INVITED FEATURE

Semi-autogenous grinding (SAG) mill liner design and development

D. Royston
Principal, Royston Process Technology Pty Ltd., Brisbane, Queensland, Australia

Abstract
SAG mill liner development draws primarily on practical experience from SAG milling operations supported by computer-based modeling of charge motion in SAG mills and on established good design practice. Liner design needs to respond to the process aspects of mill liner action that are critical to good SAG mill performance, i.e., the impact of shell liners on the grinding action and of grates and pulp lifters on pulp discharge. In recent years, the trend in large SAG mills has been to use wide-spaced shell lifters with large lifter face angles, primarily to reduce packing and ball/liner damage, and to use larger, hence fewer, mill liner parts to reduce downtime at liner change-outs.

Key words: Comminution, Grinding, SAG mill, Mill liners

Introduction
Semi-autogenous grinding mills (SAG mills) are tumbling mills that most commonly have a shell diameter-to-length ratio of around two. With this high aspect ratio, SAG mills generate both thrown and cascading ball-milling actions with shell linings shaped to lift and to throw alloy steel grinding balls of up to 150 mm (6 in.) in diameter. These actions apply crushing, attrition and abrasion comminution processes to reduce primary-crushed ores down to ball-mill sized feed. Feed ore with a top size of up to 200 mm (8 in.) and water enter the feed end of a SAG mill through a feed chute; the ore is milled in the shell and milled product exits through grates and pulp lifters at the discharge end (Fig. 1). The discharge is screened and the undersize, typically less than 12 mm (0.5 in.), provides ball mill feed and the oversize is returned for further milling. To increase mill throughput, oversized "pebbles" may be crushed before return. Napier-Munn et al. (1996) and Wills and Napier-Munn (2006) describe the design and operation of SAG mills.

SAG mills are currently the technology of choice in hard rock milling operations for reducing primary-crushed ore to ball mill feed. In recent years, the trend has been towards larger-sized SAG mills with diameters of 10.4 m (34 ft) and above, with the largest being 12.2 m (40 ft) in diameter and drawing 20 to 22 MW (Jones, 2006).

Mill liners provide the replaceable wear-resistant surface within grinding mills; they also impart the grinding action to the mill charge, and at the discharge end, remove the ground contents of the mill. In recent years, as SAG mills have grown in size, the process aspects of liner design and their impact on mill performance have become particularly important. Practical experience, the principal source of the observations on liner design made in this review, continues to be critical to good mill liner design. Increasingly sophisticated computer-based tools, used to illustrate and to quantify mill performance, and the interaction between the liners and mills charge, support established good engineering design practice.

Shell liners
Shell liner and charge interaction. Shell lifter design is critical to good mill performance. The important process objectives in SAG mill shell lifter design are:

- to provide the key between the mill charge and the mill shell for charge motion,
- to maximize the rate of delivery of thrown grinding media at the toe of the charge to gain the best milling action,
- to avoid liner and ball damage and
- to provide an economic liner wear life.

Shell liner design is driven primarily by the practical operating experience with various combinations of lifter heights, spacing and angles. Changing the face angles of shell lifters alters grinding ball trajectories, and hence the point of impact within the mill, and the spacing between shell lifters affects charge lifting rate, and hence mill performance (McIvor, 1983; Powell and Nurick, 1996).

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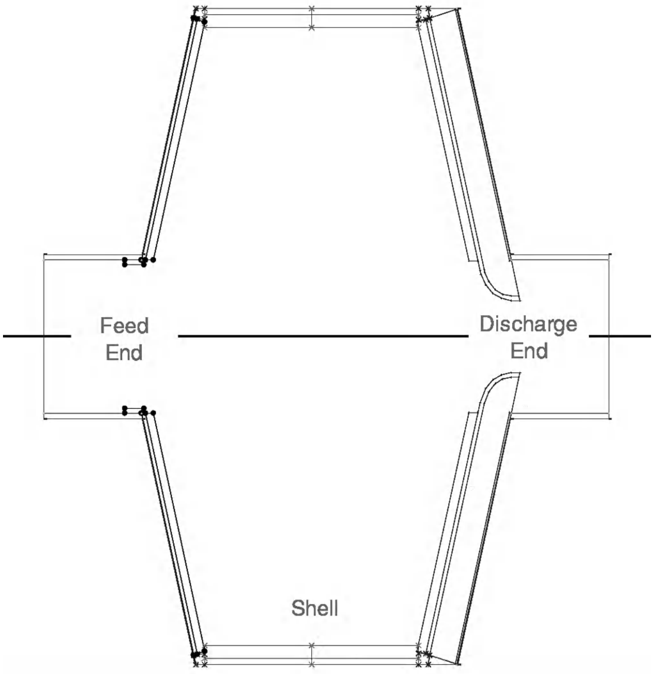

Figure 1 — SAG mill and lining in section.

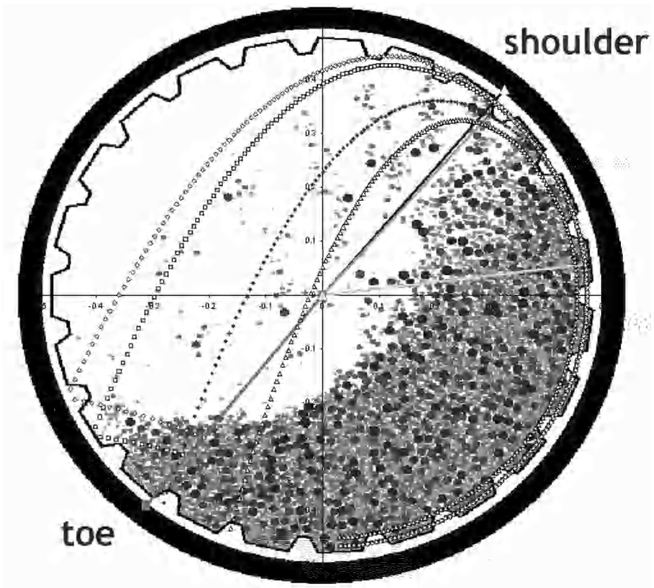

Figure 2 — Ball trajectory model outputs superimposed on (simplified) DEM model output.

Trajectory and charge structure computer models have been used for some time to support practical operating experience and engineering judgment (Powell et al., 2006). Advanced computing tools such a discrete element modeling (DEM), which now incorporate slurry effects using smoothed particle hydrodynamics (SPH), contribute to mill liner design by providing illustrations of charge motion and detailed information on the interaction between liners and mill charge motion and mill power draft (Nordell et al., 2001; Rajamani et al., 2001, 2003; Cleary et al., 2006, 2007; Herbst and Lichter, 2006). Figure 2 illustrates ball-trajectory model outputs superimposed on a simplified DEM model output (Royston, 2001).

Trajectory models (for shell lifters of various heights and face angles) generally track the fate of the "lifter ball," the ball that sits against the lifter and plate (Royston, 2001). At constant mill speed, ball trajectories should degrade (i.e., balls fall more towards the bulk of the charge than the toe) with time as the lifters wear down. Shell lifters with initially large face angles may start by directing ball impacts at the toe and come "on-grind" almost immediately only to fall-off in performance. Any practical shell-lifter design has to perform over the full life of the shell lifter/liner. Any special benefits from new shell lifter profiles may be maintained only for a short period, unless shell lifters are of substantial size, as the shell lifter profile changes through wear.

The energy required to lift and throw charge (aimed to generate high-energy ball-rock impacts at the charge toe) can be estimated from the lifting rate and height of lift of material between the shell lifters. The energy required is a minor proportion of SAG mill power and this proportion falls as the liners wear (and lifting capacity falls) even when mill speed can be increased. The major proportion of mill power is used to turn over the mill charge. It follows that repeated ball-rock short-range low-energy impacts within the tumbling charge are a significant proportion of the overall rock-breakage process throughout the life of the liner.

For fixed-speed mills, a common practice is to design shell lifters with some (slight) overthrow when new such that the liner "wears in" to come "on grind" early in the wear cycle with mill performance falling away towards the end of shell lifter wear life. The aim is to maximize the wear-life of the shell lifter. Increasing mill speed (e.g., through a change in pinion size) along with an increase in shell lifter face angle can increase both the rate of impact of balls at the toe and charge turn-over, both actions improve milling performance through increased "ball-charge participation."

Over throwing should be avoided, especially high-energy ball-on-shell impacts just above the charge toe, owing to the risk of ball-on-liner damage and excessive metal flow. In fixed-speed mills, this may be achieved by increasing charge volume; in variable speed mills, this may be achieved by reducing mill speed; and in both cases this may be achieved by design by increasing the lifter face angle.

Traditionally, the number of shell lifters used in a SAG mill is equal to twice the number of the feet in the mill shell diameter (e.g., a 34-ft-diameter mill shell would have 68 shell lifters). This is also called a 2-D shell lining. Eliminating some shell lifters increases the volume of charge between the lifters ("the bucket") and the total charge that should be lifted in each rotation of the mill, hence potentially increasing the milling action. Wider spacing can also provoke charge slippage that offsets the increase lifting capacity and induces liner wear. It is important with wider lifter spacing to adopt a large lifter face angle to direct thrown balls into the charge to avoid ball impact damage on the exposed wider plates.

With wide-spaced lifters, the thrown charge from larger buckets should disperse more than from the smaller buckets of close-spaced lifters (Royston, 2001). More dispersion should result in the loss of focus of impacts on the toe. This may explain the need to increase mill speed in some mills following a change to wider shell lifter spacing; the increase in mill speed would increase the effective number of ball hits on the toe of the mill charge from the more dispersed thrown charge. A positive outcome for fixed-speed mills is that some balls may continue to be effective in hitting the toe region for longer throughout the lifter wear cycle. Figure 2 provides an illustration of the distribution of thrown charge.

With variable-speed mills, increasing mill speed directs ball impacts at the toe as both the lifter height falls and the lifter face angle increases with wear. The impact point is usually tracked by the feedback of impact sound from microphones mounted close to the mill. If mill speeds are increased above 78% to 80% critical speed, pulp-lifter efficiencies could fall and affect overall mill performance. Using a smaller, not larger, bucket size to focus the impact of the charge at the toe, along with increasing mill speed as shell lifters wear, is a promising current development in shell liner design and SAG mill operation providing the potential for lower energy consumption, increased throughput, and start-up "on-grind" with new lifters (Veloo et al., 2006b).

Highly worn shell lifters can still deliver adequate (though not necessarily optimal) milling performance. Milling performance may be maintained by:

- increasing the mill speed (where possible) to compensate for lowered shell lifter height;
- increasing mill volume and, hence, the grinding media and charge volume as liners wear down;
- for packed mills, the effective height of the shell lifters may be maintained through most of the shell lifter wear-life as the packing thickness falls in proportion with shell lifter height;
- for both fixed- and variable-speed mills, much of the rock breakage throughout the liner life must come from the tumbling and not the thrown action, i.e., rock breakage through repeated short-range impacts, attrition and abrasion;
- increasing the spray of thrown media ("late" and "plate" balls, Royston, 2001), ensuring some balls continue to provide effective impact hits in the toe region; and
- rigidities in the mill charge structure could still provide enough lift through the shoulder of the charge for some strong cascading action, hence breakage through repeated short-range impacts.

Shell lifter designs. Many designs of shell lifters have been used over the years (Taggart, 1947; Wills and Napier-Munn, 2006). Illustrations of some current shell lifter-liner designs are shown in Fig. 3 (traditional "HiLo" plate and lifter), Fig. 4 (integral "HiHi" top-hat type) and Fig. 5 (a "HiLo" from-new type).

Current shell lifter designs commonly adopt large face angles, typically 22° but up to 35° with high shell lifters, to provide ball impact at the toe of the charge with spacing between lifters sufficient to overcome packing. Shell liners are now being designed and supplied to fit over rows of bolting with 2-D, (4/3)-D or 1-D liner spacing configurations and with substantial cross sections. It follows that there is merit in maintaining a 2-D row (with the total number of rows divisible by two and three) in new mills. The fine-tuning of spacing between lifters and the related bucket capacity can then be accommodated in the liner design and changed when and if necessary.

For large mills, using 125 to 140 mm (5 to 5-1/2 in.) feed ball size, conventional new lifter-liner dimensions are around 300 to 350 mm (12 to 14 in.) overall height above the shell, with around 100 mm (4 in.) plate thickness and around 150 mm (6 in.) top width. Detailed design depends on individual mill circumstances. Increasing lifter height usually leads to increased shell liner wear life. Changing the direction of mill rotation regularly can increase lifter life by taking advantage of the relatively lower face angle of the "trailing face" that becomes the "leading face" at each change in rotation.

Figure 3 — Traditional "HiLo" plate and lifter shell lining (after Dunn et al., 2006).

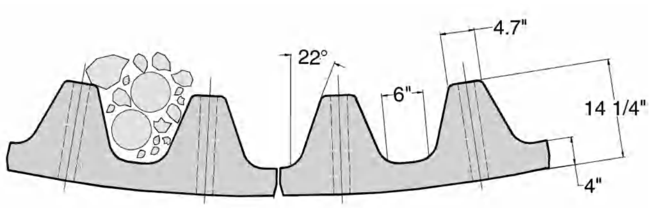

Figure 4 — Top-hat type "HiHi" shell liner system (after Veloo et al., 2006a).

In traditional "HiLo" shell liner systems, alternate rows of worn "Lo" lifters are replaced with a new "Hi" at each liner change-out and are usually of the separate lifter and plate design (see Fig. 3). This system appears to work well in some smaller mills (say, around and less than 7.3 m or 24 ft), especially in cases where packing can be controlled to the level of the "Lo" lifters. In these cases, if the "Lo" lifter height falls at the same rate as the "Hi" and the packing levels falls with the "Lo," the height of the "Hi" lifter over the packing could be almost constant, resulting in a similar impact position ideally around the toe of the charge throughout the life of the shell liners. In this situation, packing can be used to advantage, otherwise it is a disadvantage because packing reduces mill volume and in extreme cases provokes abrasive wear of the shell liners. The traditional type of "HiLo" replacement system fails in larger mills, especially in high-impact environments where it is difficult to avoid breakage of highly worn lifters. Such mills adopt "HiHi" shell lifter systems to avoid liner breakage; usually of the integrated lifter and plate "top-hat" shell lifter-liner design (see Fig. 4).

A recent development in shell liner design has been to introduce a form of the traditional "HiLo" lifter system where the "Hi" lifters are considerably larger than those used in prior practice (see Fig. 5). The "Lo" lifter is kept to a height similar to the "Hi" in a prior "HiHi" arrangement. The objectives are to improve wear life, to increase lifting rate, to continue to direct ball impacts at the toe and to change the shell liner wear (and packing) distribution along the length of the mill, while preserving the ball-impact resistance of the original "HiHi" lifter set. Such "HiLo" liner sets can also use wider spacing (that eliminates packing) and be of substantial size with an asymmetric design that requires unidirectional rotation of the mill (Weidenbach and Griffin, 2007).

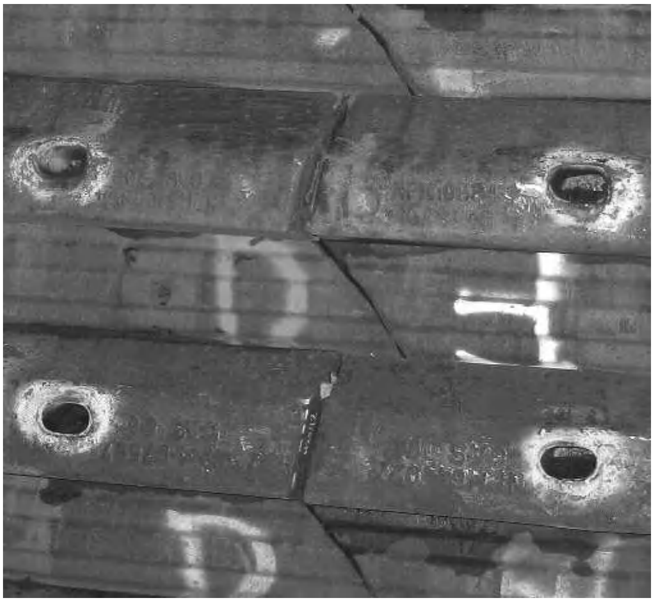

Figure 5 — New type "HiLo" lifter set (after Dunn et al., 2006).

Mill charge levels. A common practice is to run SAG mills with high ball-charge levels within low total-charge levels to maximize ball to rock ratios in the mill-charge. The outcome is to increase ball participation in the milling process and increase the frequency of ball-charge interactions and to improve mill throughput.

Operating with low charge levels can result in serious liner damage, ball and bolt breakage through ball impacts directly on to the shell lining above the mill-charge toe. These impacts allows strain forces to build in the surface of the shell liner that induce stresses in the underlying metal sufficient to cause failure by cracking even for large liner sections. The first step in the liner design response to this type of damage is usually to increase the leading face angle of the lifter so that balls can be directed into the mill charge. If impacts cannot be avoided, the design object is to remove the surface strain induced by impact either through wear (e.g., by adjusting lifter heights to induce charge flow over the impacted area) or directed metal flow. Directed metal flow requires detailed features, such a "chocolate block" pattern on the plates, that can absorb impact energy in the form of metal flow to the edges of the feature where is can be removed or worn off by the mill-charge. In some cases "plate and lifter" shell liner designs may allow some (very slight) inter-part movement for relief of stresses from part growth due to metal flow and strain.

With newer mills having high load-carrying capacity, high ball-charge levels (say up to 18%) have been used. The objective again is to increase "ball participation" through increasing the ball to rock ratio, while drawing maximum power at the maximum allowable total charge mass.

Mills with such high ball-charges operate in effect as large "primary ball mills" and appear to be associated with smaller sized and/or softer ore feeds (and these SAG mills may also use large shell lifter face angles and wide lifter spacing).

Wide-space and large-angle shell lifter experience. DEM provides detailed output on the effects of liner spacing and angles on charge motion overall. Outputs from early DEM models indicated that significant improvements in mill performance in some cases could result from the use of wider-spacing and larger lifter-face angles. This prompted changes in shell liner configuration along those lines. However, practical experience in recent years teaches that such changes may also lead to charge slippage and increase shell liner wear and damage.

A review of larger SAG mills that had changed to wider-spaced shell lifters and large face angles showed in most cases that the changes were driven principally by a need to remove packing between lifters or to reduce damage to liners and balls (Royston, 2004). As covered above, wider lifter spacing can eliminate packing and larger face angles can reduce damaging ball-on-mill impacts. With the alleviation of these immediate issues, mill performance improved. In addition, and almost inevitably with new and expanding operations, other changes occurred in the circuit and in the ore feed at the same time as changes to liner configuration. All such changes would have affected mill performance, particularly changes in ore hardness, which has a dominating effect on mill performance, and it was difficult to assign increases in mill performance just to changes in lifter angle or spacing alone.

Ore characteristics and shell lifter design. Changes in the hardness of ore fed to a SAG mill can cause significant changes in mill throughput irrespective of shell lifter design. In addition, changes in ore characteristics, such as a tendency towards packing, can affect the efficiency of the shell liners in a mill.

With harder ores, the milling rate may be maintained by increasing grinding ball size. Liner design may then have to be changed to provide shell liners (and other liners in the mill) capable of withstanding the higher impact forces of the larger ball size. Alternatively, precrushing may be used with harder ores to produce a feed more amenable to breakage in SAG milling. This would also require a change in mill operating strategy to deal with the smaller-sized hard material passing through the mill. These changes are not readily implemented (or reversed), hence the need to plan ahead for changes in ore type and size. These issues are the basis of a longstanding understanding that SAG mills operate best with ore feed with consistent characteristics; some sites deliberately mix ore types and/or operate on a campaign basis with pre-prepared stockpiles of consistent ore mix.

In this context, it is important to distinguish between ore size and ore hardness and their impact on shell lifter wear. A softer ore should lead to high mill throughputs with low wear if it does not lead to packing that might for example encourage washout at the feed-end side (FE-side) of the shell lifters. A fine, but hard, ore should lead to higher mill throughputs (without packing), but at the risk of increased abrasive wear. Both soft and fine ores can lead to difficulties in holding charge in the mill leading to increased ball-on-shell impacts and consequent damage including on the usually unaffected discharge-end side (DE-side) of the shell lifter.

Heavy packing, especially in larger mills, can reduce mill charge lift and milling performance and increase lifter wear rates significantly by promoting abrasive wear. An understanding of the packing characteristics of the ore is a critical aspect of shell liner design. If, for example, the ore supply is from a single source with constant but limited packing characteristics, it may be practicable simply to accommodate some packing as part of the liner design; in lifter and plate 2-D shell liner designs, this approach can add significantly to plate life. If packing is severe, then spacing the liners to say 4/3-D (with associated changes in face angle covered above to avoid plate damage) may provide enough gap between the shell lifters to prevent packing; then the shell lifter-liner design has to be based on an impact environment where no packing is present. Wider spacing to 1-D may ensure no packing can occur, but at the risk of damage (through ball impact) to wide exposed plates and of high liner wear rates due to charge slippage.

End-liner mechanical design

Feed end-liner design. An imaginary circular line drawn on the rotating end of the mill by the stationary "eye" of the mill charge is referred to here as the "eye-line." The position of maximum wear on the feed end (FE) lining is around this "eye-line." To prevent (rapid) abrasive wear of the end plates, lifter bars are used to deflect charge from the plate.

The FE plate itself carries a central stiffening bar (see Fig. 6). In integral FE lifter-liners, favored for larger mills, the bar forms part of the base for the lifting eyes. The stiffening bar also acts to deflect charge and limit abrasive wear on the plate. Recent trends include increasing the size of this stiffening bar to improve plate (and indirectly lifter) wear life and, for unidirectional mills, repositioning the bar better to protect the high wear region immediately in front of the FE lifter.

With FE lifters, the trend in recent years has been towards FE lifters with angled leading faces and outer taper; these designs aim to shed (i.e., avoid throwing) balls that could damage liners at the head end and to even out the wear along the FE lifter (see Fig. 6).

A change to large face angles on shell lifters results in radial-directed terminating trajectories of thrown balls. In these situations balls travel between (i.e., are not deflected by) radially distributed end lifters. Where new end liners have been installed outwards of worn, or one-off replacements are made of new liner pieces amongst old, radially directed balls can hit and damage stand-out exposed the ends of new liners at the joints between old and new liners.

Some mechanical design issues to consider for feed end-liners are:

- ensure good fit of FE parts with the conical mill head (and mount parts on sound backing rubber) — poor fit can lead to bolt failure and plate-cracking;
- limit exposure of parts to radial incoming ball impacts, i.e., avoid exposed ends, protrusions and large bolt-hole openings that provide ball impact points that can lead (through persistent impacts) to metal flow and/or fracture;
- avoid mixing new with worn end-liner parts in ways that allow new parts to stand-out and be exposed to ball-impact damage;
- preferably capture most of the wear on a limited number of parts and change out all these parts together; and
- sequence change-out of FE lifters simultaneously with shell lifters — this avoids high wear on old shell lifters.

Discharge end-liner design. The mill-side inner ends of the discharge end (DE) liner are similar in design and wear characteristics to similarly positioned parts at the feed end. Grates form the outer DE mill-side lining.

Most large mills have adopted cantilever grates, i.e., grates where the center portion sits on the pulp-lifter channel wall and the sides are essentially unsupported (see Figs. 7 and 8). This grate type can provide a large open-grate area by using intergrate gaps. Large grate open areas (and grate openings' sizes) may be required to promote pebble discharge for pebble crushing. Some mills restrict grate openings to limit rock outflows to promote a fine grind size. Water-jet systems, used for returning discharged oversize rock and steel back into a SAG mill, may have to limit the size of material that can be returned. This, in turn, would limit the size of grate slots to prevent the discharge unacceptably large materials.

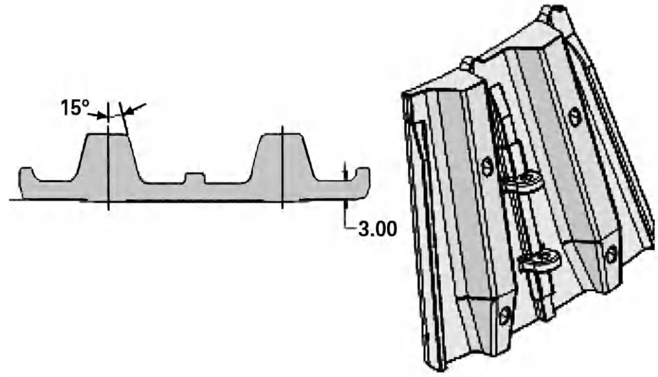

Figure 6 — Outer feed end integral angled lifter-liner (after Veloo et al., 2006a).

Figure 7 — Straight radial cantilever grates (after Veloo et al., 2006a).

Figure 8 — Curved cantilever grates (after Dunn et al., 2006)

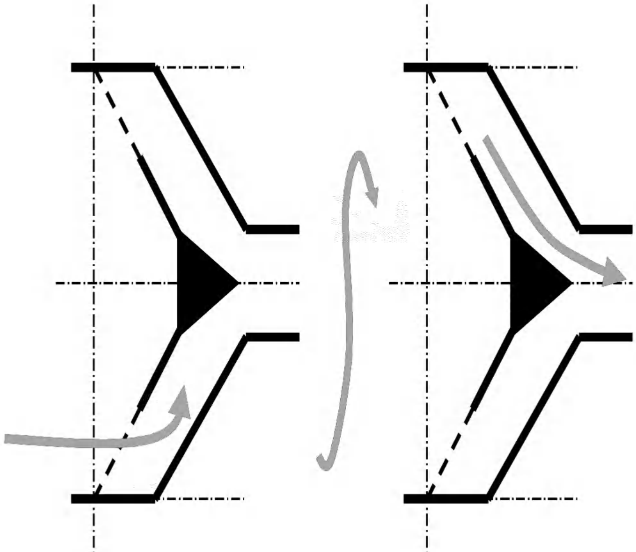

Figure 9 — Pulp flow, lift on mill rotation and discharge.

Bridging grates are supported by their edges being clamped down on the adjacent pulp-lifter channel walls by the end lifters. This type of grate is used when small open areas are required and for rubber grates.

The general structural principles outlined above for FE liners apply also to the DE. For grates and plates, the fit should be a one-on-one match with the underlying pulp lifter (see below), and worn and new parts should not be mixed so as to avoid exposing new parts to premature impact and damage.

Mechanical design issues to be considered in grate design and use include:

- *Peening (metal flow that closes the grate openings):* Review: slot location and "are the affected openings necessary"; incidents of high ball impacts; the general ball impact situation in the mill; material of construction; slot opening size; and wear rates across the surface of the grate.
- *Pegging, especially ball pegging:* Review: opening reverse taper (nominally 5 degree relief angle each side when new); ball hardness profile and worn shape, e.g., do the balls wear to pegging-prone ovoids or break-up at the pegging size; recycle of worn balls (to be avoided); the use of some inner larger low-wearing grate openings to allow an opportunity for near-pegging-size balls to discharge; and rubber grates (in extreme cases, their flexure might allow the discharge of material that might peg in a metal grate).
- *Ball-impact damage:* Review: charge level (low levels expose grates to damage); shell lifter ball throw at the head end; grate lifter ball throw; plate thickness (now for large mills >100 mm); edge support; casting integrity, especially at the extremities of the grate; web thickness; web support; look to increase plate surface wear rates (e.g., by reducing lifter height) to remove surface strains induced by ball impacts (that could otherwise lead to stresses sufficient to cause cracking); impact metal flow causing compression between liner parts; the need for a ball-deflecting ramp inwards of the grate; and the need for a steeper grate face angle (relative the mill head angle).

Pulp lifters

Introduction. Material is discharged from a SAG mill using pulp lifters. Installed at the discharge end of the mill, pulp lifters are a radial array of channels separated by channel walls also known as vanes or septums. Each channel is open to the mill at the outer end to allow material inflow through grates and at the inner end to direct discharge out of the mill through the mill trunnion (see Fig. 9) (Napier-Munn et al., 1996; Wills and Napier-Munn 2006). Typically, the number of pulp lifters employed is the number of feet in the mill diameter (a "1-D array"), i.e., a 34-ft-diameter SAG mill would have 34 pulp lifters.

Pulp lifters operate through a lifting and bailing action. Pulp lifters fill with pulp (fine rock slurry with pebbles) and, as they rotate with the mill, lift the pulp until it flows towards the center of the mill along a pulp-lifter channel. The pulp exits the mill via an inner "discharge cone" that diverts the pulp out of the mill through the trunnion opening (see Figs. 1 and 9). Pebbles that fail to discharge fall back down the pulp lifters, lowering pulp-lifter efficiency and causing pulp-lifter wear. Curved pulp lifters can improve pebble discharge and the wear lives of pulp lifters.

Pulp already in the pulp lifter can flow back into the mill through grate openings as the grates rotate out of the charge. Control of this "pulp reverse flow" is an important aspect of grate and pulp-lifter design.

Pulp-lifter charge motion. The following description of the operation of conventional (and curved pulp lifters) is based on video data of the discharge from pulp lifters, wear patterns observed in pulp lifters and a single-particle flow analysis (Royston, 2000, 2006). Curved and conventional pulp lifters have been subject more recently to DEM flow analyses with similar outcomes (Hart et al., 2001; Rajamani et al., 2003; Cleary, 2007).

The discharge for any pulp lifter has to be considered as two components: one is a fluid-like flow of a fine rock slurry (referred to here as "fluid pulp") and the other a stream of larger rocks also called pebbles. As the pulp-lifter contents begin to move in the pulp-lifter channels, it can be assumed that the more-fluid component separates from the pebbles that settle to the outer "base" of the pulp-lifter chamber. The subsequent motion of the two components is different, and they discharge at different points in the mill rotation.

The fluid pulp is the largest portion by volume of the charge in the pulp lifter. It is positioned in the pulp lifter closer to the center of the mill, hence less subject to centrifugal forces (than the rock component), and it is free to adjust its level and position (within the limits of leveling forces) in the pulp lifter. The pebbles in the pulp-lifter chamber by contrast are subject to friction forces that restrain their movement in the pulp lifter.

Fluid pulp can flow readily to the center of the mill; the outcome in conventional pulp lifter is that most of the fluid pulp is discharged around "11 to 2 o'clock" in a clockwise rotation of the mill.

The pebble component starts motion towards the center later, and the motion is more complex than the fluid pulp component. Straight-radial pulp lifters act, in effect, like shell lifters with a "zero degree" face angle and a semi-infinite length.

As a result, pebbles in the base of the pulp lifter are "pinned" by the force balance (between the outward centrifugal force and the inward radial component of gravity) and friction until the base of the pulp lifter passes through the shoulder of the mill charge. After initial motion along the rising side channel wall of the pulp lifter, pebbles disengage from that channel wall after the pulp lifter passes "12 o'clock" in the mill's rotation

Figure 10 — Rocks in pulp-lifter channel following a crash stop (after Hart et al., 2001).

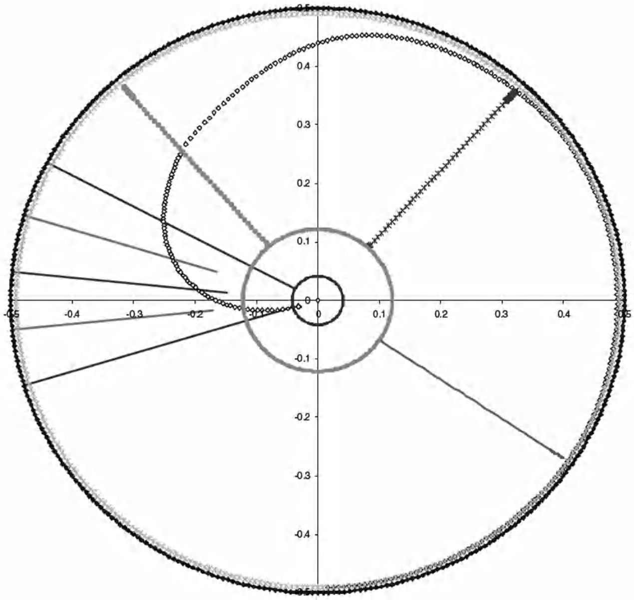

Figure 11 — Straight-radial pulp lifter - single particle track.

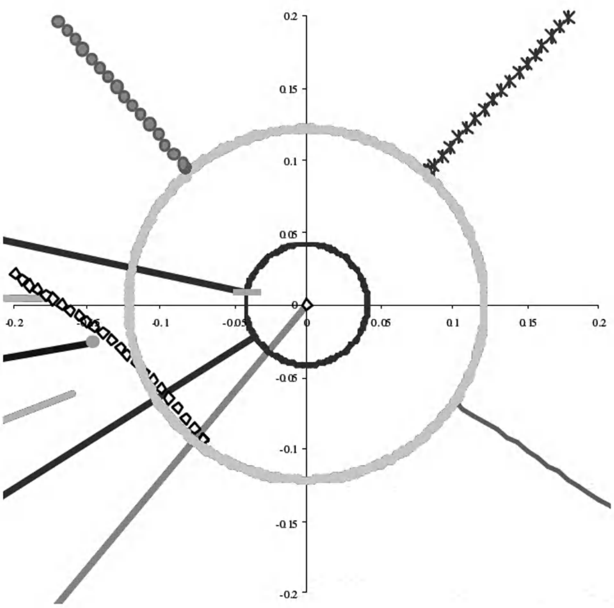

Figure 12 — Detail of particle track in discharge cone — top channel entry.

and travel across the pulp-lifter cavity to contact the opposite channel wall of the pulp lifter. After contact with the wall, the rocks slide in along the wall "falling" in the mill rotation, finally attempting to discharge into the trunnion as the pulp lifter rotates towards and through the horizontal in the mill rotation. Not all pebbles are discharged before the pulp lifter moves below the point where the inertia in the pebbles is insufficient for discharge. Any undischarged pebbles "backflow" down the pulp lifter.

Pebble backflow is a major source of wear in pulp lifters. The risk of backflow is increased in pulp-lifter systems, where two or more channels merge into one towards the center of the mill. In such systems, late-arriving pebbles fall from the upper channels into the "lowest" channel. This creates a burden of pebbles in the "lowest" channel that accelerates wear in that channel and associated pulp-lifter base. Hart et al. (2001) provided an image of a pile of pebbles near the exit from the pulp lifter into the trunnion at the point of backflow (see Fig. 10). This pebble burden pre-fills and reduces the capacity of the affected pulp lifters. The risk of poor pebble discharge and backflow increases with rising mill speed; above 80% critical mill speed loss of pulp lifting capacity can be a factor limiting mill performance.

Pebble flow in pulp lifters, especially in the discharge cone, has been addressed in a single particle computer "pulp-lifter motion tool" that covers the full flow path, including that in the discharge cone (Royston 2006). Outputs for a straight-radial pulp lifter illustrate the late arrival of a particle (representing a single pebble) at the discharge trunnion just as the pulp-lifter channel is about to rotate below the horizontal, effectively eliminating discharge of pebbles other than those arriving with high inertia (see Fig. 11). Particles from higher, shorter channels fall to the lowest channel wall, and in these examples the particle tracks indicate pebbles would have insufficient inward momentum and fail to discharge. They would also impact on the lower channel wall causing abrasive wear at the point that is reflected in the wear patterns observed in inner pulp lifters (see Fig. 12). These tracks also indicate that reducing channel wall length risks increased backflow. The velocity data from these outputs indicate that the discharge channels themselves may not choke (i.e., fill with normal out-flowing fluid charge) to prevent outflow; choking appears to be the result of "backflow pebbles" prefilling, hence restricting pulp-lifter capacity and outflow.

Pulp-lifter–grate interaction. Grates allow the controlled passage of slurry and pebbles from the charge inside the mill into the pulp-lifter chamber. For this analysis, the mill-charge can be considered to have two parts. A dense part outside the "eye" of the charge is connected to and moves upwards with the mill shell lining; inside the "eye" (towards the centre of the mill) there is a loose open structure of charge falling towards the toe of the charge. The dense rising charge structure is in close contact with and moves upwards with the grate. This dense rising charge in the mill acts as a pump, moving fluid pulp from the toe to the shoulder of the charge.

As long as grates are in contact with the rising mill charge, grate openings that are covered by charge are capable of passing

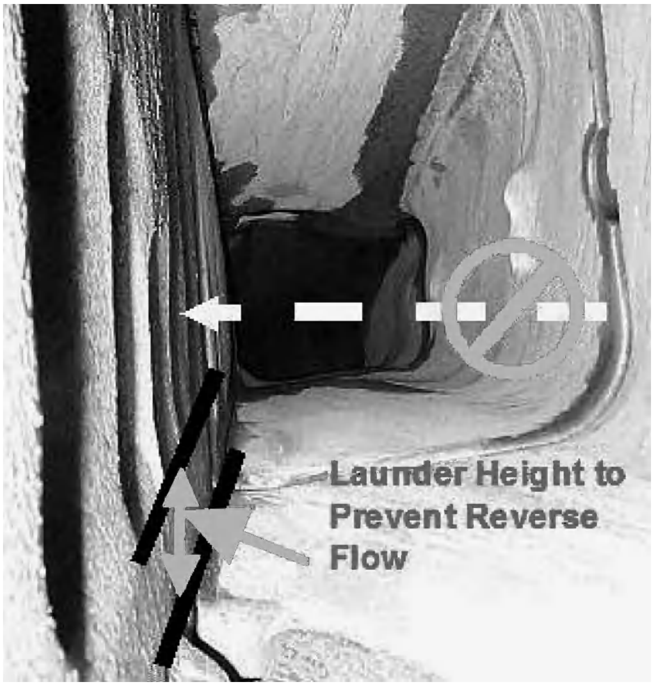

Figure 13 — Control of “static” reverse flow.

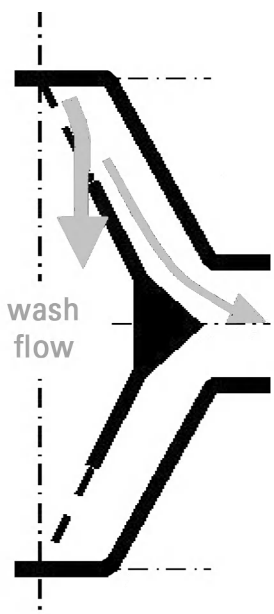

Figure 14 — “Dynamic wash” reverse flow.

fluid pulp into the pulp lifter. In mills with no slurry pool, the position in the mill rotation where most transfer takes place is around halfway between the toe and shoulder. Inside the “eye” the loose open structure of falling mill-charge presents little pulp to the grate. It follows that to be effective in receiving fluid pulp, grate openings should be positioned from the “eye-line” “outwards.” In practice, the outermost grate openings (i.e., those nearest the shell) appear to be the most effective for the transfer of pulp, hence it is important to maximize the open area in the outer part of the grate. Nevertheless, the inner openings can be important for charge transfer with new grates that have smaller outer open areas compared to worn.

For the efficient and effective performance of grates and pulp lifters, it is important to recognize the impact of “pulp reverse-flow” and the interaction between grate and pulp lifter (Royston, 2000).

During the initial “static” phase of pulp-lifter fluid motion, as the grate emerges from the mill charge, pulp is still held within the pulp lifter (due to radial centrifugal force) but is not constrained axially. Reverse flow can occur through grate openings along a path parallel to the axis of the mill. In the parts of the grate at risk of allowing reverse flow, the distance from the outer end of the grate slot to the channel wall needs to be sufficient (>50 mm) to minimize this form of reverse flow and to form an effective “launder” directing flow along the pulp-lifter channel (Royston, 2000). This criterion applies particularly to openings around the central part of the grate (see Fig. 13).

During pulp-lifter-grate rotation over the top (“vertex”) of the mill, discharging pulp washes downwards over the backs of the inner grate slots. During this “the dynamic phase” of reverse flow any exposed inner grate openings (especially inwards from the “eye” of the charge) would allow reverse flow of pulp back into the mill. This an important reason to minimize openings inwards of the “eye-line” (see Fig. 14).

Pulp lifting capacity. As noted above, pulp lifters operate by a bailing action. It follows that the size and effectiveness of the “bailing” bucket, i.e., the volume of the outer base part of the pulp lifter, needs to be maximized. Two types of pulp-lifter bases are common, one with a base parallel to the mill shell (after the illustrations in Figs. 9 and 14) and the other, the “L”-shaped pulp lifter, where the head-side forms a right angle to the base (Fig. 15). The outermost part of the front of the pulp lifter has to be positioned in each case at around the level of the tops of the shell lifters (not at the mill-shell) to allow the outer pulp lifter to be covered by a removable grate. With a “parallel-base” the front (grate-side) and the back (head-side) of the base are around the same level. For the “L”-shape the back of the base can be below level of the front, see Fig. 15. It follows, for a given pulp-lifter depth from front to back, the volume available at the bottom of an “L” – shaped pulp lifter is greater than a “parallel-base” pulp lifter and potentially offers greater lifting capacity.

Limited pulp-lifting capability, especially for high-throughput mills, can lead to a need to increase mill charge levels to produce the head required for flow through the grate to fill the pulp lifter. Increasing mill charge pulp level can work against grinding performance, especially if it results in pooling, i.e., excessive slurry at the toe of the charge ultimately to the extent of flowing out of the feed end of the mill.

Adequate pulp-lifter depths (front to back) are necessary to achieve satisfactory lifting rates. Good depth also helps to meet the “launder height” requirements to limit “static” reverse flow. For mills with no pulp recycle, a useful guide is a pulp-lifter depth from front to back of around 4% of mill diameter. For mills with high recirculating loads, or high throughputs of say soft ores, the pulp-lifter depth should be increased to limit reverse flow.

In existing mills, a partial retrofit solution for increasing pulp-lifter depth is to increase the depth of the pulp-lifter channel towards the centre of the mill in a tapered pulp lifter (see Fig. 15). Another approach (for unidirectional mills) is to use pulp lifters with pulp-lifter channel walls (normally at a right-angle to the head, Fig. 13) angled downwards from the grate towards the head (i.e., downwards to the right with respect to Fig. 13).

This forms a trough to hold pulp on the head-side of the pulp lifter and away from the grate during the lifting motion of the pulp lifter (Wills and Napier-Munn, 2006, page 163).

Practical issues such as the positioning of mill head-end casting joints can limit the number and distribution of holes used to mount pulp lifters, hence their number may be different from the typical "1-D" array (e.g., 34 in a 34-ft-diameter mill). With a lower number of pulp lifters, the charge volume in each pulp-lifter chamber is increased (adding to the risk of reverse flow of pulp back into the mill through grate openings) and each chamber could take longer to discharge and this increases the risk of backflow of pebbles. Increasing the number of pulp lifters adds to the number of channel walls between pulp-lifter chambers and, due to the additional "dead" volume of the walls, may lower the overall pulp-lifting capacity.

Curved pulp lifters

Curved pulp lifters can discharge rocks much earlier in the mill rotation, hence more effectively, and reduce pulp-lifter wear due to backflow (compared with straight-radial). However, they do require a commitment to unidirectional rotation of the mill. Curved pulp lifters with various curved shapes and forms of construction have long been used in grinding mills (Taggart, 1947; Mokken, 1978).

The retrofit curved pulp lifters and grates, discussed here, have been installed in the 7.3-m- (24-ft-) diameter (since 1996) and 8.5-m- (28-ft-) diameter SAG mills at Northparkes Mines (NPM) (Dunn et al., 2006); in the 12.2-m- (40-ft-) diameter SAG mills at Cadia (Hart et al., 2001) and in the 9.8-m- (32-ft-) diameter SAG mills at Ridgeway, which uses a dog-leg shape (Weidenbach and Griffin, 2007). The principal objective in the first case (24 ft SAG) was to improve solids flow in a pebble crushing circuit. Curved pulp lifters have also demonstrated long wear lives relative to straight-radial lifters (Royston 2006).

In the above retrofit design, the outer part of the pulp lifter and overlying grate is curved with the inner portion straight, it is known as the "hockey-stick" type. Figure 16 is an illustration of the "hockey-stick" type of pulp lifter.

Owing to the outer curve, rocks in the base of the pulp sit at an angle closer to their angle of friction (the slope angle at which a rock will slide) compared with the flat sides of a straight-radial pulp lifter. As the pulp lifter rotates, this allows the angle of friction to be overcome earlier, initiating rock motion earlier than the straight-radial counterpart. As a result of the earlier start, rocks leave the pulp lifter earlier in its rotation. Early discharge can reduce the backflow of rocks; this is reflected in the long wear lives of the curved pulp-lifter examples above.

The degree of influence of the curve on the performance of the pulp lifter depends on the curved shape of the lifter, especially near the mill periphery, and in the case of the retrofit type, the proportion of curved to straight portions in the pulp lifter.

In the current "hockey-stick" retrofit type of curved pulp-lifter designs; the curve radius has been expressed, i.e., developed, around the available bolting over two previous outer "straight-radial" pulp-lifter spaces. While this appears to be a good outcome for smaller mills, for all "1-D" pulp-lifter mills, this approach results in a similar curve radius irrespective of mill diameter (or the use of an elongated, less effective, curve). The use of the same approach in mills with fewer pulp lifters than "1-D," should allow a (relatively) larger radius curve to be expressed within the available bolting. Another approach for large mills would be to select from the available boltholes in the head over, say, three prior outer "straight-radial" pulp-lifter spaces to provide a larger curve radius.

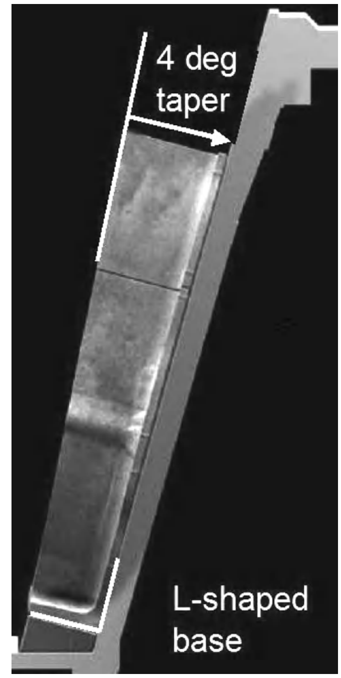

Figure 15 — "Tapered" and "L"-shaped base pulp lifter.

Figure 16 — Illustration of an array of "hockey-stick" curved pulp lifters.

Particle track outputs (Royston, 2005) show different particle motions in large compared to small mills where both have the same outer curve radius (see Figs. 17 and 18). With proportionally longer straight to curved section in the larger mill, inward motion may not be fully sustained once the charge reaches the straight portion of the pulp lifter. At this junction, the charge is subject to the same forces as would be present on a straight-radial pulp lifter. The force balance may not strongly favor inward flow, and the "rock" could even be subject momentarily to slowing forces. It follows that with the relatively longer straight portion of the large mill, the charge would take longer (in the mills rotation) to reach the center. Note the comments above on methods for increasing the curve radius, hence increasing the proportion of curved to straight channel, to improve curved pulp-lifter performance in large SAG mills.

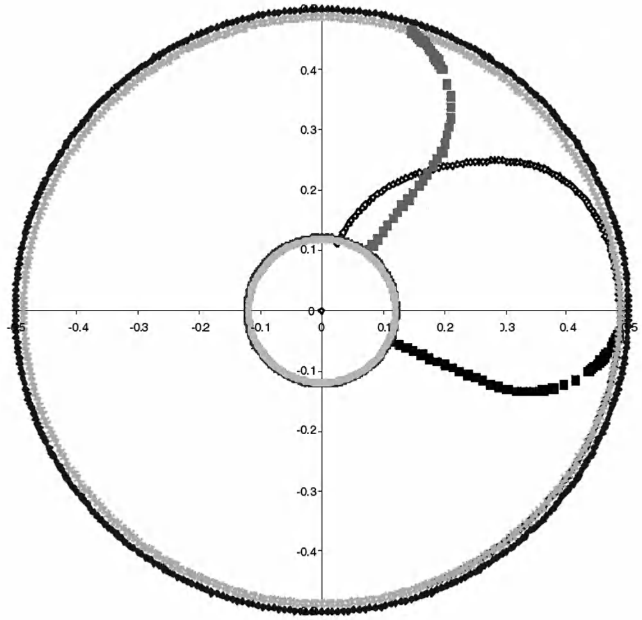

Figure 17 — Curved pulp-lifter particle track — large outer curve.

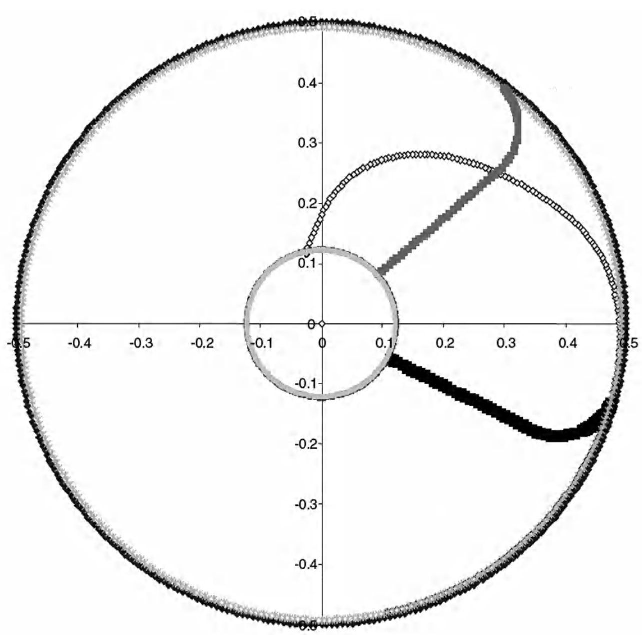

Figure 18 — Curved pulp-lifter particle track — small outer curve.

A proportion of straight (along with the curved) channel wall appears important. A curve with a large radius sufficient to extend to the center of the mill would have less curvature at the outer end (than the hockey-stick type), hence providing less assistance to the initial motion of pebbles. The inner straight portion is required to direct to the center any pulp-lifter charge that is thrown to the other side of the pulp lifter during inward charge motion after the pulp lifter rotates past the mill vertex (as with straight-radial pulp lifters). If the curve extends towards the center, late-discharging pebbles might have "to climb the back" of the curve towards the center of the mill for discharge, and this would reduce discharge efficiency.

Discharge cone wear patterns and design

With conventional straight-radial pulp-lifter discharge cones, design is focused on wear of the channel walls (also known as vanes and septums). This may involve the use of abrasion-resistant "white iron" castings in discharge cones. In composite metal-rubber parts, the channel walls may incorporate wear-resisting alloys. Multiple merged-channel diversion cones should also be designed to allow "indexing," i.e., the rotation of the cone on replacement. This allows the distribution of backflow of pebbles to unworn pulp-lifter bases, hence spreading backflow-induced wear amongst all pulp-lifter chambers to improve the overall wear life of straight-radial pulp-lifters' bases.

With curved pulp lifters, heavy wear is predominantly at the diversion curve of the cone. Typically two flow-wear-induced grooves develop on each side of the channel wall: one is assumed to be associated with fluid pulp-flow discharge before the pulp lifter reaches the mill vertex, the other with pulp and solids reaching the cone after the pulp lifter has passed the mill vertex (see Fig. 19). In this situation, the design effort is focused on the diversion and exit zones with the aim of limiting replaceable wear parts (in metal or rubber) to the diversion zone. This includes bolt-on replaceable caps to capture the final diversion wear. The bolting for these parts should be designed to avoid exposed nuts on the mill side of the part. The security of such exposed nuts can be difficult to maintain.

Liner size and materials

Double-wide and double-long large liners in are now in common use in large mills. These large parts reduce downtimes and simplify change-outs by reducing the number of liner movements in and out of the mill. Large-capacity liner-handling machines for such parts and associated bolt-removal impulse hammers have mechanized and at the same time improved the safety of change-outs (Russell, 2006; Smith, 2006).

Important issues in using "double-wide" parts are to ensure a good fit across all of the part on the underlying mill shell or part and for grates, in particular, not to overlap joints in the pulp lifters, i.e., one-on-one fit is required, or otherwise there is a risk of breakage at or near the underlying joints. A potential negative is that by removing joints between the shell liners, there is less capacity for impact strain relief through metal flow and part growth, and this has to be considered in the design. A practical issue with double-wide shell liners is the placement of the necessarily substantial lifting eyes; if these fill the space between the lifters they can provide an abrasive-wear path causing increased wear on the lifters at that point.

Traditional lifter and plate designs continue to have their place providing both opportunities to capture wear on smaller easily removed parts, and at the extreme in very high impact environments, providing opportunities (as noted above) for a liner design solution through opportunities to direct high metal flow and for inter-part movement to relieve and to counteract strain build-up (that leads to stress induced fracture).

"Chrome-molybdenum" (Cr-Mo) alloy steel, heat-treated to around 350 Brinell hardness, combines high-impact resistance, in part due to an ability to shed surface strain through metal flow and good wear life. It is still the dominant material of construction for SAG mill liners. It works best in an impacting environment where a hard skin can develop through impact to provide increased resistance to wear; it is less suited to low impact abrasive environments. Brittle "white iron" continues to be a material of choice for non-impact, high-abrasion wear-zones. Specialized hardened steel alloy formulations have been promoted to provide improved wear resistance for abrasion-prone end liners and pulp lifters where the impacts forces can be less than with shell lifters. Other liner suppliers claim harder high-carbon versions of their "standard" Cr-Mo products give similar outcomes; higher carbon appears to provide improved abrasion-resistance at similar hardness levels (assumed to be related to a higher carbide content).

One development is a bi-metallic liner using a "white-iron" insert that can give increased wear-life in low-impact abrasion-prone locations such as end liners. In addition, metal-faced rubber "Polymet"-type products with designs resistant to damage through ball impacts are growing in application in SAG mills.

Bolting

Typical bolt and nut combinations used for mill liners are, in the metric system, Class 8.8 bolts with Class 8 nuts and in the SAE system, Grade 5 for both bolts and nuts. A higher class (or grade) provides the potential for higher bolt tensions; however, with the higher tensile strength, the bolts can become vulnerable to stress raisers (e.g., from surface damage in handling and installation) and a fracture once initiated can lead to rapid failure.

Good joint compression is critical to the long-term security of bolts. If compression is lost across the joint, even though the bolt may still be in tension, there can be movement across the joint. The cyclical bending moment can lead to bolt failure (even in large diameter bolts) through fatigue cracking at a stress raising point (e.g., one thread into the nut or where the threads end on the bolt shank).

With large double-size liner parts, the single line of bolts used to mount the single part is replaced with an array of bolts with radial alignments that can only be fitted with the "doubled" part set close against the mill in its final position. By reducing the number of bolts used with these large parts, installation time (hence overall reline downtime and related costs) could be reduced. Care is required to ensure that the remaining bolts can generate sufficient joint compression to prevent movement of the large part (or risk premature bolt failure).

A certain amount of preload is required on the lining bolts to ensure joint compression is maintained under varying liner loads. Preload is a function of applied tightening torque to the nut and bolt, and the torque is affected by the lubrication applied to the bolt and nut. Bolt-supplier torque tables usually assume that the bolts and nuts have clean non-corroded metal surfaces with some light oil lubricant (sufficient to get consistent torque readings). Dry or rusty bolts will be under tensioned at the usual torque table settings. If special low-friction lubricants are used, the applied torques must be adjusted downwards to match, otherwise bolts will be over-tensioned and this could lead to breakage.

The bolt torque may be applied initially by an air-driven impact wrench "rattle-gun," and completed by a hydraulic torque wrench, preferably by rotating the bolt without stopping (i.e., tightening under constant dynamic friction) until the required torque is reached. As new liners settle with use, it is good practice to retorque all bolts after a few hours of operation; the objective is to obtain stable bolt tension.

The impact of grinding media directly on bolt-heads can lead to bolt failure. Current general practice is to bury the bolt-head well inside the part (with an opening in the liner above it) so that the head becomes exposed only at the point of maximum wear of the part. Inserts and the captive bolt systems described below have been tried to prevent localized wear across bolt openings. The common wedge-seat bolts require good bolt alignment and seating; spherical bolt-seats are a variation on the wedge seat, aimed to provide good seating even with the bolt slightly out of alignment.

Figure 19 — Trunnion-side discharge cone — curved pulp lifter (after Dunn et al., 2006).

Common sealing washer practice is to use a rubber sealing-washer captured in compression under a strong stiff steel washer cap. Many proprietary seal designs are available that are aimed particularly at sealing worn boltholes. "Nylok"-type self-locking nuts are popular, but plain black nuts are also used.

Recoilless impact hammers have improved safety and reduced the time required to remove bolts (Russell, 2006). Screw-out bolts are an alternative offered by some suppliers, these use screwed-on heads that are captured inside the liner. On liner removal, the bolt shanks are screwed out through the shell allowing the liner to fall-into the mill. One disadvantage is that if the bolt shanks will not come out, heavy liners along with the bolting have to be knocked-in which can be difficult.

Conclusions

Modern SAG liner development and design continues to rely primarily on feedback from practical mill operating experience assisted by computer models of ball trajectory and charge motion as well as established good design practice.

SAG mill liner design needs to take into account the process aspects of mill operation with the joint aims of extending liner life and assisting with mill performance. These process issues can be described and quantified for incorporation in liner design.

The integration of two or more liner parts into one large casting is a growing trend. The aim is to reduce change-out times by reducing the number of pieces to be installed, an objective supported by the availability mechanical aids such as large lifting capacity liner-handling machines and bolt-removal tools.

Chromium-molybdenum steel alloys continue to be the material of choice for large SAG mill liners, especially shell liners. Harder steel alloys and composite liners are being applied to low-impact high-abrasion areas such as pulp lifters and feed-end liners.

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