masses of marked balls were monitored at monthly intervals. The mine records of the test results are given in Tables I and II.

In Table I, the values given in column 6 were calculated from the formula

$$\frac{22[m_o - m(T)]}{m_o},$$

where $m(T)$ is the mass of a ball after T tons of new feed have been milled, and 22 t is the mass of the balls in the mill. The calculated ball consumptions (column 9 of Table I) are obtained by the formula

$$K = \frac{22[m_o - m(T)]}{m_o T}.$$

It is interesting that these figures generally decrease systematically with increasing tons milled (although there are some exceptions) in a manner suggesting that equilibrium has not yet been reached. This effect is explained below.

The marked-ball anomaly can be ascertained by comparison of the values for the grade 4 balls in column 9 of Table I with those in column f of Table II, which represent the total ball consumption of the operating mill. It can be seen that, after a total of 149,6 kt had been milled, the total ball consumption by the operating mill was approximately 0,14 kg/t, but for grade 4 marked balls the calculated ball consumption was 0,049 kg/t, i.e. the grade 4 marked balls, even though they are identical to the background, appear to be much more

durable.

Analysis of the Results of the Marked-ball Test

Because grade 4 balls constituted the background of balls within the mill, the results obtained from these balls will be discussed in some detail as an illustration of the theories.

We first consider the results from the point of view of the volume theory³. In Fig. 1, which shows the $\ln$ (ball mass) versus the tons milled for grade 4 balls, it can be seen that the points are distributed linearly. The correlation coefficient is 0,9985. The line is a least-squares fit to the experimental points and yields a value for $\ln m_o$ of 6,741, corresponding to $m_o = 846,4$ g. This value is in excellent agreement (0,4 per cent) with the known initial mass of 842,7 g. The reciprocal of the slope of the line is the tonnage constant. For grade 4 balls, we find that $\tau_4 = 362$ kt.

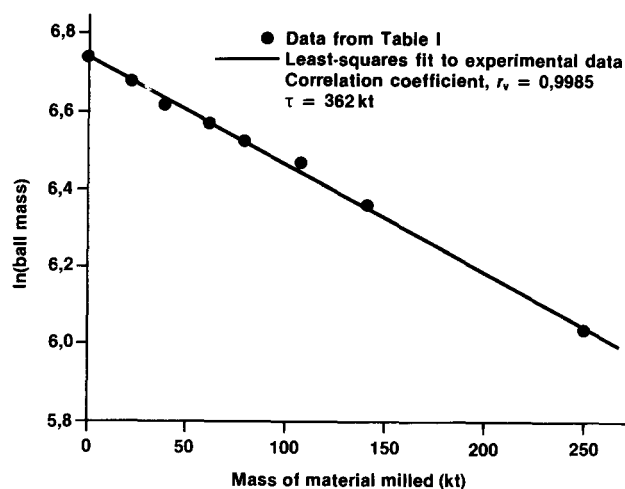


Fig. 1—Fit of the volume theory³ to the wear data for grade 4 grinding balls by a plot of $\ln$ (ball mass) versus T

TABLE II

TONNAGES MILLED AND CONSUMPTION OF BALLS IN THE NO. 3 A-STREAM BALL MILL AT WESTERN PLATINUM LIMITED

	a	b		c		d		e	f	g
	Period	Material milled, t		Balls added, t		Ball consumption				$\Delta M / \Delta T$
		Amount	Cumulative amount	Amount	Cumulative amount	kg/t		kg/t		
1	22.6.81 to 5.7.81	8 524	8 524	2	2	0,235		0,235		
2	6.7.81* to 8.8.81	21 151	29 675	3	5	0,168		0,142		
3	9.8.81 to 6.9.81	18 169	47 844	3	8	0,167		0,165		
4	7.9.81 to 11.10.81	22 458	70 302	3	11	0,156		0,134		
5	12.10.81 to 8.11.81	18 092	88 394	3	14	0,158		0,166		
6	9.11.81 to 19.12.81	27 319	115 713	3	17	0,149		0,110		
7	20.12.81 to 15.2.82	33 837	149 550	4	21	0,140		0,118		
8	16.2.82 to 23.5.82	60 006	209 556	7	28	0,134		0,117		
9	24.5.82 to 23.6.82	16 642	226 198	2	30	0,133		0,120		
10	24.6.82 to 23.7.82	18 172	244 370	1	31	0,127		0,055		
11	24.7.82 to 22.8.82	17 729	262 099	2	32	0,126		0,113		
12	23.8.82 to 21.9.82	17 683	279 782	1	33	0,118		0,057		
	New discharge grates fitted									
13	22.9.82 to 21.10.82	17 466	297 248	2	35	0,117		0,115		
14	22.10.82 to 20.11.82	17 980	315 228	1	36	0,114		0,056		
15	21.11.82 to 22.12.82	18 955	334 183	1,3	37,3	0,112		0,068		

*Marked balls added to the mill
Column f=column e÷column c
Column g=column d÷column b

It can be concluded that the function

$$m(T) = 846,4 \exp(-T/362) \dots (11)$$

is a good description of the way in which the mass of a grade 4 ball varies with the tonnage milled by the given mill.

The same data must also be scrutinized from the point of view of the surface theory⁴, which predicts that, provided the shapes of the balls remain constant during the period of the test, the cube root of the ball mass will vary linearly with the tonnage milled. It is well known that the shapes of worn grinding elements can be distinctly non-spherical. The constant-shape approximation could therefore introduce an error. The magnitude of this error was investigated by measurement of the volumes, surface areas, and mean diameters of worn balls.

At the end of the test, the balls still had a well-rounded appearance. It was found that the surface area of a worn grade 4 ball was about 11 per cent greater than that of a sphere of equivalent volume, and that the diameter of the equivalent-volume sphere was within 4 per cent of the measured mean diameter of the ball. Since equation (9) shows that quantities proportional to $m^{1/3}$, or the diameter, must be considered, we conclude that the constant-shape approximation introduces errors that vary from 0 at the beginning to almost 4 per cent at the end of the test. This error introduces an uncertainty of 4 per cent in the value of the surface-wear constant that will be obtained by the fitting of equation (9) to the data.

In Fig. 2, which shows the cube root of the ball mass versus the tonnage milled, it can be seen that the points are distributed linearly. The correlation coefficient is 0,9994. The line, which is the least-squares fit to the data, yields a value for m_0 of 837,4 g that is in excellent agreement (0,6 per cent) with the known initial mass. From the slope of this curve, we obtain the following value for the surface-wear constant of grade 4 balls:

$$b = 2,33 \times 10^{-2} \text{ g}^{1/3} \cdot \text{kt}^{-1}.$$

It can be concluded that the function

$$m(T) = (9,425 - 7,77 \times 10^{-3}T)^3 \dots (12)$$

is a good description of the way in which the mass of a grade 4 ball varies with the throughput of the given mill.

Equations (11) and (12), which represent the volume

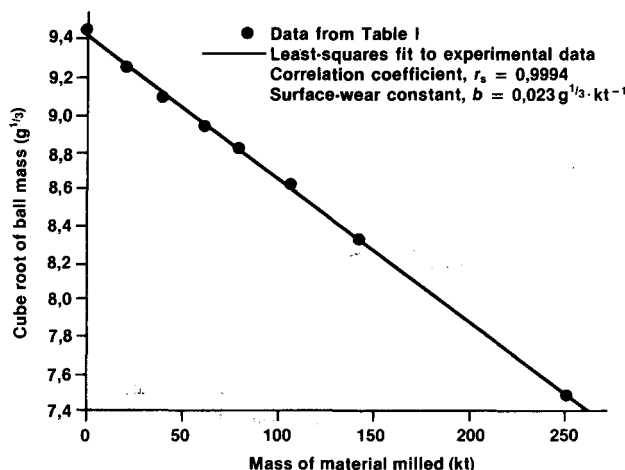


Fig. 2—Fit of the surface theory⁴ to the wear data for grade 4 grinding balls by a plot of $m^{1/3}$ versus T

and surface theories respectively, are shown in Fig. 3 together with experimentally measured points. It can be seen that either theory is in excellent agreement with the measured ball masses.

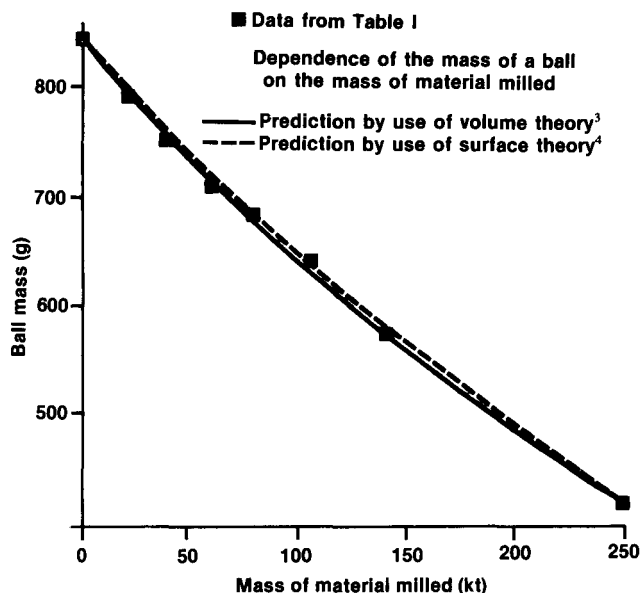


Fig. 3—Comparison of theoretical and experimental results for grade 4 balls

The results relevant to all six grades of ball were analysed in this way, and are summarized in Table III.

TABLE III
TONNAGE CONSTANTS AND SURFACE-WEAR CONSTANTS FOR SIX GRADES OF STEEL BALLS

Grade of ball	Volume theory ³		Surface theory ⁴	
	Tonnage constant τ kt	Correlation coefficient r_v	Surface-wear constant b g ^{1/3} ·kt ⁻¹	Correlation coefficient r_s
1	120	0,9926	0,065	0,9967
2	124	0,9995	0,064	0,9968
3	124	0,9993	0,063	0,9995
4	362	0,9985	0,023	0,9994
5	212	0,9968	0,039	0,9986
6	412	0,9993	0,018	0,9986

Two points of interest emerge from Table III. The tonnage constants and surface-wear constants that are associated with various grades of balls vary by a factor of more than 3. This variation must be related to the metallurgical properties of the various grades of balls. Secondly, the correlation coefficients, r_v and r_s , are all close to unity, which shows that both theories provide good descriptions of the way in which the masses of the balls decrease as a function of the amount of material milled.

Discussion

Agreement with Both Theories of Ball Wear

It has been shown that both theories of ball wear are in

good agreement with the actual wear of six grades of balls. For some grades the volume theory provides a marginally better fit (e.g. grades 2 and 6), but for other grades the surface theory offers a better description (e.g. grades 1, 4, and 5). This puzzling ambiguity is not due to the wear rate of a ball being simultaneously proportional to its mass and to its surface area. If it were, we should find that, according to the volume theory,

$$-\frac{dM}{dT} \propto m, \quad \dots \dots \dots (13)$$

and, according to the surface theory,

$$-\frac{dM}{dT} \propto m^{2/3}. \quad \dots \dots \dots (14)$$

Dividing these expressions by each other shows that $m^{1/3}$, which is proportional to the diameter of a ball, is a constant, which is absurd. Therefore, the wear rate of a ball cannot be simultaneously proportional to its surface area and to its mass.

Part of the reason for the ambiguity is that the graphs for the two functions are of the same general shape, although one represents an exponential decay of the ball mass with the tons milled, $m_o \exp(-T/\tau)$, and the other a cubic decay of the ball mass with the tons milled, $(m_o^{1/3} - 1/3 bT)^3$. These functions were brought into close correspondence with the data, and therefore with each other, by least-squares adjustment of the parameters.

The data extend over a limited range

$$(m_o/m_f) < 3,$$

where m_o is the original mass and m_f the final mass. One can always bring functions whose graphical representations are of the same general shape into close correspondence over a limited range by suitable adjustment of the parameters. This is partly why both functions are in good agreement with the data.

Another reason for the ambiguity might be that the balls are subjected to both abrasive and impactive wear.

Decrease in the Calculated Ball Consumption

The calculated ball consumption of marked balls (column 9 of Table I) was obtained with the aid of the formula

$$K = \frac{22}{T} \left[\frac{m_o - m(T)}{m_o} \right], \quad \dots \dots \dots (15)$$

where the factor 22 is the tonnage of the grinding balls within the mill. Substituting for $m(T)$ from equations (7) and (10), one obtains, by use of the volume theory,

$$K(T) = \frac{22}{T} [1 - \exp(-T/\tau)], \quad \dots \dots \dots (16)$$

and, by use of the surface theory,

$$K(T) = \frac{22}{T} \left[1 - \left(1 - \frac{bT}{3m_o^{1/3}} \right)^3 \right], \quad \dots \dots \dots (17)$$

where equation (17) is valid for $T < 3m_o^{1/3}/b$.

The relative change in mass, i.e. the quantity in brackets in equation (15) as predicted by the use of the volume and surface theories, and the data for grade 4 balls are plotted in Fig. 4. $K(T)$ is the slope of a chord from the origin to a point on either of the curves. Obviously, the slopes of chords from the origin decrease

with increasing mass of material milled. This is confirmed by Fig. 5, which shows the graph of $K(T)$ obtained by the use of equations (16) and (17) and the values for the calculated consumption of grade 4 balls obtained from column 9 in Table I.

According to both theories, $K(T)$ is a variable quantity that decreases monotonically with increasing throughput. This decrease is essentially due to the fact that the wear rates of balls decrease as they become smaller.

These considerations show that ball consumption should be related to constants associated with the test, i.e. the tonnage constant, τ , or the surface-wear constant, b , rather than to a quantity dependent on tonnage such as the ball mass.

It is a simple matter for one to formulate a cost-effective index, E , in terms of the constants of the test. In terms of the volume theory,

$$E = C/\tau,$$

whereas, in terms of the surface theory,

$$E = Cb,$$

where C is the cost per ton of the balls to the mine. The most cost-effective balls have the smallest value for E .

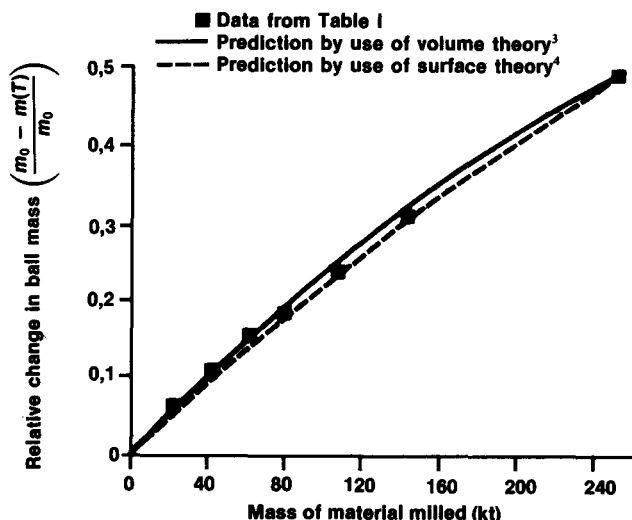


Fig. 4—The relative change in mass of grade 4 grinding balls as a function of the mass of material milled

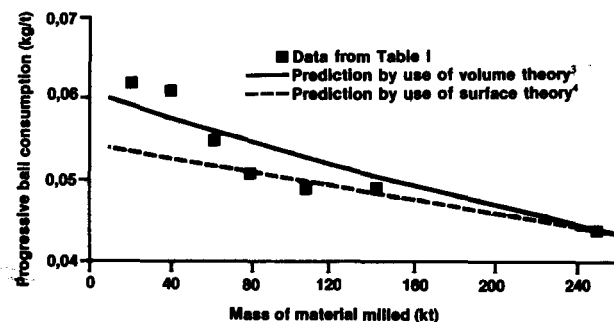


Fig. 5—Predictions of the calculated consumption of grade 4 grinding balls versus the mass of material milled

The Marked-ball Anomaly

To the mine records given in Table II in columns a to f, we have added (in column g) the values $\Delta M/\Delta T$, which represent the average ball consumption by the mill for each period of the test. It should be noted that these values represent the total ball consumption by the mill for the stated period and are not to be confused with the values for the calculated ball consumption as given in Table I, which refer only to marked balls. Fig. 6 gives the values for the average ball consumption by the mill as a function of the cumulative amount of material milled, and also summarizes the history of the test. While the discharge gates were regarded as still being serviceable, the mill was relined and charged with unmarked grade 4 balls as follows: 4 t of 40 mm balls, 5 t of 50 mm balls, and 14 t of 60 mm balls, and the plant test was initiated at $T=0$. When 8,524 kt of material had been milled, the make-up addition of 2 t of balls included the six sets of marked balls. The marked balls were monitored until $T=149,6$ kt, after which it became difficult for sufficient numbers of these balls to be found. Some balls of grades 4 and 6 were found in the mill at $T=257,9$ kt. Their masses were measured, and these measurements were taken into account in the consideration of the theories.

Fig. 6 shows that the ball consumption $\Delta M/\Delta T$ initially shows a pronounced decreasing trend, but that it tends towards a value of about 0,1 kg/t milled at the end of period 12, at which time the discharge gates were rather badly worn.

A ball consumption of 0,1 kg per ton milled implies a

tonnage constant for the mill of $\tau_m=220$ kt but, as shown earlier, the tonnage constant for grade 4 marked balls, $\tau_4=362$ kt. This is an illustration of the marked-ball anomaly: even though the marked balls are of the same type as the background ball charge, they appear to be more durable.

It has been shown that the volume and the surface theories are in very good agreement with the data available, and therefore either theory could be used in a theoretical discussion of the marked-ball anomaly. Nevertheless, we prefer to use the volume theory because the idea of a tonnage constant is useful.

We start by trying to calculate the ball consumption of the mill. The mass of the grinding balls within the mill can be written as

$$M = N\bar{m}, \dots\dots\dots (18)$$

where N is the number of balls and $\bar{m}$ is the average mass of the balls.

If it is assumed that the wear of balls of average mass is similar to that of the marked balls,

$$\left|\frac{\Delta M}{\Delta T}\right|_{\text{mill}} = \left|\frac{\Delta(N\bar{m})}{\Delta T}\right| = N\left|\frac{\Delta\bar{m}}{\Delta T}\right| = N\frac{\bar{m}}{\tau_B} = \frac{M}{\tau_B} \quad (19)$$

and

$$\tau_m^{-1} = \frac{M}{\Delta M/\Delta T} = \frac{N\bar{m}}{\Delta(N\bar{m})/\Delta T} = \frac{\bar{m}}{\Delta\bar{m}/\Delta T} = \tau_B^{-1} \dots\dots\dots (20)$$

We have added the subscript B to emphasize that the tonnage constant appearing on the right-hand sides of these equations refers to a ball that is typical of the

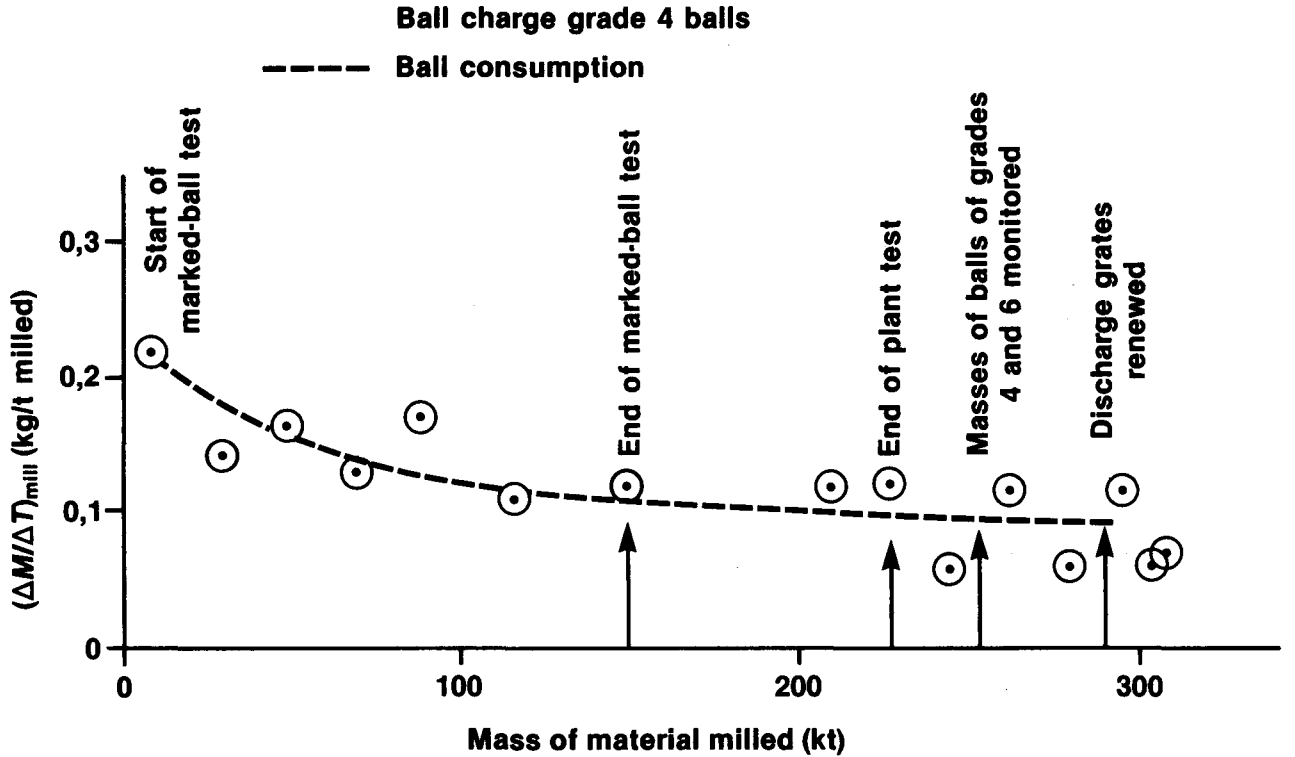


Fig. 6—Ball consumption by the No. 3 A-stream ball mill as a function of the amount of material milled

background charge of grinding balls within the mill. Equation (20) suggests that the tonnage constant for the mill is equal to the tonnage constant for a ball. The data for grade 4 balls give

$$\tau_B = \tau_4 = 362 \text{ kt.} \quad (21)$$

If this value is substituted for τ_B in equation (19), the ball consumption is

$$\left| \frac{\Delta M}{\Delta T} \right|_{\text{mill}} = \frac{M}{\tau_B} = \frac{22 \times 10^3}{362 \times 10^3} = 0,061 \text{ kg/t milled,} \quad (22)$$

which is less than the actual ball consumption by the mill, and therefore just another indication of the marked-ball anomaly.

The calculations above do not resolve the marked-ball anomaly because they ascribe the ball consumption of the mill only to the rate at which finely divided material is ground off the ball surfaces. When the balls eventually become sufficiently small, they can pass through the holes in the discharge grates. Ball remnants can always be seen on the screens of discharge trommels. The calculations shown in equations (19) to (22) do not take into account the discharge of ball remnants from the mill. We take this factor into account by writing

$$\left| \frac{\Delta M}{\Delta T} \right|_{\text{mill}} = \left| \frac{\Delta M}{\Delta T} \right|_R + \frac{M}{\tau_B}, \quad (23)$$

where the remnant term, $\left| \frac{\Delta M}{\Delta T} \right|_R$, is the total mass of the ball remnants that are rejected from the mill in unit time, and the term M/τ_B represents the rate at which finely dispersed material is being ground off ball surfaces during milling.

For the determination of the remnant term, the discharge of ball remnants from the mill was monitored shortly before and after renewal of the discharge grates. The details of these measurements are recorded in Table IV, which shows that, with severely worn discharge grates, the mill discharged 111,3 kg of balls during the time in which 3644 t of ore were fed to the mill.

Theoretically, therefore, the ball consumption by the

mill can be expressed as

$$\left| \frac{\Delta M}{\Delta T} \right|_{\text{mill}} = \frac{111,3}{3,64 \times 10^3} + \frac{22 \times 10^3}{362 \times 10^3} = 0,091 \text{ kg/t milled,} \quad (24)$$

Table II shows that, from 24th May to 21st September, 1982, when 70 226 t of ore were milled, 6 t of steel were consumed by the mill. This corresponds to a consumption of 0,085 kg of balls per ton of material milled, which is in pleasing agreement with the calculation based on theory.

Table IV also describes the discharge of remnants from the mill shortly after the discharge grates had been renewed, and it can be seen that the average mass of remnants decreased from 83 to 26 g, the average equivalent diameter from 28 to 19 mm, and the consumption of balls as remnants from 0,031 to 0,008 kg per ton milled. The condition of the discharge grates clearly has a profound influence on the total ball consumption.

According to our theory, we predict that, with new discharge grates fitted, the ball consumption of the mill should decrease to

$$\left| \frac{\Delta M}{\Delta T} \right|_{\text{New grates}} = 0,061 + 0,008 = 0,069 \text{ kg/t milled.}$$

Reference to Table II shows that, during periods 13 to 15, a total mass of 54 401 t of ore were fed to the mill and a total mass of 4,3 t of balls were added. This corresponds to a ball consumption of 0,079 kg per ton milled, which is in reasonable agreement with our calculated value of 0,069.

Therefore, when the tonnage constant for a ball and the rate at which ball remnants are discharged from the mill are taken into account, the marked-ball anomaly can be explained, and the total consumption of balls by the mill can be predicted from a marked-ball test.

It is of interest that, whereas the addition rate of top-size balls is about 100 per kiloton of ore fed, the discharge rate is about three times that number. This

TABLE IV
RESULTS OBTAINED BY MONITORING OF THE DISCHARGE OF BALL REMNANTS FROM THE MILL OVER TWO TEST PERIODS

Conditions	Date	Ore milled t	Ball remnants		Ball remnants			Consumption of balls as remnants per ton milled kg
			Number found	Mass kg	Average mass kg	Average equivalent diameter mm	Number per kiloton milled	
Test 1 Discharge grates worn	6 Sep.	150	205	16,2	0,082	28	373	0,031
	7 Sep.	302	101	9,0				
	8 Sep.	656	277	23,8				
	9 Sep.	527	190	16,4				
	10 Sep.	674	140	10,6				
	11 Sep.	668	230	18,4				
	12 Sep.	667	216	16,9				
TOTALS		3644	1359	111,3				
Test 2 New discharge grates fitted 20 Sep., 1982	10 Nov.	646	267	5,4	0,026	19	296	0,008
	11 Nov.	658	294	7,8				
	12 Nov.	616	270	4,8				
	13 Nov.	651	137	4,0				
	18 Nov.	671	157	4,6				
	19 Nov.	656	130	3,6				
	20 Nov.	606	133	3,2				
	21 Nov.	677	83	2,5				
	22 Nov.	322	159	6,8				
TOTALS		5503	1630	42,7				

suggests that some breakage of balls is taking place in the mill. A recent sample of ball remnants discharged from the mill was found to contain about 25 per cent of clearly identifiable fragments, thus confirming that a substantial degree of breakage occurs in the mill.

The pronounced initial decrease in the total ball consumption shown in Fig. 6 can be explained easily. The differential equations (6) and (8) show that the wear rate of a ball decreases with its mass. In the test, the initial mill charge comprised balls of only three different sizes: 60 mm, 50 mm, and 40 mm. The average ball mass was initially about 570 g, and a sample drawn from the mill at a later stage in the test gave an average mass of 353 g, which showed that, although only top-size balls were added, the average ball mass decreased as a function of the tonnage milled. Because the average ball size decreased, the average wear rate also decreased, and the consumption of balls per ton milled therefore decreased with increasing tonnage milled. This effect has its origin in the 'artificial' size distribution of the balls comprising the initial charge to the mill. It is generally believed that a mill produces a graded size distribution of balls and that, when equilibrium is reached, the ball consumption becomes constant.

As already shown, the consumption of the background balls in the charge can be calculated with fair accuracy from the results of a marked-ball test. However, the question arises as to what the ball consumption would be if the mill were charged with balls of one of the other grades. It can be shown that the remnant term will be inversely proportional to the tonnage constant and that the total ball consumption will therefore also be inversely proportional to the tonnage constant. For example, if the consumption of grade 4 balls is 0,09 kg per ton milled, then the consumption of grade 6 balls will be $0,09 \times 362/424 = 0,077$ kg per ton milled, where $\tau_6 = 424$ is the tonnage constant for grade 6 balls. If, in addition, the cost-effective index, $E_6 = C_6/\tau_6$, where C_6 is the cost to the mine of grade 6 balls, is lower than that for grade 4 balls, it will be advantageous for the mine to change to grade 6 balls.

These calculations emphasize that the value of a marked-ball test is greatly enhanced when it includes marked balls that are of the same type as the charge.

Summary and Conclusions

In this work, the kinetics of ball wear were considered, and formulae for the dependence of the mass of a ball on the amount of material milled by a ball mill were derived from the volume³ and surface⁴ theories of ball wear. The theoretical expressions were compared in detail with the results obtained from a marked-ball test, and it was found that the values obtained by the use of

both theories are in remarkably good agreement with the experimental data. This ambiguity can be explained if it is noted that the volume theory predicts an exponential decay, and the surface theory a cubic decay, of the mass of a ball with the amount of material milled, and that the graphical representation of such functions, which are of the same general shape, can always be brought into close correspondence over a limited range by suitable adjustment of the parameters.

One may be able to use ball-wear data to distinguish between the two theories if these data extend over a wider range, say m_o/m_t of 10 or 20, and if the ball masses are monitored at more frequent intervals. However, it should be noted that, in large ball mills, which operate at speeds higher than 70 per cent of the critical speed, the balls are undoubtedly being subjected to the mechanisms of both abrasive and impactive wear.

The idea of a tonnage constant was found to be useful in the study of the relative performance of balls and their cost-effectiveness.

The marked-ball anomaly was found to arise from the fact that the measurements of ball consumption by a mill include the scrap that is discharged from the mill, whereas the consumption of marked balls relates only to the wear of balls that are still too large to pass through the discharge grates. The dependence of the calculated consumption of marked balls on time or tonnage milled is due merely to the fact that, as the balls become smaller, their wear rate decreases. Predictions of the ball consumption in a mill were made with fair accuracy from the results of a marked-ball test. It is emphasized that the usefulness of a marked-ball test is greatly enhanced when a set of marked balls identical to the background ball charge of the mill is included in the various sets of balls under test.

Acknowledgements

Thanks are due to Western Platinum Limited, in association with Mr Jacky Detroux of Fonderies Magot-teaux, for making the results of the marked-ball test available. We are grateful to Drs P. T. Wedepohl, D. G. Hulbert, and I. J. Barker for helpful discussions.

This paper is published by permission of the Council for Mineral Technology.

References

1. VERMEULEN, L. A., and HOWAT, D. D. Analysis of the results of a marked-ball test in relation to theories of ball wear in rotary mills. Randburg, Council for Mineral Technology, Report M77. Apr. 1983. 34 pp.
2. NORMAN, T. E., and LOEB, C. M. Wear tests on grinding balls. *AIIME Trans.*, vol. 183. 1949. pp. 330-360.
3. DAVIS, E. W. Fine crushing in ball mills. *AIIME Trans.*, vol. 61. 1919. pp. 250-297.
4. PRENTICE, T. K. Ball wear in cylindrical mills. *J. Chem. Min. Metall. Soc. S. Afr.*, Jan. 1943. pp. 99-116.