Review Article

A discussion on the measurement of grinding media wear

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\textbf{ABSTRACT}

Comminution operations are the most expensive and energy consuming in the mineral industry. Any action aiming at reducing the costs associated with that step is welcome, and lowering the consumption of grinding media figures among the main concerns related to decreasing comminution costs. To reach that goal, it is necessary to know and understand the wear mechanisms that take place during the grinding process, as well as to consider the details of such process like the inhomogeneous feed and the interaction between mineral slurry and grinding media. Wet grinding can also add a corrosive component to total wear mechanism, and then wear rates are expected to rise from synergies between corrosive and abrasive components. Though corrosion phenomena are broadly accepted to happen in wet grinding – even when the ball alloy has high chromium content – studies on verifying its importance are scarce. Tests in laboratory mills can simulate most of the conditions present in the industrial mill, despite being inexpensive and much faster than the tests performed with industrial equipment.

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1. Introduction

The mining industry strongly depends on the comminution operations to promote mineral liberation. This stage is characterized by considerable consumption of power, as approximately only 10% of the power consumed is effectively spent in particles breakage [1].

Although there is some divergence regarding cost composition, the literature is unanimous in reporting that comminution may represent the highest cost in mining: Radziszewski [2] states that typical operational costs may be divided into extraction (30–70%), separation (5–20%), and comminution (30–50%); the latter being estimated at 50% due to power consumption and 50% due to the consumption of lifts and grinding media. Aldrich [3] confirms the data and adds that, in special cases, the consumption of grinding media may represent 40–45% of the comminution costs, whereas Sayadi et al. [4] have verified that comminution represents 40–50% of the whole operational cost.

The mills most used in mineral processing plants are the tumbling mills – a cylindrical metal housing, internally coated, and partially filled with ore, water and grinding media, which rotates around its horizontal axis. The grinding media may be the ore itself (autogenous grinding), bars, balls, or cylindrical, or even the ore itself together with a small amount of ball (semi-autogenous grinding). A survey found out that approximately 53% of the grinding circuits around the world use ball mills, and 38% use autogenous or semi-autogenous grinding, and therefore nearly 90% of mining operations are users of balls as grinding media [5].

Along the main goals of mineral processing, one must also list the reduction of the consumption of both power and grinding media, for both economic and environmental reasons [5]. To reduce consumption of grinding media, it is necessary to understand the wear mechanisms that are in action during the grinding process, considering the peculiarities of this process, i.e., the heterogeneity of the feed and the interactions between the mineral slurry and the grinding media, among others.

2. Literature review

2.1. Wear

Wear is the progressive loss of material from a solid body due to its contact and relative movement against a surface. The term wear is used to refer to both the wear process as to its result [6], and is known to lower the operational efficiency of machinery and its components, leading to a major source of costs in a number of industries [7].

A material’s susceptibility to wear depends on its physical and mechanical properties as well as on environmental factors, i.e., the conditions to which the material is exposed [8]. In other words, the wear is a function of the tribosystem (Fig. 1), which is made up of four elements: body, counterbody, interfacial element and environment. The action of each one of these elements can vary, as well as the interaction between them.

Some classifications of wear have been proposed in the literature. The most usual classification systems are according to: the wear mechanism, tribological action and appearance of the worn body, together with the type and shape of the wear debris. Choosing one or other classification system will depend mostly on the approach one wants to give to the problem.

Four basic wear mechanisms (Fig. 2) or any combination of them are involved in the wear process [9]. They are:

- adhesion – formation and breaking of interfacial adhesive bonds;
- abrasion – removal of material owing to scratching;
- tribochemical reaction – formation of chemical reaction products as a result of chemical interactions between the elements of a tribosystem initiated by tribological action;
- surface fatigue – fatigue and formation of cracks in surface regions as a consequence of tribological stress cycles that result in the separation of material.

During the wet grinding of an ore inside a mill, two of those mechanisms, abrasion and tribochemical reaction, are supposed to have a distinguished action over the others, and are going to be briefly discussed in the following sections.

2.1.1. Abrasion

Abrasion is the most common wear mechanism verified in industry, being accounted for more than half of the wear events [10] in several industrial segments. Concerning the mineral industry, abrasion is the major wear mechanism in mining, as well as in mineral processing operations [11].

Wear resulting from abrasion is called abrasive wear, defined as the loss of material due to hard particles or
protuberances that are forced against and move along a solid surface [12].

So, in abrasive wear, a sufficiently hard particle attacks the metallic surface at a favorable angle and acts as a cutting tool, removing scraps. This action is usually accompanied by great plastic deformation, accumulating displaced material in front of and beside the groove. The successive passage of the abrasive grain cyclically repeats these displacements, leading to material removal by low cycle fatigue. The first mechanism – micro-cutting – is much more effective, and it is favored by the following characteristics of the ore: high hardness, elevated grain size, and angular shape of the grain [13]. The presence of scratches, risks and grooves on the worn surface can be indicative of the occurrence of abrasive wear.

The origin of abrasive particles can be as diverse as wear debris, oxidation products or even from outside the tribosystem. Considering a wet grinding system, the abrasive element would be the mineral particles themselves.

2.1.2. Tribocorrosion

The interaction between tribological and electrochemical effects makes the materials wear out at a different rate from those observed under individual conditions. This phenomenon is called tribocorrosion, which refers to the surface degradation mechanisms resulting from the interaction between mechanical wear and electrochemical processes [10].

The subject concerns the interaction of corrosion and erosion, abrasion, adhesion, joints and fatigue. It is usually related to the synergy resulting of the combination of mechanical and environmental effects, although in some special cases that couplement can be antagonistic.

Wear accelerated by corrosion depends on two factors: firstly, the area on the metal that depassivates at each abrasion event, and secondly, the amount of metal that has to oxidate for the exposed area to passivate.

Corrosive wear has been described as the loss of metal due to chemical and electrochemical reactions to the environment, that is, mineral slurry and oxygen [14]. In the ASTM definition, the generic term “corrosive wear” is the “wear in which a chemical or electrochemical reaction to the environment is significant”.

Depending on the structure of the tribosystem, physical and chemical interactions among their elements can result in material detachment from the surface of the body and/or the counterbody [10].

Mischler et al. [15] describe that the total wear verified in tribocorrosion is a function of metal degradation and particle degradation. The metal degradation can occur due to fragment removal caused by one of the basic wear mechanisms (adhesion, abrasion, fatigue) or by electrochemical oxidation of the metal surface.

Particle degradation occurs in the contact area, and includes oxidation of the metallic fragments removed from the surface, which can be reincorporated into the oxide layer formed on the metal, or can be ejected from the contact, and in that case, they are called wear debris. At first, detached particles from the metal surface could be reincorporated and oxidized, forming a more compact, thicker oxide layer. The reincorporation of those particles is affected by their ability of deformation and adhesion to the metal, and both phenomena are influenced by the nature of the metal and by surface chemistry effects [15].

So, not every particle (or debris) detached from the metal surface is necessarily ejected out of the tribological contact, as they can be reincorporated and oxidized before they are released in the environment.

In the presence of the passive layer, though, the reintegration of particles by recovering becomes more difficult, thus enhancing wear. Additionally, corrosion accelerated by wear may contribute significantly for the material degradation at passive potentials [15].

2.1.3. Passivity

A number of materials take advantage of their ability of forming a film to resist corrosion. This film is called passive layer, formed by oxides, and constitutes a barrier to the charge transfer between the active metallic surface and the corrosive environment, making the corrosion rate so low that corrosion is barely noticeable.

The passive layer can be removed by mechanical efforts and in the areas where it happens, the electrical charges transfer, that characterizes the corrosion phenomenon, takes place again until the layer is recomposed [10].

Some elements present in the alloys, such as chromium, are known for their ability to form the passive layer. In alloys with significant chromium content, the passivation occurs according to the following mechanisms: chromate reduces to trivalent chromium oxide, forming a protective oxide film. Along with that, a mixed oxide film of chromium and iron hinders its breakage or eases the reincorporation of the detached particles to the film itself. Once the film is formed, the formation process stops, unless there is its rupture. For instance, the film removal by abrasion allows the reduction of chromate to take place repeatedly [15].

Similar tribochemical processes occur in surfaces in contact by sliding. The interaction of the films formed generally lead to a thinner passive layer, thus increasing the contact rate.
results in mechanically mixed layers, of nanometric thickness, formed in the shear zone between the contact surfaces. Those layers are a mixture of the components of both surfaces, originated by material transfer, product of corrosion, wear debris, and remanences passive layers, and is usually referred to as tribofilm [10].

2.2. Materials used to manufacture grinding media

Selecting a material for grinding media must take into account its resistance to wear, the availability of suppliers and the considered grinding system (ore characteristics, grinding parameters, etc.)

A wide array of materials is used to resist wear in comminution processes [3]. The main factor that influences the absolute wear rate of a grinding body is the abrasiveness of the ore, but the choice of material for the grinding body must balance characteristics as conflicting as high hardness—which maximizes abrasive wear strength—and adequate ductility—to avoid sudden ruptures and chipping.

The main materials that are commercially used for grinding bodies are steel and high-chromium white cast iron.

The major commercially used steel for balls is the low alloy high carbon steel. High carbon steels (0.6–1.4% C) are the hardest, strongest, and least ductile among all types of cast steel. They are generally used in their hardened, tempered form, which grants them expressive strength against abrasive wear as compared to other steels.

High-chromium white cast irons (HCCIs) are alloys based on the Fe–Cr–C ternary system. The amount of chromium varies from 12 to 30% and the amount of carbon from 1.8 to 4%; in commercial alloys, from 0.3 to 1.2% of silicon, besides manganese, are added [16]. These are highly wear-resistant alloys, widely used in the mining industry, both in mining and in the mineral processing operations, and particularly in the manufacture of mill balls [16,17].

The wear strength of HCCIs is attributed to the presence of M7C3 carbides in their microstructure, as they make the material more resistant to scratching, that is, they hinder abrasive wear [16,17]. This carbide represents 10–40% of the alloy volume, and its hardness ranges from 1400 to 1800 HV, harder than quartz (1000–1200 HV), which is the main responsible for wear in mining. The influence of the carbon content is connected to the formation of M7C3 carbides, and consequently, HCCIs with higher carbon content have higher wear strength than HCCIs with less carbon [17].

The raw casting microstructure of the high chromium white cast iron is usually quite heterogeneous, depending on the chemical composition of the alloy, segregation of elements during solidification, and cooling rate. The homogenization of this structure may be promoted by heat treatments, which cause the formation of the most wear-resistant micro-constituents. For most applications, that is obtained by a treatment to destabilize austenite, followed by quenching [16].

However, the wear strength of HCCIs will only be reached if the metal matrix can adequately support the carbides; otherwise, they may be fractured and removed from the matrix through the action of abrasives [18].

2.3. Wear of grinding media

One of the major problems regarding the use of ball mills is to balance the size distribution of grinding media into the mill, which is determined by the speed of consumption and rate of replacement [3], as the wear of the grinding balls requires their substitution at intervals. The consumption of the grinding media represents an expressive part of the grinding operational costs; it may reach up to 40% of the costs in a mineral processing unit [19], and wear constitutes around 60% of the cost relative to ball mills [4]. Gates et al. [20] stress the importance (also economic) of maximizing the service life not only of grinding media but also of liners and lifters in the mills.

The wear of grinding media in wet processing results from abrasion, corrosion, and impact mechanisms; however, the relative contribution of each of these mechanisms has not yet been perfectly established [2]. The great number of variables involved, as well as their interaction, combined with the difficulty in directly observing these variables, makes quantification of wear of grinding media a considerable challenge [3].

Whereas, crushing is a dry process, grinding is usually a wet process. Dry grinding is only used when water is scarce or it is important not to wet the material to be ground, as in the case of Portland cement or kitchen salt, or when there is an attempt to minimize the contamination of the grinding product by the iron debris from the grinding media and liners. The addition of water to form the slurry helps moving the ore inside the mill, dissipates heat from the operation, and avoids dust; on the other hand, the contact of minerals with water releases ions in solution. Therefore, in wet grinding, there is a change in the order of magnitude of the wear, frequently attributed to the occurrence of corrosion, as these ions may add a component of corrosive wear, which will act in synergy with the abrasive component [19,21].

Bond [22] estimated the wear of grinding balls in wet grinding as being seven times greater than that verified in dry grinding. Iwasaki et al. [23] however, draw attention to the fact that dry grinding mechanisms are essentially distinct from those in wet grinding. In dry grinding, the mineral particles strongly adhere to the balls, covering them and limiting the continuous exposure of their surface to abrasion. In wet grinding, the slurry must have a percentage of solids on order to cover the balls and thus avoid direct contact of metallic surfaces yet not cushioning the movement of the grinding media, which would drastically reduce the grinding efficiency. Therefore, it is clear that the data obtained in dry grinding may not be used to represent the abrasive component of wear in wet grinding.

Although the occurrence of corrosion in wet grinding processes is nearly consensual, its importance is not well documented [24]. The results obtained by some researchers suggest that corrosion is not only important, but it may be the dominant process of metal removal in wet grinding. In laboratory-scale batch grinding, corrosion may represent from 25 to 75% of the metallic wear, depending on the ore, metal, and environmental conditions involved [24].

In fact, wet grinding gathers all the necessary elements for the occurrence of an active corrosion process: large surface
area of the grinding media, an even larger surface area of ore being ground, an open circuit corrosion potential in the mineral particle, more noble (cathode) than the grinding media (anode), and continuous abrasion which removes any protective film that may have formed on the surface of the grinding media [21]. Additionally, the abrasive wear produces fresh surfaces, ready to undergo corrosion, and the corrosion product is easily removed by the different abrasion mechanisms. Local galvanic cells may take place between the grinding media and the slurry, which is eased in the presence of oxygen.

Iwasaki et al. [14] proposed a corrosion model for the grinding media, involving two types of galvanic cells, as shown in Fig. 3. In the differential abrasion cell, the abraded surface acts as an anode, whereas the un-abraded surface acts as a cathode, and the corresponding corrosion reactions are iron oxidation in the first area and oxygen reduction in the second. The second model involves galvanic interaction between the mineral and the grinding ball. Mineral particles (mainly sulfides) act as cathodes and the balls as anodes, and this galvanic coupling accelerates wear.

Synergy between abrasion and corrosion includes both the effects of corrosion on the increase of abrasive wear and the influence of the latter in the acceleration of corrosion [25]. For example, corrosion may increase the wear rate of a metal when it generates products that weakly adhere to the surface, and which may be easily removed by abrasion. Abrasion, in turn, may punctually accelerate corrosion by breaking the fragile superficial passivation film which protects metallic alloys against corrosion. In that case, the acceleration of the corrosive process will depend on the repassivation rate and on the intensity of wear [26].

The presence of some anions in industrial waters can have an effect on corrosion, and chloride ions are reported to be the most damaging to the grinding media [27].

2.4. Grinding media wear assessment – laboratory tests

Rendón and Olsson [11] observed that rocks and minerals subject the mining equipment to severe wear conditions, which has led the mining industry to consume growing amounts of wear-resistant materials. In handling and transport operations, it is often possible to reduce the wear of components by introducing changes to the equipment, so that it reduces the intensity of the interactions between abrasives and metal. But in comminution operations, the size reduction phenomena directly depend on such interactions and those changes are nearly unfeasible [20]. Hence, comminution plant operators must select the best wear-resistant alloy as a way of maximizing the life of wear components.

However, the practice of developments regarding wear-resistant materials is not easy, as in laboratory the abrasive/metal interaction conditions are very different from those found in practice [11]. That is the reason why the results of those tests tend not to find great acceptance by the industry.

Laboratory tests, as pin abrasion tests, rubber wheel tests, or dry wheel tests can be easily carried out at low cost and allow to cover parameters relative to wear-resistant materials. It can also allow the verification of the effects due to operational variables, such as hardness and grain size of abrasives, as well as loads and speed [28]. Those tests are usually not well accepted as performance indicators of these materials in industrial grinding equipment, as the tribological systems considered differ greatly from those observed in the industrial practice [7,28]. However, most results found in the literature regarding wear resistance for white cast irons and steels were obtained this way [28].

The first attempts to develop tests for the assessment of wear of grinding balls in grinding mills date from the 1940s [23]. In 1942, the idea of assessing the wear by marking some of the balls from the mill load was raised, carrying out the test in a batch ceramic mill. Later, in 1948, other researchers introduced marked balls in industrial mills [23].

However, the tests on grinding media in industrial conditions are costly and time-consuming, both for the suppliers of those components and for the users. Besides, they present serious methodological problems regarding the control of experimental conditions, as there is no practical possibility of prioritizing the maintenance of constant conditions of operation – essential for a performance comparison – in detriment of the production needs. In such conditions, it is nearly unfeasible to keep all the variables that may affect the results under control. Those variables are temperature, moisture, speed, size of abrasive particles, ore characteristics, among others, which limits the validity of industrial tests to the specific conditions they are carried out in [7,20,28]. Also, these tests may only be conducted at a very advanced stage of negotiations between supplier and consumer of the balls, being more often used for the approval or not of a potential supplier [28].

Therefore, a good wear test must meet three requirements: reproducibility, capacity to establish performance ranking and transferability to practice, verified by its results in service [28].

The use of laboratory mills is an alternative to performing grinding media wear tests, which are inexpensive and less time-consuming than the tests in industrial mills. In that type of test, mills of up to 1 m diameter are used, and it is possible to reproduce the interaction between bodies and abrasive media found in practice, with the exception of the intensity of impact. It is also possible to introduce and control operational variables (such as abrasive grain type and size, percentage of solids in the slurry) and variables relative to the wear-resistant material, thus allowing these tests to be used for materials development.

Tests in laboratory mills are described in Albertin and Moraes [29], Cassola et al. [28] and Albertin [13]. Their experiments were performed in a continuous grinding pilot plant,
equipped with a 40-cm diameter mill in closed circuit with a cyclone, and the wear of grinding media was assessed in the marked balls. The results obtained from those tests allowed them to organize rankings of materials performance, which were validated in industrial tests. Gates et al. [20] corroborate the validity of the results obtained in laboratory mills to evaluate wear resistance of grinding media.

The methodology used in [13,28,29] was effective in determining the overall wear rate of grinding media, but provided no information about the contribution of abrasion and corrosion to that rate. Massola [30] found a qualitative correlation between the overall wear rate of steel and high chromium cast iron balls and the electrochemical behavior of those materials in iron ore slurries, but could not assess a quantitative contribution of each wear mechanism.

The mathematical treatment of data obtained in laboratory grinding mill may consider volumetric or superficial variation [19].

The volumetric theory of ball wear states that the rate of a ball is proportional to its mass and, therefore, it is also proportional to the cube of its diameter (that is, to its volume). The origin of this theory considers that most comminution events result from impact mechanisms— which do not occur in laboratory mills, given their reduced diameter as compared to industrial mills. In general terms, it would be best applicable to grinding processes fed mainly with coarse materials. The linear (or superficial) theory of wear, in turn, considers that most comminution events occur due to the abrasion mechanism ball-particle-ball; in this case, the wear rate should be proportional to the surface of the ball, that is, to the square of the diameter. This is the most widely accepted theory at present to characterize the constant yet slow consumption of grinding media in rotary mills.

According to the linear theory of wear [31], at each instant “t” after the grinding body is thrown against the mill load, the rate of its mass loss will be directly proportional to the superficial area exposed to the gradual abrasion and/or corrosion mechanisms.

3. Conclusion

This article aimed to review and discuss the available literature on the wear of grinding media. The consumption of the grinding media represents an expressive part of the grinding operational costs, reaching up to 50% of it.

During grinding, a combination of abrasion, corrosion and impact results in wear of grinding media. The influence of corrosion on the wear mechanism of balls is still not well explored, constituting a research theme on which there is much work to be done.

The performance of grinding media is directly related to the operation settings in which they are used: type of ore to be ground, pH, the presence of anions in the slurry, among others; as a result, tests to assess this wear must consider those conditions.

Laboratory mill tests can be an alternative to assess the wear of grinding media, as they can reproduce, at least partially, the conditions of an industrial ball mill. Moreover, they are less expensive and less time-consuming than the tests performed at industrial mills. Furthermore, it may contribute to the development of materials for grinding media, as well as offering users an efficient tool for the quality control of this essential supply.

Conflicts of interest

The authors declare no conflicts of interest

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