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Review

A Review of the Grinding Media in Ball Mills for Mineral Processing

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Abstract: The ball mill is a rotating cylindrical vessel with grinding media inside, which is responsible for breaking the ore particles. Grinding media play an important role in the comminution of mineral ores in these mills. This work reviews the application of balls in mineral processing as a function of the materials used to manufacture them and the mass loss, as influenced by three basic wear mechanisms: impact, abrasion, and corrosion. The effect of grinding media geometries and density on the mill performance was also reviewed to determine what the research has recommended as the most suitable grinding media for different grinding applications. Although considerable work has been carried out in that area, the influence of grinding media shape on the liberation of minerals, as well as the effect of various mill conditions on the performance of mixed grinding media shapes, are still poorly understood. Thus, the review opens up opportunities for further research to improve the grinding processes, especially considering that even a slight improvement in the process efficiency significantly reduces the production costs.

Keywords: grinding media; ball mill; comminution; ball size distribution; wear; alloy; cast iron

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1. Introduction

The mining industry has been battling decreased head grades and increasing mineralogy complexity over the years, owing to the rapid depletion of high-grade ores. This has seen the processing of low-grade ores taking center stage and now almost dominating the industry, forcing many mines to upgrade the size of their tumbling mills to increase the mill throughput.

Tumbling mills convert electrical energy into mechanical energy, generating many fracture opportunities in the process. They all effect particle breakage using the same basic principle, regardless of the grinding media used. The grinding media impart the forces required for size reduction [1] and determine the category of tumbling mills: autogenous, rod mills and ball mills. Autogenous and semi-autogenous mills are used in primary grinding whilst rod and ball mills are used in secondary grinding, with the ball mills being the most commonly used. The ball mills are either used in a dry-milling or wet-milling set-up depending on the needs of the industry in which they are utilised. The cement and pharmaceutical industries normally use dry grinding whereas the mineral processing industry mostly resorts to wet-milling. In mineral processing, grinding, which is key to the liberation of valuable minerals from gangue, is achieved in primary, secondary and tertiary applications as well as regrind mills. These mills are further categorized by the nature of the discharge configuration: trunnion overflow mills operated in open or closed circuits or grate discharge mills [2].

On the one hand, the grate discharge mill, as the name implies, is fitted with a discharge diaphragm or grates between the cylindrical shell of the mill and the discharge trunnion so that particles greater than the openings of the grate are not discharged. In this mill, particles are barely overground, resulting in the discharge of a larger percentage of coarse particles. On the other hand, the overflow discharge mill, which is most widely used due to its simplicity, has material fed through the trunnion at one end and discharged through another trunnion at the other end as overflowing pulp. In both types of mills, a portion of the charge is lifted along the perimeter of the shell during the mill rotation and, after exceeding the angle of repose, part of it slides down while the other part cataracts and drops to the toe of the shell, imparting the grinding action in the process. The impacts resulting from the falling balls are considerably significant in the grate discharge owing to the continuous draining of the slurry during the grinding process, whereas the presence of a slurry pool in the overflow mill gives rise to very insignificant impacts between the balls and particles. This therefore translates to different media wear dynamics in these mills and, eventually, media consumption. In a grate discharge mill, the impact is a major player in the media consumption, followed by abrasion and corrosion, which are considerably lower because there is limited slurry pooling. However, in overflow mills, the wear mechanisms are mostly dominated by abrasion and corrosion, which is an offspring of the frictional force from slurry [3].

Therefore, the grinding action is achieved by attrition, abrasion, and impact between the ore itself and between the ore particles and grinding media [4]. Factors that influence the grinding efficiency include mill design, liner design, mill speed, mineralogical composition of the ore, charge ratio, and grinding media properties [5]. The grinding efficiency of a ball mill is determined by the product size distribution, energy consumption, and the grinding costs. According to Hassanzadeh [6], about 37% of the costs are used for grinding media only,13% for liners, and about 50% is used for energy in an industrial ball mill. This is evidence that media consumption has its fair share of the operating costs of the beneficiation process of ore. Thus, it became a fertile field of research, with many grinding-media-related papers produced, which are worthy of review work.

It is important to mention that the media wear phenomenon is complicated in both mills and is also influenced by the operational parameters, which are complex and interactive in nature. These parameters are the fractional ball filling (J), the fraction of critical speed (fc), the fraction of the mill volume filled by powder (fc), powder filling (U), solids concentration, and ball and feed size distributions. For instance, Gupta and Yuan [1] observed that a corresponding 2% of ball grinding media is consumed for every 1% change in mill speed. At a low mill rotational speed, Soni and Mishra [7] perceived that bigger balls move near the periphery of the mill and smaller balls clutter around the kidney of the charge, in which very little grinding work is performed. The small media in the kidney rub against each other and wear into cubic shapes. At higher mill rotational speeds, Soni and Mishra [7] observed that it is the bigger balls which occupy the kidney area, while smaller balls move closer to the periphery. However, at intermediate speed, the charge dynamics attain a perfect transition state, representing the uniform distribution of contacts.

Volumetric mill filling also influences grinding media wear rates, among other performance parameters. The effect of the kidney-shaped is more pronounced by the volumetric mill filling, which is composed of ball filling and slurry filling. When the charge of a volume is equal to or greater than half the volume of the mill, it hinders the free fall of the grinding media, which holds the charge together, thus expanding the kidney-shaped mass. Conversely, when the size of the charge is optimal, the kidney-shaped mass is small, which gives the balls room to fall from the free maximum height. When the mill is overloaded, fines accumulate at the toe of the mill, which promotes the cushioning effect. The cushioning effect absorbs the impacts that affect particle breakage. Also, the direct proportionality relationship between ball wear rate and the surface of the media charge led Clermont and de Haas [8] to conclude that higher ball filling promotes the extensive wear of balls. Through monitoring interactions between pulp angles and media angles to detect load expansion, the authors observed that at high ball filling, a certain percentage of balls roll down without breaking any particles, instead wearing each other.

To date, considerable work has been carried out to understand the role of grinding media in mill performance and important factors that influence their operations. This review paper is mainly going to focus on the work done so far, zooming on the applicability of different types of media considering the mineralogy, the mechanism of grinding wear, and the effect of grinding media shape, size, and density on the mill performance with reference to the mineral processing industry. This is based on the understanding that grinding media directly affects energy consumption, product size, and consequently the grinding costs [9], and that proper selection of the grinding media reduces energy and material consumption in a ball mill. Also, different performances are achieved when different sizes and shapes of grinding media are used [10]. Good grinding media should have high wear and impact resistance and last longer, thus increasing their service life and that of mill liners, and hence reducing the cost of comminution.

2. Grinding Media Materials and the Applicability of Grinding Media

Grinding media are the main components of the grinding process involving a ball mill. Research has been carried out to select the most suitable materials to manufacture improved grinding media [11–14]. Although the selection of grinding media is generally based on wear, it is also influenced by other parameters, such as the mineralogy, the water chemistry, and the mill characteristics. Good grinding media should have high hardness, fracture toughness, wear resistance and corrosion resistance, but at the same time, should have adequate ductility to minimize sudden ruptures and chipping. Grinding media can be classified according to the materials used to manufacture them (cast iron or steel), according to the process used to make them (forged or cast, rolled) or according to shape (cubes, spheres ellipsoids, cylinders). It is interesting to note that although iron, steel, chromium alloys (Cr 15%–30%), ceramic and pebble are used to make various grinding media used in industry, iron, and steel balls, grinding media are widely used in various grinding applications on account of their low cost [15]. The grinding media significantly influence the downstream process behaviour through the grinding chemistry, such as the floatation of the PGMs and, eventually, the recovery of the minerals in UG2 ores [16]. Although there are several types of grinding media, which include inert grinding media such as ceramic, zirconia, agate, and glass, this section is going to focus on cast iron and steel grinding media, together with their applicability in ball mills. Cast iron carbon content is generally between 2 and 4 wt. %, whereas steels contain a carbon content of less than 2 wt. %. Alloys are made by the addition of alloying elements like chromium, nickel, molybdenum, and manganese.

2.1. Cast Iron Grinding Media

Cast iron can be grey or white, but white cast irons are commonly used in abrasive wear applications in the comminution process. Cast iron grinding media are one of the ancient media, which were first used in mineral processing and can be grouped into cast low-chrome and high-chrome white iron [17]. The cast irons are heat-treated to adjust the amount of retained austenite and vary the carbide size and distribution, resulting in a microstructure with superior hardness and abrasion resistance. High-chromium cast iron is ferrous-based, and alloyed with 11–35 wt.% chromium and 1.8–7.5 wt.% carbon. Thus, their excellent wear resistance is due to the high-volume fraction of hard chromium carbides, which forms in a softer ductile matrix. The chrome carbides in the matrix provide superior corrosion resistance. Gates et al. [18] found that high-chromium white cast irons are better than martensitic steels for highly abrasive wet grinding conditions using five abrasives (slag, ilmenite, staurolite, quartz and garnet). According to Rajagopal and Iwasaki [19], the wear rate of high-chromium white cast irons was 10 times lower than that of cast or forged steel when used in dry grinding applications. Rahman et al. [20] found high-chromium cast iron (HCCI) balls, which are alloys based on the Fe–Cr–C ternary system, to have excellent wear resistance, which, in turn, can be widely used in mineral processing, coal, and cement. The amounts of chromium and carbon in HCCI balls vary from 12% to 30% and 1.8% to 4%, respectively, and that makes them wear-resistant and suitable for manufacturing mill balls. Their wear resistance is due to the presence of M_7C_3 carbides in their microstructure. Chenje et al. [21] compared five types of grinding media balls (eutectoid steel, low-alloy steel, medium-chromium cast iron, cast semi-steel and unalloyed white cast iron) and found that heat-treated medium chromium (HTMC) cast iron balls had superior qualities in terms of microstructure and wear resistance despite, their high cost per ton. The cast irons had a relatively high carbon content in their microstructure, which gave them high hardness compared to other ball types. The hardness of HTMC balls was higher than unalloyed cast iron (UCI).

Zhang et al. [22], conducted a comprehensive study comparing the performance of cast iron and ceramic-based media. Their results show that a higher recovery of chalcopyrite was achieved with the use of ceramic-based media. This was among other factors caused by the lower pH and Fe^{3+} concentration in the pulp obtained by the ceramic media compared to cast-iron-based media. The cast-iron-based media also produced products with a high surface roughness and serious corrosion, in contrast to those yielded by the ceramic-based media, which had more even and smoother surfaces that led to better hydrophobicity and floatability. This aligns with Nie et al. [23], who found that grinding sphalerite with ceramic media produced a weaker electrochemical interaction than that with cast iron media, and they attributed this to the existence of the only local cell action of sphalerite for ceramic balls.

Johnson [24] proposed that an improved media performance, reduced media wear and cleaner floatation with low reagent consumption and improved floatation kinetics is achieved when non-steel-based media is used. Earlier studies have also shown that high-chromium balls with only hard martensite exhibits increased wear under an oxygen environment, whilst those with both soft ferrite and hard martensite exhibited decreased wear. However, Bruckard et al.'s [25] review has shown that chrome alloy balls limit the formation of hydroxides in the pulp in some systems, which benefits the floatation performance.

2.2. Steel Grinding Media

Steel grinding media are usually forged, and water-quenched. Their properties are governed by their carbon content, alloying element content, and heat treatment. Most commercial grinding media at present are produced from martensitic low-alloy steels. The grinding media can adapt to most milling conditions and have a favourable cost-to-wear ratio. Low-alloy high-carbon steels are the strongest, hardest, and least ductile; therefore, they offer high resistance to abrasive wear compared to other steels when used in the tempered form [26,27]. Their hardened and tempered form render them extensive strength against abrasive wear as compared to other steels. High-chrome steel-grinding media are an economical media based on their wear performance and the positive change they provide in pulp chemistry, which may affect subsequent processes. The results obtained by Cullinan et al. [28] showed that the floatation recovery of galena using high-chrome steel balls (26% chromium) was higher than that obtained using high-carbon steel balls (1% chromium) during floatation. Mu et al. [29] found the same results when 30% chrome steel media produced the highest pyrite recovery of 91.3% compared to forged steel-grinding media, with 59.1% pyrite recovery in a laboratory rod mill at a pH of 5–7. Experimental results by Song et al. [30] revealed that chrome steel balls had higher recoveries for UG2 PGM ore than forged and stainless-steel balls. These results are consistent with what Xu et al. [31] found. However, further studies by Mu et al. [29] at a pH of 8.5 produced contrasting results, whereby the highest pyrite recovery of 60% was obtained using forged steel compared to 30% chrome steel, which had a recovery of 14.6%, although forged steel-grinding media produced the highest iron contamination. This may be attributed to the difference in interaction between the collector, mineral surface, ions in solution, and the grinding media at different pH values. Corin et al. [10] found that the floatation recovery of nickel and copper from a base metal sulfide was higher when the ore was ground with forged steel balls compared to 21% chrome steel balls. From the reviewed studies, it is interesting to note that high-chrome steel-grinding media are mostly used when there is great concern regarding contamination in downstream processes.

A comparison of steel balls with other media has shown that they are outperformed for some ores by other grinding media. For sulfide ore, inert grinding media such as ceramic ball or pebbles have shown a superior performance to steel pebbles. This is due to the sulfide mineral surface being covered by the iron hydroxides produced by oxidation, which then negatively influence the floatation behavior during the downstream process [22]. A similar floatation behavior was also observed for galena particles when ground by mild steel balls. Furthermore, Liao et al. [32] also reported the negative influence of steel medium grinding on the floatation of chalcopyrite due to the formation of oxidation species on its surface. However, as for pyrite processing, grinding with steel balls proved to be better, and is therefore used for copper-activated marmatite floatation [33].

3. Mechanisms of Grinding Media Wear in Ball Mills

The performance of grinding media in a ball mill is measured in terms of wear rate, which is a function of the media composition, hardness, phase structure, and corrosive–abrasive characteristics of the slurry. The wear mechanisms involved in a ball mill are impact, abrasion, corrosion, and erosion. Their individual contributions are difficult to assess during the grinding process owing to their complex interactions and thus have not yet been perfectly established [19]. Over the years, various methods of assessing grinding media wear rate have been developed, including pin abrasion tests, rubber wheel tests, or dry wheel tests, but the marked ball test is the most used. In that test, several balls are loaded in the mill, with unique marks for each ball, and the average mass loss during grinding is determined by weighing the balls before and after grinding [34]. However, the marked ball test can result in marked ball anomaly when interpreting the results, especially when the marked ball is more durable than other balls of the same type. Iwasaki et al. [35] successfully investigated the effect of different milling conditions (wet, dry, organic liquid) on the wear rate of mild steel, high-carbon low-alloy steel (HCLA), and austenitic stainless steel, using the marked ball test. Austin et al. [36] mentioned that the wear rate is also crucial for the determination of the the best mixture of make-up ball size that would provide steady-state conditions. The number of balls in the make-up must be equal to the number of balls worn below a certain size.

3.1. Corrosion Wear

Corrosion wear is the loss of material on the grinding media surface due to galvanic interactions between the ore (cathode) and the grinding media (anode) or between the abraded and unabraded points on the surface of the grinding media due to differences in electrochemical potentials, as shown in Figure 1 [37]. Mass loss by corrosion is due to oxidative electrochemical reactions where oxygen is reduced and iron is oxidised. Iwasaki and Rajagopal [19] outlined that corrosion wear depends on the abrasion and corrosion resistance of the grinding media, the presence of oxygen in the mill and the abrasiveness and electroactive nature of the ore. Corrosive wear is greatly dominant in wet grinding when using ferrous grinding media and is responsible for up to 50% of ferrous grinding media consumption [38]. Despite the widely accepted phenomenon that wet grinding is a fertile environment for corrosion wear regardless of the chromium content of the balls, studies to verify its importance are few and far between [39].

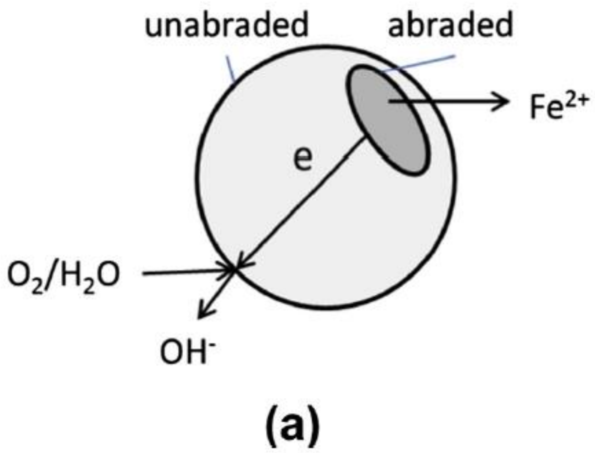

Figure 1. Showing corrosion wear for (**a**) differential abrasion cell (**b**) ball—mill galvanic cell. Adapted from [37].

The extent of grinding media wear is governed by ore mineralogy, media characteristics and process conditions, such as pH, among other operational parameters. Iwasaki and Rajagopal [19] proposed a direct proportionality relationship between the corrosion resistance of ball materials of any composition and the pH of the slurry. The pH, along with the metal solution potential and the composition of the metal solution, plays an important role in maintaining a thin passive layer with low electrical conductivity that is stable on the media surface, thus strengthening the corrosion resistance. Results found by Pazhianur et al. [40] showed that the corrosion rate increased with a decrease in the pH of the solution. The corrosion inhibitors also help to reduce ball wear during the wet grinding process, and they depend on the nature of the mineral slurry to maintain a passive film on the surface of the balls, thus reducing the wear of balls [19]. However, if the inhibitor is wrongly chosen, the downstream process suffers, especially if it involves floatation, since this could negatively affect the surface property of the ground mineral, and hence the floatation behaviour. Also, when grinding sulfide ores, the freshly abraded surfaces may coat the ore particles, affecting the interaction between the grinding media and the ore and hence lowering the corrosion rate. This effect is more pronounced when dealing with magnetic ores. Furthermore, some sulfide ores behave differently in the presence of oxygen. A review by Aldrich [37] showed that the corrosion rate when milling galena decreased through an oxygen-scavenging mechanism whilst the corrosion rate increased through galvanic coupling when milling chalcopyrite.

In some instances, corrosion is accelerated by abrasion when it generates products that weakly attach to the surface and are easily abraded away. Abrasion achieves this by breaking the fragile superficial passivation film that protects the metallic alloys against corrosion. The wear rate would then tend to depend on the re-passivation rate and the intensity of wear [39].

Chromium grinding media possess a high corrosion resistance in the presence of oxygen. An increase in chromium content augments corrosion resistance but the resistance is somehow compromised by the formation of chromium carbides, which consume a large proportion of the chromium. Rajagopal and Iwaski [19] found that there is a critical chromium level above which no pitting corrosion is observed. Allahkarami et al. [41] also found that the galvanic interaction between galena and the grinding media significantly decreased with an increase in chromium content. Findings by Fletcher and Moats [42] confirmed that the increase in chromium content increases the corrosion resistance of grinding media in high-chrome white cast irons. The presence of chromium causes a passivation effect, whereby a protective oxide layer is formed on the grinding media surface after the rapid initial corrosion of the grinding media surface [39]. Austenite and ferrite in high-chromium alloys have a better corrosion resistance than martensite. According to

Jang et al. [43], the marked ball test using high-chrome steel media showed that a suitable combination of martensite and ferrite within the same ball can minimize the wear rate of the grinding media due to the difference in the passivation behaviours of the two phases. This was confirmed by Dalbert et al. [44], who found that a combination of martensite and ferrite had better corrosion resistance than ferrite only from their experimental results. However, galvanic coupling may be established between the two phases.

3.2. Abrasion Wear

Abrasion wear is the removal of material on the grinding media surface due to scratching by hard particles [45]. Ores have different abrasiveness owing to their mineralogical composition. Quartz is one of the most pervasive abrasive materials in mineral processing. The chemical composition, microstructure and hardness of grinding media influence the extent of abrasion wear during milling. Abrasion wear also depends on the rheology of the slurry, which is dependent on the viscosity and the percent solids of the pulp [46]. Martensite has good abrasion resistance compared to pearlite and ferrite. Generally, materials with high hardness are more abrasion-resistant but the microstructure also plays a vital role; therefore, hardness cannot fully describe wear resistance alone [47]. Microstructural parameters such as retained austenite, inclusions, carbides, matrix structures and notches must be considered. Gangopadhyay and Moore [48] observed that high-chrome low-alloy steel (HCLAS) was more abrasion-resistant, although it had a lower hardness than martensitic stainless steel (MSS) and nickel-hardened cast iron (NHCI). This observation was attributed to the difference in the microstructures of the balls. Chandrasekaran et al. [49] found that ball wear cannot be correlated with surface hardness; instead, the carbide distribution in the matrix dictated the wear behaviour of the forged steel balls. The authors concluded that the least wear occurs on grinding media with intermediate hardness and a sufficient amount of retained austenite and martensite. Their results agreed with the findings of other researchers. Pourasaibi and Gates [50] also observed that balls with lower hardness had better abrasion resistance in quartzite using Nbc bearing high-chromium white cast irons. From the studies, it is apparent that hardness cannot be used as the only parameter to determine abrasion resistance when comparing grinding media with different microstructures [19]. It is important to mention that abrasive wear strength should be maximized considering the balance of conflicting characteristics such as hardness and ductility. The former allows for the ball to withstand abrasive wear whilst the latter prevents sudden ruptures and chipping.

3.3. Impact Damage Mechanism

Impact results in the loss of grinding media material due to repeated high-energy tangential impacts. Some impacts that crack the hardened surface layer and/or lead to the transformation of austenite to martensite that cracks locally cause spalling, which can generally be controlled at the heat treatment stage through the phase composition of the grinding media.

Impact on the grinding media is influenced by the surface hardening of the ball, the spalling tendency, which usually affects larger balls, and the resistance to breakage under the repeated impacts it must experience [19]. The degree of impact is affected by parameters such as mill speed, ball size, mill diameter, mill filling volume, interstitial filling, and particle size. Impact, among other wearing mechanisms, causes spherical balls to wear into non-spherical fragments [51].

Grinding media with nearly noo retained austenite and a purely pearlitic structure through the cross-section have excellent impact toughness but inferior hardness. Higher amounts of retained austenite of above 15% lead to macro-spalling and fracture owing to the transformation from austenite to martensite [52]. An increase in impact wear usually results in a decrease in abrasion wear.

It is commonly assumed that increasing the mill speed would lead to more impact-related damage mechanisms, which cause grinding media such as cast irons to perform poorly. A recent study by Ali et al. [53] revealed that increasing the impact severity index (ISI), which is a relative average measure of the degree of impact inside the mill, increased the performance of white cast irons using ores of different abrasiveness levels (quartz, basalt, Tumbulgum quartzite, copper ore). The ISI was manipulated using rotation speed, mill-filling volume and feed particle size. To explain the unexpected observations, a hypothesis formulated by the authors was that the microfracture of the chromium carbides is more promoted by tensile stresses due to tangential sliding interactions rather than the compressive forces caused by high-angle impingement. The authors concluded that ball mills with a diameter of less than 600 mm do not have impact effects because all the wear occurring will be abrasive in nature. Thus, it is yet to be determined whether the impact levels in industrial mills that cannot cause macro-scale fractures in white cast irons do or do not promote microfracture wear mechanisms. A review by Zambrano [54] also found similar results. In addition, Radziszewski [55] found that the impact velocities attained in laboratory tests are low compared to industrial applications and illustrate only low energy impacts. Colak et al. [56] agreed that studies regarding impact wear in laboratory mills have limitations because their contribution to the total wear is insignificant.

4. Effect of Grinding Media Size, Shape, and Density on Mill Performance

Ball mill efficiency directly affects the cost of mineral processing. Grinding media play a vital role in enhancing the efficiency of a ball mill through their direct effect on the breakage rate, mill load behaviour, power draw, and general energy consumption. These factors have a crucial effect on the energy consumption of tumbling mills and on the general operating costs [57]. Therefore, selecting the most appropriate operating parameters (ball size distribution, mill speed, pulp density and media filling) and ball properties (size, density, shape, microstructure, and hardness) improves the performance of the mill. The grinding media affect the power consumption by ball mill, breakage parameters and the product particle size distribution (PSD). They should thus have the largest possible surface area and be as heavy as possible.

4.1. Effect of Grinding Media Size on Mill Perfomance

Different sizes of grinding media have different influences on the grinding performance [58]. Ball sizes that are used in grinding should be large enough to break the largest and hardest ore particles. Optimal ball sizes depend on the feed/product size ratio, mill dimensions, and breakage kinetics parameters. Usually, larger balls grind coarser ore particles efficiently and smaller balls grind fine particles more efficiently [59]. Larger balls break particles through impact, whilst smaller balls break through attrition. Sometimes, the smaller balls do not have sufficient impact energy to break an ore particle; therefore, both media sizes are vital. An optimal ball size range should provide sufficient energy to break coarse ore particles, but at the same time should not produce unnecessary ultrafine particles.

From the experiments conducted by Lameck [60], larger balls were effective for large feed sizes due to their impact, although they had a reduced surface area, whilst small balls were effective on small feed sizes because of their attrition and higher surface area. Kabezya and Motjotji [61] observed that 30 mm diameter balls were better than 10 mm and 20 mm diameter balls in grinding a quartzite ore of a feed size from −8 to +5.6 mm. However, there was an increase in efficiency when the feed size from −2 mm to +1.4 mm was ground by 20 mm diameter balls. Hlabangana et al. [62] observed that a three-ball mix of 10 mm, 20 mm, and 50 mm was the most effective in grinding a coarser feed, and a binary mixture of 10 mm and 20 mm was most effective in grinding a finer feed. Petrakis et al. [63] used a seasoned ball charge of (12.7 mm, 25.4 mm, and 40 mm) balls and the 25.4 mm balls alone, resulting in a decrease in energy consumption by 24% and 31%, respectively, compared to the smaller-sized balls (12.7 mm). Hassanzadeh [6] found that using mono-sized balls reduces attrition grinding, and this results in the production of a coarser product. In the experiment, mono-sized balls of 80 mm were compared with a binary ball size containing 60% of 60 mm and 40% of 80 mm. The binary charge produced a product with more fines of less than 75 µm, by 4%. Therefore, studies show that ball size distribution affects mill performance.

Mathematical modelling by Austin et al. [64] revealed that the size of grinding media influences the ore breakage rate. For a make-up ball charge consisting of single ball sizes assuming a linear wear law, the mass distribution in the mill is given by:

$$m(d) = \frac{d^{4-\Delta} - d_{min}^{4-\Delta}}{d_{max}^{4-\Delta} - d_{min}^{4-\Delta}} \quad (1)$$

where *m(d)* is the mass fraction of balls smaller than d in the load, d_{max} is the largest ball size in the mill, d_{min} is the smallest ball retained in the mill, and Δ is a constant which determines the steady state of *m(d).*

For make-up balls of two sizes, d_1 and d_2, of mass fraction of m_1 and m_2, respectively:

$$m(d) = \begin{cases} \frac{d^{4-\Delta} - d_{min}^{4-\Delta}}{K.d_{max}^{4-\Delta} + (1-K).d_2^{4-\Delta} - d_{min}^{4-\Delta}}, & d_{min} \leq d < d_2 \\ \frac{K.d^{4-\Delta} + (1-K).d_2^{4-\Delta} - d_{min}^{4-\Delta}}{K.d_{max}^{4-\Delta} + (1-K).d_2^{4-\Delta} - d_{min}^{4-\Delta}}, & d_2 < d \leq (d_1 = d_{max}) \end{cases} \quad (2)$$

k is the wear parameter given by:

$$k = \left[1 + \frac{m_1}{m_2}.(\frac{d_1}{d_2})^3\right]^{-1} \quad (3)$$

Equations (2) and (3) can be used to calculate the ball size distribution at any given time and simulate the wear rate of the grinding media in the mill.

The rates of breakage for smaller ball diameters are greater than bigger balls because the number of contact points increases with a decrease in ball diameter. Deniz [65] found that the specific rate of breakage of clinker, trass, and limestone in a laboratory ball mill under standard conditions can be expressed in terms of feed size and ball diameter. The results confirmed that the specific rate of breakage was higher for smaller-diameter balls (9.5 mm) than larger-diameter balls (25.4 mm and 41 mm) when the particle sizes were less than 0.3 mm for all the materials. Another study by Deniz [66] also confirmed that smaller-diameter balls (15 mm) had a higher breakage rate than larger-diameter balls (25.4 mm and 40 mm). The specific rate of breakage decreased with an increase in ball diameter for all particle size fractions. Yu et al. [67] confirms that the average grinding rate increases with a decrease in media size. From the study, the optimal media size was 40 mm for a feed size of −2 + 0.45 mm and 30 mm for a feed size of −0.45 + 0.15 mm. Cayirli [68] also agrees with the fact that larger balls can crush large particles better but at a lower grinding rate whilst smaller balls are unable to break large ore particles but grind smaller particles at a higher grinding rate. However, Petrakis et al. [69] found that the breakage rate increases with ball size as the feed particle size increases.

Another factor to consider when selecting the optimum media size is the mill speed since, at each mill speed, there is an optimal ball size. Shin et al. [70] found that the size of balls comprising an optimal ball size distribution decrease in size as mill speed increases. Small balls have a low kinetic energy but a high number of contact points, whilst big balls have a high kinetic energy but a low number of contact points. A comprehensive review by Wei et al. [71] concedes that the ideal ball size decreases with increasing mill speed for efficient milling. Table 1 presents data on the relationship between grinding performance and the optimum grinding media size range from various literature sources.

Table 1. Optimal media sizes and their performances.

Media Size	Grinding Performance	Author(s)
20–40 mm	For the range of ball sizes investigated, a finer product was achieved by a combination of smaller balls and higher ball charge.	[72]
70 mm–20 mm ball size	Breakage rate and particle size have a maximum for each ball size distribution using a pilot-scale ball mill on clinker.Particle size at maximum breakage (X_m) is strongly related to top ball size (D_b) in terms of ball charge.	[73]
10, 7 and 5 mm	For a mechanochemical synthesis of the sulfide solid electrolyte Li_3-PS_4. The largest relative grinding media (10 mm), highest rotational speed (1200 rpm), and medium grinding media filling ratio (0.3) optimized the process.	[74]
40, 25.4, and 12.7 mm	Balls of 25.4 mm and a mixed load of balls with varying sizes results in a 31 and 24% decrease in energy requirements, respectively. The size of 25.4 mm produced a much finer product.	[63]
10–30 mm	Larger balls are effective in breaking coarse particles and have a smaller surface area, whereas smaller balls have a larger surface area and are effective in breaking smaller particles. The mixture of three ball sizes performed better than the 30 mm balls.	[60,61]
10, 20 and 50 mm	The feed and desired product size distribution determine the optimal ball size. A three-ball mix was more effective for coarser feed whilst the two-ball mix of 10 mm and 20 mm was effective for a finer feed.	[62]
9.5, 25.4 and 41 mm	Specific rates of breakage are a function of feed size and ball diameter. Specific rates of breakage decrease as ball size increases for six mono-sized fractions of the feed for a barite sample.	[66]
30–80 mm	Average grinding rate increased from 0.4697 to 0.9062 as media size decreased from 80 to 40 mm. The 40 mm grinding media performed the best for raw material −2 + 0.45 mm. The size of 30 mm was optimum for raw materials of −0.45 + 0.15 mm and −0.15 mm.	[67]
12–40 mm	The optimal ball size distribution was 12 mm (40%), 20 mm (40%), 32 mm (10%), and 40 mm (10%) for dry fine-grinding of calcite ore. Finer ball loads were unable to break coarser particles nipped in the feed.	[68]
6.5 and 12.7 mm	Breakage rate is dependent on feed size and grinding media size. Coarse particles (−3.35 + 1.7 mm) had higher breakage rates when using 12.7 mm balls than 6.5 mm balls, whereas feed fraction (−0.3 + 0.15 mm) was milled at a higher grinding rate when using 6.5 mm balls compared to the 12.7 mm balls.	[69]
1, 2, 3, 5 and 10 mm	As mill speed increases, the optimal ball size decreases when milling aluminum powder. Balls of 2 mm are optimal at 153 rpm, 3 mm balls are optimal at 100 rpm and 5 mm balls are optimal at 50 rpm.	[70]

4.2. Effect of Grinding Media Shape on Mill Performance

Grinding media shape, among other parameters, has been reported as essential during grinding and has a significant influence on downstream processes such as flotation [58]. It is also an influential parameter in mass transport, and research has shown that power draw is sensitive to media shape at different charge filling levels. The difference in media shape results in different surface areas, bulk densities, and contact mechanisms during grinding. Different grinding media shapes have different toe and shoulder positions in the mill, resulting in different power draws and load behaviours. Toe and shoulder positions are the angular positions at which the liner comes into contact with the charge and when the charge departs from the liners, respectively. According to Shahbazi et al. [57], friction coefficients between media and lifter and media–media affect the media position in the mill. Also, the surface area, which is affected by media shape, causes the charge to become more defiant and move between media layers, hence effectively lifting the load. Table 2 presents the grinding performance for each specific shape from the literature compared to spheric balls.

Table 2. Grinding media shapes that have been tested other than spheres.

Shape of Grinding Media	Findings	Author(s)
Relo 	Grinding rate of Relo at 100% circulating load is the same at 250% circulating load using balls.	[75]
Cylpebs 	Cylpebs produce a slightly less oversized product than balls due to the greater surface area in single-stage batch grinding tests, but the same undersized products as balls.	[58]
	Cylpebs have higher grinding kinetics than spherical grinding media [57]	[37,57,76,77]
Eclipsoids 	Dropweights for eclipsoids produced less material of the target size class compared to balls. However, both balls and eclipsoids performed well, reaching the targeted PSD.	[76]
Cube 	Cubes have lower breakage rate than spheres and eclipsoids, which makes them the least efficient grinding media compared to eclipsoids and spheres.	[77]
Worn balls 	Worn balls perform more poorly than spheres, reduce the grinding chamber in the mill, and increase power consumption.	[9]

Spherical balls are mostly used for ball mill processes but are associated with high foundry production costs when compared to other types of media [57]. They change their shape over time due to the wearing away of the outer layer. According to experiments conducted by Dökme et al. [9], spherical balls produced 27% finer particles and consumed 5% less power than worn balls, which suggests that worn balls should be constantly removed from the mill since they affect the breakage kinetics of ore particles. Worn balls reduce the grinding surface area compared with spherical balls. However, there is a need to investigate the relationship between worn balls and mill speed, liner profiles, or filling ratios. Another comparative study by Kolev et al. [75] indicated that Reualeaux–tetrahedron shaped grinding media (RGM) had a 14% more undersized product than spherical balls at different circulating loads rotating at the same mill speed. For spherical balls, there is a substantial relationship between the ball filling and the toe and shoulder angles, and this type of media has been associated with the production of more slime when compared to cylpebs and worn balls.

Findings from Lameck [60] showed that cylpebs have the highest shoulder position and lowest toe position compared to spherical and worn balls, at a critical speed of more than 60%. The higher shoulder positions of cylpebs compared to other media shapes are due to cataracting and premature centrifuging. The lower toe positions for the cylpebs were due to the close packing and locking of the media such that their cascading speed was less than the mill speed. The shoulder positions of spherical and worn balls increased with charge filling, but the toe positions for all media shapes were similar for speeds below 70% of the critical speed. Cylpebs showed a small variation in shoulder positions with a change in mill speed. Cylpebs drew more power at speeds less than 72% of the critical speed, followed by worn balls, and lastly spherical balls. In a review written by Shahbazi et al. [57], cylpebs produced a less oversized product than steel balls with the same mass and a similar size distribution. The cylpebs had 14.5% more surface area and 9% greater bulk density compared to spherical media. From the various completed experiment, the spherical balls had the lowest shoulder position. It was found that shoulder positions do not solely rely on media shape, but also rely on on mill filling. The shoulder position increased while the toe position decreased as the mill filling increased. Cylpebs had the lowest power draw at speeds more than 72% of the critical speed and a more cataracting behaviour than worn and spherical grinding media. Shi [58] reported that, at an equal specific energy input level, the cylpebs could produce a slightly less oversized mill product. This was due to their greater surface area compared to spherical balls. Similarly, a comparative study with a laboratory tumbling mill under the same conditions (mass and feed load) showed a faster breakage rate for the cylpebs [78].

Another essential phenomenon during the grinding process that is affected by the media shape is grinding kinetics. In one comparative study between spherical and non-spherical media shapes, cylpebs proved to have higher grinding kinetics than spherical grinding media [57]. Cuhadaroglu et al. [79] obtained similar results, where the specific rate of breakage obtained and the model parameters showed that cylinders have a higher breakage rate than spheres. Ipek [78] also obtained the same results. Aldrich [37] found that the specific breakage of cement clinkers was higher with cylpebs grinding media than with steel balls in a ball mill. In another study undertaken by Simba and Moys [77], mixing different shapes of grinding media enhanced the grinding kinetics. Kolev et al. [72] also confirmed that a mixture of grinding media with different shapes increases the volume of the grinding zone, which will improve milling kinetics. In addition to this, research conducted by Kfiiger et al. [80] showed that replacing some of the spherical grinding media with concave–convex balls provided a 10% increase in the fineness of the ground product. However, increasing the number of concave–convex balls replacing the spherical media decreased the grinding efficiency due to the irregular movement of the concave–convex grinding media. Concave grinding media have larger specific areas than spheres, which increases the grinding efficiency.

In another study by Kiangi et al. [81], spherical balls and a multifaceted polyhedron with grinding media filling (J) = 16% and 20%, respectively, had a negligible difference in their power draw. This was due to the inefficient interlocking of the multi-faceted polyhedron because of the charge strength compromise; therefore, they behaved like the spherical media. As J increased to 25%, the power used by the multi-faceted polyhedron media decreased slightly at mill speeds greater than 75% of the critical speed. This was due to an increase in the cataracting of balls within the load. The study showed that grinding media shape has a small impact on power draw when the mill filling level is low. Lameck [60] also reported that polygonal balls and flat chips have a greater contact area than spherical balls.

4.3. Effect of Grinding Media Density on Mill Perfomance

In order to increase the efficiency of the grinding mill, Stoimenov et al. [82] suggested that the grinding media density should be increased. The author discovered that low-density balls are less efficient than high-density balls when grinding material is subjected to the ultrasonic milling method. Harriss et al. [83] also included grinding media density as one of the variables that affect power consumption. Yildinm et al. [84] found that mill power draw was linearly proportional to media density using grinding media of different densities. Cleary [85] found agreeing results; however, the difference in specific power consumption was negligible for grinding media of the density 4000 kg/m^3 and 7800 kg/m^3.

Kelsall et al. [86] investigated the influence of grinding media density on the grinding behaviour of a small amount of quartz in calcite in a continuous ball mill using different grinding media of different densities. The authors found that the breakage rate constantly decreased with a decrease in grinding media density. The decrease was more significant when grinding coarse particles as compared to fine particles.

It is interesting to note that a higher density and a rougher surface grinding media significantly improve the grinding efficiency of sulfide ores because of the larger impacts and frictional forces, albeit with a higher production of much finer particles and more corroded and rough mineral surfaces. The roughness and density of the grinding media directly affect milling performance. Thus, the magnitude of the impact and frictional forces is a function of the density and the roughness of the grinding media during the milling process.

5. Effect of Grinding Media on the Mineral's Liberation

Inside the ball mill, the enhanced liberation of the valuable mineral provides a homogenous product particle size, improves the technical index of the classification circuit, and improves the concentration in subsequent processes. The grinding media, such as steel balls, generate a breakage force that causes fractures on the mineral interface. The ore should not be underground or overground as this will cause inefficient separation in concentration processes. Different grinding media sizes and shapes, and different media filling rates, have different effects on the liberation degree of the valuable minerals.

The variation in grinding media sizes produces a dissimilar extent of mineral liberation. In experiments performed by Si et al. [87] using eight different sizes of steel balls, i.e., 10 mm, 13 mm, 16 mm, 19 mm, 22 mm, 25 mm, 28 mm, and 32 mm, the mineral liberation analyser showed that some magnetite particles were incompletely liberated whilst others were still intergrown. The 10 mm and 13 mm steel balls had reduced efficiency due to their small diameter, but their mineral liberation degree was better compared to other ball sizes. However, they were rendered inappropriate, and 22 mm steel balls were found to provide a better liberation and the desired product size. As the ball diameter increased from 25 mm to 28 mm, the mineral liberation decreased. This was confirmed by Nava et al. [88], who found that the liberation degree decreased with increasing ball size. Yang et al. [89] found that the liberation of the locked minerals is dependent on both the mill filling rate and ball size. The liberation of the desired product in the range from 0.038 to 0.154 mm increased with ball size at a mill filling rate of 30%. However, at a mill filling range of 40%–45%, the effect of ball size decreased, and a coarser product was produced. From the same study, it was found that an increase in smaller-sized balls in binary ball mixtures resulted in an increase in overground product. Guo et al. [90] discovered that increasing grinding mill filling reduced the liberation of lithium ore. Grinding media and material were centrifuging at 60% mill filling volume whilst this centrifugation was insignificant at the ball filling of 30%.

The grinding media shape used can affect downstream processes such as floatation due to the different degrees of mineral liberation. Li et al. [91] found that rod-milled scheelite was more liberated than ball-milled scheelite because the amount of oversized particles generated by rods was less than that produced by balls. The rod-milled product had a higher adsorption and floatation recovery using oleate as the collector. Wang et al. [92] noticed that short cylinders exhibit a higher liberation degree of 20.97% compared to balls, with 9.57%, due to their higher specific surface. The floatation recoveries of copper from chalcopyrite were higher for short cylinders than balls. The impact energy if generated by a suitable ball diameter was found to produce a higher degree of mineral liberation during the grinding of magnetite ore [87]. This was linked to the breaking of the magnetite particles along the interface of different minerals. The 22 mm diameter ball performed that task better than other ball diameters of 10–32 mm, producing 56.66% magnetite particles in the range $-75 + 20$µm. Mu et al. [29] showed that grinding with chromium steel resulted in higher rates of pyrite floatation than forged steel at a higher collector concentration.

Liao et al. [32] also showed that, although steel ball grinding is beneficial to the flotation of pyrite, nano-ceramic media grinding produces better selective flotation in chalcopyrite than steel media grinding. In another study by Corin et al. [10], it was shown that, at a particular degree of fineness, the grinding media shape had no influence on the downstream performance, which was floatation.

6. Research Outlooks

From the review carried out on the use of grinding media in ball mills for mineral processing, various areas were observed that are still green as far as research is concerned, and thus would be improved by further research.

The wear results and models generated from laboratory mills were shown to be inapplicable in industrial mills. Therefore, more research should be carried to find models which can make actual predictions in the industrial mill. According to Pourasiabi and Gates [45], cast irons have provided disappointing results that did not tally with the laboratory results. Ali et al. [53] suggested further work to determine whether normal impact levels in industrial ball mills, which are insufficient to cause macro-scale fractures, promote micro-fracture wear mechanisms such that the behaviour of white cast irons in industrial ball mills can be fully understood. Further studies need to be carried out to find grinding media that can withstand impact wear and abrasion wear. Moema et al. [52] indicated that there must be a compromise in terms of hardness and ductility for grinding media to withstand both wear mechanisms. Although this is easy to say, implementing it practically would require a lot of experimental work. It has been shown through experimental work that increasing the hardness of the grinding media also increases the abrasion resistance of the media, but is not the only factor; hence, the correlation between corrosion resistance and hardness must be established [21]. Since Dalbert et al. [44] found that a combination of ferrite and martensite has a better wear rate than martensite alone, studying the interaction between these two phases to minimise their galvanic coupling may be insightful and give rise to improved grinding media wear resistance.

A few studies were conducted using other grinding media shapes, like ellipsoids and cylpebs, which are not spherical. Although spheres eventually proved to be the best, there is a chance of obtaining a superior performance from other shapes if the relationship between media shape and other operating parameters (milling speed, liner profiles and filling ratio) is further investigated. In some experiments, using polyhedral and spherical media, the power consumption difference was negligible, and at a slightly higher mill filling, the polyhedral media consumed less power [79]. Although there have been many ball mill power models to date, they do not incorporate the effect of media shape, which has been shown by many studies to significantly affect load behaviour inside the mill [60]. There is so much information regarding the effect of grinding media size distribution on the grinding rate, mill efficiency and energy consumption; however, there is little information on the influence of grinding media shape on the liberation of minerals, which makes this a research gap that needs to be explored and filled. Little is known about the effect of various mill conditions on the performance of mixed grinding media shapes. As milling proceeds, spherical balls tend to change shape. Some mixtures of media shape may be beneficial, whilst others can have a negative impact on the mill performance. A mixture of spherical and worn shapes resulted in a decrease in mill performance whilst pebble and steel balls enhanced the mill performance [75]. Therefore, there is a need to further investigate the effect of mill conditions on various mixed grinding media shapes.

According to Hlabangana et al. [62], there is a need to find a correlation factor between the ball size distribution and feed size to further enhance mill performance since the authors found that the performance of a particular ball size distribution is dependent on the feed size.

It would also be worthwhile to conduct a comprehensive review that analyzes the impact of various media types on grinding parameters such as load behavior, power draw, toe position, shoulder position, contact mechanism, and kinetic and product particle size in tumbling mills. It is also interesting to note that grinding media selection is more often than not informed by their abrasive and corrosive wear properties rather than the downstream properties [48], hence the need for a paradigm change.

7. Conclusions

Over the years, research has been conducted to improve the quality of grinding media so that they can withstand the highly abrasive and corrosion environments in the ball mill. Grinding media have also been improved to minimise slurry contamination such that downstream processes such as floatation are not affected. High-chrome white cast irons are used in highly abrasive environments, whilst high-chrome steel balls are used where slurry contamination should be minimised. Studies have been conducted on the methods of production, be they forging or casting, and the heat treatment processes to determine the effect on the micro-structure of the grinding media. However, there is still ongoing research on grinding media that can be both abrasion- and impact-wear-resistant with a prolonged service life. Various shapes of grinding media have been manufactured, including cylpebs, ellipsoids, cubes, and truncated cones, which have the ability to compete with the commonly used spherical grinding media. The grinding media properties affect the overall performance of the grinding process, with grinding media size distribution being more significant than the density, shape, and hardness. Operational parameters such as grinding media filling, pH, mill speed and wear also affect ball mill efficiency. Grinding media with low wear rates are the most appropriate, as they serve for longer and produce less debris, which affects downstream processes. However, there are still many areas concerning the ball mill operation as a function of the grinding media that still need to be studied to obtain a profound understanding of the grinding process. The properties of grinding media, such as shape, hardness, and size, should be further exploited to increase mill efficiency. Since most grinding media that are currently in use, such as high-chromium cast iron and high-carbon low-alloy steel, have certain levels of both martensite and austenite. In the ball structure, martensite with high hardness and austenite should be used to minimize grinding wear. Some ores, such as gold and copper, which are abrasive, produce high grinding media wear rates.

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