Grinding media quality assurance for the comminution of gold ores

J.S. MOEMA, M.J. PAPO, G.A. SLABBERT and J. ZIMBA

Mintek

The current global economic climate has adversely affected the resources industry in general. For the gold mining industry, even though the gold price has been stable as compared to other resources, there is still a need to cut costs even further in order to be profitable and sustainable. Of all the costs that are associated with mining, comminution of ore accounts for the majority. Comminution costs constitute mainly electricity, grinding balls and liners. Of these three components, grinding balls form the major portion of the consumable costs, and can be as high as 40%–45% of the total. As a result, proper grinding ball selection is a key consideration towards reducing mining costs. This paper discusses quality control procedures that can be conducted in order to select the best grinding balls for a particular application.

Keywords: grinding balls, forged, semi steel, hardness, chemical, metallography, wear testing, impact test

Introduction

One of the basic operations in minerals processing is grinding of the ore to the point where valuable minerals are liberated from the host rock. Subsequent operations then separate the desirable minerals from the gangue or waste. The grinding balls form the major portion of the consumable costs, and can be as high as 40% to 45% of the total costs of comminution. Grinding is essential to the efficient separation of minerals, is the key to good minerals processing. To produce clean concentrates it is necessary to grind the ore fine enough to liberate the minerals, but over-grinding inflates energy costs and can lead to the production of untreated fine ‘slimes’ particles. Grinding is therefore a compromise between recovering clean high-grade concentrates, and minimising operating costs and fines losses.

Annually, large tonnages of ferrous grinding media are consumed around the globe, costing several million dollars. Highly abrasive ores, such as those in the gold industry, can consume about 1 to 2 kg of grinding media per ton of ore milled.

As a result, grinding media replenishment is one of the highest above-the-ground consumable cost for mines – therefore an improvement in wear characteristics and life, or decrease in price of grinding media, can represent a significant saving. Mintek has assisted mines, as grinding ball producers and distributors for more than 25 years to develop and maintain a quality control programme (QC) to ensure that grinding balls meet some sort of standard. Mintek has over the past 20 years maintained a quality programme that is supported by a comprehensive array of equipment. A selection of key equipment available is shown in Table I.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Description</th>
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<tr>
<td>Milling media</td>
<td>Grinding balls, forges, semi steel, hardness, chemical, metallography, wear testing, impact test</td>
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Steel grinding media fail if there is a significant variation in chemical composition, hardness and microstructure of the balls. Common failure modes of grinding balls observed in different semi-autogenous grinding (SAG) applications are misshapen; surface spalling, shelling, capping and half balls. This paper discusses the main quality control criteria that the producers of grinding media and mines can use to minimise incidences of premature failure.

Quality control procedures

Poor quality grinding balls influence the whole grinding system, including that included ball consumption, effectiveness of grinding, power consumption and so forth. It is therefore essential to develop and maintain a quality control programme (QC) to ensure that grinding balls meet some sort of standard. Mintek has over the past 20 years maintained a quality programme that is supported by a comprehensive array of equipment. A selection of key equipment available is shown in Table I.

Ball manufacturers perform continuous quality control on their products. However, differences in composition, heat treatment and other variables occur and these can affect service performance. Ball users can improve ball performance and cost by monitoring ball quality and service performance on a regular basis. This grinding ball quality control programme includes inspection of each shipment to catch occurrences of breakage as quickly as possible, and chemical composition and hardness test profiles to check these against the specifications supplied by the manufacturer. These quality control procedures are extensively described in further detail, later on.

Compositional effects

Steel grinding balls are produced from a range of carbon/iron (Fe/C or Fe-C) alloys to be used in milling conditions. The alloy systems used include AISI 1020 mild steel, high carbon low alloy forged steel, forged martensitic
stainless steel, forged austenitic stainless steel, Ni-Hard, 20% chromium, 27% chromium and 30% chromium white cast irons. By increasing the carbon content to produce cast irons, both the hardness and wear resistance are improved significantly. High carbon content of the cast steel leads to a microstructure consisting of primary carbides instead of austenite or one of its transformation products (i.e. pearlite, martensite, etc.) as a primary phase. Most international specifications tend to avoid the hyper-eutectic phases because the occurrence of primary carbides is associated with sharp decrease in toughness and wear resistance, especially under high stress abrasion. Table II shows the typical metal alloys used for production of grinding balls that are used in the mining industry.

Casting and forging defects
Before proceeding with any tests, it is deemed critical to ascertain the integrity of the supplied cast or forged balls. Casting defects such as shrinkage and gas porosity, as shown in Figure 1, will lead to premature failure of the grinding media during mill operation. The casting defects lead to a local reduction in the wear resistance of the grinding balls because of the lack of supports for the carbide by the matrix. Shrinkage cavities and internal porosities are shown in Figure 1.

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Table I
The following types of test equipment at Mintek

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spark emission spectrometer</td>
<td>Chemical analysis for verification of alloys against a specification</td>
</tr>
<tr>
<td>Metallurgical microscopes</td>
<td>Extensive metallurgical evaluation on the macro and micro levels</td>
</tr>
<tr>
<td>Experimental ball mills</td>
<td>Comparative abrasion wear testing using actual mine ore</td>
</tr>
<tr>
<td>Pin-on-belt (POB) test machine</td>
<td>High stress abrasion wear testing</td>
</tr>
<tr>
<td>Dry rubber wheel abrasion test (DRWAT)</td>
<td>Low stress abrasion wear testing</td>
</tr>
<tr>
<td>Drop tester</td>
<td>Impactive wear testing</td>
</tr>
</tbody>
</table>

Table II
Metals that are commonly used as materials for grinding ball in ball alloys

<table>
<thead>
<tr>
<th>Alloys</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>High carbon (C) and high manganese (Mn)</td>
<td>Steel with alloying elements such as molybdenum (Mo), chromium (Cr) or nickel (Ni). These balls are especially made for ball mills and are uniformly through-hardened to 60-65 Rockwell C. They represent the highest quality of all metal balls and most operators insist on using them.</td>
</tr>
<tr>
<td>Cast nickel alloy</td>
<td>This is also very popular and, as it is basically a white metal ball, it causes less metallic staining than other types. The principal objection is its rough outer surface and projecting nubs typical of cast balls. It requires long conditioning periods before being placed into general use.</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Because of its high cost, stainless steel is only used for special work that requires an acid resistant and non-magnetic ball.</td>
</tr>
<tr>
<td>Forged low carbon steel</td>
<td>The chill iron and low carbon steel are the cheapest metal balls obtainable. They are recommended for rough grinding only, where metallic contamination is not objectionable.</td>
</tr>
</tbody>
</table>

Table III
Typical nominal composition of the grinding balls

<table>
<thead>
<tr>
<th>Balls</th>
<th>Elements wt %</th>
<th>Hardness (HB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Cr</td>
</tr>
<tr>
<td>Cast semi-steel</td>
<td>≥2.30</td>
<td>≥0.25</td>
</tr>
<tr>
<td>Cast steel</td>
<td>≥3.5</td>
<td>≥3.00</td>
</tr>
<tr>
<td>Forged steel</td>
<td>0.80 max</td>
<td>1.0 max</td>
</tr>
</tbody>
</table>

Gas porosity
Shrinkage cavity

Figure 1. Photograph of sectioned cast grinding balls showing casting defects such as gas porosity.
porosity of the grinding balls must be corrected, since it will have detrimental effects of both impact and abrasion resistance of the grinding ball.

The forged grinding balls also need to be free of defects. The surface smoothness and freedom from defects such as flats, pits, soft spots and cuts need to be monitored on delivery of balls at the mine. Balls must be free of such defects when inspected without magnification.

The mean diameter between two parallel planes on the ball surface, sphericity or the deviation from a true spherical form (out-of-round condition) is also an important step in quality control. A typical example of the defects found in forged grinding balls is shown Figure 3.

**Microstructure**

Steels with purely pearlitic structures through the cross-section possess excellent impact toughness, but have inferior hardness. Their milling performance is, however, very good in conditions where very hard charge materials such as gold ore are milled, especially in large ball mills. The effect on impact toughness is attributed to the presence of continuous networks of hard and brittle primary carbides in a pearlitic matrix as shown in Figure 4. The impact resistance can be improved by appropriate heat treatment to produce a discrete carbide morphology. Although heat-treated medium chromium cast iron has the desired combination of microstructure, mechanical property and wear performance, economic considerations and ease of production favour the use of unalloyed cast iron as the grinding media of choice, particularly for abrasive ores such as gold ores (quartzite). For these harder gold ores, changes in the chemical and physical metallurgical characteristics of the grinding balls play a minor role. The continuous cementite network will lower the impact strength of the balls, since the continuous cementite phase provides a path of least resistance for crack propagation after a crack has initiated. As a result, these balls are likely to fracture under highly impact conditions.

A typical example of nonuniform microstructure of a forged steel grinding ball is shown in Figures 6 and 7. The balls consist of martensite (α') near the surface and a mixture of α' plus pearlite nodules at the centre. Some of the badly heat treated forged steel grinding balls contain an undesirably high level of retained austenite (γ_{ret}), as shown in Figure 8, which can be deleterious during high impact conditions in a mill.

![Gas porosity and shrinkage cavity in a forged grinding ball](image)

**Figure 2. Photograph of cast grinding balls showing casting defects such as shrinkage and gas porosity**

![Continuous cementite network in a pearlitic matrix](image)

**Figure 4. Micrograph of cast grinding ball showing grain boundary cementite network in pearlite matrix**

![Out-of-round and forging lap in a forged grinding ball](image)

**Figure 3. Photograph of forged grinding balls showing forging defects**

![Continuous network of carbides in a pearlitic matrix](image)

**Figure 5. Micrograph of cast grinding ball showing continuous network of carbides in a pearlitic matrix**
Amount of retained austenite

One of the major causes of ball breakage is the internal stress that results from delayed austenite to martensite ($\gamma \rightarrow \alpha'$) transformation induced by low temperatures or by impacts. These stresses add to existing residual stresses that lead to the balls bursting during storage and/or service. A typical example of a forged steel ball that failed prematurely during storage is shown in Figure 9. This amount of retained austenite is substantiated by the microstructure shown in Figure 6.

As part of the quality control procedure, X-ray diffraction (XRD) analyses are performed on the samples removed from near the surface of the cast or forged grinding balls in accordance with ASTM E915 and SAE J784 standards. This is done to determine the volume percentage of retained austenite $\gamma_{\text{ret}}$. The measured retained austenite ($\gamma_{\text{ret}}$) values are compared against a value of 10%, which is generally agreed to be an upper limit for high impact wear conditions.

Hardness

A steep hardness gradient is usually viewed as undesirable because of faster wear of softer constituents. Surface hardness of the produced cast or forged grinding balls is measured on the Rockwell or Brinell Scales prior to shipment to the mine. The tests are performed in conformance with the manufacturer’s specification. Minimum hardness for the grinding balls varies according to the material and desired toughness. A typical example of the hardness values for different grinding balls, showing hardness profiles from the surface to the centre, is shown in Figure 10.

The hardness influences the abrasion resistance of the grinding balls. The surface hardness values of 620 to 650HB (Brinell hardness) yield a grinding ball with good abrasive wear resistance. The grinding balls should be heat treated properly to obtain the required hardness and to achieve good impact resistance. The forged steel grinding balls show a steep gradient as compared to the cast steel ball; this is in accordance with the microstructures shown in Figures 5 and 6. The wear performance typical of this ball is expected to be better than that of a cast steel ball.
Impact toughness

The impact fatigue resistance (IFR) of the grinding ball is very important and needs to be controlled by a proper heat treatment step. The impact fatigue resistance decreases with increasing amount of retained austenite (Arret). Ideally, the retained austenite content should be less than 10% for high impact wear conditions. The forged grinding balls shown in Figures 11 and 12 had comparable amounts of retained austenite of above 15%, which led to macro spalling and fracture. It follows, therefore, that the increased quantity of austenite that is present in the grinding balls will naturally result in transformation to martensite, and consequently a high degree of spalling. The drop tests are performed on the balls to evaluate their resistance to impactive wear. The test consists of dropping a ball from a height of 3.4 m onto a 500 mm diameter by 150 mm thick hardened steel anvil, see Figure 13. The balls are dropped until they either spall significantly or break. Prior quality control work at Mintek has shown that, if 2 000 drops are successfully completed, and then the impact properties can be regarded as sufficient for most milling operations.

The repeated impact of the grinding balls may cause one (or more) of the following to happen to the ball:

- The surface of the ball may deform plastically
- Small pieces of the surface may spall off (flaking or micro-spalling as shown in Figure 12)
- Large pieces of the surface may spall off (macro-spalling)
- The ball may fracture through the centre (breaking, see a typical example in Figures 13 to 15).

Pre-existing flaws such as quench cracks, gas and shrinkage cavities, and centreline shrinkage in continuous cast bar before forging, and forge laps in surfaces serves as stress concentrators that often lead to premature breakage of balls. The examples of failure due to the latter defects are shown in Figures 13 to 15. The ball manufacturer has primary control over breakage through casting (i.e. through best practices in casting), forging and heat treatment processes and through quality control practices that prevent the accidental supply of such balls to the clients.
Abrasive wear

In ball milling, materials consumption by wear represents a very high production cost, and must be minimised by proper selection of materials, especially those for balls [15]. Abrasive wear has been classified into the following three types:

- Gouging abrasion, typified by the macroscopic penetration of the working surface by coarse abrasive particle
- High stress grinding abrasion, in which abrasive particles are crushed under the grinding influence of moving metal surfaces
- Low stress scratching abrasion, in which the stresses are sufficient to cause only microscopic penetration of the working surface and no crushing of the abrasive.

Experimental abrasive testing

The wear tests are performed on marked balls from each set in a 0.6m diameter by 0.6m in length experimental ball mill, as shown in Figure 16. Actual ore from a particular mine is fed to the mill at a constant rate of about 300 g per minute. The water feed is regulated by a flow meter to a rate calculated to maintain the solid content of the pulp at 75%. The ball mill speed is typically 46 rpm.

A conditioning run of 20 hours is first performed to remove any adhering scale and surface decarburized layer, which may not be representative of the ball. The balls are then tested for a total of 100 hours excluding conditioning. The masses of the balls are measured between each 20 hour run. The mass loss of the balls (in grams) is recorded for each interval and the wear rate of all the balls calculated. An example of a plot of the cumulative weight loss of the balls as a function of milling time is presented in Figure 17. The wear rate over a 100-hour test period is given by the slope \( y = mx + c \) of the graph.

High stress laboratory abrasive wear test (POB)

The purpose of the high-stress abrasion test or pin-on-belt (POB) test is to determine the resistance of a given material against the abrasive action of particles, which are generally harder than the abraded material, in a two-body abrasion configuration (see Figure 18). The abrasive particles are normally bonded to a backing surface to provide proper mechanical support in order for the particles to perform as small machining elements, and to prevent any rolling or similar movements as encountered in the three-body test. The abrasive materials such as Silicon carbide (SiC), Garnet, Corundum (Al₂O₃) and Quartz (silica) are used in this test[15]. A detailed description of this laboratory wear test machine is given in Smith’s work[16].

Figure 14. Photograph of fractured cast steel grinding balls due to casting defects after drop testing

Figure 15. Photograph of fractured cast steel grinding balls used in the gold mining industry after drop testing

Figure 16. A schematic representation of the experimental ball mill set-up at Mintek

Figure 17. The relationship between cumulative weight loss versus time

Figure 18. Diagram of the high-stress abrasive wear test (POB)
The results obtained from this test are correlated with those of ball mill test. The correlation is intended to show the extent to which the pin-on-belt abrasion test can be used to rank alloys for further testing.

Conclusions
A full metallurgical characterization that includes chemical analysis, hardness profile, microstructure, and retained austenite measurement plays a vital role in the selection of a cost effective grinding ball.

A good quality control programme will ensure a constant supply of good quality grinding balls, which could lead to cost effective milling.

Mintek's Advanced Materials division (AMD) and Mineral Processing division (MPD) Division offer a whole range of laboratory facilities and test work to the mining and minerals industry.

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