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Energy efficient rotor design for HIGmills

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ABSTRACT

Extensive research with HIGmill grinding rotors has shown that flat grinding discs in stirred media mills in hard-rock applications experience poorer process performance compared to castellated rotors. The first industrial size equipment to benefit from this is Kevitsa Cu-Ni mine, where the energy improvement from flat to castellated discs was 28–50%. This observation was investigated further through different size pilot scale units, which clearly confirmed a step change shift in the specific grinding energy versus the product particle size at 80% passing. The design of the rotors was further developed and fine-tuned with DEM (Discrete Element Method). The validated results have allowed the castellated rotor design to be applied as a standard to all HIGmills.

1. Introduction

Simple ore bodies are becoming rarer and more complex ore bodies with lower grade need to be used. Finer grind sizes are required to enable mineral liberation for downstream beneficiation processes. Fine grinding using stirred milling is becoming more common in the mineral processing industry. When grinding finer in a stirred mill, the general grinding law dictates that more energy is required, this energy is proportional to the grind size to the power of a constant generally ranging from -1 to -3, and as such energy efficiency is an important consideration for stirred milling (Kwade and Schwedes, 2007). Typically stirred mills are used for applications requiring a $P_{80} = 75$ to 5 µm, but are being considered for coarse grinding applications. Stirred mills have a stationary shell, with a rotating shaft and mixing elements to agitate the small diameter media.

The mixing elements design varies with each manufacturer's proprietary design (Jankovic, 2002, Radziszewski and Allen, 2014, Rahal et al., 2011):

- Flat discs – Used by VXPmill Deswik (FLSmidth), IsaMill™ (Glencore)
- Radial posts (radial pins) – Used by Stirred Media Detritor (SMD) (Metso).
- Archimedes screw – Used by EIRICH TowerMill (Nippon Eirich), VertiMill (Metso).
- Castellated rotor called Grindforce™ – HIGmill™ (Outotec)

Theuerkauf and Schwedes (1999) and Kwade (1999) explored the operation of both horizontal mills with flat disc stirrers and vertical pin mills. When comparing the mixing achieved by disc and pin type stirrers, it was found that pin type stirrers exhibited higher and more fluctuating circumferential fluid velocities than the disc stirrers. Therefore, for applications requiring intense dispersion, a stirrer with pins should be used over flat discs.

Sinnott presented DEM results for a double helical screw in a tower mill and a pin mill in SMD. The Archimedes' screw was found to be an effective mixer due to strong convective axial transport of the media by the screw agitator and strong diffusive radial mixing (Cleary et al., 2006). This assists with rapid distribution of feed material throughout the mill body. The radial pins were found to have very poor mixing in the axial direction and the mixing in the radial direction was only half of the mixing observed with the Archimedes screw (Radziszewski and Allen, 2014, Cleary et al., 2006).

Eswaraiah et al. (2015) studied the effect of vertical stirred mill agitator designs and their effect on grinding energy efficiency. The agitator designs investigated were a standard pin type and a CSIRO designed double helical screw stirrer. The results concluded that the double helical screw had significant better energy efficiency than the pin type design.

Heath et al. (2017) conducted DEM modelling to compare flat discs to castellated rotors. The grinding beads were found to be slipping on the flat disc surface and adding castellations to the disc reduced the slippage by holding autogenous layer of beads at the surface. Further to this, the

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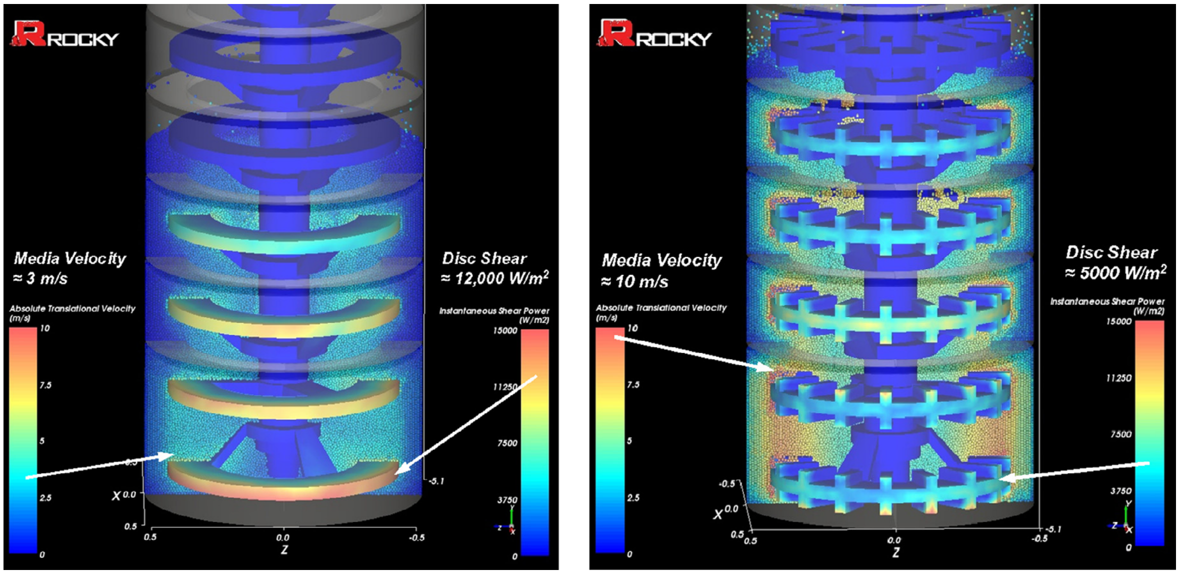

Fig. 1. Flat discs: energy goes into disc wear; castellated rotors: energy goes into grinding, from Heath et al. 2017.

castellated rotors forced more bead-to-bead shear further away from the rotors into the bulk of the bead volume. The difference in disc shear and media bed velocity is shown in the DEM Kevitsa models in Fig. 1.

Previous published work in this area has focused on the power draw and grinding rotor wear rates in HIGmills (Lehto et al., 2016). This paper explores the difference in energy efficiency observed between the castellated rotor and a flat discs in the Kevitsa full industrial scale HIGmill, and in a pilot scale HIGmill.

2. Kevitsa: Flat discs vs. Castellated rotors

The Kevitsa mine is located approximately 170 km northeast of Rovaniemi, Finland. Production at the Kevitsa mine started in 2012. Mining is carried out in an open pit mine. Kevitsa concentrator produces copper and nickel concentrates with gold, platinum and palladium by-products. The primary comminution circuit consists of multiple crushing stages, autogenous grinding (AG) mills and a pebble mill (Nielsen et al., 2016). Recovery is through sequential flotation of copper and nickel as illustrated in Fig. 2. Flotation process is selective flotation.

First floats the easily floating copper minerals on Cu rougher phase, rougher concentrate is guided to second cleaning phase. Cu rougher tails is feed to the Cu rougher/scavenger phase. Cu rougher/scavenger concentrate is guided to the HIGmill to improve mineral liberation. HIGmill product is guided to second copper cleaning phase. There are four cleaning phases in copper circuit. Combined copper flotation scavenger and cleaning tails is feed to the Nickel flotation. Ni rougher concentrate is guided to the third cleaning phases. Ni scavenger concentrate is guided to first cleaning phase. After second cleaning concentrate is guided to regrind mill to clean surface of the particles and improve the liberation of the particles. Ni regrind product is guided to the third cleaning phase. Totally there are four cleaning phases in Ni circuit. Nickel flotation tail is feed to the sulphur flotation. In the sulphur flotation pyrrhotite and other sulphide minerals are floated, for getting lower sulphur content at the tailings pond.

The valuable minerals are finely disseminated in the ore body requiring a primary circuit grind of 75 µm. Because of increasing primary mill throughput (> 950 t/h), the flotation feed grind usually comes coarser. This highlights the need to enhance Cu regrinding to improve mineral liberation (Cu-Ni separation).

In February 2015 a 700 kW HIGmill is installed at Kevitsa in the copper circuit processing rougher/scavenger concentrate to produce a combined circuit product of P_{80} = 25 µm and a HIGmill product size of P_{80} = 40 µm. The HIGmill has been effective in particle size reduction. The installation improves the copper grade at Kevitsa by one to three percent and the recovery by five to ten percent for the copper circuit (Lehto et al., 2016). This is attributed to adequate liberation of minerals.

Initially, the Kevitsa HIGmill was equipped with the flat discs. In order to improve efficiency of the power draw and prolong the life of the discs, castellated rotors were installed into the mill in August 2015. In 2015 there were nine castellated rotors installed, which were increased to 10 castellated rotors in 2016. In 2017, the castellated rotor design was further optimized using DEM modelling and operational experiences, which resulted in a new improved castellated rotor design.

This new castellated rotor, fine-tuned according to DEM results, was tested at first in the laboratory and in the pilot-scale HIGmills. Successful testing results at the small-scale pilot led to a full production-size operation at Kevitsa. The results of this pilot work are not presented in this paper. With this new castellated rotor design, it was possible to lower the slippage between the grinding disc and the grinding media.

Follow-up of the process parameters around the HIGmill grinding circuit at site is possible and reliable due to Kevitsa's advanced DCS system. The data is being collected continuously and is accessible at different intervals. One-hour average from the plant DCS system were chosen for this study. This interval retains the data amount reasonable and dampens high peaks, which may appear in special process situations, such as start-ups and shutdowns.

Plant data parameters available during the test work were: mill power, SGE (kWh/t), mill speed (rpm), cumulative power, 12 mill shell temperature points, flow rate, feed pump current, feed pump speed, flow, density, dry tons to the mill, mill feed particle size and product particle size. These variables supported the overall understanding around the circuit. All the variables were monitored to spot any differences or changes in the process, which may affect the circuit performance. The main process parameters used in the data interpretation were specific grinding energy (SGE, kWh/t), flowrate (m^3/h), slurry density (t/m^3), particle size for feed, F_{80} and product, P_{80}.

Particle size analysis is by online particle size analyser, Outotec PSI500. Sampling points are in the HIGmill feed and product pipeline. Analyser and samplers are connected to the plant DCS system. The analyser relies on Malvern Instruments' optical measuring head. It is proven industry standard of laser diffraction particle sizing technology, which is used routinely all over the world in many laboratories and

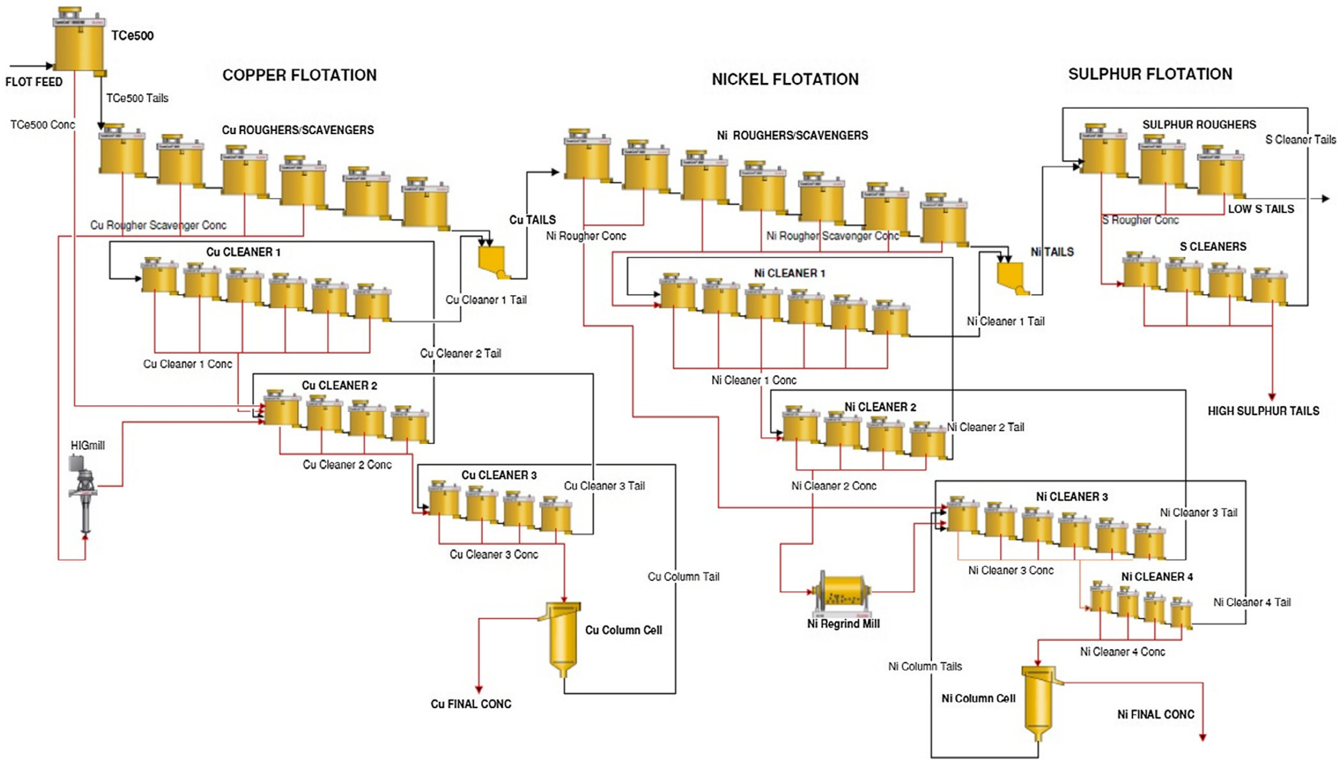

Fig. 2. Kevitsa flotation flowsheet (Lehto et al., 2016).

plant operations. The most desired values for circuit operation efficiency were F_{80} and P_{80} values. These values were recorded in accordance with other values from the DCS system.

3. Pilot scale: Flat discs vs. Castellated rotors

A pilot scale HIGmill called a HIG25 was used to compare the performance of the castellated rotor and a flat disc. The process parameters such as density and flow were held constant. The process was operated under steady state conditions, which allows direct comparison of the mixing element performance.

Two testing programs were completed on two different iron ore materials A and B, these materials were totally different to the Kevitsa operation. The first test program A involved thin flat discs compared to a castellated rotor. Only 6 castellated rotors out of the possible 12 were used in this test program, however all the castellated rotors were covered with beads, and additional discs would not have contributed to the grinding. The thin flat discs were only 5 mm in thickness compared to the castellated rotor with 22 mm thick rotors.

Test program B was commissioned to eliminate this thickness variable and the number of castellated rotors. The second test program B involved a fat flat disc of the same 22 mm thickness as the individual rotors on the castellated rotor. This was to underline the difference in design between the flat and castellated disc. The castellated rotor design was the same in both test programs. Ten castellated rotors were used in the bottom section of the mill and two thin flat discs in the top section of the mill. All the 10 thick flat discs and ten castellated rotors had the same internal diameter to allow fine product size material to travel upwards.

The pilot scale process parameters were kept as constant as possible for each test program. Media bed depth was held constant as this affects the residence time in the beads. The specific gravity and media size distribution was held constant for both test programs. The feed flowrate was held constant as this affects the residence time which in turn affects the grinding efficiency, where less residence time can reduce grinding efficiency. When determining the feed density for each experiment, a Marsh funnel was used to ensure that the slurry viscosity was below critical limit. The feed slurry density was held constant, which ensured that the viscosity was constant. The feed material was blended prior to mixing in the feed tank. By holding these parameters constant, a direct process performance comparison was made.

3.1. Equipment, HIG25

The HIG25 pilot scale HIGmill is as follows:

- 30 kW unit
- 19 L internal volume
- 12 rotors/discs installation capability
- Vertical orientated body

Test Program A		Flat discs	Castellated discs
Disc arrangement*		12 × F (5)**	1 × F (5) + 6 × C (22) + 5 × F (5)**
Media level	%v/v	60	60
Media SG		3.9	3.9
Media type		ceramic	ceramic
Media size distribution		50% 2–3 mm, 50% 3–4 mm	50% 2–3 mm, 50% 3–4 mm
Slurry density	% w/w	56	56
Flowrate	l/h	360	360
Residence time	s	120	120
F_{80} (wet sieve)	µm	90	90
P_{80} (target)	µm	30	30

* Listed from the bottom: F = flat, C = castellated, Thickness in mm in parenthesis.
** See Fig. 3.

Fig. 3. Thin Flat Discs (left) and Castellated Rotors (right).

Fig. 4. Fat Flat Discs (left) and Castellated Rotors (right).

Test Program B		Flat discs	Castellated discs
Disc arrangement[*]		10 × FF (22) + 2 × F (5)	10 × C (22) + 2× F (5)
Media level	%v/v	68.4	68.4
Media SG		3.9	3.9
Media type		ceramic	ceramic
Media size distribution		50% 2–3 mm, 50% 3–4 mm	50% 2–3 mm, 50% 3–4 mm
Slurry density	%w/w	52	52
Flowrate	l/h	360	360
Residence time	s	120	120
F_{80} (laser)	µm	190	190
P_{80} (target)	µm	30	30

** See Fig. 4.

* Listed from the bottom: F = flat, FF = fat flat, C = castellated, Thickness in mm in parenthesis.

3.2. Test procedure

The test procedure involved homogenisation of the feed dry and then splitting into buckets. The sample is batch mixed in the feed tank to the required milling density. The feed tank has a total volume of 200 L with 120 L used as the batch volume. Slurry is pumped through the HIGmill with a SPX15 hose pump at the required flowrate. The mill speed is set in advance to achieve the required power draw. Mill shaft power draw and mill speed is recorded in the data logging system.

Milling density (% w/w solids) and flow rate (m^3/h) are measured from mill discharge. The product samples are taken after four volume changes in the mill, which represents steady state or balanced conditions. After each sampling point, the operational speed is changed according to the test plan. Samples were marked and stored for the particle size analysis. Particle size analysis were made with Malvern laser sizing or by wet screening. Performance graphs were generated for Specific Grinding Energy (SGE, kWh/t) versus the product particle size (P_{80}, µm).

4. Results and discussion

The design of the mixing elements, grinding discs in this case, directly affects the degree of mixing of beads and slurry. It allows the material transport to occur, such as transfer of coarse feed material to high intensity breakage zones and the transfer of fine product material to low intensity breakage zones. In addition to this, mixing elements allow the product material to exit the mill. It is important to verify that design change does not adversely affect to the grinding result or slurry transport inside the mill.

High intensity breakage zones inside the HIGmill are in the outer shell in the bottom part of the mill. Due to the gravity the grinding beads sit in the bottom part of the mill. When going upwards the mill shell the grinding beads can more freely move. It leads to lower intensity zones in grinding wise. Centrifugal force pushes the biggest particles to the outer shell. Finest particles can go upwards the HIGmill next to the shaft, which prevents over grinding. Due to gravity and centrifugal force the biggest particles have the longest route inside the mill, along the outer parts of the HIGmills grinding chamber.

4.1. Kevitsa results

Immediately after the installation of the castellated rotors, the benefit in the energy efficiency was described by the SGE vs P_{80} performance graph Fig. 5. The line of best fit for the flat discs and castellated rotors have a significant difference in energy efficiency at the target grind size of 40 µm and they approach unity at the 20 µm level. The required SGE for the 40 µm grind size for flat discs is 22.7 kWh/t and for castellated rotors is 16.3 kWh/t, a 28.2% energy saving.

After prolonged operating time the castellated rotors gave significantly better energy efficiency over the original flat discs. Fig. 6 shows the SGE vs P_{80} performance graph for flat discs versus the castellated rotor design in 2017. The line of best fit for the flat discs and castellated rotors are close to parallel, which represents a significant

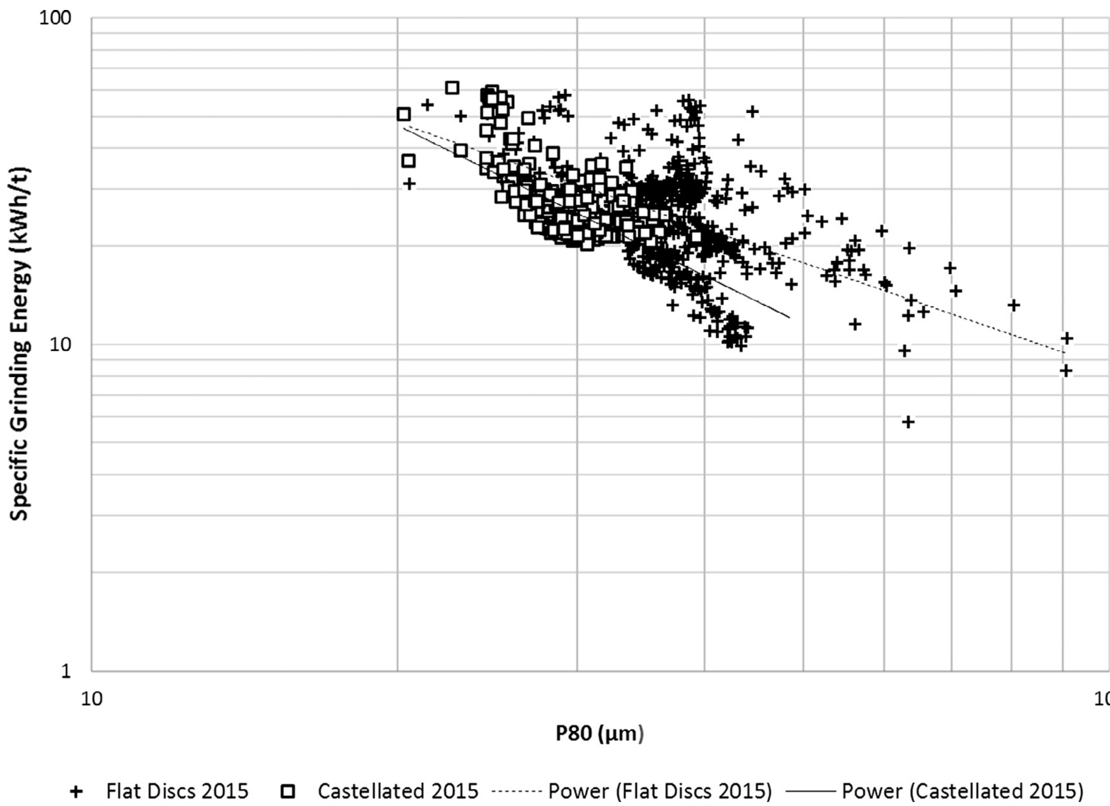

Fig. 5. Specific Grinding Energy (kWh/t) versus the particle size (P_{80}, µm) for Flat Discs versus Castellated Rotors in 2015.

step change in the performance curve. The required SGE for the 40 µm grind size for flat discs is 22.7 kWh/t and for castellated rotors is 11.3 kWh/t, a 50.3% energy saving.

The design optimization resulted in a second castellated rotor design. Fig. 7 shows the SGE vs P_{80} performance graph for the first castellated rotor design Case A versus the second castellated rotor design

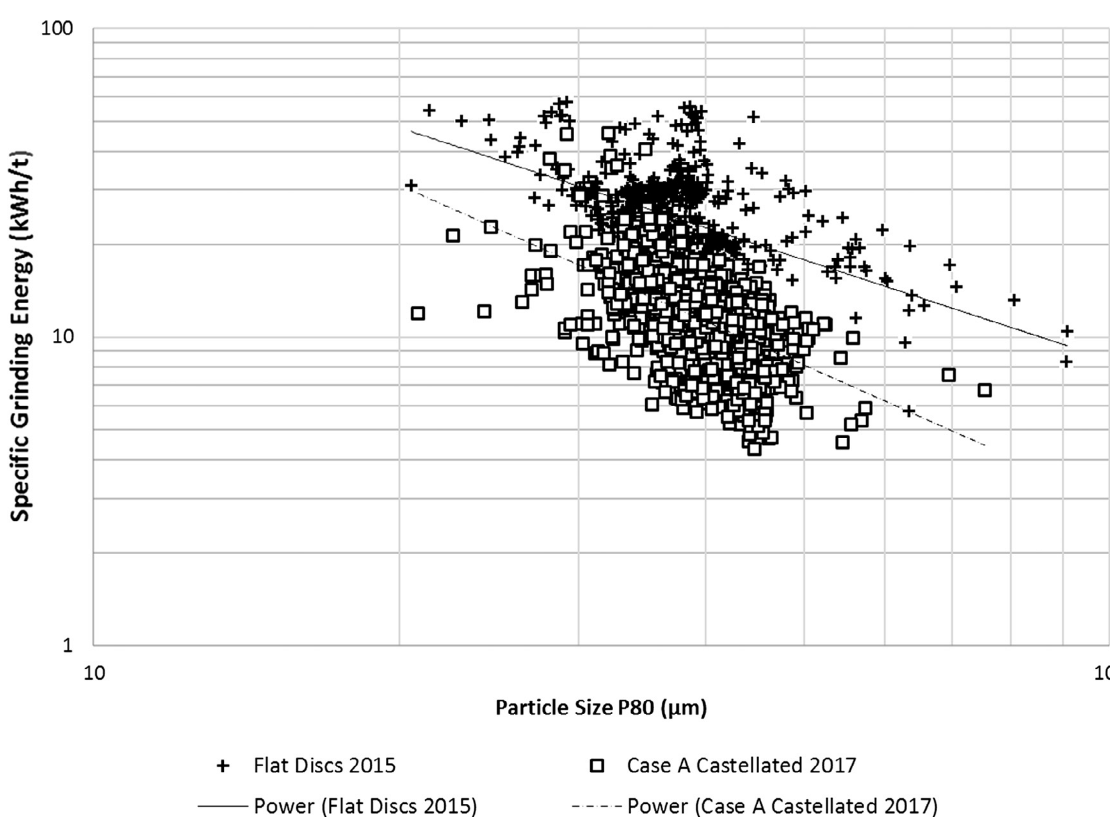

Fig. 6. Specific Grinding Energy (kWh/t) versus the particle size (P_{80}, µm) for Flat Discs 2015 versus Castellated Rotors Case A in 2017.

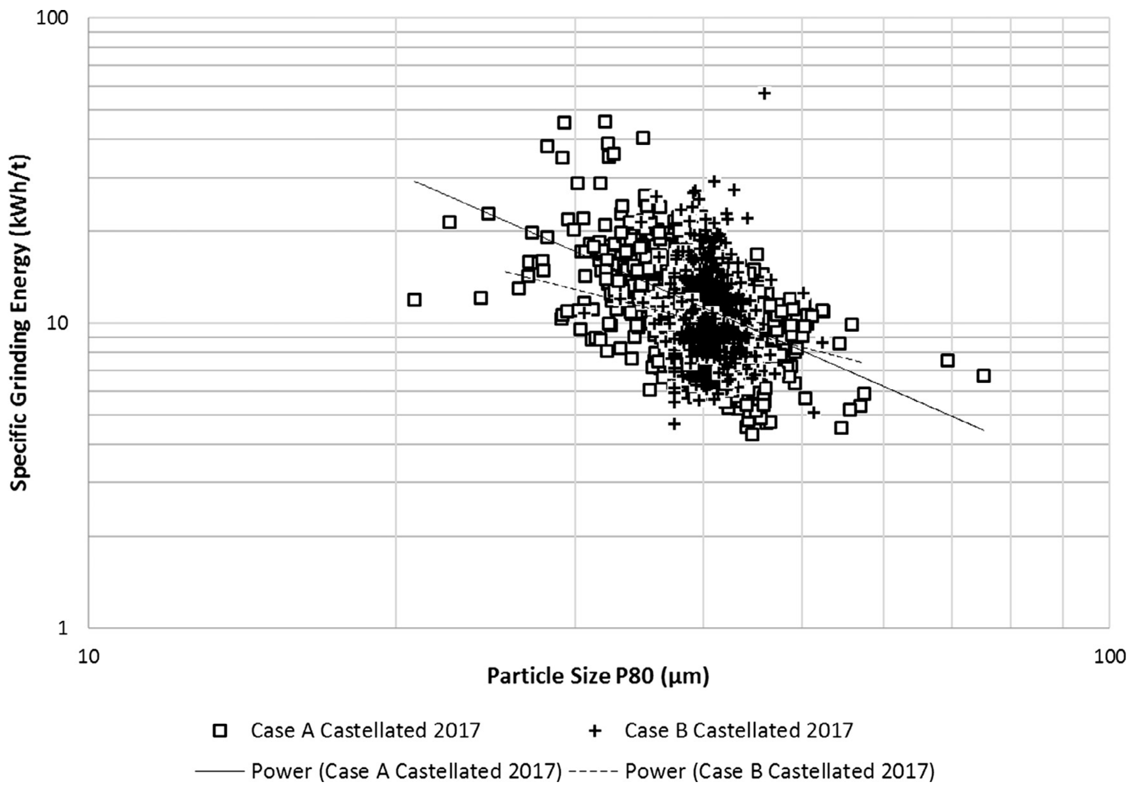

Fig. 7. Specific Grinding Energy (kWh/t) versus the particle size (P_{80}, µm) for Castellated Rotors Case A versus Castellated Rotors Case B in 2017.

Case B in 2017. The data for the Case B are closely grouped and nearly matching the Case A castellated rotor. The required SGE for the 40 µm grind size for Case A rotor is 11.3 kWh/t and for Case B rotor is 10.1 kWh/t. This is a 55.5% energy saving for Case B against the original flat discs or an increase of energy efficiency of 5.2% compared to Case A.

Particle size is analyzed continuously with online particle size analyzer, PSI500, as an hourly average connected to the plant DCS. PSI500 analyzer was calibrated and cleaned, according to manufacturer's recommendations. The average F_{80} was 96.1 µm ± 7.2. This variation in average feed size is very low and considered acceptable for the comparison. Example feed and product particle size distributions for Kevitsa HIGmill, Fig. 8.

The process flowrate increased from 2015 to 2017. The HIGmill retention time for each case was:

● Flat discs 2015	4.3 min
● First castellated design 2015	4.0 min
● First castellated design Case A 2017	2.5 min
● Second castellated design Case B 2017	2.3 min

The average slurry density for the cases was 1.42 ± 0.04 t/m^3 during the whole time of the testing. Large variations in slurry density at the high and low scale can significantly affect grinding energy efficiency. The slurry density is deemed to be within acceptable variability limits for this study.

The bead size used in the mill has not varied. In the mill, the bead addition size was 3–4 mm ceramic beads. Only one-size beads has been used to top up the worn beads. During shutdowns, seasoned bead charge PSD was monitored 1–3 times per year, without any peculiarities in any of the results.

The HIGmill operational conditions are held constant. If there is a major disturbance in the upstream process, the HIGmill is bypassed. This is to ensure stable process conditions to the downstream flotation. Occasional test campaigns related to the upstream process improvement were made. However, those tests have been only temporarily 1–2 weeks at time at maximum. During those times there was no recorded significant difference in the HIGmill feed (flow, F_{80}, density, temperature, etc.), which would have affected the HIGmill long term average operating parameters.

4.2. Pilot scale results

Fig. 9 shows the SGE vs P_{80} performance graph for Case A, where the energy efficiency is clearly better for the castellated rotor over the thin flat disc. The fitted regression lines for each data set are parallel on the log-log plot, which represents a significant change in the performance curve. For the target grind size of P_{80} = 30 µm, the castellated rotor required 8.8 kWh/t and the thin flat disc required 10.7 kWh/t. The castellated rotors are 21.4% more energy efficient than the flat discs for the 30 µm sieve target P_{80}. The values presented in Fig. 9 fall in the middle in the general grinding law, where energy is proportional to the grind size to the power of a constant ranging from −1 to −3, Kwade and Schwedes, 2007.

The pilot scale test work was repeated with the flat discs versus a complete set of castellated rotors. Fig. 10 shows the SGE vs. P_{80} performance graph for Case B, where the energy efficiency is again clearly better for the castellated rotor over the fat flat disc. For the target grind size of 30 µm, the castellated rotors required 8.0 kWh/t and the thick flat disc required 10.5 kWh/t. The castellated rotors are 30.9% more energy efficient than the thick flat discs.

The pilot testwork was conducted in strictly controlled conditions to minimize experimental error, to allow direct comparison of the mixing element types. The feed sample was thoroughly homogenized in the dry state before mixing small feed tank batches, the feed tank mixer speed was constant and feed fully suspended, the feed flowrate was kept constant and the media level and media type was constant.

Figs. 9 and 10 show a high coefficient of determination (R^2) number of 0.85–0.98 for Case A. Fig. 10 represents the best fitted regression lines with values 0.97 and 0.98 for Case B. This number is a statistical

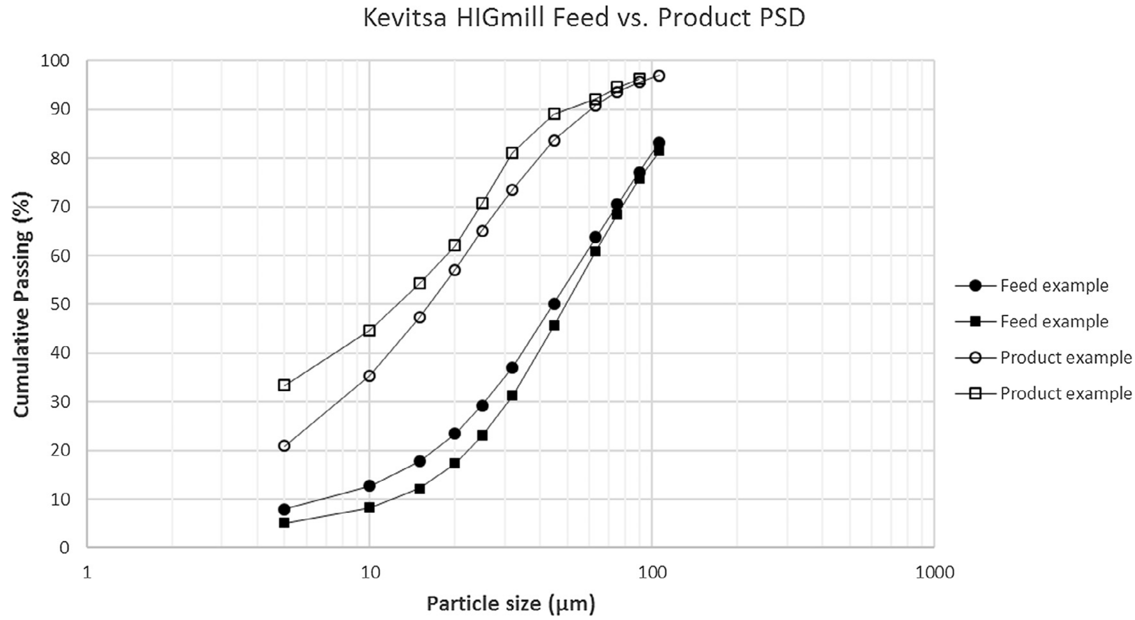

Fig. 8. Example of feed and product particle size distribution variation for Kevitsa HIGmill.

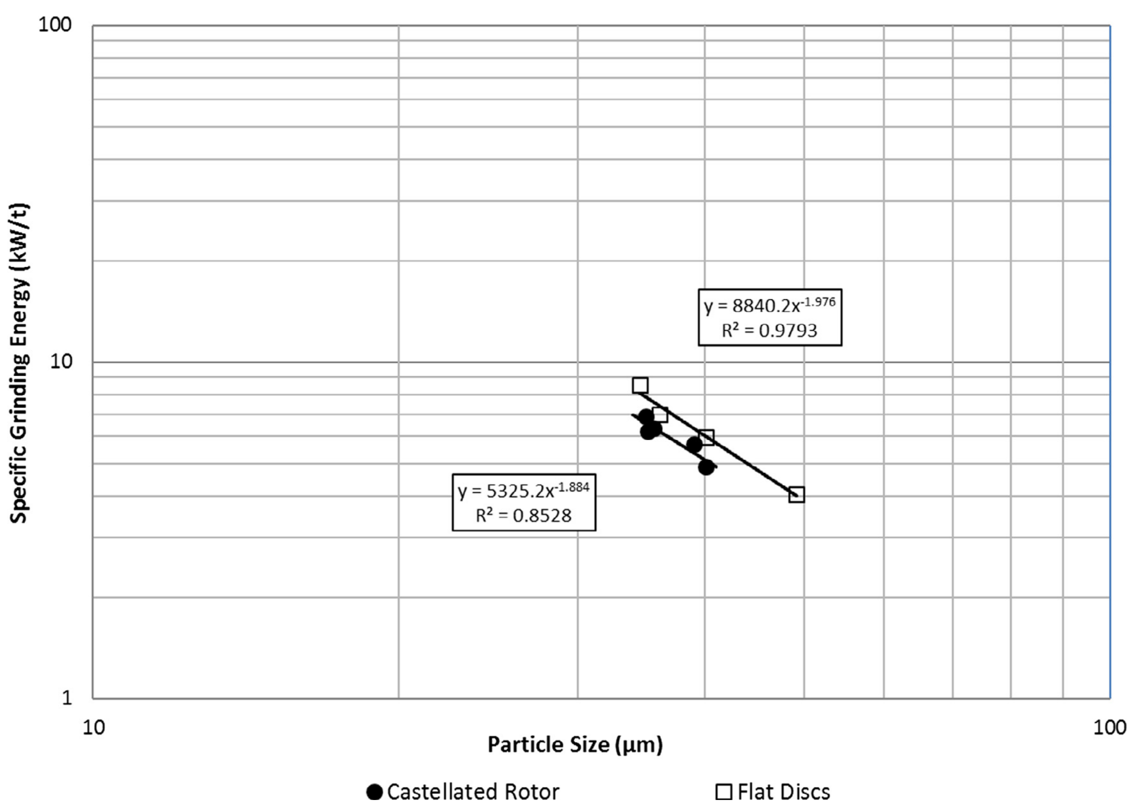

Fig. 9. Specific Grinding Energy (kWh/t) versus the particle size (P_{80}, µm) for Case A.

measure of how close the data is to the fitted regression line. A low number close to zero indicates poor fitment and a number closer to one indicates very good data fitment.

Example of pilot scale feed and product particle size distribution between the castellated and flat discs, in the Fig. 11.

5. Conclusions

During the first years of HIGmill in full plant size operation Outotec has been developing the grinding disc design. Design improvement has been done with computer aided DEM, laboratory and pilot size mills as well as with industrial size mills. Three different ore types have been used in the SGE efficiency validation of the castellated rotor design.

The work presented in this paper showed that castellated rotors provide better energy efficiency than flat discs. Rotors with castellated design used at Kevitsa mine improved the energy efficiency by 28.3–50.3%, compared to the flat discs. The optimization of the castellated rotor design at Kevitsa improved the grinding efficiency by a further 5.2% against the flat disc benchmark. The pilot scale testwork under controlled conditions have improved energy efficiencies from

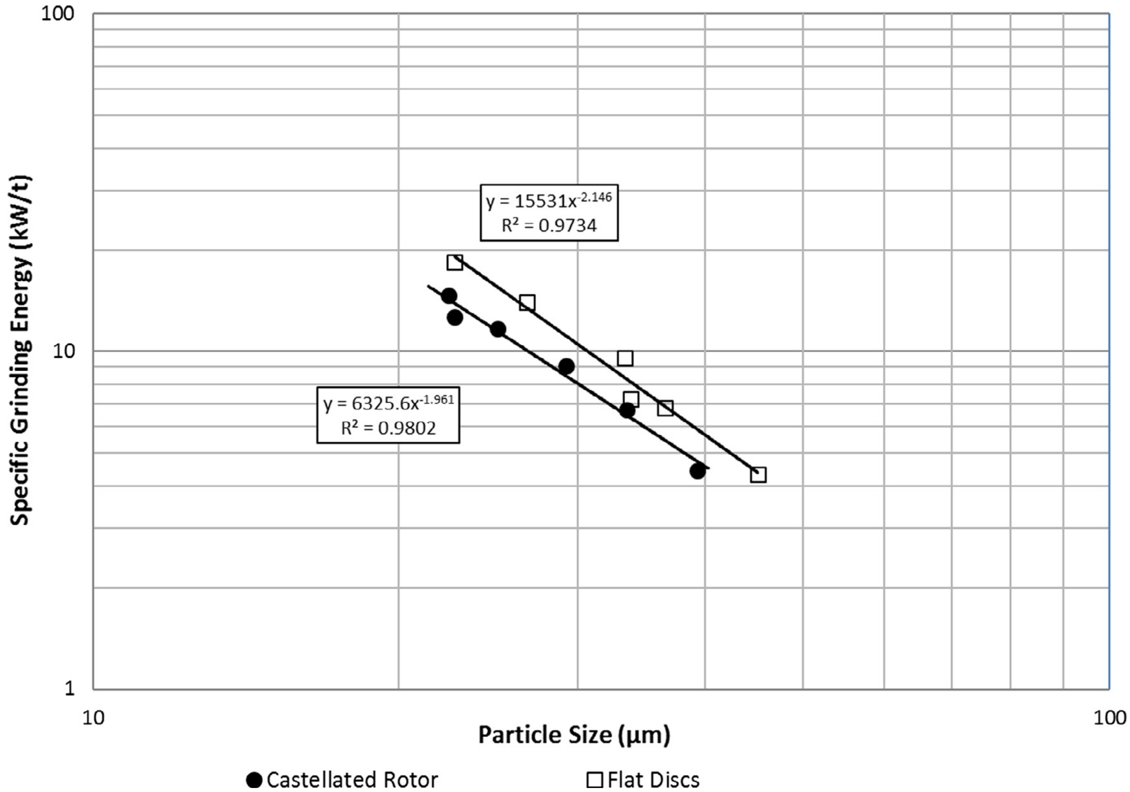

Fig. 10. Specific Grinding Energy (kWh/t) versus the particle size (P_{80}, µm) for Test Program B.

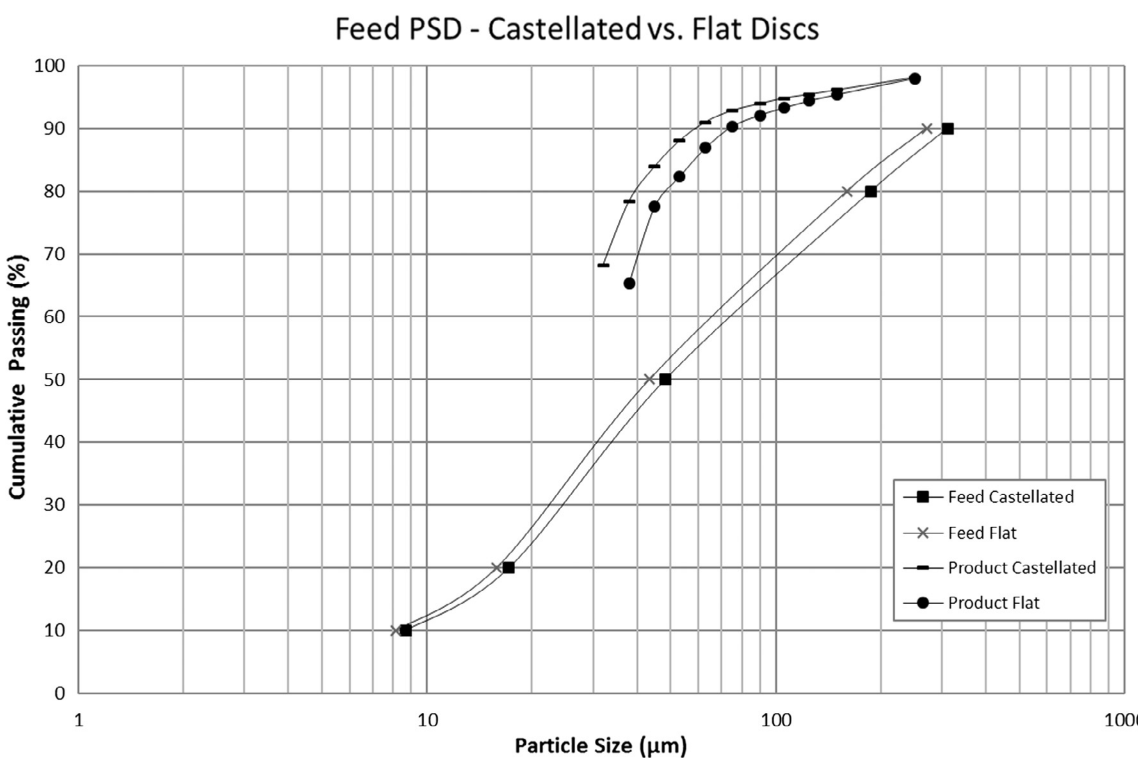

Fig. 11. Feed and product example of PSD for castellated and flat discs.

21.4 to 30.9% against the flat disc benchmark.

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