Wear of grinding media in the mineral processing industry: An overview

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Abstract — *Within the mineral processing industry, a range of grinding conditions exists which include semiautogenous grinding (SAG), rod milling, and conventional ball milling. Each of these mill environments presents a unique environment for grinding media, requiring the application of specific physical and chemical properties for optimum grinding media performance. The environments are characterized by varying degrees and combinations of abrasive, corrosive, and impact wear. An extensive test program has been conducted to determine the extent wear rates vary between these different applications. Test results are related to production results, ball size, and mill operating conditions.*

Introduction

In the mineral processing industry, there are different grinding environments in which grinding media are used. These include semiautogenous (SAG) mills, rod mills, conventional ball mills, and tower mills. The different types of grinding media available for these grinding applications include heat-treated and as-rolled grinding rods, forged steel balls, cast steel balls, cast high chrome iron balls, and cast slugs (or cypebs). Some media types are best suited for specific grinding applications. However, the areas of application often overlap, allowing a choice of more than one type of media for a given grinding application.

The consumption of grinding media in the mineral processing industry represents a substantial cost to the comminution process. Second to energy, grinding media is most often found to be the next highest consumable cost involved in mineral processing (Henderson and Crowell, 1980). To allow selection of the most cost effective media, one must determine the specific wear mechanisms present in a given grinding application and decide which media system addresses these mechanisms most economically.

The effectiveness of grinding media in the mineral processing industry is evaluated in terms of wear resistance and grinding performance. Wear resistance is a function of alloy selection and processing, mill operation procedures, and the mill environment. The weight consumption of media vs. tons milled or operating hours are common methods of inferring wear resistance. Factors influencing grinding performance include media size selections, shape considerations, and media quality. Grinding performance is measured in terms of throughput, fineness of grind, or the ability to produce desired size distributions in the product. It is the combination of a media's wear resistance and grinding performance in relation to its cost which establishes the true cost-effectiveness of the grinding media.

This paper was written in order to provide the grinding media user with some tools and insight on how to evaluate grinding media. The primary focus is on grinding balls, but the same analysis can be applied to grinding rods. The wear law for grinding media is discussed, and the relationship between marked ball wear test data and production wear rates is demonstrated. Test results from each of the major grinding ball application categories are presented.

Wear law

Over the years, there have been many investigations aimed at determining the appropriate mathematical formula, or wear law, that accurately describes the wear behavior of grinding balls in rotating mills. The basic wear law can be written:

$$\frac{dW}{dt} = kD^n \tag{1}$$

where W is ball weight, t is time, k is proportionality constant, D is ball diameter, n is wear rate exponent

Simply stated, the wear rate of a grinding ball is proportional to the ball diameter raised to some power, *n*. Davis (1919) reported from his experiments that wear rate was proportional to the ball's weight, $n = 3$; Norquist and Miller (1950) found that the wear rate was proportional to the ball's surface area, $n = 2$; and Bond (1943) concluded that wear rate was proportional to the ball's diameter raised to a power of $n = 2.21$.

More recent investigations suggest that the relationship between wear rate and ball diameter is not fixed but rather, is dependant on the wear environment. Austin and Klimpel (1985) reviewed several data sets and found some sets followed the surface area law while others did not. Vermeulen and Howat (1986) also saw a range in the calculated wear rate exponent and postulated what they termed the theory of combined wear, in which part of the total wear was abrasive wear (proportional to D^2) and part was impact wear (proportional to D^3). They speculated that the relative intensities of the two wear mechanisms were determined by several factors including the mechanical properties of the balls, mill diameter and speed, ball recharge size, liner design, and pulp density. Azzaroni (1987) found a relationship between the wear rate exponent, mill diameter, ball diameter, and charge volume. He concluded that as mill diameter and ball diameter increases and charge volume decreases, the impact forces increase, making the overall wear rate exponent increase.

These theories account for the contributions of only two wear components: abrasion and impact. One must also consider the third component of wear, corrosion, as a contributor to the total wear mechanism. Corrosion is a surface dependant reaction and is therefore proportional to D^2. Hoey, Dingley, and Freemen (1977) stated that when milling in a corrosive environment with an abrasive ore, the corrosion component will be enhanced by the continued exposure of fresh media surface to the corrosive slurry, accelerating overall wear. It is more appropriate to view the abrasion component

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M.J. Meulendyke, member SME, and J.D. Purdue are with Armco, Inc., Kansas City, MO. SME preprint 89-168, SME Annual Meeting, Las Vegas, NV, February, 1989. M&MP paper 89-632. Manuscript Jan. 10, 1989. Discussion of this paper must be submitted, in duplicate, prior to Jan. 31, 1990.

discussed above as an abrasion/corrosion component when considering corrosive grinding environments.

Eq. 1 can be solved and rewritten as follows:

$$K = \frac{D_i^{3-n} - D_f^{3-n}}{t\,(3-n)} \qquad (2)$$

where k' is the wear constant or wear speed, D_i is the initial ball size, D_f is the final ball size, t is time, and n is wear rate exponent.

From Eq. 2, if the wear rate exponent is equal to 2, a plot of ball diameter vs. time is a straight line. If the wear rate exponent is greater than or less than 2, then the curves deviate from linear as illustrated in Fig. 1.

Armco's results (Azzaroni, 1979, 1979a) of classifying entire ball charges of industrial mills grinding copper ore demonstrated that the wear rate exponent was between 2.0 and 2.2 for these particular mills. Balls were classified into 5 mm size increments, weighed, and counted. The number of balls in each size increment was essentially equal, which would be expected for a seasoned ball charge developed from a single ball size recharge practice. A seasoned ball charge is a charge with a surface area corresponding to a natural ball size distribution. Based on these results, using a wear rate exponent equal to 2 provides a practical solution to the wear law for conventional ball milling. When n is equal to 2, the production wear rate is directly proportional to the surface area of the ball charge, and the rate of diameter loss per unit time (wear speed) is a constant.

In SAG mill environments, the wear rate exponent is found to be much greater than 2 due to the large component of impact wear. Azzaroni (1987) tested different size balls in production SAG mills and calculated the wear rate exponent to be 2.8. This implies that SAG balls wear fastest at their full size and wear progressively slower as their mass is decreased.

Accepting a wear exponent of 2.8 for SAG mills is valid when describing the ball's wear when the ball is still relatively large [>75mm (3 in.)]. However, a wear rate exponent of 2.8 predicts an accumulation of small balls relative to large balls in the charge, and observations of SAG mill charges do not show this to be true, even for balls of nearly constant cross-sectional hardness profiles. For SAG mills equipped with discharge grates approaching 75mm (3 in.) in width, this prediction becomes a moot point since balls exit the mill when they reach the grate size. However, in SAG mills equipped with small grate openings, the absence of small balls signifies that a transition to a different wear mechanism, presumably breakage, must occur. It is easy to envision that small balls, like the ore itself, are crushed by the large balls in the mill charge.

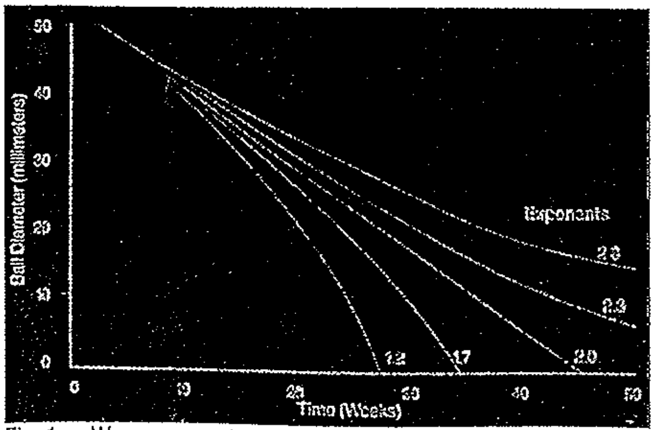

Fig. 1 — Wear exponent comparison.

Marked ball wear test (MBWT) procedure

The MBWT is an excellent tool for comparing wear rates of different materials under identical production milling conditions. Direct comparisons can be made, eliminating the need to compensate for differences in ore hardness, feed rate, mill volume, etc., factors which have been associated with historical comparison testing and parallel production testing. The MBWT method also avoids the time necessary to convert a mill charge from one type of ball to another to conduct a full production test. A final feature is that production wear rates can be accurately predicted directly from MBWT results.

In preparation for testing, selected groups of balls are identified by some means to allow decoding of recovered balls at the conclusion of each recovery period. There are two popular means to identify balls for MBWT. One method is to drill each ball with an identical hole, place an identification tag in the bottom of the hole, and then fill the hole with a low melting point metal alloy plug to secure the tag. At recovery, the plug is melted and the identification tag is recovered. A second method of marking balls is to use different combinations of holes, hole diameters, and hole orientations to differentiate between test groups. Typically, two holes of equal or different sizes are drilled at 90∞ or 180∞ orientations. With this method, the initial weight of all balls within a test group must be essentially the same since wear rate calculations are based on average initial and final weights.

Marking of the balls must be done carefully or excessive localized heating in the drilled region may occur, causing transformation products in the microstructure of some alloys. These transformation products may reduce the impact resistance of the ball, influencing the test results. When this is a major concern, electrical discharge machining is the preferred method of creating the identifying holes.

Oversized test balls, relative to the host charge ball size, are frequently used to aid in the recovery process. When the wear exponent is equal to 2, the diameter loss per unit time of balls in grinding mills is independent of ball diameter. Therefore, the wear rate information gained from using oversized test balls is representative of the wear rates that would be experienced by balls of the host charge ball size. When the wear rate exponent is greater than 2, the absolute wear speeds of oversize balls will measure slightly higher than those of the host charge. However, the relative wear rates between different test balls of equal size will be unaffected. When making comparisons between two types of balls under these conditions, it is important that both ball types have the same size.

The coded groups of balls are individually weighed prior to placing them into an operating production mill. Periodically, when the mill is down for scheduled maintenance, the test balls are recovered, decoded, and reweighed. Assuming the balls remain as perfect spheres, the ball weights are converted to ball diameters and a plot of ball diameter vs. time is generated. The wear speed and wear speed exponent are determined from interpretation of this plot.

Marked ball wear test (MBWT) results

Calculation of production wear rates

Fig. 2 presents results from a MBWT conducted for 17,000 operating hr. Note that the plot of ball diameter versus time is a straight line.

The slope of the line is a direct measure of the rate of the diameter loss, termed wear speed, where:

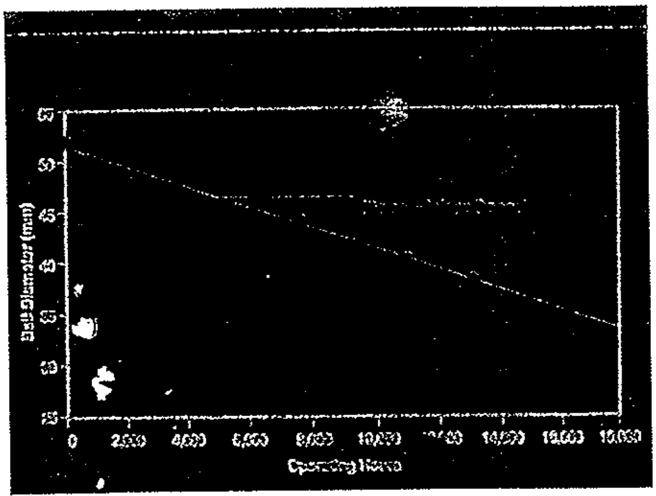

Fig. 2 — Actual marked ball wear test results.

$$\text{wear speed} = \frac{D_i - D_f}{t} \qquad (3)$$

Note that Eq. 3 is identical to Eq. 2 when the wear rate exponent, n, is equal to 2.

When evaluating results of a MBWT, it is important to compare the results in units of diameter loss per unit time (wear speed). In this form, the results relate directly to production wear rates. For a seasoned ball charge employing a single ball size recharge practice, the relationship between production wear rates and MBWT results is as follows:

$$WR = \frac{R\,(WS)\,(CW)}{(D_R - D_d)\,(\text{tph})} \qquad (4)$$

Where WR is wear rate in lb per ton, WS is wear speed in µm per hr, CW is charge weight in lb, D_R is ball recharge size in µm, D_d is ball discharge size in µm, TPH is feed rate, and R is purge period coefficient

$$R = \frac{4(1-\delta)}{(1-\delta^4)}; \quad \delta = \frac{D_d}{D_R}$$

It is important to note that Eq. 4 is valid only if the wear exponent is equal to 2. Also, it is for a *seasoned* ball charge with a single recharge size. Mills that have been classified and recharged with a ball size mix resulting in an artificial ball size distribution having greater or less total charge surface area than that resulting from a natural ball size distribution cannot use Eq. 4 to predict actual production wear rates. In these cases, the easiest solution is to use a computer program designed to keep track of ball size distributions and surface area changes, as discussed by Lorenzetti (1980).

The importance of Eq. 4 is that it demonstrates how wear speed is directly related to production wear rates. The same differences in wear rates measured in the marked ball wear tests are found in true parallel production tests. Furthermore, Eq. 4 also illustrates that ball quality is only one factor influencing the wear rate. Total charge weight, ball size, and the feed rate are equally important considerations. Table 1 summarizes the effects of various milling parameters on wear rate.

Results by application

Over the years, Armco Grinding Systems has conducted extensive MBWT's in all of the major milling environments. Results of these tests are summarized in Fig. 3.

Table 1—Factors that affect grinding media wear

	Factors	Trend	Effect
A.	Grinding Charge		
	1. grinding media size	> size	< wear rate
	2. grinding media distribution	> small size	> wear rate
	3. charge weight	> charge weight	> wear rate
B.	Ore		
	1. work index	> work index	> wear speed
	2. hardness	> hardness	> wear speed
	3. density	> density	> wear speed
	4. concentration/grade	> concentration/grade	> wear speed
	5. abrasion/nature of gangue	> silica contents	> wear speed
C.	Particles		
	1. feed size	> size	> wear speed
	2. product size	> size	< wear speed
	3. shape	sharp corners	> wear speed
D.	Slurry		
	1. corrosion	< pH	> wear speed
	2. viscosity	> viscosity	< wear speed
	3. % solids	< % solids	> wear speed
E.	Nature of Contact		
	1. impact velocity	> velocity	> wear speed
	2. impact angle	> angle	< wear speed
F.	Mill		
	1. discharge type	overflow → grate	> wear speed
	2. diameter	> diameter	> wear speed
	3. speed	> speed	> wear speed
G.	Circuit		
	1. throughput	> throughput	< wear rate
	2. circulating load	> circ. load	> wear rate
H.	Grinding Media Quality		
	1. hardness: - surface or avg. volumetric	> hardness	< wear speed
	2. grain size	> grain size	> wear speed
	3. C contents	> C contents	< wear speed
	4. alloy contents	> alloy contents	< wear speed
	5. shape	sphere	min. wear

Key

With (>,<) "Trend", the "Effect" (<, >): > = Increasing, < = Decreasing, > = Increases, < = Decreases.

Primary grinding-SAG mills

The highest wear speeds are measured in SAG environments, where large diameter balls [100mm-140mm (4-5 $^1/_2$ in.)] are used in mills with diameters up to 36' (11 M). In these environments, the wear speed is much less sensitive to the ore abrasiveness, and impact induced wear represents the largest component of wear. The presence of large impact forces in SAG mill environments is in good agreement with the conclusions reached by Dunn and Martin (1978) in their experiments studying the forces experienced by balls in tumbling mills. They concluded that the impact forces could exceed the yield strengths of grinding media materials, resulting in permanent deformation or fracture.

In a SAG milling application, a hot worked grinding ball has the advantage of retaining greater impact resistance at higher hardness levels relative to cast products (steel or high chrome). In order to survive the severe impact conditions, the cast products require lower hardness to obtain the necessary

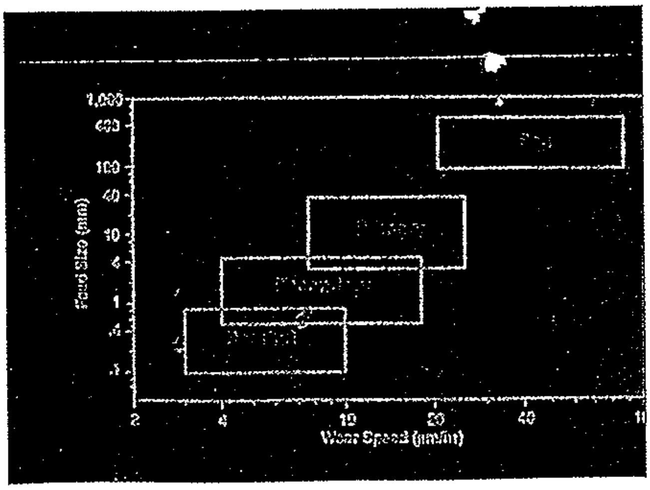

Fig. 3 — MBWT summary.

toughness. In the case of cast steel, lower hardness results in higher overall wear rates compared to forged steel. In the case of the cast high chrome alloys, the bulk hardness is reduced by tempering, but the microstructures still contain approximately 20 vol % eutectic carbides which provide excellent abrasion resistance. Consequently, a cast high chrome product at a lower hardness can wear equal to or slightly better than the forged steel product in SAG mill applications.

Unlike conventional ball milling, in SAG milling the wear speed of a ball is a function of both ball size and mill volume. The wear law for SAG milling predicts that as impact conditions increase, the ball's wear speed will increase. Table 2 illustrates how wear speed varies with ball size. In all three tests where a second (smaller) ball of equal metallurgical quality was tested, the measured wear speed was lower. These results help explain the observation that production wear rates can be similar for different size balls. The increase in the bigger balls wear speed offsets the reduction in the surface area of the corresponding ball charge so that the hrly consumption remains about the same. The effect of mill ball charge volume on wear speed in SAG mills was first reported by Tarifeno, et al. (1984). Tarifeno observed that in MBWT's conducted during times of different hrly recharge rates (corresponding to different ball mill volumes) that measured wear speeds varied significantly. Our own test work showed the same effect, and Table 3 lists Tarifeno's results along with our one observation. These results demonstrate that hourly ball consumption will not vary linearly with mill ball volume (as is true in conventional ball milling), but predicts ball consumption to increase rapidly as ball charge volumes are increased.

Table 2—Wear Speeds in SAG Milling - Ball Size Effect

Ball Size	Relative Wear Speed* Site 1	Site 2	Site 3
5" (125 mm)	100	100	—
4" (100 mm)	82	92	100
3" (75 mm)	—	—	65

* Lower values represent better wear resistance.

Table 3 — Wear Speeds in SAG Milling — Mill Ball Charge Volume Effect

Mill Ball Volume	Relative Wear Speed* Torifeno	Armco
High	100	100
Low	67	62

*Lower values represent better wear resistance.

Primary grinding-ball mills

The environment in primary ball milling can best be described by giving equal considerations to both impact and abrasive conditions. The relatively large ball sizes employed [75-100 mm (3-4 in.)] contribute a significant impact component to the overall wear. The number of impacts in primary ball mills are far more frequent but have less magnitude than those experienced in SAG mills. The increased frequency is due to the increase in charge volume (35 to 40% versus 5 to 10%), higher mill speeds, and the larger number of balls per unit charge weight. The lower impact forces are due to a combination of both smaller ball masses and lower drop heights resulting from the use of smaller balls and smaller mill diameters, respectively.

The feed ore in primary grinding mills is typically very abrasive owing to its particle size, shape, and mineralogy. Wear speeds approaching or exceeding 20 µm/h. have been measured for very abrasive gold, copper, and molybdenum ores, while wear speeds on the order of 10 to 15 µm/h. have been encountered in softer primary ores.

Steel grinding media used in primary grinding must be designed for maximum abrasive wear resistance while maintaining good toughness. Toughness is particularly important in grate discharge mills where pulp levels at the discharge end of the mill can approach zero (Mine and Smelter, 1979). Moroz and Lorenzetti (1981) found that maximum abrasion resistance is achieved by the combination of alloying with maximum amounts of carbon and heat treating the balls to their optimal microstructure.

High chrome media for primary grinding will typically contain maximum levels of eutectic carbide (30 to 35% by volume) and are heat-treated to their maximum hardness (HRC 65 to 68). However, not many high chrome balls are used in primary grinding because the improvement obtained in wear resistance relative to steel, typically 25 to 30%, is not enough to offset the higher cost.

In primary ball milling, wear speed is largely independent of ball diameter and mill volume (The same is true for secondary, tertiary, and regrind grinding). In these applications, Eq. 4 can be used to quantitatively predict how ball size and ball volume changes will affect wear rates. For example, a 5% increase in charge volume (42% vs. 40%) will increase hourly ball consumption by 5%. If a corresponding 5% increase in feed rate is not also achieved, then the wear rate (pounds per ton) will be increased. The same analysis can be made for ball size.

Secondary grinding-ball mills

In secondary ball milling, abrasive and corrosive conditions predominate. The smaller balls [< 65 mm (2 $^{1}/_{2}$ in)] typically used in secondary milling environments effectively reduce the impact component of wear to the point where grinding media must be primarily designed to reduce abrasive and corrosive wear. It can be seen in Fig. 3 that the range of wear speeds in secondary grinding widely overlap the range of wear speeds measured in primary grinding. This represents the large variations in abrasive and corrosive wear conditions found at the various testing locations. The best way to compare primary vs. secondary grinding conditions is to review MBWT data from primary and secondary applications for the same concentrator. This comparison is presented in Table 4. The wear speeds in secondary grinding are found to be 25 to 40% lower than those seen in primary milling when grinding the same, but finer, ore. This comparison shows that the reduction of the impact component of wear due to the smaller media size offsets the increase in an abrasive wear expected when grinding to finer product sizes.

Table 4—Comparison of Primary and Secondary Wear Speeds

Mineral	Application	Wear Speed Ball Size	Relative (µm/hr)	Wear*
Au Ore	Primary	3.5" (90mm)	24.0	100
	Secondary	2" (50mm)	16.2	68
Ag Ore	Primary	3" (75mm)	9.4	100
	Secondary	1" (25mm)	5.6	60
Cu Ore	Primary	3" (75mm)	11.2	100
	Secondary	2" (50mm)	8.3	74

* Lower values represent better wear resistance.

The performance of high chrome balls in secondary grinding depends on the abrasive/corrosive environment of the mill. In most secondary gold, copper, and molybdenum grinding, the relative wear rates of high chrome compared to forged steel show a performance improvement of 25 to 30%, similar to that seen in primary grinding. However, for corrosive environments with low abrasion, the high chrome ball can result in improvements of 50% or more compared to forged steel. This is particularly true for some secondary grinding (primary ball mills) of magnetic iron ores. In magnetic iron ore grinding, the silica levels are continually being decreased from crushing to rod milling to ball milling by intermediate concentration steps. Subsequently, the wear environment becomes progressively less abrasive. Meulendyke, et al., (1987) reported that it is in the low abrasive environments where the corrosive component of wear can become quite significant. In these environments, if the proper high chrome alloy is used to avoid corrosion pitting, then high chrome balls can become cost-effective.

Table 5—MBWT Results from Phelps Dodge Chino

Mill Type	Ball Size	Ball Type	Wear Speed (µm/hr.)	Relative Wear*
SAG	5" (125 mm)	Forged Steel	38.0	100
		High Cr	32.9	87
Secondary Ball	3" (75 mm)	Forged Steel	13.4	100
		High Cr	9.4	70
Tower Mill	1.5" (38 mm)	Forged Steel	6.6	100
		High Cr	4.1	62

*Lower values represent better wear resistance.

Secondary grinding-tower mills

Interest in tower mills has increased over the last several years due to claims of the increased energy efficiencies possible with these machines in fine grinding applications.

Recently, the Phelps Dodge Chino Mine tested a tower mill in a secondary grinding application. Concurrent with their test, a MBWT was undertaken to evaluate forged steel and hi chrome iron grinding balls in this non-traditional milling application. Results of this test are listed in Table 5 along with test results from earlier MBWT's conducted in Chino's SAG and secondary ball mills.

These results illustrate the influence of the impact component on overall wear rates. The absolute wear speed of both the steel and chrome balls vary by application, decreasing from SAG to ball to tower milling.

It is interesting to compare the ball mill results to the tower mill results since in this comparison the feed is identical, and the two notable differences are ball size and the lack of any significant impact in the tower mill. The results show that the absolute wear speeds of both the forged steel and cast high chrome balls are half in tower grinding, and that the relative wear rates between steel and chrome have remained essentially the same. Eq. 4 predicts that the wear rate measured in pounds per ton will remain the same when adjusted for unit charge weight. This is because, for a given charge weight, the surface area of the tower mill charge will be double the surface area of the conventional ball mill charge due to the ball size ratios.

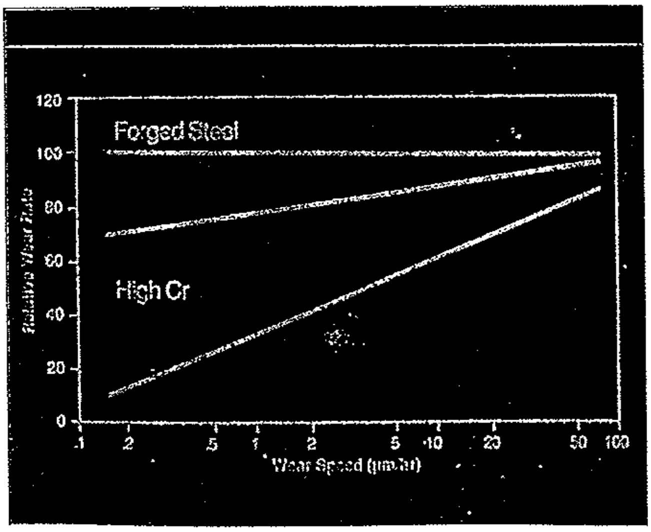

Fig. 4 — Wear rate of forged steel vs. high chrome.

Forged steel vs. cast high chrome

The decision of whether to choose heat-treated, forged steel media, or heat-treated, cast high chrome media must be made after assessment of the cost of each with respect to the expected consumption. Fig. 4 shows the relative wear rates of forged steel and cast high chrome measured in actual MBWTs conducted over the range of wear speeds.

As the overall wear speed (or wear rate) decreases, the relative wear rate of the high chrome ball improves, with the exact performance improvement being a function of the overall corrosivity of the slurry and the abrasivity of the ore. A summary by application is given in Table 6.

Table 6—Relative Wear Rates of Forged Steel Versus Cast High Cr

Application		Relative Wear Rate* Steel	Cr
Semi-autogenous		100	85 - 110
Primary		100	65 - 80
Secondary	- Au/Ag	100	55 - 70
	- Cu	100	65 - 75
	- Fe	100	40 - 70
Regrind	- Cu	100	70 - 80
	- Fe	100	30 - 50

* Lower values represent better wear resistance.

Summary

- The three recognized components of wear are: impact, abrasion, and corrosion. Impact wear is proportional to the ball's weight (μD^3) while abrasive and corrosive wear is proportional to the ball's surface area ($\propto D^2$).
- The wear behavior of grinding balls can be mathematically represented by the wear law equation:

$$\frac{dW}{dt} = kD^n$$

- The wear rate exponent, n, is essentially equal to 2 for conventional ball milling. When $n = 2$, the production wear rate is directly proportional to the wear speed, as determined by MBWT, according to the equation:

$$WR = \frac{R\,(WS)\,(CW)}{(D_R)\,(\text{Tph})}$$

In addition to wear speed, ball size, and recharge practice, charge volume and feed rate are significant factors affecting the actual production wear rate. Wear speeds are largely independent of ball size and ball charge volume.

- The wear rate exponent for SAG milling was experimentally determined to be $n = 2.8$. This corresponds to stating that impact is the predominant component of wear in SAG milling environments. At wear rate exponents greater than $n = 2$, a ball will wear at its greatest rate at its initial size. As the ball wears to smaller diameters, the wear rate decreases proportionally. In SAG milling, wear speeds are dependent on ball size and ball charge volume.

- The relative performance of high chrome balls to forged steel balls is dependent on the milling environment:

a) In high wear rate applications like SAG and primary grinding, the high chrome ball has 0 to 30% lower wear.

b) In low wear rate applications, the high chrome relative performance will depend on the corrosivity and abrasivity of the environment. In high corrosivity environments, the high chrome balls can have less than half the wear of forged steel.

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