Selection of Grinding Media for Use in the Gold Processing Industry- A Review

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Abstract

The ability to liberate valuable minerals from their host rocks is often achieved by several stages of size reduction. Grinding, the final stage of size reduction in minerals processing, is accomplished in the mining industry by employing steel balls as media. The quality of steel balls utilised in milling circuits have the potential to influence grinding efficiency, mill product quality and comminution circuit expenditure. The iron in the steel balls undergo several reactions and can dissolve via anodic reactions. In addition, the iron ions in solution produced by corrosion of forged steel balls form iron oxy-hydroxide species, thus consuming alkaline pH modifiers such as lime and may also coat precious mineral surfaces. These actions reduce mineral extraction efficiency. This article presents important factors to consider when selecting steel balls for the gold processing industry.

Keywords: Comminution, Hardness, Chemical Composition, Microstructure, Heat treatment.

1 Introduction

Comminution processes are an integral part of mineral beneficiation, which reduce particle size in order to promote mineral liberation (Semsari, *et al.*, 2020). To aid in particle size reduction, grinding media in the form of balls, made of either cast iron or steel are used in tumbling mills (Scieszka *et al.*, 1991). Commonly, two tumbling mills, which serve as primary (SAG), and secondary (ball) mills are used in the mining industry. Due to the mechanism of breakage that takes place in either mills, thus impact and abrasion by SAG or ball mills respectively, steel balls used in these mills differ in size and mechanical properties. SAG mill balls are bigger in diameter (80-125 mm) compared to ball mill balls (50-60 mm). In terms of mechanical properties, SAG mill balls possess higher toughness and wear resistance (Mular, 1965), while ball mill balls possess high wear resistance (Stalinskii, *et al.*, 2017). In Ghana, it is quite a challenge to produce steel balls of suitable mechanical characteristics due to insufficient knowledge of the metallurgy of steels and the relatively high cost involved (Stalinskii, *et al.*, 2017). These reasons have resulted in the production of low-quality steel balls in the country. Poor quality steel balls pose several threats in mineral processing. Some of these threats are, high rate of steel ball consumption as a result of wear (Impact, abrasion and corrosion) leading to high cost arising from rampant replacement of worn out balls (Aldrich, 2013). In the mineral processing industry, comminution is significantly one of the most expensive processes and it is estimated that about 30-50% of mining operation cost is attributed to comminution, as reported by (Moema *et al.*, 2009). Of this percentage, liner wear and grinding media consumption account for 50% of comminution expenditure (Wei and Craig, 1AD; (Radziszewski, 2002).

Another threat posed as recorded by Adam *et al.*, 1984) is the release of iron ions from the grinding balls into solution, coating mineral surfaces thereby making it difficult for lixiviants to penetrate. Yao *et al.*, 2019) noted that the dissolution of iron ions from steel balls into solution occurs through anodic reactions. The iron ions in solution can act as cyanicides and could also form iron oxy-hydroxide species, thereby consuming alkaline pH modifiers (lime), oxygen and cyanide during gold cyanidation process (Rabieh, *et al.,* 2016). One or more of these actions reduces mineral extraction efficiency and recovery, and increase cost of production (Fleming *et al.*, 2011). However, cost of comminution regarding media consumption could be reduced significantly if quality grinding balls with properties matching a given application are produced (Shaburova, 2019).

It is expected that, with Ghana's large steel industry, there should be more companies producing grinding balls, but it is not the case currently. Less than 10% of the large steel industry is a grinding media producing company and is unable to meet the demands of end users in terms of quality and quantity. Meanwhile, Ghana's mining companies contribute about 5% to the total GDP of which minerals make up 37% of total exports with gold accounting for about 90% (Badu, *et al.*, 2017). Due to inability to source quality steel balls locally, most of these mining companies import steel balls with just a few patronizing locally produced ones partially, leading to loss of foreign exchange and contributing to the high rate of unemployment in the country (Tandoh *et al.*, 2019).

It is therefore important to examine the suitability of grinding media for ores by considering intrinsic and extrinsic factors before usage (Abdelhaffez, *et al.*, 2022). Ore hardness, feed size, product size, pulp density, mill size, speed, and throughput are intrinsic factors, while media quality such as hardness, chemical composition and microstructure are extrinsic factors affecting media consumption (Moema *et al.,* 2009). Usually, one or more of these factors influence media failure, hence, both manufacturers and end users play an important role in determining quality of steel balls for use as grinding media to help mitigate effects of using low quality ones.

Summary of factors that influences steel balls selection

i) **Grinding Media Characteristics**: The composition and metallurgical properties of the grinding ball, size, grinding ball size distribution, hardness, shape, charge weight, production method and grinding ball selection methodology are the most important parameters to consider as these factors directly affect grinding media quality (Moema *et al.*, 2009).

Chemical Composition

In the mineral processing industry, grinding balls are manufactured from Iron-Carbon alloys (steel and cast iron) with the aid of iron carbon systems. An increase in carbon content increases the hardness and wear resistance of grinding balls (Stalinskii, *et al*., 2021). However, high carbon content results in a microstructure consisting of primary carbides (which is hard) instead of austenite or its transformed state. Other alloying elements such as chromium, silicon, molybdenum and manganese are important as they improve the corrosion resistance and uniformity of hardness (Fuerstenau, *et al.,* 1985). Further addition of carbon, (>0.85) in forged alloy steel balls causes them to be brittle thereby increasing its susceptibility to fracture (de la Concepción, Lorusso, *et al.*, 2015).

In cases where a corrosive environment is created because of chemicals, water, acidic/basic pH and ore characteristics, the grinding ball is expected to be corrosion resistant. This can be achieved by high chromium content in the grinding ball. Usually, high chromium content grinding balls have a longer lifespan and maintain their shape compared to the low chromium content grinding balls. The table below shows a summary of SAG and ball mill ball sizes with their elemental composition and corresponding hardness.

Table 1 Chemical composition of SAG mill balls and their corresponding hardness

Size (mm)	Chemical Composition (%)				Hardness (HRC)
	C	Mn	Si	Cr	
90-115	0.70-0.90	0.30-1.40	0.30-1.85	0.50-1.00	60-63
125-133	0.70-0.90	0.30-1.00	0.50-1.85	0.30-1.00	60-62
133-150	0.70-0.90	0.60-1.00	0.15-0.35	0.70-1.00	60-63

Table 2 Chemical composition of Ball mill balls and their corresponding hardness

Size (mm)	Chemical Composition (%)				Hardness (HRC)
	C	Mn	Si	Cr	
20-80	0.75-1.02	0.73-0.95	0.15-0.35	0.25-0.55	59-63
20-80	0.86-1.00	0.80-1.00	0.40-0.75	0.35-0.80	61-63
20-80	0.90-1.10	0.80-1.00	0.40-0.95	0.35-0.80	59-63

It can be seen from the table that both balls were produced from high carbon steels (0.60– 1.25 wt. % and a manganese content of 0.30 – 0.90 wt. %.). These type of steel balls possess the highest hardness and toughness and are wear resistant because they are easily hardened and tempered.

Microstructure

Several microstructures are developed from alloys used in the manufacturing of grinding balls. The microstructure is the main parameter responsible for mechanical properties of the grinding balls and it is achieved by heat treatment (Saldana-Garza *et al.,* 2016). Different microstructures are responsible for various mechanical properties hence, based on the application of grinding balls; appropriate heat treatment procedure must be selected to obtain the required microstructure (Shaburova, 2018). Grinding balls with purely pearlitic microstructures possess good impact toughness but poor hardness while grinding balls with purely martensitic structures possess excellent hardness but poor toughness. It is necessary to produce grinding balls with optimum characteristics; hence, heat treatment procedures are employed to produce a tempered martensitic structure, which possesses optimum toughness and hardness (Chenje, *et al.,* 2004).

Hardness

Hardness profile must be consistent from the surface of the grinding ball to its core. Hardness affects abrasion resistance of grinding media. Harder balls wear less, however, when the balls are too hard, they tend to be brittle, thus having less impact toughness resistance thereby failing by spalling, pitting and spilling (Gündüz, 2009). It is therefore important to obtain an optimum hardness and toughness in order to minimize wear by abrasion and impact. Minimum hardness varies based on raw material, desired toughness required by the end user and the type of ore being milled (Onel and Nutting, 1979). Figures 1a and b show as received balls from supplier and worn out balls from the ball mill respectively while Figure 2 shows examples of premature failures of grinding balls.

Figure 1a. As-received grinding balls from supplier

Figure 1b. Worn out balls from ball mill

Figure 2. Examples of Premature failures of grinding balls

ii). **Ore Characteristics:** Nature of the ore, particle sizes, hardness (abrasiveness), work index, density, shape and ore mineralogy and lithology are the most important parameters of the ore that also affect grinding media performance (Massola, *et al.*,, 2016).

Work and Abrasive Index of Ore: The work index is the energy required to reduce the size of the ore (Ozkahraman, 2005). High work and abrasive index mean the ore is competent or hard and abrasive. This results in the use of relatively high amounts of energy and time to achieve optimum size. (A Gupta and Yan, 2008). It is therefore important to subject the ore to grinding balls that can withstand these conditions, thus, grinding balls must be harder and tougher than the ore for grinding to be achieved (Spero *et al.,* 1991). Also, ores that contain high amounts or a mixture of several minerals such as quartz, sulphides, and carbonaceous matter tend to be more competent than ores containing few minerals. To enable the grinding balls perform for longer hours, it is advisable to subject these types of ores to grinding balls, which can withstand the higher energy that the ores possess (Yusupov *et al.,* 2007).

iii) **The mill**: Mill size and type, speed and discharge type are factors of the mill that need to be taken into consideration before choosing a specific media type since these factors contribute to the wear rate and failure of grinding media (Zheng and Yang, 1997). SAG mills have long diameter and short length hence breakage is mainly by impact while ball mills have long length and shorter diameter resulting in breakage, which is mainly by abrasion. Therefore, impact resistance should be higher in SAG mill balls compared to ball mill balls (Zheng *et al.,* 1997; Nomura, *et al.,* 1991). Meulendyke *et al.,* (1989) described three main speeds that occur in the mill; cascading, cataracting and centrifuging. When the mill is operated at a slow speed resulting in fine grinding but high wear rate of grinding balls, it is known as cascading. At a faster rotation speed, cataracting takes place, which reduces grinding ball wear rate to some extent. In the centrifuging regime, no grinding takes place hence there is little or no wear rate (Santos *et al.,* 2016; Aissat, *et al.,* 2020). Since the mill speed directly affects the wear rate of grinding balls, it is expedient to also consider them when choosing grinding balls. The figure below shows motion of charge and zones in a tumbling mill.

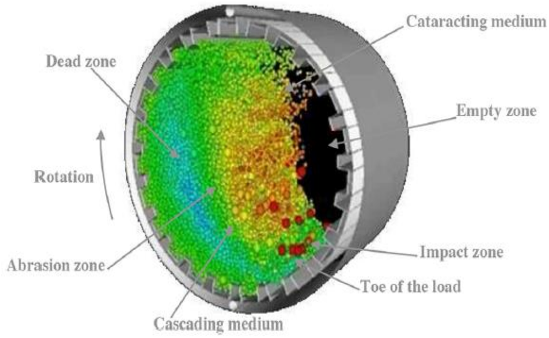

Figure 3. Motion of charge and zones in a Tumbling Mill (Aissat, *et al.,* 2020)

iv) **The grinding environment**: According to Rabieh *et al.,* 2017), milling conditions such as pH, percent solid, viscosity, Eh, gas purging (air, oxygen and nitrogen), temperature, rheological properties, water chemistry (anions: Cl^-, SO_4^{2-}; cations: Ca^{2+}, Mg^{2+}, Fe^{2+}, Fe^{3+}) and galvanic interaction between grinding media and mineral in wet grinding are the important parameters that directly affect grinding media performance especially wear by corrosion. These factors need to be addressed in order to minimize the wear rate caused by corrosion (Rabieh, *et al.,* 2017).

v) **The grinding circuit**: This section considers throughput (input feed to ball mill), circulating load and grinding time (Foszcz *et al.,* 2018). Several differences exist between balls supplied by various manufacturers; hence, end users cannot only rely on hardness, composition and microstructure of the grinding media but also take into consideration their ore type and milling parameters. It is therefore necessary for users to provide manufacturers with some information about the above intrinsic parameters before sourcing grinding balls. Users should also specify the minimum impact life especially the spalling rate and abrasive wear standards required based on some tests and simulations since these are the commonest failure that occurs in the mills.

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2 Conclusion

It is important to select the correct grinding media for application since different materials and processes require different media. Given these information, manufacturers can improve and select the best grinding media by considering user's specifications. This will eventually help manufacturers to produce and classify balls based on specific applications such as ore type, mill type and milling conditions. Subsequently, steel ball consumption will reduce significantly and extraction efficiency will improve.

3 Recommendations

User must keep a historical data of grinding ball consumption with corresponding ore type and milling parameters to provide manufacturers with some information to enable them produce appropriate grinding balls to suit users' needs.

User should develop some standards for specifying grinding balls since composition, hardness and microstructure is not enough information to determine grinding ball quality.

Existing standards should be modified, as grinding balls are improved and correlations between grinding ball consumption data and pilot scale data are developed for various types of balls, ore types and mill types

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