Investigating the Effect on Power Draw and Grinding Performance when Adding a Shell Liner to a Vertical Fluidised Stirred Media Mill

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Highlights

- Demonstrated that the addition of a stationary shell liner has the potential to increase the power draw of vertical stirred media mills.
- Evaluation of Shear Based Power Model against experimental data.
- Evaluated the effect of stirrer design on grinding performance.

Abstract

A comparative testwork programme was conducted using a laboratory scale vertical fluidised stirred media mill. The mill was operated with and without the presence of a disc liner on the shell. Results showed that when the mill was operating with pin and disc type stirrers, the addition of a stationary liner to the mill shell significantly increased the mill power draw. In grinding experiments conducted with silica, it was found that the production rate was enhanced as a result of the higher power draw. No detrimental effect on the grinding energy efficiency was observed. It was postulated that the addition of the disc liner increased the stress intensity of the milling operation. The results of this study show that the addition of stationary internal disc liners have a potential to increase the production capacity of fluidised stirred media mills. Further work is recommended to confirm that these observations are valid at a larger scale and in continuous milling configuration.

1 Introduction

Comminution processes are used in metallurgical operations to reduce the particle size of the minerals being treated. The main objective is usually to liberate the valuable minerals of interest, in order to facilitate their recovery in the downstream separation and extraction stages. The process of particle size reduction requires a large amount of energy. It is estimated that comminution accounts for about 34% to 52% of the direct electrical energy usage in a typical mining operation (Napier-Munn, 2015). An exponential relationship exists between the size of the product produced and the amount of energy needed. The implication is that finer product grinds require significantly more energy to generate, as compared to coarser product grinds, (Bond, 1961; Hukki, 1962; Morrell, 2004). Stirred media mills are used for fine grinding applications and employ a rotating central shaft fitted with agitators to generate movement of the mill charge. Ceramic beads are usually used as grinding media. These types of mills can be classified as either gravity induced or fluidised, depending on the charge movement characteristics (Wills & Finch, 2016; Ntsele & Allen, 2012). The design and operating parameters of a stirred media mill have an effect on the efficiency of the grinding process occurring in the mill. There are many factors that can influence efficiency. Some of the main factors are the physical mill design, the choice of grinding media size and density, the speed of the stirrer, and the slurry density (Jankovic, 2003). The comminution energy required for a stirred milling application is therefore not a fixed value, but is influenced by the operating conditions employed, and the physical mill configuration.

Using the shear based power model, Radziszewski (2013) postulated that the power draw of a vertical stirred media mill, operating with pin or disc type stirrers, might be increased by adding stationary liners to the mill shell. If the hypothesis holds true, this approach might be used to improve the design of stirred media mills for new applications. It might also be used to optimise existing mills, by modifying the mill internals. In existing mills a higher power draw could lead to a smaller equipment footprint, or to a larger throughput capacity. The aim of this investigation was to test if the addition of a stationary shell liner will increase the power draw of the stirred media mill. The effects on the production capacity and energy efficiency when adding the disc liner were also evaluated. The discrete element method (DEM) was used to obtain qualitative insight into the bead movement present in the mill, when operating with different internal geometries.

2 Background

2.1 Fluidised Stirred Media Mills

The main types of fluidised stirred media mills currently being used in the metallurgical industry include the IsaMill, SMD, VXP, and HIG mills. Fluidised stirred media mills can be configured with either a vertical or a horizontal shaft orientation. The IsaMill has a horizontal orientation while the VXP, SMD, and HIG mills are oriented vertically. The designs and operating ranges of these mills do differ somewhat from each other, a comparison is presented in Table 1. The horizontal IsaMill shaft is fitted with eight disc agitators that rotate at tip velocities ranging from around 19 to 22 m/s. Feed slurry is pumped into the feed end of the mill and the media and slurry flows through the mill towards the outlet side. Slurry then exits the mill and media is retained by centrifugal forces and a rotor system that pumps liquid back into the mill. The IsaMill can accept feed particles with sizes of up to around 500 µm. Ceramic bead sizes of around 1.5 to 6 mm are used. This mill is available in different sizes with installed capacities ranging from 335 to 8000 kW (Glencore Technology, 2015). The shaft of the Metso SMD mill is fitted with pin type agitators. Feed slurry is introduced at the top of the mill at a feed angle that directs the material to the bottom of the slurry-media vortex that forms during mill operation. Milled product overflows at the top of the mill through stationary screens that act to retain the media. The SMD is typically used with feed particles of 200 µm and smaller. Bead sizes used range from around 1 to 3 mm. Installed capacities of 90 to 1100 kW are available (Metso, 2018). Stirrer tip speeds used in industrial applications are close to about 8 m/s, but in laboratory scale the SMD mills are usually operated at tip speeds of 5-6 m/s (Bailey, 2016).

The Outotec HIG mill utilises either a disc or castellated type of agitator design (Keikkala et al. 2018). The vertical stirrer shaft is fitted with agitators and the mill vessel is fitted with static counter discs. Feed slurry is pumped in at the bottom of the mill and then flows in an upwards direction, the product discharges at the top of the mill while the media is retained by means of a screen at the outlet. The number of stationary and rotating disc sets varies up to a maximum of around 30 depending on the application. The HIG mill can typically accept feeds as coarse as around 100 to 300 µm on an 80% passing basis, with media sizes ranging from around 0.5 to 6 mm depending on the application. Stirrer tip velocities in the HIG mill range from 4-8 m/s for the smaller units to 8-12 m/s in the larger units (Lehto et al., 2011). The HIG mill is available in different sizes with installed capacities ranging from 132 to 5000 kW (Astholm, 2015). The FLSmidth VXP mill was previously known as the Knelson-Deswik mill. The shaft is fitted with disc type agitators. In this design the slurry also enters the mill from the bottom and exists at the top flowing through a media retention screen. Industrial VXP mills were designed to operate with tip speeds ranging from 10-12 m/s, and can operate with beads in the size range of 1.5 to 12 mm (FLSmidth, 2011). The VXP disc mill has been designed to accept feed particles no coarser than about 300 µm to 400 µm on an 80% passing basis, (Rahal, 2011). Capacities range from 110 to 3000 kW for industrial sized units (FLSmidth, 2011).

Table 1: Comparison of main types of fluidised stirred media mills used in the metallurgical industry

	IsaMIll	SMD	HIG	VXP
Manufacturer	Glencore	Metso	Outotec	FLSmidth
Shaft orientation	Horizontal	Vertical	Vertical	Vertical
Stirrer tip velocity	19 – 22 m/s	*Laboratory scale:* 5 – 6 m/s *Industrial scale:* 8 m/s	*Smaller units:* 4 – 8 m/s *Larger units:* 8 – 12 m/s	10 – 12 m/s
Stirrer type	Discs	Pins	Discs/Castellated	Discs
Internal mill configuration	Smooth liners	Smooth liners	Disc liners	Smooth liners
Capacity	335 – 8000 kW	90 – 1100 kW	132 – 5000 kW	110 – 3000 kW
Maximum feed particle size	500 µm	200 µm	P_{80}: 100-300 µm	P_{80}: 300-400 µm
Bead size	1.5 – 6 mm	1 – 3 mm	0.5 – 6 mm	1.5 – 12 mm

2.2 Shear Based Power Model

Radziszewski (2013) proposed the shear based power model for stirred media mills which states that the power draw of a stirred media mill might be calculated using the formula shown in equation 1. Where P_τ is the power draw in units of Watt, μ (Ns/m^2) is the viscosity of the mill charge which consists of the fluidised slurry and media mixture, ω is the rotational speed of the stirrer in units of rad/s, and V_τ is a term that is called the shear volume with units of m^3.

$$P_\tau = \mu\omega^2 V_\tau \qquad (1)$$

The shear volume is a value that is derived from the geometry of the mill under consideration and is calculated from the contribution of all of the parallel shear surface pairs in the mill. A general guideline is that if one parallel surface is found on the rotating impeller and the other parallel surface is found on the chamber then these surfaces would constitute a parallel shear surface pair. A formula for shear volume is presented in equation 2, (Radziszewski, 2013). Where A is the area over which the shear force is acting, r is the radius over which the shear is acting, and y represents that gap over which the shear is acting.

$$V_\tau = A\frac{r^2}{y} \qquad (2)$$

Radziszewski (2013) then evaluated various hypothetical vertical stirred media mill geometries including configurations with pin and disc agitators on the stirrer shaft. It was found that the shear volume could be significantly increased by the addition of liners to the mill shell as shown in Table 2. In the case of the pin stirrer the shear volume could be increased by 32% using pin liners, and up to 211% using disc liners. In the case of the disc stirrer the shear volume could be increased by 28% using pins as liners, and by 55% by adding discs as liners. According to the shear based power model the power draw of the mill is proportional to the shear volume under similar operating conditions. Based on this it was then postulated that the power draw of a mill operating with pin or disc type stirrers might be increased by adding liners to the mill shell, however no supporting experimental work was presented. The objective of the current investigation was to conduct a test work programme to provide data to assess the hypothesis. It is interesting to note that the HIG mill already utilises stationary disc liners. The other main types of stirred media mills used in the metallurgical industry do not currently employ this design philosophy.

Table 2: Shear volume for various hypothetical mill geometries (Radziszewski, 2013)

Geometry	Shear Volume (m^3)	Relative Magnitude of Shear Volume	Increase in Shear Volume due to Shell Liner Addition
Pin type stirrer			
3 x 6 pin stirrer	0.114	1.00	
3 x 6 pin stirrer with pin liners	0.150	1.32	32%
3 x 6 pin stirrer with disc liners	0.355	3.11	211%
Disc type stirrer			
3 disc stirrer	1.618	1.00	
3 disc stirrer with pin liners	2.079	1.28	28%
3 disc stirrer with disc liners	2.503	1.55	55%

3 Methodology

3.1 Equipment

Experimental tests were conducted using a laboratory scale stirred media mill test rig located at Mintek, Figure 1a. The rig can be fitted with various different stirrer and mill vessel designs, and is instrumented with a speed sensor and torque measurement via a load cell arrangement, Figure 1b. The shaft speed and torque are logged to a computer system and the power draw is calculated in real time using equation 3.

$$P = \frac{2\pi T\omega}{60} \qquad (3)$$

Where *P* is the mill power draw (W), *T* is the shaft torque (N.m), and ω is the angular velocity of the shaft in units of revolutions per minute (rpm). The power draw (W) for each one second interval can also be used to calculate the incremental energy input (kWh) to the mill during that period. The accumulated energy input per mass of solids sample in the mill (kWh/t) is tracked over the duration of the test run and recorded. The mass of solid sample being milled is an input by the user before the start of the run. The test rig used for this work is the same rig that was used by Lisso (2013). The maximum stirrer tip velocity achievable with the equipment configuration was 4 m/s. Similar types of laboratory test rigs have been used by numerous investigators for studying stirred media milling (Tüzün, 1993; Edwards, 2016; Norejko, 2018; Bailey, 2016; Tamblyn, 2009; Eswaraiah, 2015; Yang, 2017; Kim, 2008; Conway-Baker, 2002; Barley, 2004; Mankosa, 1986). Pictures of the stirrers and mill vessels used during experimental testing are shown in Figure 2 to Figure 4. The smooth mill chamber measured 180 cm in diameter and 230 cm in height. The disc liner vessel had similar dimensions, but was constructed as two half pieces that were bolted together to allow the fitting of the stirrer. The pin stirrer consisted of two sets of six pins spaced equally around the shaft with an overall stirrer diameter of 144mm. The disc stirrer had the same diameter and spacing between sets, but the agitators were constructed from an outer circular ring connected to the shaft with four spokes. The spacing between the bottom of the stirrer and the mill was 20mm. Detailed dimensions of the equipment are shown in Figures 5 and 6. The shear volume calculated for each of the four geometries are shown in Table 3. Due to the smaller parallel shear surface areas, the pin stirrer had a lower shear volume of 6.28×10^{-4} m^3, as compared to the disc stirrer with a shear volume of 3.72×10^{-3} m^3. The addition of a disc liner to the mill vessel increased the shear volume of the pin stirrer configuration with a factor of 1.75. In the case of the disc stirrer the additional liner on the shell increased the shear volume with a factor of 1.44.

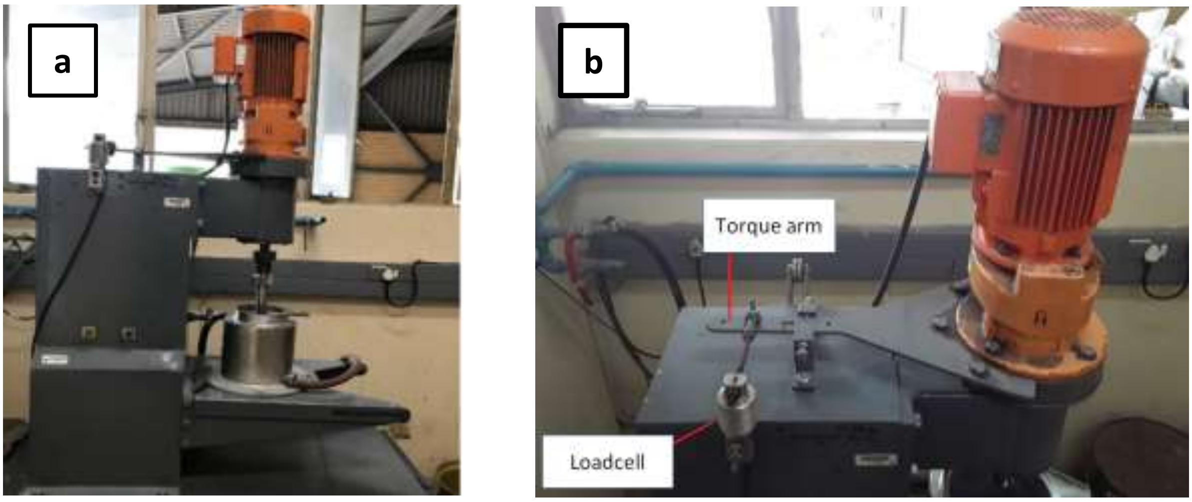

Figure 1: a) Stirred media milling test rig b) Torque arm and load cell arrangement

Figure 2: Disc and pin stirrers used during experiments

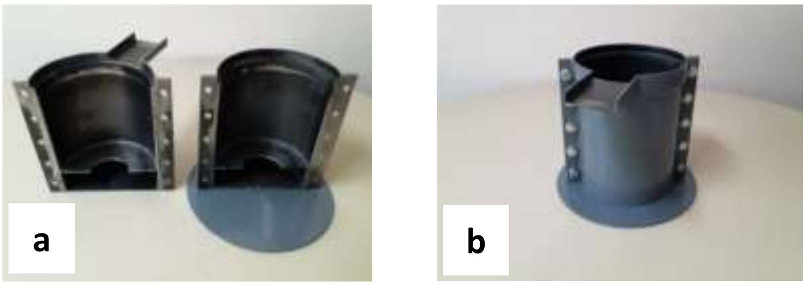

Figure 3: Disc liner mill vessel a) two pieces b) assembled

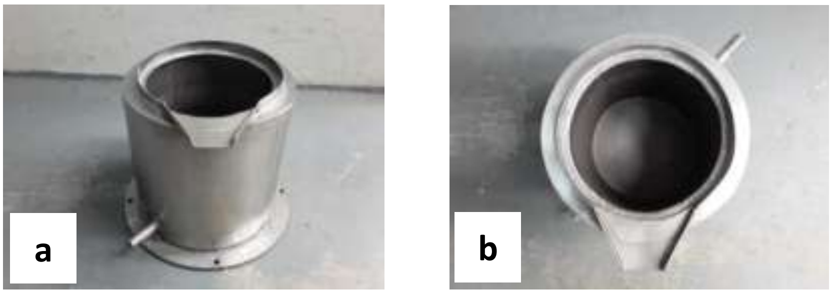

Figure 4: Smooth mill vessel a) side view b) top view

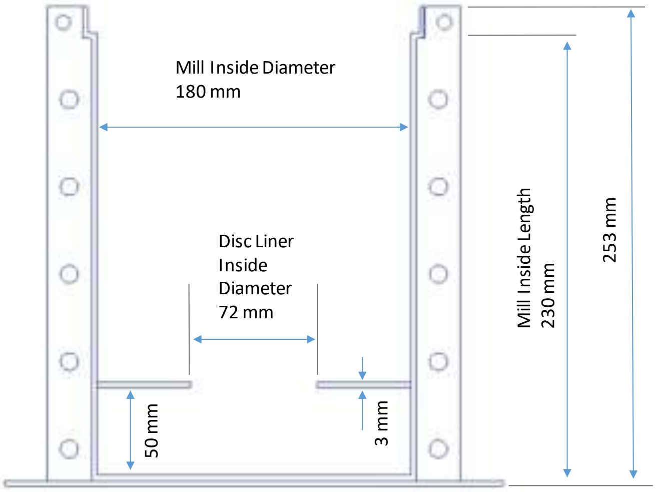

Figure 5: Cross section drawing of disc mill vessel showing dimensions

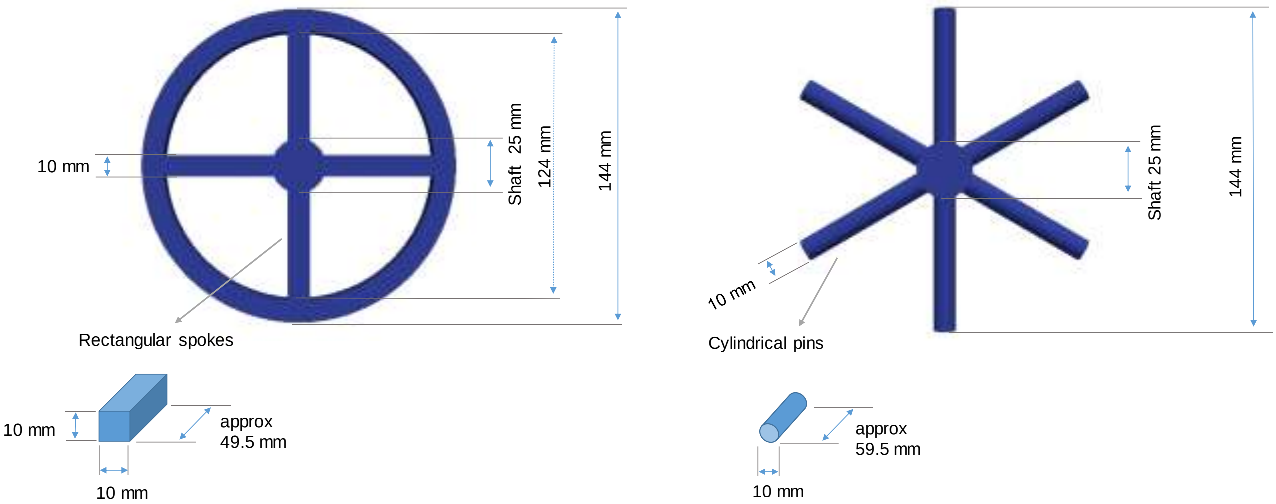

Figure 6: Agitator dimensions

Table 3: Radziszewski shear volume calculated for the various experimental geometries

Geometry	Shear Volume (m^3)	Relative Magnitude of Shear Volume	Increase in Shear Volume (factor)
Pin stirrer - smooth vessel	0.000628	1.00	
Pin stirrer - disc vessel	0.001098	1.75	1.75
Disc stirrer - smooth vessel	0.003720	5.93	
Disc stirrer - disc vessel	0.005342	8.51	1.44

3.2 Experimental Programme

A series of milling tests were conducted. A summary of the test work programme is shown in Table 4 and the test conditions are presented in Table 5.

3.2.1 Bead and Water Tests

The aim of the bead and water tests was to measure the power draw of the different mill geometries when operating with different bead sizes and stirrer speeds. Bead sizes of 1, 2 and 3mm were used and the stirrer tip velocity ranged from 2 to 4 m/s.

3.2.2 Repeatability Tests

Grinding tests were conducted to measure the repeatability of the milling results generated. Five tests were conducted with the silica flour feed material. The SG of the silica flour used was 2.65 g/cm^3. The pin stirrer – smooth vessel configuration was used with 3mm beads and a stirrer tip velocity of 3.0 m/s. The feed PSD for the silica flour is shown in Figure 7. For each test individual batches of silica flour were milled for three different energy inputs of 5, 10, and 20 kWh/t respectively and the milling times were recorded. Sieve analysis was conducted on each of the products. The PSD data were used to determine the energy (kWh/t) and time (min) to reach various different grind sizes. For each grind size the coefficients of variation (CV) of the time and energy required to reach the target grind were calculated. The CV values were used as measurements of the experimental variability.

Table 4: Experimental Test work Matrix

Geometry	Stirrer Tip Velocity (m/s)	Energy Input (kWh/t)	Bead Size (mm)
Beads and water			
Pin stirrer - smooth vessel	2 to 4		1, 2, 3
Pin stirrer - disc vessel	2 to 4		1, 2, 3
Disc stirrer - smooth vessel	2 to 4		1, 2, 3
Disc stirrer - disc vessel	2 to 4		1, 2, 3
Repeatability Tests – Silica Flour			
Pin stirrer - smooth vessel (five tests)	3	5, 10, 20	3
Mono-sized Tests -150 +106 µm silica			
Pin stirrer - smooth vessel	3	2.5, 5, 10, 15, 20	3
Pin stirrer - disc vessel	3	2.5, 5, 10, 15, 20	3
Disc stirrer - smooth vessel	3	2.5, 5, 10, 15, 20	3
Disc stirrer - disc vessel	3	2.5, 5, 10, 15, 20	3
Mono-sized Tests -106 +75 µm silica			
Pin stirrer - smooth vessel	3	2.5, 5, 10, 15, 20	3
Pin stirrer - disc vessel	3	2.5, 5, 10, 15, 20	3
Disc stirrer - smooth vessel	3	2.5, 5, 10, 15, 20	3
Disc stirrer - disc vessel	3	2.5, 5, 10, 15, 20	3
Silica Flour Tests – Natural PSD			
Pin stirrer - smooth vessel	2, 3, 4	5, 10, 20	3
Pin stirrer - disc vessel	2, 3, 4	5, 10, 20	3
Disc stirrer - smooth vessel	2, 3, 4	5, 10, 20	3
Disc stirrer - disc vessel	2, 3, 4	5, 10, 20	3
Beads only – Data for DEM Calibration			
Pin stirrer - smooth vessel	3		3
Pin stirrer - disc vessel	3		3
Disc stirrer - smooth vessel	3		3
Disc stirrer - disc vessel	3		3

Table 5: Test Conditions

	Beads and Water	Silica Flour	Repeatability	Mono-sized silica
Solids mass (g)	0	1275	1275	1277
Water mass (g)	1756	1275	1275	1275
Solids %	0	50	50	50
Solids SG (g/cm^3)	-	2.65	2.65	2.67
Bead SG (g/cm^3)	3.25	3.25	3.25	3.25
Bead mass (g)	5706	5706	5706	5706

3.2.3 Mono-sized Silica Grinding Tests

Testing was conducted using a different silica material with an SG of 2.67 g/cm^3. Feed was prepared into two narrow size fractions of -150 + 106 µm and -106 + 75 µm respectively, refer to Figure 7 for particle size distribution data based on sieve analysis. Grinding beads with a diameter of 3mm and density of 3.25 g/cm^3 were used. A stirrer tip velocity of 3 m/s was used for all the tests. For each test individual batches of silica were milled to various specific energy inputs of 2.5, 5, 10, 15, and 20 kWh/t respectively. The time to reach each energy input was recorded. A sieve analysis was conducted on the product from each energy input to determine the fraction of mass remaining in the parent particle size class. The data were then used to fit the time based (S_i) and energy based (S_i^E) rates of breakage for each test (Austin et al., 1984; Herbst & Fuesternau, 1973). The time based rate of breakage was used to assess the effect of the additional liner on the productivity of the mill, while the energy normalised rate of breakage was used to assess the effect on energy efficiency.

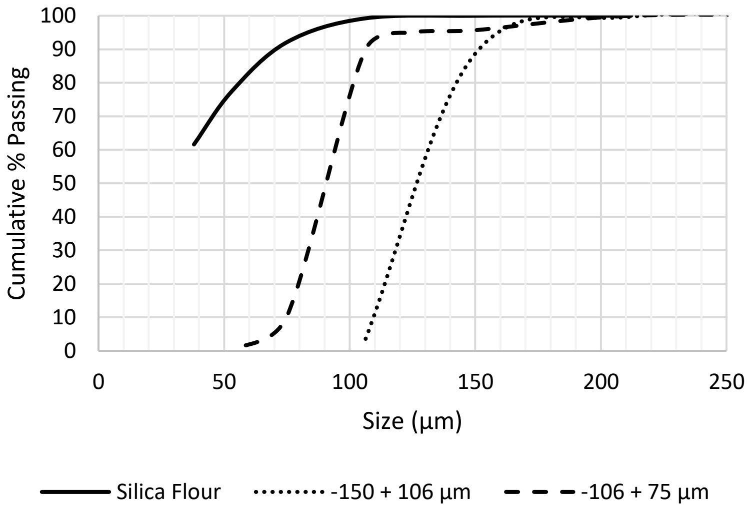

Figure 7: PSD of silica feed materials

3.2.4 Silica Flour Grinding Tests

A series of grinding tests were conducted on the silica flour material. Testing was conducted for each of the four geometries at three different stirrer tip velocities namely 2, 3, and 4 m/s. Beads with a diameter of 3mm and a density of 3.25 g/cm^3 were used as grinding media. During each test three individual feed batches were milled to energy inputs of 5, 10, and 20 kWh/t respectively. The time required to reach the target energy input was recorded. A full particle size distribution was conducted on each of the products. The data were used to determine the energy (kWh/t) and time (min) required to reach various different grind sizes. The data from each test were compared to assess the effect of the addition of a shell disc liner on the mill performance. The time to reach a given grind target was used to assess the productivity, and the specific energy input to reach a given grind size was used to evaluate the energy efficiency.

3.3 Discrete Element Modelling

The discrete element modelling method (DEM) was applied to study the bead movement in the different mill geometries under comparative conditions. The aim with DEM was to obtain a qualitative comparison between the different geometries and not to model the exact physics occurring in the mill. In order to model the physics more accurately a combined CFD-DEM model would be required to simulate both the bead and the slurry phases. The complexities involved with the CFD-DEM approach was outside of the scope of the current investigation. In this current work only the bead movement was modelled using the soft particle DEM formulation. This approach has been described extensively in literature, (Mishra & Rajamani, 1992; Weerasekara et al., 2013; Cleary, 1998; Mishra & Murty, 2001). A linear spring-dashpot model was used to model the normal and tangential forces occurring between particles in contact with each other. The DEM simulations were conducted using the LIGGGHTS®-PUBLIC version 3.8.0 software. LIGGGHTS®–PUBLIC is an open source discrete element method particle simulation software, distributed by DCS computing, GmbH, Linz, Austria. LIGGGHTS stands for LAMMPS improved for general granular and granular heat transfer simulations (www.cfdem.com, 2019). The Hooke/stiffness contact model in LIGGGHTS was used to implement the linear contact force model. The DEM model was calibrated against torque measurements obtained from bead only experiments. In order to simplify the parameter calibration process it was assumed that the bead to bead and bead to steel contact parameters were similar. So single values for the coefficient of friction and coefficient of restitution were assumed. During the bead only experiments 5706 g of beads with a diameter of 3mm and density of 3.25 g/cm^3 were used. The mill was operated at a stirrer tip velocity of 3 m/s and torque and power draw measurements were taken for each of the four different mill geometries. The set of calibrated parameters used for the DEM simulations are shown in Table 6. The simulated torque acting on the shaft, forces acting on the beads, as well as velocities and positions of the beads were logged at regular intervals from LIGGGHTS.

Table 6: Calibrated DEM Model Parameters

Parameter	Value used in DEM	Parameter	Value Used in DEM
Bead density (g/cm3)	3.25	Coefficient of restitution	0.95
Bead diameter (mm)	3	Coefficient of friction	0.45
Poisson Ratio	0.22	Normal spring stiffness (N/m)	438 267
Characteristic velocity (m/s)	2.93	Tangential spring stiffness (N/m)	384 099
Maximum overlap (%)	1.0	Normal Damping (bead-bead)	0.1037
Stirrer tip velocity (m/s)	3	Normal Damping (bead-wall)	0.1466
Number of particles	124 200	Tangential Damping (bead-bead)	0.0970
Number of time steps	18 666 666	Tangential Damping (bead-wall)	0.1372
Time step (seconds)	1.07×10^{-6}		

4 Results and Discussion

4.1 Power Draw Results

The power draw results from the bead and water tests are reported in Table 7. Average power draw measured during the silica grinding tests are shown in Table 9. The data shows that in all cases the addition of the stationary disc to the mill vessel increased the mill power draw. For the pin stirrer the addition of a disc liner resulted in a power draw increase by a factor of between 1.71 and 2.71. For the disc stirrer the power draw increased by a factor of 1.29 to 1.95. For both the smooth vessel and disc vessel configurations the power draws measured with the pin stirrer were higher than the power draws measured when using the disc stirrer.

4.2 Grinding Test Results

4.2.1 Repeatability

Five repeatability tests were conducted on the silica flour material with the pin stirrer in smooth vessel configuration, results are reported in Table 8. The coefficient of variation (CV) was calculated for each data set. The repeatability of the energy input (kWh/t) to reach a given target grind ranged from 2.66% to 5.32% based on the CV. On a time basis the repeatability to reach a given grind size ranged from 1.58% to 2.76% as measured with CV.

4.2.2 Results of Mono-sized Silica Grinding Tests

The breakage rates for the -150 + 106 µm and -106 + 75 µm size fractions are shown in Table 10. It was found that first order breakage kinetics applied in all cases. The results indicate that the addition of the disc liner to the mill increased the rate at which particle breakage occurred. For the pin stirrer the Si (min^{-1}) rates increased by factors of 2.81 and 2.37 for the -150 + 106 µm and -106 + 75 µm size fractions respectively. With the disc stirrer the rates increased with a factor of 1.69 for the -150 + 106 µm feed, and with a factor of 1.61 for the -106 + 75 µm feed. Based on the energy normalised rates of breakage, Si^E $(kWh/t)^{-1}$, the addition of the disc liner resulted in a slight improvement in energy efficiency. For the pin stirrer the energy normalised breakage rate increased with a factor of 1.26 for the -150 + 106 µm feed, and with a factor of 1.08 for the -106 + 75 µm feed. In the case of the disc stirrer the rates increased with a factor of 1.09 for the -150 + 106 µm feed and with a factor of 1.02 for the -106 + 75 µm feed. The results of the mono-sized milling tests therefore show that an increase in mill productivity can be obtained by adding a disc liner, without a negative impact on the energy efficiency of the milling process. It was noted that the pin stirrer design provided better energy efficiency compared to the disc design. The energy normalised breakage rates, Si^E $(kWh/t)^{-1}$, measured for the pin stirrer configurations where higher compared to those measured for the disc stirrer.

4.2.3 Results of Silica Flour Grinding Tests

The silica flour grinding test performance data are shown in Table 11. The addition of the disc liner resulted in significantly increased mill productivity, as measured from the milling time required to reach a given grind size. For the pin stirrer the milling time to reach a given grind size was reduced by around 52.6% to 65.3%. For the disc stirrer the milling time was reduced by about 33.0% to 47.6%. This shows that the additional power draw generated by the disc liner translated into faster breakage in the mill. For the pin stirrer the addition of the liner resulted in somewhat of an improvement in the energy efficiency of the grinding process. The pin stirrer-disc liner configuration required around 6.5% to 17.1% less energy compared to the smooth vessel. In the case of the disc stirrer the effect on energy efficiency was insignificant. Some of the experimental data points show an improvement in energy efficiency while other points show a reduction in energy efficiency. The change in the energy requirement for reaching a given grind size ranged from around -10.9% to 3.6% with the majority of the data points falling within the experimental error range. The effect of the addition disc liner on the energy efficiency of the disc stirrer is therefore negligible.

It was observed that the pin stirrer design provided better energy efficiency and faster milling times as compared to the disc stirrer design. For the smooth vessel configurations the disc stirrer required around 0.7% to 13.4% more energy (kWh/t). Also the production rate for a given grind size was around 18% to 55.3% lower compared to the pin stirrer. For the disc vessel the difference in stirrer performance was more significant. For this scenario the disc stirrer required around 5.9% to 28.1% more energy than the pin stirrer. The production rate was about 73.9% to 119.5% lower compared to the pin stirrer. It seems that the energy efficiency of the pin stirrer was enhanced by the addition of the disc liner, while the energy efficiency of disc stirrer remained unaffected. These observations are also confirmed by the operating work indices (OWi) calculated for the different scenarios, Table 11. In general the operating work indices are lower for the pin stirrer operation compared to the disc stirrer. The higher tip velocity of 4 m/s resulted in more efficient grinding conditions for all scenarios, as is evidenced by the reduction in operating work index. Although differences were observed in terms of energy efficiency and production rate, it is interesting to note that the different types of mill configurations resulted in very similar PSD profiles, an example is shown in Figure 8.

Table 7: Bead and Water Tests Power Draw

Geometry	Power (Watt) 2.0 m/s	2.3 m/s	2.6 m/s	2.9 m/s	3.0 m/s	3.2 m/s	3.4 m/s	3.7 m/s	4.0 m/s
1mm Beads									
Pin stirrer - smooth vessel (Watt)	29.8	36.0	43.8	53.5	59.2	64.8	74.9	83.0	95.8
Pin stirrer - disc vessel (Watt)	64.4	82.9	96.7	113.3	121.7	128.6	140.9	158.2	176.2
Power increase (factor)	*2.16*	*2.30*	*2.21*	*2.12*	*2.06*	*1.98*	*1.88*	*1.91*	*1.84*
Disc stirrer - smooth vessel (Watt)	28.5	33.9	39.2	42.2	45.6	50.5	59.8	73.8	86.9
Disc stirrer - disc vessel (Watt)	44.3	54.5	64.9	80.0	88.8	93.4	103.1	115.8	133.6
Power increase (factor)	*1.55*	*1.61*	*1.66*	*1.90*	*1.95*	*1.85*	*1.72*	*1.57*	*1.54*
2mm Beads									
Pin stirrer - smooth vessel (Watt)	41.7	50.8	61.0	74.1	80.7	86.1	96.4	105.5	115.4
Pin stirrer - disc vessel (Watt)	73.1	93.1	115.9	140.4	155.3	168.5	195.6	222.5	256.2
Power increase (factor)	*1.75*	*1.83*	*1.90*	*1.89*	*1.92*	*1.96*	*2.03*	*2.11*	*2.22*
Disc stirrer - smooth vessel (Watt)	35.7	42.3	49.2	58.9	68.4	79.3	96.1	109.9	124.0
Disc stirrer - disc vessel (Watt)	52.9	63.1	75.0	89.8	97.3	105.4	124.2	145.0	172.7
Power increase (factor)	*1.48*	*1.49*	*1.52*	*1.52*	*1.42*	*1.33*	*1.29*	*1.32*	*1.39*
3m Beads									
Pin stirrer - smooth vessel (Watt)	49.8	60.2	73.0	85.5	91.8	97.3	111.8	124.7	138.2
Pin stirrer - disc vessel (Watt)	85.2	106.7	132.1	162.4	180.4	198.3	238.5	284.0	334.4
Power increase (factor)	*1.71*	*1.77*	*1.81*	*1.90*	*1.97*	*2.04*	*2.13*	*2.28*	*2.42*
Disc stirrer - smooth vessel (Watt)	39.9	47.3	56.4	66.0	71.5	78.0	90.7	102.7	109.1
Disc stirrer - disc vessel (Watt)	58.6	70.3	83.3	98.9	107.9	117.2	137.5	159.8	185.8
Power increase (factor)	*1.47*	*1.49*	*1.48*	*1.50*	*1.51*	*1.50*	*1.52*	*1.56*	*1.70*

Table 8: Milling Test Repeatability

% Passing 38 µm	**Energy (kWh/t)** Test 1	Test 2	Test 3	Test 4	Test 5	Mean	Standard Deviation	Coefficient of variation (CV) %
70	3.41	3.25	3.20	2.95	3.10	3.20	0.17	5.32
75	5.48	5.19	5.11	4.72	4.96	5.11	0.28	5.48
80	7.64	7.21	7.20	6.95	7.10	7.20	0.26	3.60
85	9.81	9.22	9.28	9.29	9.25	9.28	0.25	2.66

% Passing 38 µm	**Time (minutes)** Test 1	Test 2	Test 3	Test 4	Test 5	Mean	Standard Deviation	Coefficient of variation (CV) %
70	2.73	2.81	2.76	2.61	2.76	2.76	0.07	2.68
75	4.43	4.49	4.42	4.18	4.42	4.42	0.12	2.76
80	6.44	6.25	6.30	6.18	6.37	6.30	0.10	1.58
85	8.45	8.01	8.18	8.30	8.34	8.30	0.17	2.03

Table 9: Power Draw - Grinding Tests

Mill Configuration	Average Power (W)	Increase (factor)
-150 + 106 µm Silica		
Pin stirrer - smooth vessel	86.4	
Disc stirrer - smooth vessel	63.9	
Pin stirrer - disc vessel	184.6	2.14
Disc stirrer in disc vessel	99.7	1.56
-106 + 75 µm Silica		
Pin stirrer - smooth vessel	81.5	
Disc stirrer - smooth vessel	61.6	
Pin stirrer - disc vessel	176.6	2.17
Disc stirrer - disc vessel	97.5	1.58
Silica Flour 2 m/s		
Pin stirrer - smooth vessel	43.8	
Disc stirrer - smooth vessel	31.9	
Pin stirrer - disc vessel	82.3	1.88
Disc stirrer in disc vessel	48.9	1.53
Silica Flour 3 m/s		
Pin stirrer - smooth vessel	82.2	
Disc stirrer - smooth vessel	60.2	
Pin stirrer - disc vessel	171.4	2.08
Disc stirrer in disc vessel	102.7	1.71
Silica Flour 4 m/s		
Pin stirrer - smooth vessel	112.7	
Disc stirrer - smooth vessel	94.3	
Pin stirrer - disc vessel	305.0	2.71
Disc stirrer in disc vessel	170.1	1.80

Table 10: Breakage Rates for Mono-sized Silica Grinding Tests

Mill Configuration	Si (min^{-1})	Increase due to disc liner (factor)	Si^E $(kWh/t)^{-1}$	Increase due to disc liner (factor)
-150 + 106 µm Silica Feed				
Pin stirrer in smooth vessel	0.136		0.123	
Disc stirrer in smooth vessel	0.081		0.098	
Pin stirrer in disc vessel	0.382	2.81	0.155	1.26
Disc stirrer in disc vessel	0.137	1.69	0.107	1.09
-106 + 75 µm Silica Feed				
Pin stirrer in smooth vessel	0.149		0.138	
Disc stirrer in smooth vessel	0.097		0.120	
Pin stirrer in disc vessel	0.353	2.37	0.148	1.08
Disc stirrer in disc vessel	0.156	1.61	0.122	1.02

Table 11: Silica Flour Grinding Tests Disc versus Smooth Vessel

	Energy (kWh/t)			Milling Time (minutes)		
Grind % Passing 38 µm	Smooth Vessel	Disc Vessel	Energy % Change with addition of disc	Smooth Vessel	Disc Vessel	Milling Time % Change with addition of disc
Pin Stirrer 2 m/s						
70%	3.56	2.97	-16.5%	6.14	2.70	-56.0%
75%	5.73	4.75	-17.1%	9.95	4.32	-56.6%
80%	8.00	7.11	-11.1%	14.07	6.49	-53.9%
85%	10.47	9.60	-8.3%	18.52	8.77	-52.6%
OWi	26.9	23.9	-11.2%			
Pin Stirrer 3 m/s						
70%	4.21	3.69	-12.4%	3.84	1.65	-57.0%
75%	6.41	5.78	-9.9%	5.88	2.58	-56.2%
80%	8.45	7.62	-9.8%	7.79	3.39	-56.5%
85%	10.80	9.45	-12.5%	10.04	4.21	-58.1%
OWi	28.4	25.6	-9.9%			
Pin Stirrer 4 m/s						
70%	3.18	2.97	-6.5%	2.19	0.77	-64.9%
75%	5.08	4.75	-6.5%	3.50	1.23	-64.9%
80%	7.26	6.69	-7.8%	4.92	1.71	-65.3%
85%	9.44	8.73	-7.4%	6.34	2.20	-65.3%
OWi	24.4	22.5	-7.8%			
Disc Stirrer 2 m/s						
70%	3.77	3.51	-6.9%	8.76	5.45	-37.9%
75%	6.13	5.84	-4.7%	14.42	9.07	-37.1%
80%	8.60	8.75	1.7%	20.57	13.65	-33.7%
85%	11.86	12.29	3.6%	28.76	19.26	-33.0%
OWi	28.9	29.4	1.7%			
Disc Stirrer 3 m/s						
70%	4.39	3.91	-10.9%	5.48	2.87	-47.6%
75%	6.64	6.16	-7.2%	8.39	4.54	-45.9%
80%	8.76	8.32	-5.0%	11.18	6.16	-44.9%
85%	11.55	10.80	-6.5%	14.82	8.05	-45.7%
OWi	29.4	27.9	-5.1%			
Disc Stirrer 4 m/s						
70%	3.60	3.68	2.2%	3.09	1.67	-45.7%
75%	5.68	5.81	2.2%	4.78	2.64	-44.9%
80%	7.59	7.78	2.5%	6.13	3.51	-42.7%
85%	9.50	9.75	2.6%	7.48	4.39	-41.3%
OWi	25.5	26.1	2.4%			

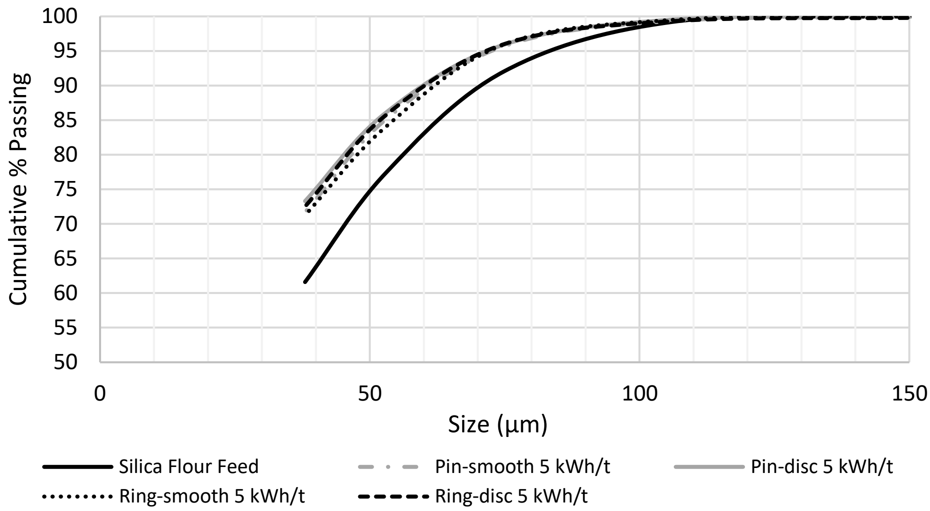

Figure 8: Silica Flour Particle Size Distribution, 3m/s

4.3 Discrete Element Modelling Results

Summarised DEM results are presented in Table 12 and corresponding visualisations are shown in Figure 9. Based on the qualitative DEM simulations, the addition of the disc liner had the effect of reducing the average bead velocity in the mill chamber, but the average forces acting on the beads were higher. It seems that the disc resulted in a restriction of media movement, hence the lower bead velocities. The higher forces acting on the beads seems to indicate that the disc liner acted to increase the stress intensity of the milling operation. The stress intensity, also called the stress energy, SE_p of a stirred media mill is an indication of the maximum energy that can be transferred to product particles. The SE_p for a given milling operation can be described by equation 4 (Breitung-Faes & Kwade, 2014).

$$SE_p = f_{Mill} d_{GM}^3 \rho_{GM} v_t^2 \left(1 + \frac{E_{Feed}}{E_{GM}}\right)^{-1} \qquad (4)$$

Where f_{Mill} is a mill geometry factor, d_{GM} is the grinding media diameter, ρ_{GM} is the grinding media density, v_t is the stirrer tip velocity, and E_{Feed} and E_{GM} are the feed particle and grinding media modulus of elasticity. As is evidenced in the equation, the stress energy is dependent on the mill geometry, which relates to the stirrer and chamber designs and dimensions. For the results presented in Table 12 all of the parameters were kept constant except for the mill geometry, f_{Mill}. If the forces acting on the beads are assumed to be proportional to the stress energy, then the addition of the disc liner results in a higher f_{Mill} factor. Also when operating in the same mill geometry, the pin stirrer produced higher forces on the beads compared to the disc stirrer. The pin stirrer design therefore seems to provide a higher stress intensity compared to the disc design, and therefore a higher f_{Mill} factor.

Table 12: DEM Model Torque versus Actual Measured Torque, velocity, and forces acting on beads

Mill Configuration	Measured Torque (N.m)	DEM Model Torque (N.m)	Difference (%)	Average Bead Velocity (m/s)	Average Force on Beads (N)
Pin stirrer in smooth vessel	3.09	3.25	5.2%	0.71	5.17×10^{-2}
Disc stirrer in smooth vessel	2.30	2.59	12.6%	0.56	4.23×10^{-2}
Pin stirrer in disc vessel	5.80	4.71	-18.8%	0.47	6.18×10^{-2}
Disc stirrer in disc vessel	3.97	3.80	-4.3%	0.39	5.35×10^{-2}

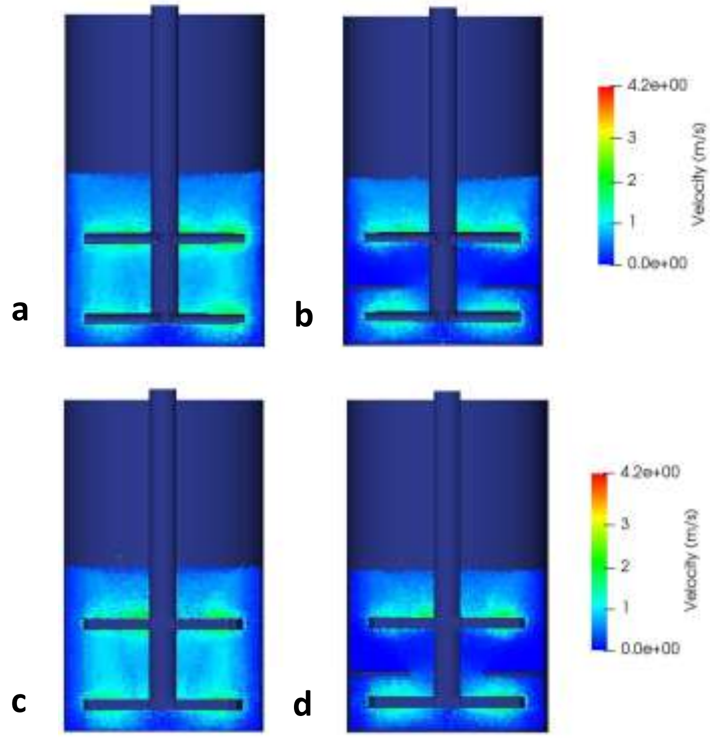

Figure 9: DEM simulations a) pin – smooth, b) Pin - disc, c) disc-smooth, d) disc-disc

4.3.1 Observations on the Shear Based Power Model

Based on the shear volume calculated for each of the geometries, Table 3, it was predicted that the addition of the disc liner will increase the power draw of the mill. The experimental results confirm that an increase in mill power draw was achieved. However the shear based power model also predicted that the disc stirrer design will produce a significantly higher power draw as compared to the pin stirrer. This was not observed during the experimental work. On the contrary, the pin stirrer consistently produced a higher power draw. Interestingly the torque trends obtained from the DEM models, Table 12, were more accurate in predicting the relative differences between the stirrer designs.

5 Conclusions

The experimental results showed that the power draw of the pin and disc stirrer mills increased with the addition of a stationary disc liner to the mill shell. It was found that the addition of the disc liner did not have a negative effect on the energy efficiency of grinding. For the pin stirrer a slight increase in energy efficiency was observed with around 7% to 26% reduction in specific energy requirement. For the disc stirrer the energy efficiency was unaffected.

The results of this investigation shows that there could be a potential to improve the productivity of vertical stirred media mills by adding stationary disc liners to the mill vessel. The higher mill power draw could lead to smaller equipment footprints for new mill designs. Alternatively it could lead to higher throughput rates or finer grind sizes in existing mills that have been converted to this design. The current investigation only focused on conducting laboratory scale testing in a batch setup. Further work should be conducted to evaluate how these results translate to continuous mill operation at a larger scale. It should be noted however that the Outotec HIG mill already utilises a disc liner design while the other mills commonly used in the metallurgical industry do not currently incorporate this type of design. The idea of using disc liners therefore seems feasible in practice but the process benefits of such a design should be compared against the traditional smooth shell designs. The test rig that was available for this current investigation could only provide tip velocities up to around 4 m/s. It is recommended to also conduct testing at higher tip velocities that are closer to industrial scale operating ranges.

It was found that the shear based power model correctly predicted that the addition of the disc liner will increase the mill power draw. The shear based power model also predicted that the disc stirrer will draw significantly more power than the pin stirrer. However from the experimental results it was evident that the pin stirrer had a higher power draw than the disc stirrer which contradicts the model prediction. Interestingly the DEM model predicted the relative power draw trends correctly. Analysis of DEM model data showed that the addition of the disc liner resulted in larger magnitudes of forces acting on the beads. It was postulated that the addition of the disc liner increased the stress intensity of the milling operation.

Declaration of Interest

The authors have no competing interests to declare.

Author Contributions

Elizma Ford: Conceptualization, Funding acquisition, Methodology, Investigation, Writing - original draft. Natasia Naude: Supervision, Writing – review & editing.

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