Ceramic bead behavior in ultra fine grinding mills

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Abstract

A preliminary review of the developing morphology of ceramic beads during extended operations in high energy stirred mills is presented.

Ceramic beads are produced from various formulations and processes; these certainly affect the cost of the media; but significantly, they impact the competence and performance.

Mills operate with a ‘Working-Mix’ or ‘Seasoned-Charge’; invariably this means that worn beads of various sizes are present in the mill.

These beads can have effect on ‘mill efficiency’, ‘overall media wear’ and particularly ‘mill wear’.

This study reports preliminary findings of wear profiles of typical ceramic media and some of the potential effects of extended use.

1. Introduction

Saint-Gobain Zirpro has been instrumental in the development of ceramic media for ultra-fine grinding applications in stirred mills. The history and experience are long, dating back to the mid nineteen seventies. The company was in-fact established in 1971 to refine Zirconium Oxide to meet the Saint-Gobain Glass requirements for high performance refractories. The history of the Glass division is somewhat longer and it celebrated its three hundred and fiftieth anniversary last year.

Zirconia (Zirconium Oxide) and Zircon (Zirconium Silicate) turned out to be significant raw materials necessary to manufacture high quality ceramic beads. Initially beads were produced by a fusion process; the operation required high temperatures and the beads were formed in a molten state. The resulting product (ER120) was based on Zircon and had a density of 4.0 g/cc. The beads were round and non-abrasive and were ideal to replace the glass and natural sand products used in the burgeoning stirred or bead mill applications. A comparative increase in density of over
high density (6.0 g/cc) stabilized Zirconia beads as the media of... today the evolution has continued with the general acceptance of... product (RIMAX) which gave exemplary performance in many... with extended bead lifetimes. Zirpro again developed a class lead-... tion (sintering) at high temperature. The products proved to be... required low temperature forming before densification... resulted was the evolution of sintered beads, initially based on the... the same chemistry and having the same density as the fused products. These beads required low temperature forming before densification (sintering) at high temperature. The products proved to be... many of the new applications, providing tougher beads with extended bead lifetimes. Zirpro again developed a class lead-... producing RIMAX which gave exemplary performance in many... Chemistry. Today the evolution has continued with the general acceptance of... high density (6.0 g/cc) stabilized Zirconia beads as the media of... and Nonnet, 2007). The higher density provides the potential for superior and economic grinding and although ini-... machinery, the controlled wear provides an overall cost effective... solution. Zirpro developed a premier product ‘ZIRMIL’ now widely adopted and widely used in the processing of the most... demanding applications, such as pharmaceuticals and ceramics. Mill design has also evolved to meet the ever increasing demands for ever more specialized materials and applications. At the forefront of these developments are two extremely different projects; the first is nano grinding of electronic materials and the second the ultra-fine grinding of ore bodies in the mining industry. For nano grinding, beads sizes of approximately 100 μm are required and potentially bead densities increasing beyond of 10 g/cc. For mining the environment is severe and beads must withstand high impacts from hard and large feed materials in dilute slurries. In the nano application Zirpro has launched a derivative of the ZIRMIL range. Advanced ceramic technology and process engineering have enabled the production of 100 and 200 μm beads in industrial quantities at economic price levels. The material is cur-... Roic: Ceria and similar stabilization can be achieved at a more... to Yttria is Ceria and similar stabilization can be achieved at a more affordable rate. Zirpro have developed an additional product for the mining industry ‘CERMIL’. It finds application in the mining industry in specific mill types where high bead densities are required. The general range of media for the mining industry is actually more affected by the choice of available and cost effective raw materials; for example kaolin, Alumina and Zircon. From these the majority of formulations can be achieved. The raw material choice can also affect subsequent processing possibilities as the natural plasticity of kaolin can be exploited; alternatively additional organic plasticizers need to be added. The range of formulations and chemistry has significant effect on the nature and behavior of the bead. Density is the primary consideration (Becker et al., 2001) with products ranging from a low of 2.7 g/cc to a high of 6.2 g/cc; predominantly however a mid-range of den-... the majority of mining applications. The physical properties of the beads are also linked to original formulation; factors such as hardness, toughness and strength are fundamentally affected. A point of consideration here might be an analogy with a ‘brick wall’; the individual grains of the bead (the bricks) have extremely good physical characteristic but the actual performance is more dependent on the binding agent (the mortar); it is often the consistency and make-up of grain boundaries of a bead which dictate its performance. The processing of ceramic materials these days is more of an advanced engineering operation, but there certainly remains an element of the artisan or craftsman. An example of this is the relation-... and properties of the product. Ceramics are said to have a ‘memory’ and this refers to the fact that forces and stresses experienced in forming become manifest in the final structure of the product (Ford, 1967). For beads there are two main forming processes; dripping and granulation. The dripping process involves forming a plasticized paste which is extruded through fine forming nozzle. The process provides a high degree of homogeneity in the formed bead. This is important in subsequent firing procedures as the uniformity assist in grain growth and densification at high temperature. The main drawback of the process is the lack of uni-... is a potential problem when the bead is in use. The other...
process is granulation; here a seed is progressively coated with a plasticized mixture of the raw materials. The process eliminates the issue of the droplet shape and tends to produce overall very round beads. The main issue is control of process and the ‘memory’ factor. If the layers are built too quickly then internal stress can develop; these become exacerbated during firing and can result in delamination (see Figs. 2 and 3). Both processes have their own merits, fundamental to both is the management of raw materials (particularly grain size) and tight production and quality control procedures. The final stage in the manufacture of a bead is the ‘firing’ or ‘densification’ step (Kingerly et al., 1991). This too is critical and its optimization is integral to the successful performance of the bead. The firing must be controlled and accurate, suited to the specific materials employed. The old adage to improve performance, simply ‘fire at higher temperature’ does not work for beads. At the temperatures and firing cycles most commonly used (1250–1450 °C) firing higher for a particular formula potentially would result in high glass formation and tendency for the bead to be prone to spalling. There are obviously many options to produce beads but there are only two final criteria for their design; they must be ultimately competent and provide economic operation.

2.2. Available ultrafine milling equipment

The mining industry has a requirement to treat fine feed materials (50–250 μm), a target difficult or ineffective for traditional milling processes such as SAG or Ball milling. Even for more modern machinery such as High Pressure Grinding Rolls (HPGR) it is at the extreme of their capabilities. The favored route has been the use of ‘stirred’ or ‘agitated’ bead mills. Just as there is a great variation in the beads available, there is also a considerable choice in machinery for ultra-fine grinding in mining applications. There are four main equipment’s available as follows, Stirred Mill Detritors (SMD manufactured by Metso Minerals), Isamills (manufactured by Glencore), VXPMill (manufactured by FLSMI) and HiGMill (manufactured by Outotec). Essentially the fundamentality’s are the same; there is a vessel and an internal stirring mechanism designed to agitate the beads. The stirred beads are accelerated to a level where inter bead collisions have sufficient energy to break the target slurry particles and thus affect grind. Practically this operational feature is potentially all that the mills have in common. Mills can have a vertical or horizontal configuration. They can use discs or stirring bars. The size of the mill can less than 100 L or reach as high as 45,000 L. Power can range from a few Kilo-Watts to a few Mega-Watts. The speed of the agitators can be as low as 4 m/s and as high as 22 m/s. The power profile (Watts per unit mill volume) can vary significantly as can the throughput profile (liters flow per unit mill volume). All these factors have a profound effect on the performance and efficiency of the bead employed. Certainly it is not a case of one size (bead) fits all! Bead selection needs to be appropriate to the application and to the mill type proposed. Optimization of bead is a serious question and should be determined by laboratory and pilot testing prior to implementation. In-correct choice can affect the overall efficiency and potentially the viability of the process. Beads are an important factor and must be closely matched to operating conditions (Curry and Clermont, 2005).

3. Results and discussion

3.1. Bead wear issue

The other effect of optimizing bead would be to provide controlled bead wear profiles. Initially beads are selected to fit purpose and provide economic grind. However the media will wear and the way in which they wear will have impact on the process efficiency. Firstly if the conditions in the mill are imbalanced then severe bead wear can result. In such circumstances we can expect beads to delaminate, split, crush and spall. Some example of beads after severe wear are giving in Figs. 4–6. All are extremely undesirable resulting in rapid loss of mill efficiency and increased mill wear (Kotze, 2012).

Less severe but equally detrimental is the generation of flat or faceted beads in the mill charge (Figs. 7 and 8). These
phenomenon results from preferential wear of the media. This type of wear is somewhat due to the initial shape of the bead but also due in great part to the operational conditions of the mill. It is greatly exacerbated by limited or restrictive bead flow in the mill ‘dead-spots’. These ‘dead-spots’ can be due to hydraulic packing or simply due to less agitated parts of the mill chamber. The worn beads generated tend to remain in the mill, but their contribution to grinding is extremely limited. In severe cases the efficiency of the mill is absolutely compromised.

Not with-standing these dramatic forms of wear, good beads in good mill conditions will also ultimately wear (Gallimore, 2010).

3.2. Effects of bead wear

Mills operate with a ‘working mix’ or ‘seasoned charge’. It is rather this ‘working mix’ rather than the initial bead size which determines mill performance. Original bead size selection must take this factor into consideration and provide a suitable ‘working life’ of bead. This ‘working life’ refers to beads which contribute to grinding. Once beads fall below a certain size they cannot be accelerated sufficiently and cannot affect grind. These beads merely dilute the grind and absorb energy. In many industries where continuous mill operations are standard it is estimated that up to 30% of input energy can be lost by generating high levels of media fines. As an example size distribution of initial beads are compared to beads size after 1000 h for a mineral milling application in Fig. 9. This shows that only approximately 25% of the used beads remain in the initial media size range; greatly compromising overall efficiency.

The phenomenon cannot be overcome, it is a factor present in all mills in all industries. The only recourse is to control the issue as much as possible. In some applications it is possible to replace the entire charge periodically. The opportunity for this is indeed rare and certainly not applicable in the mining industry. The only alternative is to use more durable beads with extended media lifetimes. The effect here is to reduce the speed at which fines are generated and consequently maintain a higher proportion of contributing beads for as long as possible. Consistently the
A 'working mix' for more durable beads is proportionately larger in size and achieved grinds significantly superior (Hassall, 2008).

3.3. A case study: HIG mill installation at FQM Kevitsa Finland

3.3.1. Process presentation

The FQM Kevitsa, Nickel-Copper-PGE mineral deposit is located in Finnish Lapland. Production at the mine started in summer 2012. The site produces copper and nickel concentrates with gold, platinum, palladium and cobalt by-products. Primary and secondary mill cyclone overflows are selectively floated in three phases as illustrated in Fig. 10. In recent times, higher mill throughputs with coarser grades highlighted the need to enhance Cu regrinding to improve mineral liberation (Cu-Ni separation). This requirement led to the installation in February 2015, of a HIG700 mill to Cu flotation circuit. The HIGmill feed is copper rougher scavenger concentrate and product guided to first copper cleaning phase.

Cyclone underflows report to a HIG feed tank and the overflow goes to the HIG mill product tank. The feed slurry is pumped.

Fig. 10. Kevitsa flotation circuit flow sheet. HIG mill is circled (Lehto et al., 2016).
through the mill and overflows into the product tank. Samplers (PSI samplers – Outotec) are located before and after the HIGmill. A PSI500 analyzer (online particle size analyzer – Outotec) is connected to these samplers and it monitors continually the feed and product sizes (Fig. 11).

The HIG mill is configured with stationary discs on the liner and rotating discs attached to the drive shaft (Fig. 12). Slurry is pumped through the feed inlet, located at the bottom of the mill. Centrifugal action forces coarse particles and media to the outer shell. Gravity keeps the media compact during the operation and most of the grinding is done by attrition. All particles have to pass through the entirety of the mill and face multiple grinding stages.

HIGmill operation is being controlled by a preset value of the Specific Grinding Energy (SGE) related to dry tons. Flow and density meters measure the slurry characteristics in real time. The mill speed is constantly being changed with the VSD to meet the changing flow. All HIGmills are equipped with a VSD to provide control to the operation and to avoid overgrinding.

Minerax grinding media is introduced into the mill from a feed tank via the HIGmill feed pump. A screw feeder adds media once every hour, depending on the kWh used in the mill. This ensures that the grinding media level remains constant and that the best possible grind efficiency is maintained.

Ore feed size to the mill (F80) vary between 80 and 120 μm; however despite the large variance, P80 can be maintained at the desired level due to the adaptable and controlled mill operation. Currently the P80 is at 35 μm. Installation of the HIGmill has resulted in significant increases in tonnages processed through the primary and secondary grinding stages while always retaining the correct particle size for flotation.

3.3.2. Initial results

HIGmill feed and product particle size distributions are shown in Fig. 13. Achieved grind (P80) was 32 μm compared to target at 30–35 μm. SGE of 13–15 kW/t was used to control the grind.

![Fig. 12. Grinding philosophy of the Outotec HIGmill (Lehto et al., 2016).](image)

![Fig. 13. Feed and product particle size distribution after HIG mill in Kevista mine operations.](image)

![Fig. 14. Cu distribution and grade in Copper Concentrate before and after HIG mill.](image)

![Fig. 15. Media general state after six weeks commissioning.](image)
Copper grade and total Cu recovery increased after HIG mill installation as presented by Lehto et al. elsewhere (Lehto et al., 2016). Benefits of improved Cu/Ni separation are illustrated by an increase in Cu deported to all the size fractions below 75 $\mu$m (floatable size range), see Fig. 14. Correspondingly the Cu grades in the detailed size fractions also increased.

### 3.3.3. Media considerations

Commissioning of any new equipment is intrinsically complicated; with various parameters being defined and numerous operational conditions experienced. It is a particularly arduous for stirred mills in terms of the milling media. Start/stop operations, with extremes of speed and throughput can have a detrimental effect on the charge. It was therefore important to check the bead condition immediately after the commissioning period. An audit was carried out specifically looking for damaged beads and any excessive media wear. The basic results are detailed in Figs. 15 and 16.

The main observation was that the working mix was already established, with the majority of the bead falling into a 2.5–3.15 mm range. The bead significantly remained round and polished, with no broken or severe abrasion evident. Beads were collected from both the top and bottom of the mill; the wear profile from each was seen to be controlled with no perceived issues to report. There were no fines observed at this stage, potentially as the running time of the mill was limited.

The next audit was taken after a period of 6 months where a more ‘steady state’ of mill operation had prevailed. Again samples were taken from various locations in the mill. The results are detailed in Fig. 16.

Again the working mix profile was well detailed and remained consistent across the mill. The charge remained predominantly in the 2.5–3.2 mm range, although there was an increased proportion in the 2.0–2.2 mm sizing. A very high proportion of the media remained round and polished, providing good media flow and restricting mill wear. An increase in damaged beads was observed as detailed in Fig. 17.

The only identifiable issue was faceted beads; which were approaching 10% of the charge. The limited severity of the facets and the relatively low levels; were not expected to have any detrimental effect on continued operation or ultimately mill efficiency. In-fact no perceivable decline in achieved grind or efficiency were evident.

Again there were few fine beads observed below 1.8 mm, and after 6 months there should have been sufficient time for the bead profile develop fully. The phenomenon is not yet explained as there were no broken beads evident within the mill and no solid beads escaping the mill. The issue needs further investigation.

The mill has continued to run successfully. Further audits will help to develop a broader understanding of the evolution of the ‘working mix’ and its long term effects on HIGmill operations.

### 4. Conclusion

The observed results are extremely encouraging; reflecting the accurate modelling and testing carried out prior to installation. The mill achieved target grind and provided an efficient and cost effective process. The correct choice of bead type and bead size was a fundamental contributor to the level of success. This optimization in media selection provided a competent, problem free and assured mill operation. Ultimately the bead wear was controlled and delivered a working mix which was efficient in grinding target particles. There were no observed media issues and consequently mill wear was also minimized.
References
