AA04 - Bauxite Particle Size Requirements for the Bayer Process: Back to Basics

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Abstract

This paper examines the bauxite particle size requirements for the Bayer Process. A closed circuit Semi-Autogenous Grinding (SAG) mill with a hydrocyclone is considered to be the most suitable for a high bauxite throughput operation. SAG Mills do more than just grind, they tumble, separate, and size classify the feed through multiple size reduction steps (grate, trommel and hydrocyclone). The small aspect ratio (L/D ~ 0.5) and use of pulp lifters allows for the immediate removal of up to 35 % of the fine solids (< 2 mm) from the crushed feed. Lateritic bauxites are usually classified as soft, using the drop weight test hardness criteria (> 150), and have an exceptionally low specific energy (< 5 kWh/t) and explains the short residence time inside the mill. In the mill abrasion, attrition and chipping of the larger and harder bauxite particles takes place. Eventual breakage of these particles allows their removal. Very small differences in bauxite hardness or density, mainly through variability in the content of iron-containing hard-cap, can lead to an increased recirculating load. This also leads to a longer residence time, with the possibility of a build-up of a critical size inside the mill. When a new bauxite stockpile is reclaimed any small difference in size or hardness will impact on the established steady state grinding conditions. The shrinking core digestion model for aluminous particles in liquor is controlled by particle size, temperature, holding time, alumina and caustic concentrations. Alumina losses are usually found in the coarser size fractions and for this reason a finer grind will always achieve a higher extraction. The size distribution of the milled bauxite therefore becomes an important parameter and can influence the bauxite usage factor. Monitoring, care and maintenance of: crusher gaps, ball charge management, grate hole and mill liner wear, screen and trommel wear, hydrocyclone wear will all contribute towards improved particle size control.

Keywords: Ma'aden, crusher, mill, SAG, hydrocyclone.

1. Introduction

Alumina production is a high-tonnage, low-profit margin operation where alumina must be produced as cost effectively as possible. Milling targets a high tonnage throughput to produce a product with a particle size appropriate for the Bayer process. When necessary digestion temperatures and liquor characteristics can be adjusted to maximise dissolution of coarser particles. In a refinery the Alumina production is paramount and high liquor flow rates are critical for maximum productivity. This primary consideration may be at the expense of a reduced alumina extraction from the bauxite. Optimal particle sizes are also necessary for: pumpability, to avoid settling in pipes and tanks, and for high desilication and digestion rates.

The mill-types and configurations used for bauxite are usually limited to those detailed in Table 1, the choice of mill, size and number of mills will be based on experience, cost and recommendations of the design engineers. High Pressure Grinding Rolls (HPGR) is rarely considered as lateritic bauxites are too soft to warrant this technology. Only for hard diasporitic bauxite, where digestion feed sizes of P80 -75 µm are required would it ever be considered. Rod and ball mills can readily handle bauxite on account of its very soft nature. However, it is the tonnage throughput and the product size that are the two critical factors that must be met in assessing the optimal mill design. Despite the simplicity of open circuit rod mills, the operation of numerous small mills has now become antiquated. Likewise, the 2-compartment combination mill is also considered outdated. For rod mills they constantly requires stoppage so that more rods can be recharged and tangled, and broken rods removed. More recently these mill options have been replaced by larger SAG mills that can treat a larger feed size and allows a higher tonnage throughput and requires reduced maintenance.

2. Mine-to-Digestion

Bauxite can be found in a number of different physical forms including: pisolitic, friable and hardcap. Each bauxite will have its own distinctive crushing and milling characteristics. Bauxite can be highly variable through the mine pit profile, both vertically and horizontally. Often large blocks from blasted or ripped bauxite can be upto 1–2 m^3 in size, and while present in only a small volume the process flow path must still consider these and be capable of crushing them to a suitable size for materials handling purposes, and to avoid damage to the conveyor belts. Improved blasting may be necessary if there are too many large blocks of hardcap. Crushing is achieved by a combination of steps that may include jaw crusher, sizer, rolls and hammer crushers. Open circuit and closed-circuit crushing circuits are operated, as well as multi-step crushing routes which are possibly used more often to maximise tonnage throughput. Crushing initially reduces the bauxite to a size that the mill can handle, and then the mill delivers a product size suitable for the refinery feed.

Milling of the crushed bauxite product (Table 2) takes place in caustic spent liquor at temperatures of ~ 75 °C and delivers a slurry for desilication and digestion. Bauxite is considered to be "soft" when using the drop-weight-test hardess criteria (~ 150) and is far softer than most other ores [1]. For this reason, bauxite has a low specific energy (< 5 kWh/t) and should have a short residence time inside a mill. A high open area on the mill grates allows the fine particles of bauxite to move as a slurry and immediately exit through the mill grate and mill trommel. The SAG mill with an installed pulp lifter is designed to promote rapid tonnage throughput. The larger and harder particles are retained and have a longer residence time in the mill requiring increased breakage before fully exiting through the mill grate. Modern SAG mills are considered to be the modern process route for bauxite processing and have minimal down time. The installation of a pulp lifter at the rear of the SAG mill are recommended for bauxite processing. This unit may consume over < 50 cm of the width of the mill yet justifies its installation as it enhances the ability of the mill to flush and pump out the finer size fractions (~ 35 % < 2 mm) in the rejected slurry and allows milling to focus on the larger and harder particles retained in the belly of the mill.

Table 1. Types of conventional mills and mill configurations for bauxite processing.

Bauxite Mill Configuration	Description / Characteristics / Top Size
Rod Mill	Rod Mill, usual length to diameter ratio ~ 1.25, feed < 60 mm topsize, discharge ~ 2-3 mm top size
Ball Mill	Ball Mill, usual length to diameter ratio ~ 1.50, feed ~ 2 mm topsize, discharge < 1 mm top size
SAG Mill (Semi Autogenous Grinding)	SAG Mill, usual length to diameter ratio ~ 0.50, feed ~ 10–20 cm topsize, discharge ~ 2 mm top size high slurry flow, the grate and pulp lifters efficiently remove the finer fractions from the feed and prevents slurry pooling.
SAG Mill + Ball Mill	SAG Mill + Ball Mill delivering < 1 mm top size
Rod Mill + Ball Mill	Rod Mill + Ball Mill delivering < 1 mm top size
Combination Mill	Rod & Ball Combination Mill (= 2 compartment Rod/Pebble Mill) potentially delivering < 1 mm top size
HPGR + Ball Mill (High Pressure Grinding Rolls)	For hard diasporic bauxite only, delivering < 1 mm top size
	Definitions
Open Circuit (no size classification)	No size classification of exit stream. Size control by controlling residence time in the mill and controlling the input size into the mill
Closed Circuit (with size classification)	Size classification on mill exit stream. This is usually a hydrocyclone or a Dutch State Mine (DSM) screen. The DSM has a finite top size cut and creates a more controlled size product to digestion. This avoids coarse particles settling in tanks and pipes and also reduces erosion and abrasion.
Mill-Crash-Stop (Rapid mill stop) Mill-Grind-Out (Stop mill after grinding away any coarse bauxite)	Reveals ball and bauxite content inside the mill, (turn off bauxite + turn off liquor + turn off mill) Reveals only the ball content inside the mill. (turn off bauxite, then later turn off liquor + turn off mill) Routine Grind Outs - Removes coarse bauxite, and reduces the hard-dense iron particles in the recirculating load
Top Size (mm) P80 size (mm or µm)	Largest particle dimension in a processed bauxite sample (assume all particles to be equidimensional) 80 % of the sample mass is smaller than the defined size

Table 2. Progressive particle size reduction following different size classification routes.

Option	Mill Grate	Mill Trommel UF	Hydrocyclone OF	*DSM UF	*Vibrating Screen UF
1	<25 mm	<12 mm	<2 mm		
2	<25 mm	<12 mm		<1.8 mm	
3	<25 mm	<12 mm			<1.5 mm
4 (DSM + HydroCy)	<25 mm	<12 mm	<2 mm	<1.8 mm	

Note – Cut point of screens very accurate. Top size accurately controlled. Acts as a security screen.
UF – Underflow, OF – Overflow

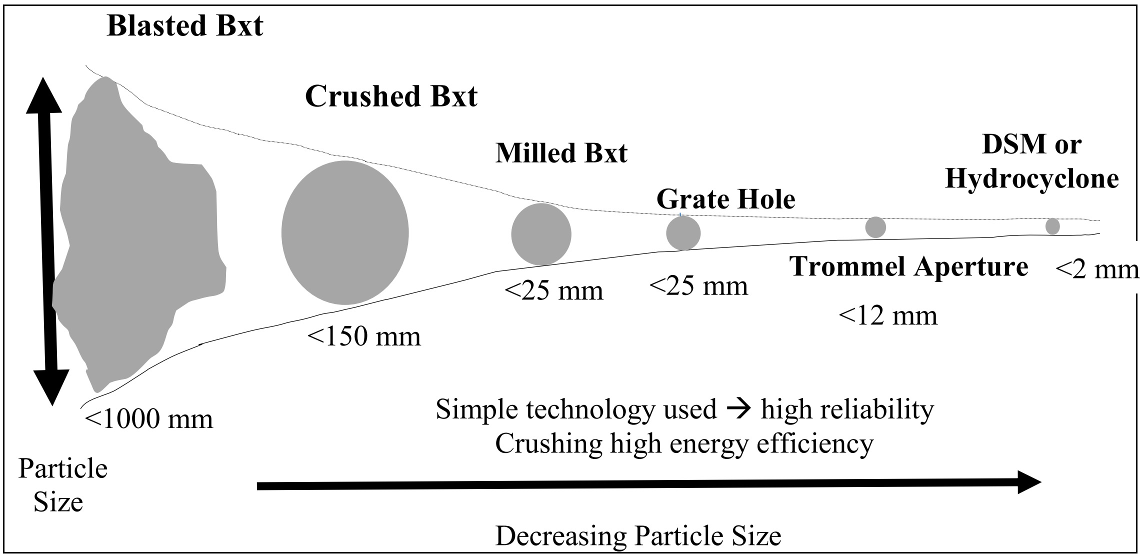


Figure 1. Illustrates the decreasing particle size at each classification step.

For open circuit milling the feed material should have a controlled tonnage throughput and constant input size and hardness and will then be transfered out of the mill and delivering a fixed particle size. Changing any of the input parameters will change the product size. Closed circuits allows for more bauxite feed size variability and are usually still able to deliver a consistent sized product, typically the discharge is classified using screens or hydrocyclones (Table 2, Figure 1) and the coarser product returned back to the mill. The attraction of hydrocyclones is the high throughput, low cost and reduced maintenance as compared to the use of screens. For hydrocyclones particle size and density of the mineral particles are controlling factors during size separation. For this reason, coarse hematite particles and metal scats preferentially report to the underflow stream of the hydrocyclone and add to the recirculating load. The screens can be either vibrating stacked screens or fixed (e.g. DSM). Fixed screens often have blinding problems, even when they are routinely turned and hosed down. Generally, the finer the screen aperture (i.e. below 1.8 mm) the more problematic. The vibrating screen can be a substitute for the DSM screens and has the potential to deliver a marginally finer product. Vibrating multi-deck stacking screens will partially overcome some of the blinding difficulties, however, the extra mechanization and moving parts operating in a corrosive environment may create other operational difficulties. While screens are considered to be an old technology which require a lot of maintenance, they deliver a well defined top size which is attractive for controlling the desilication and digestion feed size. Oversized material can lead to erosion and abrasion in tanks, pipes and valves. Within flash tanks the high speeds of coarse particle that survive digestion will promote excessive metal wear rates.

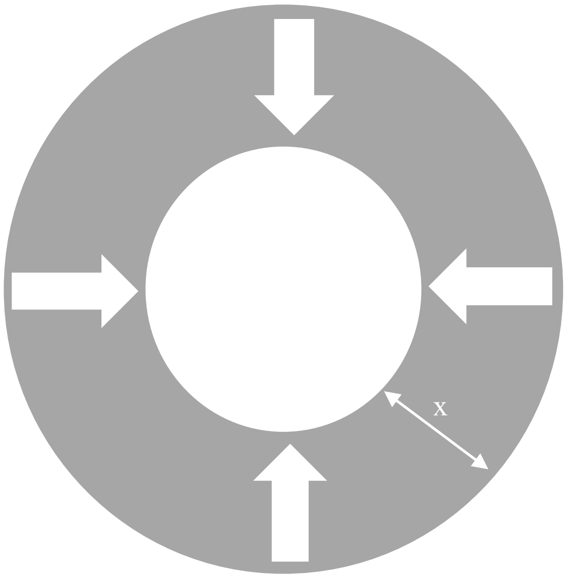
A high silica bauxite (e.g. Ma'aden, $TSiO_2$ ~ 8.2 %) can contain coarse kaolinite particles (~ 1 mm) and lead to low desilication rates (55 to 65 % after 15 hours). This is through slow reaction of large particles, kaolinite intergrown with boehmite, Desilication Product (DSP) rim formation on the kaolinite particles, and the presence of ~ 1 % quartz. Finer milled kaolinite particles in general would be expected to desilicate more completely. Rates of desilication can be raised by increasing holding time, temperature, reducing particle size and increasing Total Caustic (TC). Desilication is best quantified using soda content of the reacted bauxite solids which indicates the content of DSP in the residue and the amount of conversion (Table 3). Reduced desilication rates can give rise to below design caustic consumption in predesilication tanks, and only in during digestion will the remaining silicates react and be converted to DSP. This extra unreacted silica in digestion will increase DSP scaling in piping and lower the effective TC in the digestion slurry. For this reason, extra caustic need to be accounted for in calculations when targeting a selected Alumina to Cautic (A/C) ratio.

Digestion models (see Figure 2) can be calibrated for different refineries using a dissolution factor estimated from laboratory digestion work using the mill discharge sample. It may then be possible to integrate a Mill model with a simple digestion model and this could help justify the business case for finer and improved grinding.

Table 3. Important calculations used during testing of grind size on desilication.

Important Calculations	Comments
Tie Factor = ($Fe_2O_3 + TiO_2$) in bauxite / ($Fe_2O_3 + TiO_2$) in mud	Tie factor calculations accounts for changes in mass following digestion. Inert elements unaffected in digestion TiO_2 very consistent, small standard deviation (SD) in Ma'aden bauxite samples. Average 3.4 - 0.2 % SD
SiO_2 conversion in PDS % = ((Exit Na_2O-Bxt Na_2O)/62/0.666)/((Exit SiO_2-Bxt SiO_2-Bxt Qzt/Tie-F)/60) ×100	Desilication reaction Ideally conversion of silica should be > 85 % Ma'aden desilication tends to be low < 70 %
Extraction of Al_2O_3 = Bxt Al_2O_3 – (Mud Al_2O_3 x Tie-F)	Extraction factor - accounts for the mass and volume loss during digestion
For high $RSiO_2$ bauxites (> 4 %) Bauxite Charge = (TC x ΔRatio x 100) / (%TAA + ($RSiO_2$ x (Na_2O/SiO_2) x Target Ratio)	Calculation to help estimate the extra TC consumed by the high $RSiO_2$ content of the bauxite during desilication.

Relative rates of particle dissolution: -
Gibbsite >> Boehmite > Diaspore



Shrinking bauxite particle over a unit time.
Delivering an incremental decrease
in particle radius (x µm).

Rate of dissolution of particles will depend on:

- Particle size (radius)
- Residence time in hot liquor (min)
- Temperature of hot liquor (°C)
- Liquor composition (A/C)

As the Kotte diagram [1] suggests →

- Rate will approach zero when the A/C liquor reaches its solubility limit
- The driving force of dissolution is highly dependent on the under saturation of the liquor, i.e. high at low ratios (> 0.34), slow at higher ratios (> 0.64)
- As TC is increased the dissolution rate will increase
- As bauxite dissolution progresses the A/C ratio increases, and the rate will progressively decrease
- Shorter digestion times may avoid boehmite reversion issues in digestion and flash tanks

Figure 2. Simple shrinking core model for an aluminous particle.

Those bauxites enriched in quartz (e.g. Western Australia and Venezuela, 10 to 20 % quartz) are highly weathered and laterized granites. The quartz tends to be highly angular and leads to extreme abrasion and erosion in crushers, pumps, valves, pipes, spools and tanks. Quartz also leads to high ball and liner wear in the milling circuit. These bauxites are more preferably milled in rod mills (P80 ~ 500 micron) to deliver a coarse product to avoid wasting power on over grinding the hard quartz. This also avoids the generation of ultra fine quartz particles which can react and consumes both caustic and alumina from the liquor. The coarse quartz in a hot Blow-Off (BO) mud slurry can be processed and removed in a sand trap, this unit operation has a large diameter hydrocyclone-type design and is able to separate the quartz-sand fraction for further water washing in rakes. This removal avoids any later problems relating to settling of the coarse sand in setters and washers. Instead of the use of rakes a multistage hydrocyclone processing arrangement could be used for washing the BO slurry to remove a clean sand product.

3. Mill Modelling

The grinding mechanism inside rod and ball mills is different to that inside a SAG mill in that they rely wholley on the cascading movement of the media (rods and balls), for particle breakage by abrasion and attrition. A pure SAG mill operation with a very coarse feed (Top size 15 cm) can achieve significant breakage on the larger rocks through Rock-on-Liner or Ball-on-Rock or Rock-on-Rock breakage through high energy particle trajectories inside the mill. Drop weight testing simulates such bauxite-breakage and allows an estimate to be made on the bauxite hardness and breakage characteristics. However, it is likely that in the processing of soft bauxite SAG mills are operated as ball mills with the bauxite having a short residence time in the mill and grinding by abrasion, chipping and attrition mainly occuring within the cascading media in the mill. The JKSimMet SAG mill model for bauxite tends to be very sensitive to the feed size and it may be worth considering modelling the SAG mill as a simpler ball mill for usability.

During the planning of a new refinery for determining the size of an operating mill, the mill sizes often assumes a standard aspect ratio length / diameter (L/D), ~ 0.5 for SAG mill, ~ 1.25 for a rod mill and ~ 1.5 for a ball mill. Numerous calculators are available from various mill engineering companies and consultancies. It is advisable to use as many of these as possible as a cross check and take a rough average estimate of the recommended size of the mills (L/D) and the mill motor sizes. The final stage of evaluation is supplemented by a desk study using JKSimMet. JKSimMet mill models have been validated against actual operating mills and can provide an important confirmatory guide to throughput and particle size. For this reason, such models have gained a lot of acceptance and industrial approval and are thought to give a reliable prediction of mill performance. It would be pointless to deliver the correct tonnage throughput and not the correct particle size, and even when the mill has been correctly sized an extra contingency factor should be considered to account for any small changes in bauxite hardness. Alternatively, this may be for a future scenario if there is a need to process a different bauxite supply with different grinding characteristics, or for a refinery expansion. An accurate mill size estimate can usually be quickly determined assuming the input variables are accurately known (e.g. F80 and P80) (see Tables 4 and 5). These simple Bond Work Index calculations will also determine the required number of mills and the mill motor power. Further confidence on the mill size can be made after comparison with other projects and existing refineries processing comparable bauxites. A second or third opinion may be warranted using industrial experts to help confirm calculations together with confirmation on delivery of the correct product size and tonnage throughput. Also, it is recommended that JKSimMet mill modelling be carried out by an independent, experienced user of the software.

Table 4. Input information required for mill sizing using Bond Work Index calculators.

Information required during first pass Mill size evaluation (throughput)	
Feed Rate (tonnes)	Ball Charge (%)
Dry Solids SG (g/cm^3)	Ball Size (mm)
F80 Feed size (microns)	Pulp Charge (%)
F80 Product discharge size (microns)	Ball or Rod Charge (%)
WI Crushing (for SAG Only)	Mill Cone Angle (degree)
WI Rod Mill (kWh/t)	Open or Closed circuit (yes or no)
WI Ball Mill (kWh/t)	Liner Allowance (0.15m)
Required Critical Speed (rpm)	Abrasion Index (number)
Fractional Mill Filling (%)	Fractional porosity of charge = 0.4
Estimates of Diameter (D)	Estimates of Length (L)

Table 5. Input information required for JKSimMet modelling evaluation.

Requirements	**Comments on input values**
Drop weight test	Could assume a number for soft bauxite – e.g. 130 to 150
Ball Mill Index	Target product size needed. Depends on lower sieve screen size used.
Rod Mill Index	Target product size needed. Depends on lower sieve screen size used.
Liquor Density	Usually 1.26 g/mL for liquor. Can it be assumed that liquor phase is water?
Particle Size of samples	Use screen sizes that match inputs into JKSimMet.
Density of Bauxite	2.8 g/mL. Bauxite can be porous and may reduce this value.
Dimensions of Mill	In meters.
Grate characteristics	Open area volume % (holes or slots).
gpL solids	

4. Operation Issues and Improvements

During the optimisation and control of the mill operation a good understanding and quantification of the discharge size (P80) as a function of tonnage throughput is ideally required. What can be measured can then be managed and improved and ball charge volume optimised. When steady state conditions prevail in the mill (input tonnage (mill feed) = output tonnage (hydrocyclone OF)), attempts must be made to reduce the P80 size of the mill product. The use of other monitoring tools, that include: mill acoustics, power draw, weightometer and density flow data, mill and wear models can all help and support such evaluations. When available the load cell is the ultimate tool for accurate modelling of mills, whereby the whole mass of mill (metal + balls + liquor + bauxite) can be monitored accurately during the course of operation and an accurate recirculating load can be quantified. This return stream may be upto 100 % of the feed tonnage and explains why the high throughput mills are so sensitive to small changes in particle hardness and density (= iron-rich material).

For an incremental particle size reduction, the ball charge management and mill ball wear issues must be addressed (Table 6). Ball charge management is required in order to ensure: mill charge (load and power), control stability, capacity and grind size is maintained. It is comprised of ball charge reconciliation and continuous charging of media. The ball charge readjustment follows a so called "grind out" (Table 1) which completely removes bauxite from the charge inside the mill. This process allows the inventory of balls inside the mill to be measured and allows the mass of balls required to be added into each mill to be calculated. The required ball mass can then be transferred to the mills as a continuous addition. The routine addition of small quantities of balls is required to be made owing to wear and breakage losses and to keep the size distribution of balls inside the mill constant.

For planned maintenance there are a number of wear related issues that need to be monitored as these can ultimately affect the particle size contribution. The grate holes can be plugged, peened, or scaled (see Figure 3). This reduces the operational grate open area, and the flow of slurry is reduced unless they are regularly monitored, and the holes unplugged. Lifter bar profile needs to be monitored through visual observation or more accurately measured using an internal mill laser scan (e.g. mill mapper). This also helps predict when liners are required to be replaced. The trajectory and movement of the bauxite and balls in the mill charge will be dictated by the wear on the lifter and the mill speed may be required to be adjusted as lifter wear continues and internal volume incrementally increases. The wear rate being a function of the tonnage treated, bauxite hardness and presence of abrasive minerals (e.g. quartz) in the bauxite. Poor mill practice may also increase mill ball – liner contact and lead to increased wear on both liners, grates and balls.

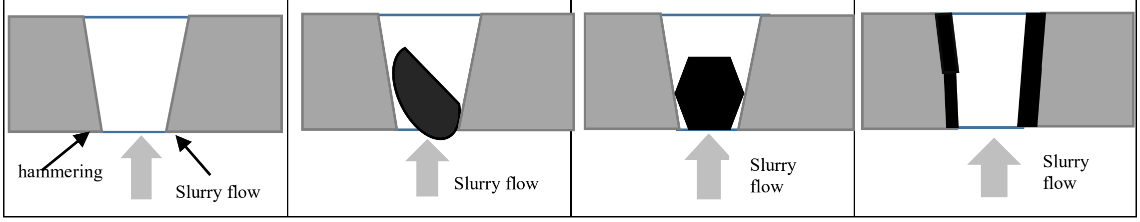
Wear on the consumable parts in a hydrocyclone, namely spigot and vortex finder need to be monitored and a wear model developed for the parts. Small changes in the worn parts can start having an impact on the cut size. Also change in aperture sizes within trommels and on screens will also have a small incremental change on the bauxite product size. Modelling and quantifying the various high wear regions need to be carried out and will help prioritise areas which require routine attention and replacement.

Table 6. Monitoring ball content and wear following a grind-out.

Ball reconciliation actions	Monitoring wear and grate hole blinding
During grind out –record Load cell data, also record Power draw and speed to estimate the mass of balls within the mill. Ensure mill belly is empty of bauxite and full grind-out has been achieved. Enter mill belly and measure the distance from the centre line of the mill to the ball charge surface. The extra balls needed will be calculated and then delivered to the mill.	While inside the mill record the following: • Grate hole open size (look for peening and wear) and open area by counting clean / plugged holes in at least 2 grate segments • Liner heights (at all locations along belly length, and at the end of the lifter bars at all locations along length, measure grate thickness) • Estimate ball size distribution • Estimate broken balls or non-spherical scats (indication of breakage) • Estimate any accumulated lump material (critical size) • Measure trommel panel exit aperture size (rear of mill). Monitor any blinding or plugging wear Photograph and record each with a reference measure in each photo. Develop a spreadsheet to track the open area, hole sizes, and liner dimensions for each mill. Progressively clean individual holes in grates and maintain open area volume.

Long distance shipping of bauxites to an alumina refinery, for either a refinery feed or for sweetening purposes is costly, these bauxites are required to be milled finer than normal to ensure complete extraction and minimise bauxite usage. Prior to milling the supplied bauxite can be crushed finer if the mill is not delivering on particle size or tonnage throughput. Other potential levers to control the size distribution include mill speed and % volume ball charge. Particle classification can be further controlled through changes in grate design and grate hole dimensions, trommel aperture and hydrocyclone design.

Peening	Plugging (metal scat)	Plugging (bauxite)	Scaling
Metal around grate hole hammered by balls which reduces the grate hole diameter	Metallic particle (scat) plugging hole	Hard bauxite particle plugging grate hole	TCA scale may build-up on the inside of the grate holes (reaction of $CaCO_3$ with liquor)



Note - Diameter in grate for the Ma’aden SAG Mill grate design – front 25 mm to back 32 mm

Figure 3. Common reasons for mill grate hole size reduction at Ma’aden.

5. Conclusions

In the Bayer process the milled bauxite must be of a size appropriate for desilication and digestion purposes. Finer particles in digestion will always be preferable as the individual particles will dissolve and shrink more rapidly and release alumina into the liquor. This will help the rapid achievement of the target ratio and require a shorter residence time. Other process benefits of finer grinding include reduced abrasion / erosion in: pumps, valves, pipes and flash tanks. For coarsely ground bauxite the digestion temperature, TC, liquor ratio (A/C) and holding time become controlling parameters in digestion control. Alumina losses will occur in the coarser size fractions due to incomplete digestion. In a gibbsite-boehmite containing bauxite the coarser boehmite grains will always be the dominant alumina loss to the waste mud. Mine-to-Digestion studies where size reduction of the bauxite on its journey from blasting through to crushing, milling, desilication and to digestion will help identify and prioritise incremental improvement steps and help deliver a reduced particle size.

A coarse grind can be resorted to when quartz is present in the bauxite, this is to avoid wastage of energy during grinding and generation of reactive ultrafine quartz particles (<10 microns). Coarse quartz can be recovered after digestion using sand traps, rakes, screens and hydrocyclone washing circuits. For these reasons coarse milling can be tolerated as long as the refinery is initially designed around such bauxite feed characteristics.

Close circuit SAG mills are now considered to be the most suitable mill for processing soft bauxites and can handle a range of particle feed sizes and hardnesses. The small aspect ratio (L/D ~ 0.5) and the use of pulp lifters allows a rapid flushing out and separation of the finer particles (< 2 mm) from the crushed product, allowing grinding to focus on the remaining coarser and harder particles. SAG mills treating bauxite are often operated like ball mills, mainly on account of the soft nature of the bauxite and size of the crushed feed (< 10 cm). The actual sizes and number of mills used to deliver a selected particle size can be estimated using conventional bond ball calculators and JKSimMet modelling. Mill models can predict the size distribution of the mill product with reasonable accuracy.

Incremental improvements can also come from maintenance of key equipment which effects particle size, notably: lifter bar wear, grate hole wear, trommel wear, hydrocyclone and screen wear. Routine grind outs will also ensure the removal of larger hard and dense bauxite particles in the mill and also reduce any build up of the circulating load.

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