MILLING TECHNOLOGY SELECTION FOR THE TATI ACTIVOX® PROJECT BASE ON PILOT SCALE ULTRAFINE MILLING TESTWORK ON NICKEL SULPHIDE CONCENTRATES

G J Nel
Norilsk Nickel Africa

Abstract

The Tati Hydrometallurgical Demonstration Plant (HDP) ultra fine milling circuit was equipped with four of the leading ultrafine milling technologies currently in the world, Isa, Metso, Bradken and Deswik mills. Three of the four mills were vertical stirred and one a horizontal stirred mill. Several milling testwork campaigns were completed over a three year period using Phoenix, BCL and Nkomati nickel sulphide concentrates. The following variables were measured during the testwork campaigns: feed densities, feed rates, grinding media types, inlet temperatures, outlet temperatures, net power consumption, feed- and product particle size distributions. The mills were evaluated based on specific cumulative breakage rates, product size distributions, mill complexity and operability. The mill evaluations were used to select the appropriate ultra fine milling technology for the Tati Activox® Project (TAP).

To conclude, the low speed vertical ultra fine mill A (mill number not related to mill order shown above) did not produce the desired final product size distributions at the TAP mill feed densities. Separation of the grinding media and mill product happened in a settling zone above the mill product discharge launder and grinding media exit the mill with the final product at high mill feed densities. The specific cumulative breakage rate (SCBR) from the horizontal ultra fine mill was 0.024 with ceramic grinding media; or 2.4 % of the concentrate coarser than 10 micron was reduced to particles smaller than 10 micron with 1 kWh/t specific energy input. Using silica-alimina-zirconia (SAZ) grinding media increased the horizontal mill's SCBR to 0.051. The low speed vertical ultra fine mill B had the highest SCBR value of 0.03 using ceramic grinding media; or 3 % of the concentrate coarser than 10 microns was milled to smaller than 10 microns with 1kWh/t specific energy input. The product size distribution for the low speed vertical mill B was not as per the target compared to the horizontal and high speed vertical mill. The High speed vertical mill with SAZ grinding media had a SCBR of 0.04. The final product size distribution improved with SAZ grinding media compared to ceramic grinding media.

1. Introduction

The Tati Hydrometallurgical Demonstration plant, commissioned mid 2004, was constructed to demonstrate the Norilsk Process Technology's propriety Activox® process and to collect design information for the Tati Activox® Project (TAP). The plant selectively extracts base metal sulphides from the Phoenix nickel sulphide concentrates. The first step in the process is the reduction of the concentrate particles to 80 % passing 10 microns followed by a low temperature and pressure leach. Four of the leading ultra fine milling technologies in the world, Isa, Metso, Bradken and Deswik, were tested in the HDP plant. A detail description of the equipment tested is given in Table 1. The milling technology selection for the TAP project was based on the mill performance evaluations.

Table 1: Mill descriptions.

		High speed horizontal Stirred mill	Low speed vertical Stirred mill A	Low speed vertical Stirred mill B	High speed vertical Stirred mill
Volume	l	40	400	200	25
Stirring Mechanism		disks	pin	Pin	disk
Dimensions					
Length	mm	1000	1500	1000	1500
Diameter	mm	300	500	1000	350
Installed power	kW	32	30	18.5	30
Average Power density	kW/ m3	240	33	69	600
Tip speed	m/s	11.9 - 14	2.4	1.9	16
Product classification		2 mm screen *	Settling zone	2 mm screen	2 mm screen
Figure		1	2	3	4

*The pilot unit used product classification screen. Commercial units use centrifugal product classification

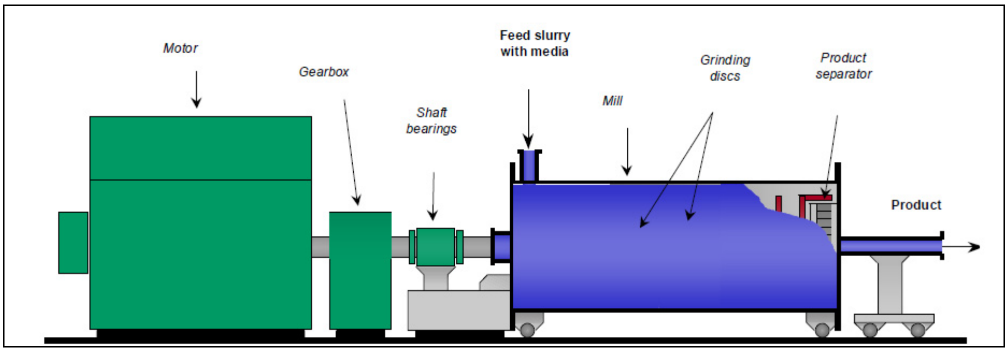

Figure 1: High speed horizontal stirred mill (2009).

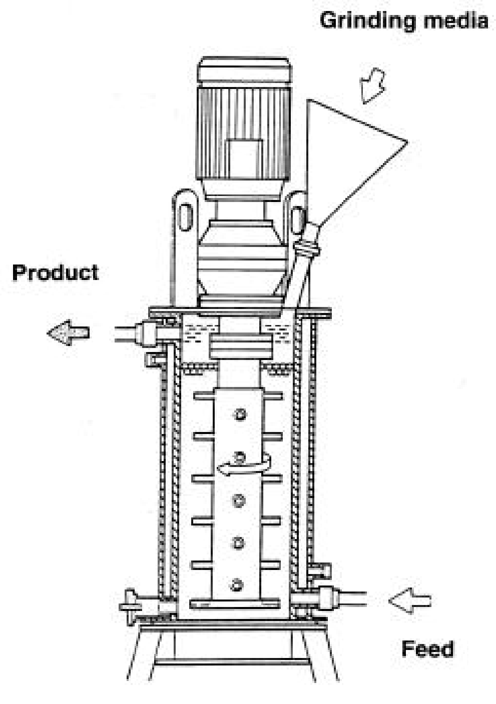

Figure 2: Low speed vertical stirred mill A (Weller & Gao, unknown)

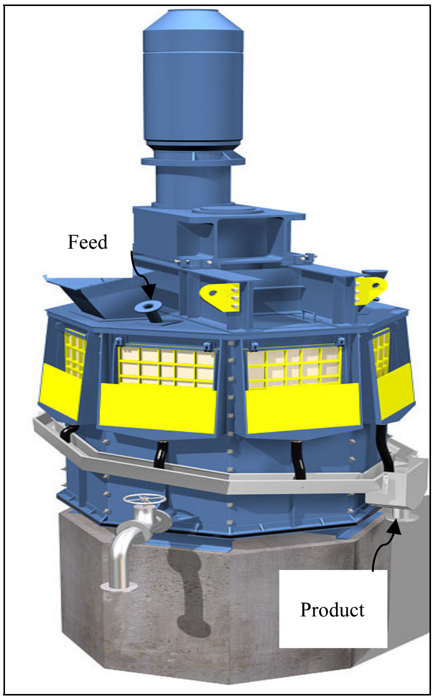

Figure 3: Low speed vertical stirred mill B (Mets, 2009).

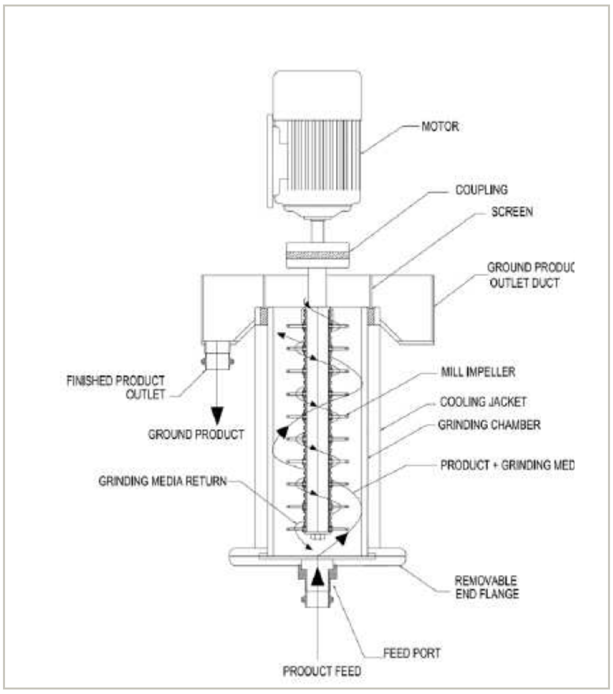

Figure 4: High speed vertical mill (Sverak, 2007)

This paper will outline the mill performance evaluation process used and results obtained from the evaluation. The paper also gives an overview of the selection criteria used for the TAP design.

1. Mill Performance Evaluation

1.1 Theory Used in the Evaluation

The direct role of energy expenditure in the comminution process was first appreciated by Von Rittinger and Kick in the 18th century and further developed by Bond in the nineteenth century. Bond argued that the 80 per cent passing sizes of the feed and product particles from a comminution process could be related to specific energy input [kWh/t] by expressions of the form given in Equation 2.1, Kelly (1995:115).

$$E = \left(\frac{C_{80}}{n-1}\right)\left(\frac{1}{d_P^{n-1}} - \frac{1}{d_F^{n-1}}\right), n \neq 1 \qquad (2.1)$$

with d_F and d_P the 80 per cent passing sizes of the feed and product respectively, and C_{80} a constant for a particular ore type. The most popular variant of these expressions is Bond's so-called third law of comminution given in Equation 2.2

$$E = W_I\left(\frac{10}{\sqrt{d_P}} - \frac{10}{\sqrt{d_F}}\right) \qquad (2.2)$$

with E the specific energy in kWh/t and the particle size in microns. The Bond equation commonly used today fails to provide complete size distribution information, especially at finer liberation sizes. Modern population balances express the product size distribution P_i (mass fraction less than a given mesh size d_i) of a crushed or milled product in terms of the cumulative size distribution of the feed F_i, the specific energy input, ξ (kWh/t), and the specific cumulative breakage rate function (SCBR) , K_i^E (Hinde, 2005:1). For continuously fed mills, it is assumed that the mill behaves as a number of fully mixed segments in series where each segment behaves as a fully mixed reactor given by Equation 2.3 (Hinde, 2005:1).

$$P_i = \frac{F_i + \xi K_i^E}{1 + \xi K_i^E} \qquad (2.3)$$

The specific cumulative breakage rate function K_i^E gives the fractional amount of material greater than size d_i in the feed that breaks to be below this size per unit specific energy input and can generally be approximated by a logarithmic polynomial function given by Equation 2.4.

$$K_i^E = \kappa \exp\left(a\ln(d_i) + b(\ln(d_i))^2 + c\ln(d_i))^3\right) \tag{2.4}$$

The parameters of the specific cumulative breakage rate function can be estimated directly from plant data using the net power consumed, feed and discharge size distributions. The benefit of the equation is that it also caters for changes in the feed size distribution and specific energy input.

The specific energy input was calculated as the net power consumed divided by the throughput (Equation 2.5).

$$\xi = \frac{P_w}{F} \tag{2.5}$$

with P_w the net power in kW and F the feedrate in t/h.

The temperature differential was calculated using Equation 2.6.

$$\Delta T = \frac{T_{out} - T_{in}}{\xi} \tag{2.7}$$

with T_{in} the inlet and T_{out} the outlet temperature in °C.

The Net power in kW was calculated as the total power consumed (during tests) minus the total power consumed (running the mills empty)

1.2 Mill Performance Testwork

The mills were operated in parallel during a milling testwork campaign with the same feed source to each mill. The feed rate, density (30 – 50 % solids) and type of grinding media (seasoned 1 - 5 mm sand sourced from the Eggo quarry, South Africa, CARBO LITE® 8/14 1 - 3 mm ceramics and 1 - 2 mm silica-alumina-zirconia (SAZ) grinding media) were varied. The following variables were measured during the milling campaigns: feed density, feed rate, grinding media type, inlet temperature, outlet temperature, net power consumption, and feed- and product particle size distributions. The mill evaluations were based on the specific cumulative breakage rate functions, product size distributions, mill maintainability, operability and run time.

2.3 Mill Performance Evaluation

2.3.1 Mill Comparison

The SCBR values of the four mills, to reduce the Phoenix concentrate to 80 % passing 10 microns, were calculated from the net energy inputs per mill, feed rates to the mills; and the feed- and product particles size distributions. The SCBR values for the four mills at different final product sizes are shown in Figure 5. For the results given in Figure 5the concentrate feed density was 45 % solids with ceramic grinding media in three of the four mills and silica-alumina-zirconia grinding media in the horizontal and High speed vertical mills.

For the horizontal ultra fine mill with ceramic grinding media, 2.4 % of the particles bigger than 10 microns were reduced to less than 10 microns using 1 kWh/t specific energy input, thus 33.3 kWh/t specific energy was required to mill Phoenix concentrate to 80 % passing 10 microns. Replacing the ceramic grinding media with SAZ grinding media in the horizontal mill almost doubled the SCBR value or halved the specific energy required to reduce Phoenix concentrate to 80 % passing 10 microns.

The low speed vertical mill A, with ceramic grinding media, required 66.7 kWh/t specific energy to reduce Phoenix concentrate to 80 % passing 10 microns (SCBR 0.012). The low speed vertical mill A only met the target final product size at concentrate feed densities of less than 40 % solids. The mill had no mechanical form of classification prior to the product exiting the mill and grinding media exit the mill with the final product at higher concentrate feed densities.

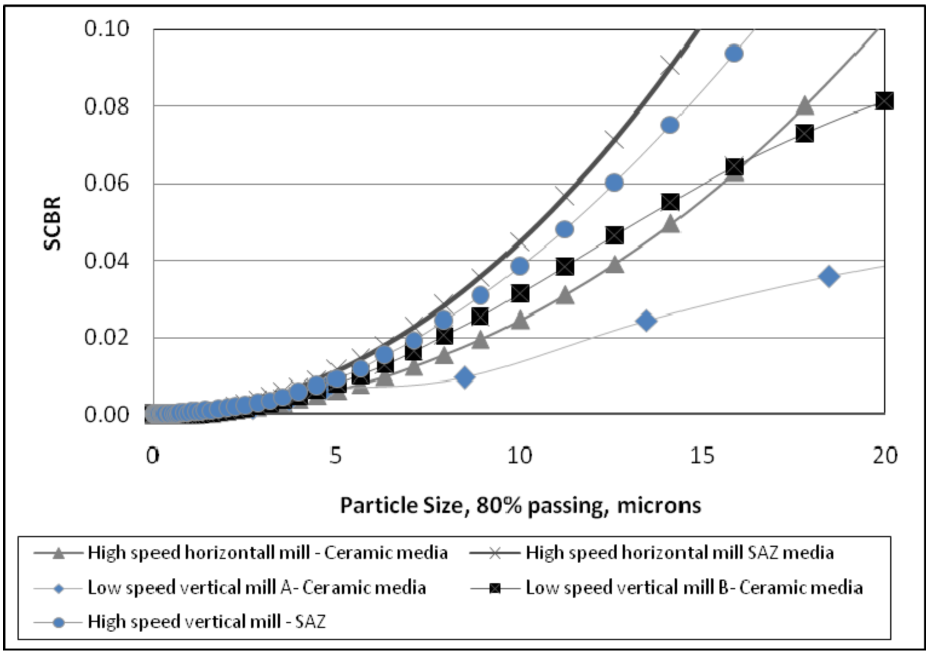

Figure 5: Specific cumulative breakage rates for four mills using ceramic and SAZ grinding media with a feed density of 45% solids.

For ceramic grinding media, the low speed vertical mill B had the highest SCBR at 0,03 and required 26.7 kWh/t specific energy to produce the target Phoenix concentrate product size. The High speed vertical mill, with SAZ grinding media, had a SCBR of 0.04 or 20 kWh/t specific energy was required to reduce the Phoenix concentrate to 80 % passing 10 microns.

For the two media types: the horizontal mill with SAZ grinding media and the low speed vertical mill B with ceramic grinding media gave the highest SCBR or lowest specific energy requirement to reduce the Phoenix concentrate to 80 % passing 10 micron.

2.3.2 Mill throughput based on the specific cumulative breakage rates

The maximum throughput for the high speed horizontal ultra fine mill with ceramic grinding media was 289 kg/hr based on 33.3 kWh/t specific energy, 9.6 kW net power and a product at 80 % passing 10 microns. Replacing the ceramic grinding media with SAZ grinding media in the horizontal mill almost doubled the SCBR value and increase the mill throughput to 562kg/hr.

The low speed vertical mill A, with ceramic grinding media, required 66.7 kWh/t specific energy with a maximum throughput of 189 kg/hr and 13.1kW net power. The maximum throughput for the low speed vertical mill B was 515kg/hr with ceramic grinding media. The High speed

vertical mill, with SAZ grinding media, had a maximum throughput of SCBR of 0.04 or 20 kWh/t specific energy was required to reduce the Phoenix concentrate to 80 % passing 10 microns.

For the two media types: the horizontal mill with SAZ grinding media and the low speed vertical mill B with ceramic grinding media gave the highest SCBR or lowest specific energy requirement to reduce the Phoenix concentrate to 80 % passing 10 micron.

2.3.3 Grinding Media Evaluation

The horizontal mill was used to compare the SCBR using seasoned sand, ceramic and SAZ grinding media. Seasoned sand and ceramic grinding media were also tested on the vertical mills. Figure 6 gives the SCRB values for the horizontal and the low speed vertical mill B at different product sizes with the three grinding media types.

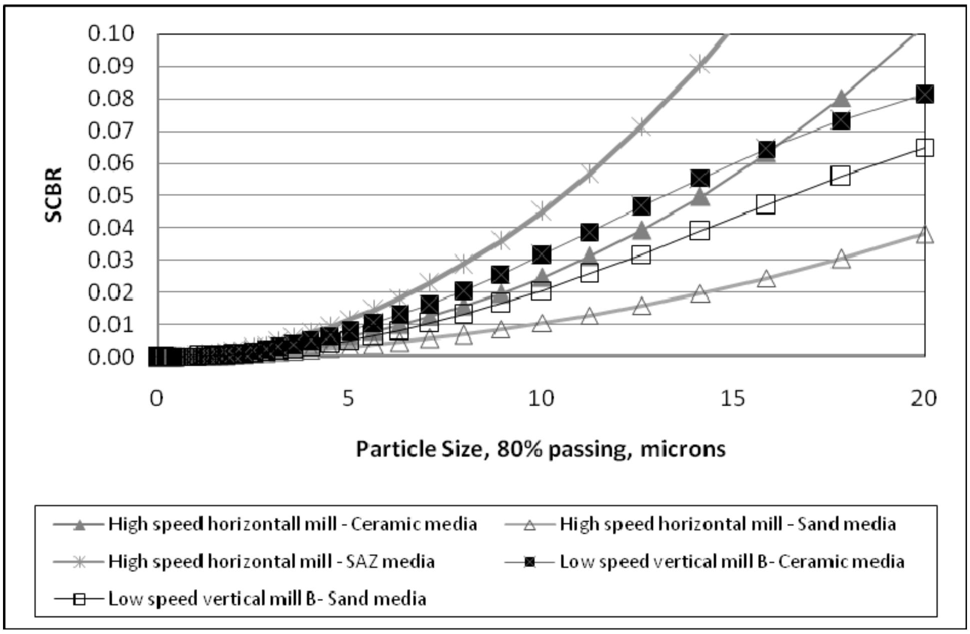

Figure 6: Specific cumulative breakage rates using seasoned sand, ceramic and SAZ grinding media.

The horizontal mill, with SAZ grinding media, had a SCBR of 0.045 at 10 microns compared to 0.025 with ceramic grinding media; and 0.011 with sand grinding media. Thus ceramic grinding media almost halved the vertical mill specific energy input to reduce Phoenix concentrate to 80 % passing 10 microns compared to sand grinding media Figure 6. The specific energy input is

further reduced by 44 % with SAZ grinding media. Using ceramic grinding media in the low speed vertical mill B increased the specific cumulative breakage rate from 0.02 to 0.03 at 10 microns (Figure 6), thus ceramic grinding media improve the milling efficiency with 50% for the low speed vertical mill B. Similar results were obtained for the low speed vertical mill A.

The grinding media consumptions, power and operating costs per ton of Phoenix concentrate is given in Table 2.

Table 2: Grinding media evaluation

Type	Size	Media SG	Media consumption	Specific energy	Power	Media	Operating Cost
	mm		kg/t feed	kWh/t	(R/kWh)	R/t	R/t
CARBO LITE® 8/14	1-3	2.71	0.5	32	0.19	12 699	19
Eggo Sand	1-5	2.5.-2.65	2.5	73	0.19	1 058	31
Silica-alumina-zirconia	1-2	3.9-4.1	0.2	18	0.19	371 900	74

Seasoned grinding media from previous pilot plant campaigns (continues operation for five weeks) were used as first fill in the mills. The media consumption were calculated based on the top up of new grinding media to maintain the power input into the mills over a five week continues operational pilot campaign.

The SAZ grinding media had the lowest media consumption (0.2 kg media per ton Phoenix concentrate feed) compared to 0.5 kg/t for ceramic and 2.5 kg/t for sand grinding media. The ceramic grinding media was the most economical grinding media for TAP, with a total operating cost (grinding media plus power) of R 19 per ton Phoenix concentrate. The operating cost using sand grinding media was 63 % higher (due to increased power consumptions) and 390 % higher using SAZ grinding media due to the high cost of SAZ media.

2.3.4 Final Product Size Distributions

The final product size distributions for the four mills, with SAZ grinding media in the High speed vertical mill and ceramic grinding media in the other mills, are shown in Figure 7. The

High speed vertical mill with the SAZ grinding media gave the best final product size distribution with the least amount of particles smaller than 5 microns and bigger than 15 microns. This result was expected considering that SAZ grinding media gave the highest SCBR to produce a final concentrate at 80 % passing 10 microns. Less energy was wasted to reduce particles to less than 5 microns. The detailed final product size distribution for the horizontal mill with SAZ grinding media was not available.

For ceramic grinding media, the horizontal mill gave the best final product size distribution (with the least amount of particles smaller than 5 microns and bigger than 15 microns) compared to the low speed vertical mills. The horizontal mill had 8 milling chambers in series with an internal classifier. The design prevented course material from short circuiting. The low speed vertical mill had the worst final product size distribution with the most amount of particles smaller than 5 microns and bigger than 15 microns. There was limited classification inside the mill and the grinding efficiency in the mill was severely affected by high concentrate feed densities.

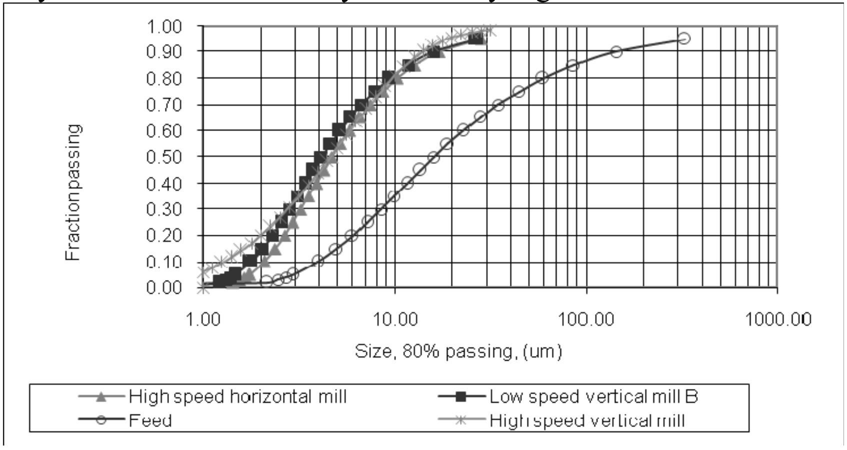

Figure 7: Final product size distributions for the four mills.

HDP testwork with mills in series gave improved final product size distributions with less material finer than 5 microns and coarser than 15 microns.

2.3.5 Mill Temperature Control

The product temperature inside the mill was critical for the material selection for the mills. The slurry solution was acidic (pH less than 3) and contained up to 5g/t chloride. The mills could be constructed from carbon steel, rubber lined components provided that the slurry temperature did not exceed 60°C. The only alternative suitable material above 60°C, for the process conditions, was Hastalloy(R) C276. The costs for Hastalloy(R) C276 components were orders of magnitude more compared to carbon steel, rubber lined components. The wear rate for the Hastalloy(R) C276 was not confirmed. Higher slurry product temperature also increased the recycle load around compartment one in the autoclaves due to increased energy inputs. The higher product temperatures were also an indication of increase milling inefficiencies.

The temperature differential inside the mills was calculated based on the specific energy input, mill input temperatures and output temperatures (Refer to Figure 8). The temperature differential for the horizontal mill was 0.68 °C per 1 kWh/t specific energy input. Based on Section 2.3.1, the mill product temperature will be (33.3x.68)+25=47.6 °C at 33 kWh/t specific energy input and an input temperature of 25 °C. The temperature differential for the low speed vertical mill B was 0.43 °C per 1 kWh/t specific energy input and the final product temperature will be 36.5 °C.

The sulphide concentrates are re-pulped using an acidic copper raffinate solution at 40 °C. The final product from the high speed horizontal mill would be at 62.7°C compared to the low speed vertical mill B product at 51.5°C. The higher product temperature, using high speed milling, increased the costs of material of construction for the circuit. The high tip speeds increase friction losses and energy inefficiency. The leach process is exothermic and the additional energy in the circuit (due to higher temperatures) have to be removed using a flash recycle system on the autoclaves.

The High speed vertical mill could not maintain the final product temperature below 60 °C without indirect cooling. The cooling water consumption was 1.8 m^3 per ton feed to the mill. None of the other mills required indirect cooling of the slurry and additional equipment will be required to recycle the cooling water.

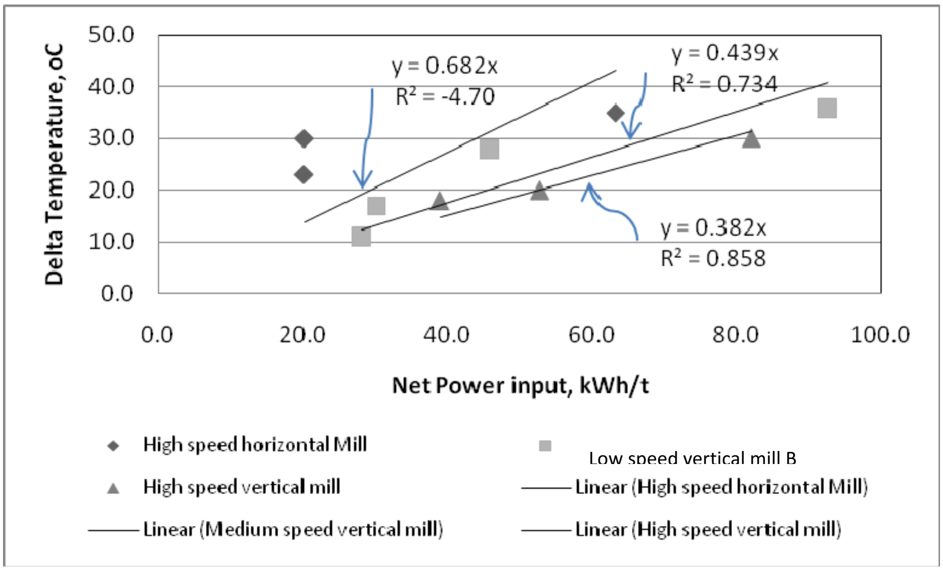

Figure 8: Temperature increase per specific energy input.

The low speed vertical mill B gave the lowest final product temperature at the same product target grind of 80% passing 10 microns. The energy efficiency of the mill was higher based on the SCRB value and the mill had more open area (increased evaporation losses) compared to the other mills.

2.3.6 Mechanical design evaluation

The mechanical design evaluation for the four mills was based on:

- Material of construction
- Extent of component exposure to process slurries
- Wear rates
- Maintenance requirements

The low speed vertical mills were constructed from carbon steel rubber lined and polyurethane materials. The mill components exposed to process slurries were simple to repair and/or replace on site. The horizontal mill and High speed vertical mills were constructed from stainless steel rubber lined, SAF2005 and polyurethane materials. Repair and replacement of components was more complex, more expensive and took longer compared to the low speed mills. For all four mills, the shell, rotating shaft with stirring mechanism and classification mechanisms were exposed to process slurries. The horizontal mill also had a mechanical seal exposed to the process slurries and the High speed vertical mill had cooling coils. The horizontal mill also operated under pressure compared to the vertical mills that were open to atmosphere.

The liner wear rates for the low speed vertical mills were low with flexibility to further improve the liner wear life and cost of replacement in the low speed vertical mill B. The average liner wear life was estimated at 16 mm per year and pin life at 3 replacements per year (the maximum liner wear rate was measured at 83 mm per year and was due to high (above 60°C) operating temperatures inside the mill. The horizontal mill had moderate liner wear rates with the highest wear rate on one side of the stirring mechanisms. The average liner wear life was estimated at 24 mm per year and disk life at 4 replacements per year. The high speed vertical mill had high wear rates on the lower parts of the stirring mechanism. The lower parts of the mechanism were replaced almost on a weekly basis during continuous operation. The low speed vertical mills were the simplest to repair with easily removable components. The horizontal and high speed vertical mill took longer to repair with more complex components.

2.3.7 Operability of the mills

The operability evaluation for the four mills was based on the following:

- Number of control variables
- Run time
- Operator feedback

The low speed vertical mill had the least number of control variables: feed flowrate, density, final product size and outlet temperature. The High speed vertical mill had the additional complication with the cooling system and the horizontal mill with the mechanical seal system and over pressure protection for the mill. The low speed vertical mill had the highest run time, followed by the low speed vertical mill A (additional downtime due to the blockage of the mill feed system). The other two mills had similar run times and the main reasons for downtimes were operator error, feed blockages and discharge screen blockages. A significant portion of the downtimes on the low speed and high speed vertical mills were due to blocked feed lines, discharge lines and / or product classification screens. One of the advantages of the horizontal mill is the use of centrifugal product classification inside of product classifications screens inside the mill.

It was relatively quick to drain the grinding media out of the vertical mills compared to the horizontal mill and the media addition was also more problematic in the horizontal mill due to the pressurized system. All four mills could be started under load, but the horizontal mill start up was the least affected by extended periods of downtime. The ultra fine milling circuit operators and maintenance personnel (total 14 people) were asked to rate the four mills based on how long it took them to learn how to operate the mills, ease of operation, ease of maintenance, amount of time they spend monitoring the mills during operations and what will be their preferred milling technology for the commercial plant. The bulk of the operators preferred the low speed vertical mill B. It should be noted that the horizontal and low speed vertical mill B was the longest in operation at the HDP.

The test results were based on Tati Nickel Mine concentrates.

3 Commercial Project Design

The low speed vertical mill B technology was selected for the TAP design based on the mill performance evaluation. Some of the benefits of the milling technology are:

- The mill had the lowest specific energy input to produce the desired final product size with ceramic grinding media.
- The final product size distributions were acceptable for the mills and could be improved by arranging the mills in series.
- The mill had the lower temperature rise per specific energy input.

- The mill was the simplest to maintain and operate.
- The mill can operate in acidic process liquor

Some of the disadvantages of the milling technology:

- The TAP design required 12 of the biggest mills offered by the vendor for the duty. The mills were arranged in series to improve the final product size distribution.
- The large number of mills increased the total maintenance time for the circuit, but improved the circuit availability as production would only be reduced by 8.3 % if one mill is taken offline for maintenance. The TAP design allowed for a complete standby mill to mitigate production losses during maintenance.
- The number of mills complicated the concentrate - and grinding media feed system feed rate control, support services design and control philosophy for the milling circuit.

CARBO LITE® 8/14 1 - 3 mm ceramics grinding media was selected for the TAP design based on the economical evaluation given in Table 2.3.1. The TAP design allowed for separate media feeding systems and flexibility to feed different size media to the primary and secondary milling bank.

5. References

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The Author

Gerhardus Johannes Nel, *Project Manager Hydrometallurgy*, Norilsk Nickel Africa

Gerhard Nel completed his B.Eng in Chemical Engineering in 2001 and started his career at Nkomati Mine as Engineer in Training in the Massive Sulphide Concentrator. He was later promoted to Metallurgist, Senior Metallurgist and Metallurgical Superintendent. In 2004 he

moved to Anglovaal Head Office as Project Engineer and worked on the Nkomati Activox® Project. He joined Tati Nickel Mine in 2004 as Senior Metallurgist on the Tati Activox® Hydrometallurgical Pilot plant where the Activox® hydrometallurgical technology was tested on various nickel sulphide concentrates from Tati, Nkomati and BCL. He was transferred in 2006 to Norilsk Nickel Africa Head Office (formerly LionOre) as Process Lead to work on the Bankable Feasibility Study for Tati commercial Activox® plant. The project was approved in June 2006 and execution started in October 2006. Norilsk Nickel Africa decided in June 2008 to suspend the TAP project. He has worked since on TAP close out, metallurgical consulting at Tati and Nkomati.