Evaluation of Abrasive Wear Measurement Devices of Mill Liners

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Abstract

Measurement of the liner wear in the mill of an ore dressing plant is one of the critical parameters in the context of mill downtime and production performance. The total downtime cost during measurement can be reduced by a significant fraction by using appropriate measurement devices. Due to the different quality attributes of a measuring device, e.g. the cost, accuracy, reliability and accessibility, it is necessary to select an appropriate device based on the specific needs of the industry. The main aim of this study is to determine a unified measure or quality index for the service quality of the measurement device across selected attributes. Each quality index will then correspond to the total predicted usability of the particular measurement method based on the industry needs. Furthermore, this study includes test of selected measurement methods and discusses the advantages and disadvantages for the same. It also proposes a new concept of an indirect measurement method to reduce the downtime during inspection.

Keywords

Mill Liners, Wear measurement, Mining, Mills, Measurement devices, Evaluation, Quality index

1. INTRODUCTION

Mills used in the mining industry and ore dressing plants are examples of major bottlenecks in the context of downtime concerning the production of metals (expert). The mills have to be stopped due to planned or unplanned repair, and these stoppages lead to heavy monetary losses due to production losses. Inside the mill, abrasive actions take place due to the comminution of ore, and therefore the inner part of the steel shell is protected by liners, made of rubber and metal or combinations of both. According to [1] and (expert), protection of the mill shell from the aggressive impacting and abrasive environment inside the mill is the primary purpose of mill liners. Furthermore, mill performance and liner wear are known to be correlated to the lifter bar geometry and size [2].

A case study has been carried out together with a mining company, M, and a mill liner manufacturing company, L. The study focuses on a particular a grinding mill. A detailed description of the grinding mill is given in section 2.2. The present study is a part of a research project whose goal is to find a cost-effective maintenance decision system for mills in ore dressing plants.

For the case study, according to a preliminary analysis of maintenance data, out of 6-8 mill stoppages, two stoppages are usually used for pure replacements of liners, and the remaining 4-6 stoppages are used for pure measurements of the dimensions of the liner (expert). However, this information has to be verified in a future study.

In general, abrasive wear occurs when hard, sharp particles or rough surfaces contact soft surfaces and remove material by shearing it from the softer surface [3]. This abrasive wear, caused by the ore and the milling process, will decrease the liner thickness gradually until the mill has to be stopped for replacement of the liners. Since the repair of the mill shell will be costly if the protecting liner is too thin, it is important to check the liner thickness periodically. This procedure is time-consuming and will contribute to the total downtime costs of the mill.

This study focuses on devices for measuring the abrasive wear of mill liners. The study is a survey of the existing and possible future methods for direct measurements and possible indirect methods for measurements of liner wear. The study uses a systematic approach to determine the quality index of liner wear and also suggests the most promising existing methods, both for use today and for possible use in the future. The output of this systematic approach can assist both suppliers and users of the measurement equipment concerning the optimum choice of measurement method.

The literature study and the opinion of the expert group in the present study indicate clearly that the existing methods today are all based on manual measurements inside the mill, and that the mill has to be stopped in order to make it possible for personnel to enter the mill and perform the measurements. Since the largest contribution to the downtime is due to the stopping and starting-up procedure of the mill, it would be extremely beneficial if it were possible to perform the measurements without stopping the mill (expert).

The liner replacement time should be based on an economic comparison of the mill efficiency and the total lining costs. The performance of the mill is defined as the throughput of the desired particle size coming out of the mill (expert). The economic break point occurs when the cost associated with the drop of monetary output due to wear of liners is equal to the cost of relining. The replacement policy used today is due to customary to replace the liners when they reach the critical thickness in order to avoid the damage of mill shell. However, theoretical methods like the Discrete Element Method (DEM) are widely used in order to predict the wear of the liner as a function of time, see for example [4,5].

2. LITERATURE SURVEY

This section provides a brief introduction to the mill studied, to facilitate a better understanding of the problem of liner wear. The section briefly presents the different types of existing methods for measuring liner wear. It also discusses methods for indirect measurement of liner wear which does not involve the mill having to be stopped.

2.1 A brief introduction to the mill

The mill studied in the present case study has a diameter of 5.7 m and a length of 5.5 m. The power of the electric motor is 1800 kW and the capacity is around 100 tons/hour (experts). Inside the mill, abrasive actions take place due to the comminution of ore, and therefore the inner part of the steel shell is protected by liners, made of rubber and metal or combinations of both. Figure 1 shows that there are 18 high lifters and 18 low lifters in the studied mill.

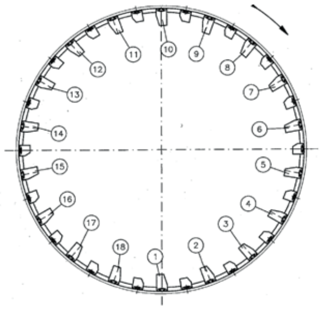

Figure 1 Layout of the liners

However according to [6], suggested that the advantages of a High/Low arrangement are lining cost savings and performance benefits as a profiled configuration is always maintained. On the other hand the main advantage of an equal height design is reduced downtime as a result of fewer stops for maintenance and for monitoring of wear rates.

2.2 Importance of measurement devices

The motivation of this study is due to the economic consideration of the mill liner replacement interval and inspection. The measurement time during inspections leads to a significant amount of downtime cost. But the additional cost due to process synchronization time also needs to be considered as significant amount of money is lost due to loss of metal at output end (experts). In the present context the process synchronization time is the time duration during when the material flow in the process becomes streamlined. Therefore a time efficient measurement device is required which can take measurement as quick as possible.

Another economical aspect related to the measurements is due to the replacement decision of mill liners. The current policy of the case study, the liner replacement decisions mainly depends on liner wear and risk of damaging the mill shell. Generally, the efficiency of the milling process depends on the behaviour of the load inside the mill, which governs the nature of ore presentation of breakage sites and subsequent transport. It is however well known

Choosen liner will lose efficiency due to wear [7]. For determining time based performance i.e. throughput capacity of the mill, a number of wear measurements are necessary during the life cycle of mill liners. The liner wear reading can be used to calculate available volume inside the mill as the inside mill volume for ore grinding is a function of volume of mill liners. The measurement of liners can also be used to estimate the grinding performance and the monetary output of the mill.

2.3 Terminology

This section briefly describes the important terms and which has been frequently used in the paper.

2.3.1 Expert group (personal communication, Feb 2008): In the present case study, the authors have obtained inputs and information regarding process and maintenance related to grinding mill after visiting and discussing with concerned expert groups of the mining and liner manufacturing industry. Detailed information such as work profile and experience in years is provided in table 1.

Tabel 1: Brief description of expertise of the expert group for the study

Current position at *Company (M)* & *Company (L)*	**Expert field & experience (year)**
Maintenance engineer (M)	Maintenance of stationary equipments in mining industry (15)
Maintenance engineer (M)	Maintenance of process systems & mobile systems (14)
Manager maintenance (M)	Maintenance in plant (15)
Senior metallurgist (M)	Autogenously comminution & ore dressing processing (20)
Technical expert (M)	Process control & measurement of mill parameters (38)
Manager R& TD (L)	Product development of mill liner (11)
General manager, R&TD (L)	Engineering , wear properties & application of mill liners (35)
Technical support engineer (L)	Applications & performance of mill liner (42)
Vice president mill lining (L)	Marketing & need finding for mill liner (39)
Service & Maintenance (L)	Measurements & maintenance of mill liner (10)

2.3.2 Demand limits: In this study the term "demand" is defined as the minimum requirements on the measurement device which must be fulfilled. Therefore, a measurement device will be selected for assessment only when it will fulfil the minimum requirement of each quality attributes. The investigation of measurement devices therefore considers the demand limits in order to achieve the threshold limits of all the quality attributes.

2.3.3 Quality Index (QI): In the study, the authors have introduced "quality index" which is defined as a quality measure for a particular measurement device. The quality index is unified quality measure of a device which considers together other quality attributes i.e. cost, reliability, accuracy and accessibility. It is also important to notice that an individual value of quality index doesn't provide any exact information about a specific measurement device. It provides an overall relative importance of measurement devices in the particular investigation.

2.3.4 Quality attributes:

Based on the detailed discussion with the experts of the companies of the case study, four suitable quality attributes are identified which are Cost, Reliability, Accuracy & Accessibility. For overall assessment of various measurement devices and determination of the corresponding quality index, the following quality attributes are briefly described.

The demand limits is decided on the recommendation of the expert group of the case study.

2.3.4.1 Cost

To calculate the total cost, the following cost elements are included in the cost structure, as shown by Figure 2. Since we are considering two types of measuring devices, firstly the one procured through purchase, and secondly the one procured as a service provided by a supplier, we must include the required cost elements to determine the overall cost.

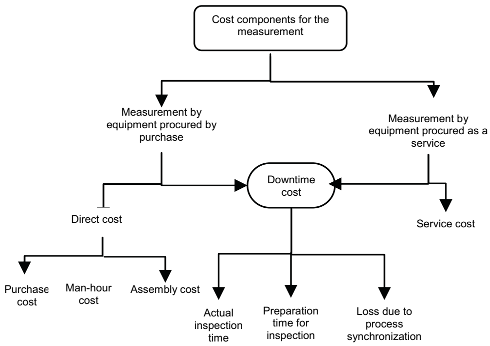

Figure 2: Overall cost structure, including the inspection cost breakdown structure, for the measuring equipment

In the present case study the total cost of equipment includes the downtime cost, purchase cost and service cost. The other cost components such as assembly cost and labour cost are included in downtime cost.
For the mill from the case study, the loss of production due to the downtime of the mill costs approximately *US$10,000/h* depending on the type of ore, the time used and the amount of ore based on the information from experts of the case study.

Demand limits: The demand limits for cost component is set to *US$ 14860* (including downtime cost) based on current practices of the case study. The reason for setting this demand limit is that the authors do not want to exclude measurement equipment from the study, which has promising properties concerning other important quality attributes. The cost of the equipment used in case study includes both purchasing cost & downtime cost during measurement. See table [5, 6]

2.3.4.2 Reliability

The equipment has to be reliable when it is required to perform measurement. In the study the reliability aspect of the equipment is defined as the percentage of the total measurement time when the measurement device is functional. This reliability dimension includes the fragility of the equipment.
Demand limits: The demand limit for reliability attribute is 95%. This implies that the equipment will be considered for investigation if it is 95% reliable when it is required for use. However, the measurement devices which is being used

2.3.4.3 Accuracy

The measurement accuracy is very critical in terms of taking replacement decision of mill liners. The objective of taking overall measurement of mill liners is not only important in terms of risk of damaging mill shell but also to determine the capacity which eventually leads to estimate the instantaneous mill revenue. The term accuracy is defined as the measurement accuracy of the respective measurement methods, in conditions without any harmful disturbances and without sensitivity to disturbances.

The measurement accuracy of rubber liners are defined in two categories spot measurement and overall measurement.

Spot measurement: Spot measurement is concerned of taking measurement at certain point on liners and which is important in order to estimate the risk of damaging mill shell. Spot measurement not only deals with the thickness at the spot but also the profile measurement of liners. A spot measurement tells us how much rubber material is left leading to estimation of remaining time until when the rubber liner needs to be replaced in order to avoid the risk of the damaging mill shell.

Overall measurement: Overall wear measurement of rubber liners corresponds to determine the inside capacity of the mill during measurement period which is used to determining mill production capacity. However some measurement equipments take only the spot measurement and based on these measurements wear of other liners and overall mill volume are estimated.

Demand limits: The risk of damaging mill shell the measurement accuracy concerning critical measuring spots on the liners should be +/- 5 mm. Also, for determining the exact inside mill volume the accuracy for overall measurement of mill liners should be +/-20 mm.

2.3.4.4 Accessibility

The accessibility aspect is defined as the ease of handling of the equipment and the ease of taking measurements. For direct measurement of the liner wear, the inspector has to go inside the mill, which is not possible due to anthropometric consideration whenever the device exceeds certain dimensions concerning both weight and volume. The key indicator for the assessment of the accessibility dimension can be defined in terms of the weight, volume and height of the device. The weight influences the ease of carrying the equipment and the volume affects how the inspector handles the space constraint while entering into the mill and carrying the equipment.

Demand limits: The measurement equipment will be qualified for investigation at least if it can be taken inside the mill for measurement. During the case study data and information have been collected from the expert group consisting of personnel from both the companies. A questionnaire was designed to determine the different quality dimensions and the priority vectors among all the dimensions.

2.4 Collection of measurement methods

This section briefly describes the characteristics of most of all existing measurement devices. It also describes the qualification criteria for each measurement method for investigation and the determination of quality index based on demand limits. For more clear understanding all measurement methods are divided in to three categories.

A. Methods selected for determining quality index based on demand limits
B. Methods developed but not used in real mills.
C. Experiments on the methods for indirect measurements concerning overall performance.

2.4 Category A: Methods selected for determining quality index based on demand limits

Methods under this category qualify the minimum demand limits of all quality attributes hence they are considered for this category.

2.4.1 Measurement method (M_1)

Method 1 is a direct measurement method based on the technique of a terrestrial 3D laser scanner and data processing algorithms to create a three-dimensional thickness map. It is an active imaging system that measures the range to an object in a series of uniform increments of arc, resulting in a three-dimensional map of the object. All the surfaces with a line-of-sight from the scanner are measured and stored as a three-dimensional coordinate file together with the reflectivity intensity, the latter being used to shade the scan cloud for a natural appearance. The range is typically measured by the time-to-flight of a laser pulse or an amplitude-modulated, continuous wave signal [8].

Terrestrial laser scanners are subject to systematic and random errors, but calibration systems for taking care of significant error sources that are typical of the conditions in a real mill have been developed by [8]. The complete system is today widely used at several plants [9]. See Figure 3.

Approximately five minutes is needed for pure measurement (entering the mill and exiting from the mill are not included) in order to measure all the liners [8] as per the information provided by supplier.

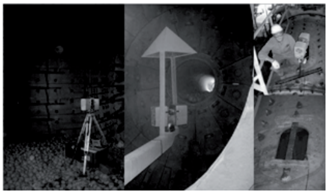

Figure 3 Terrestrial 3D laser scanners

2.4.2 Measurement method (M_2)

Method 2 is a mechanical wear reading device which consists of a frame and 5 rods and gives measure of the profile at the measurement point by means of manual inspections. This method is used today at the mill considered in the present study, see Figure 4. The device requires approximately 30 minutes for measuring 12 important liners in the mill. However, based on these measurements, it is possible to estimate the dimensions of the other liners. The accuracy of the instrument is +/- 5 mm and the disturbance sensitivity is equal to zero. Based on these measurements the accuracy of overall measurement is +/- 13 mm (expert). The thickness capacity covers more than 400 mm. The volume of the transporting box within the device is approximately 12 dm^3 and the weight is less than 2 kg.

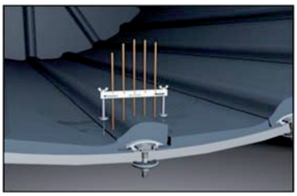

Figure 4 Mechanical wear reading device

The other added advantage of this method is due to moisture and temperature resistant. As the mill is shut down the inside surface (above the charge) is typically flushed with water to make inspection easier and from safety point of view to minimize the risk for falling objects.

2.4.3 Measurement method (M_3)

Method 3 consists of ultrasonic apparatus and probes. In resonance-type ultrasonic thickness equipment, a frequency-modulated continuous-wave signal is produced [10]. This provides a corresponding swept frequency of sound waves which are introduced into the part being measured. When the thickness of the part equals one half-wavelength, or multiples of half-wavelengths, standing-wave conditions or mechanical resonances occur. The frequency of the fundamental resonance, or the difference in frequency between two harmonic resonances, is determined by the instrument's electronics. However, the curved liner surfaces will make it difficult to capture thickness measurements that are orthogonal to the liner back, so the readings can easily be biased [8]. It is also claimed by [8] that this method typically only yields a few dozen point measurements at unreferenced locations, and it is virtually impossible to re-measure the same location during any subsequent survey, which causes repeatability problems and therefore survey campaign inaccuracies. However, in the present case study this method has been successfully tested for a rubber liner with a thickness of 400 mm with an accuracy of +/- 2 mm.

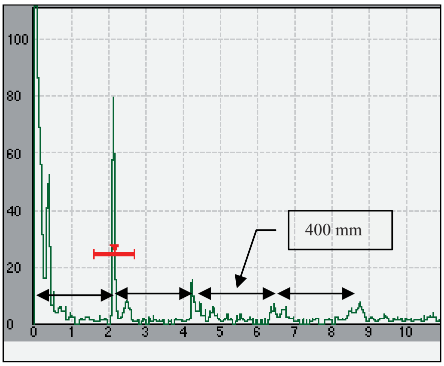

Figure 5: Response curve obtained from transducer

Figure 5 shows an example the output from the measurement device. The y axis is indicating a dimensionless voltage which is proportional to the detection level of the sound wave. The x-axis is indicating a dimensionless time because of the propagation time of the signal, which will be transformed to corresponding thickness of the measured object. In this particular case, the object was a piece of rubber of the same material as the liner and with a thickness of 200 mm. The horizontal mark on the high response peak is due to a manual choice of the signal to be detected. Since amplitude of this peak is large compared with the scatter it can be concluded that a thickness of 200 mm is no problem. Also rubber with a thickness of 400 mm has been successfully been measured.

2.4.4 Measurement method (M_4)

Method 4 consists of laser equipment with dimension of (15cm x 10cm x 10cm). It takes 2 dimensional measurements diametrical with in a range of 270 degree. The principle of the method is to obtain an obstacle free distance between measurement equipment and object. The measurement instrument has been successfully tested inside the mill when new liners are installed inside the mill. As shown figure 7 the wear measurement of all the liners in the range of 270 degree is taken all together. The measurement accuracy of the instrument was found to be +/- 5-10 mm.

Figure 6: *measurements made with a laser scanner and portable PC (Source: Damill AB)*

The overall measurement time for the whole mill was found to be about 85 minutes which includes entering into the mill and instrument set up time (25 min), measurement time (10 min) at a given location. Two measurements at same location at two occasions are needed, since the measurement principal is based on relative measurements.

The authors have collected information and specifications of this measurement instrument from the supplier of the measurement equipment.

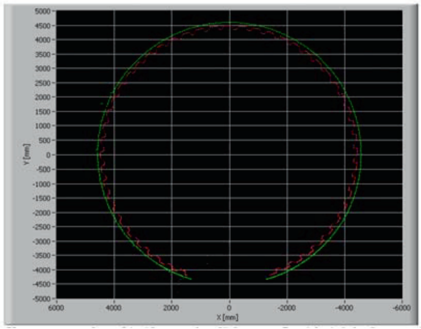

Figure 7: *Liner measurement on inside the secondary mill. The non lined by green dots also lined by the red dots (Source: Damill AB)*

Advantages:

1. The instrument is capable to obtain the liner thickness of three quarter of mill at the same location.
2. The method provides the profile of each liner and plate as well.

Disadvantage:

1. The thickness measurement is based on two relative measurements. Therefore it is not possible to obtain the liner thickness at the one time measurement
2. A small change in orientation of the instrument leads to error in wear measurement.
3. The measurement needs to be performed at exactly same location where previous measurement was taken.

2.5 Category B: Methods not used in real mill

Under this category a description has been given for measurement methods which have been tested in the laboratory but not used in real mill.

2.5.1 Measurement method (M_5) (existing as a prototype)

Method 5 is a direct measurement method, consisting of a thin-film sensor made up of a conductive element embedded in the liner to be measured [11]. The element comprises a first end positioned at a first distance from the wear surface, at least one conductive loop covering a wear portion positioned at a second distance from the wear surface proximate to the first end, and a circuit coupled to at least one element for determining a continuity of the conductive loop. According to [11] this can be practically solved by means of using a conductive trace, for example copper film, on a suitable substrate, resulting in a printed conductive circuit. The substrate can then be fastened to the liner by means of rolling it like a tube and gluing it into a suitable hole in the liner. In principle, this idea has been tested by company L for measurements of rubber thickness in pumps, but the authors could not find any real proof of any testing results in mills or any existing prototypes of this measurement device that would be usable for liners. The conclusion is that this particular concept has to be evaluated further by means of testing it in a real mill. See Figure 8.

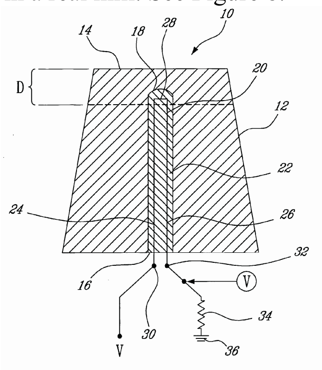

Figure 8 Measurement device inserted in liner [11]

Since this method is not used in the real mill and specific mill liners needs to be made to fit the device it provides the wear measurement of specific liner in which this circuit is embedded, hence overall measurement of all the liners will be predicted based on wear of the specific liner. Therefore this method is not considered for the investigation.

2.5.2 Measurement method (M_6) (not developed yet)

No. 6 is an indirect method based on the measurement of vibrations on the fastening bolt of lifters, using accelerometers and analyzing the measured data in the frequency domain with Fourier transforms. The system can typically consist of a 20 kHz accelerometer, data memory, an amplifier and a suitable electric battery. Indirect measurements of different parameters, such as unwanted collisions between ore and the liner because of too high angular velocity of the mill, the density of the pulp inside the mill, the amount of ore in the mill, the viscosity of the pulp etc, have been performed more or less successfully through measurements of vibrations on the mill shell or the fastening bolts for the liner, see for instance [12,13, 14]. Since the size of the liner most probably will affect the forces acting on the liner, it is here assumed that it should be possible to calibrate measured vibrations on the fastening bolt with real mechanical measurements of the liner wear and thus achieve a useable method for predicting the wear of the liner without stopping the mill. A prototype has been developed by Process IT Innovation at Luleå University of Technology, see Figure 9, which shows the prototype mounted on the fastening bolt of a lifter on the shell of a mill.

Figure 9 Device for measurement of vibrations

According to [15], liner wear is a very complex phenomenon, since it results from several complicated and simultaneous processes. The liner hardness and design, the size and hardness distribution of the charge, the mill speed etc will all affect the wear rate. An attempt to utilise vibration analysis to predict the amount of liner wear was reported in [15]. This study was performed on two 10.6 m-diameter SAG mills in India. The mills are fitted with 48 lifters and operated with a 25% filling with a 6-8% ball load and at a mill speed of 10.4 rpm. An accelerometer was latched to the surface of the gear box. Continuous vibration signals were obtained over a period of 3 days. The vibration data was analyzed in the frequency domain. This data was obtained for both of the mills, one of which was operating with newly installed liners, while the other one was using worn liners (more than half the estimated liner life having been used). Statistical analysis of data from these two mills showed that the intensities of the peaks were higher in the case of the newly lined mill compared to the worn-out mill. The conclusion from the above study is that measurement principle no. 5 is promising and should be developed further. But on other hand it is doubtful that the accuracy concerning wear of liners is sufficient.

However the most important usability of this method is measurement without stopping the mill which leads to a huge savings due to downtime. Since it is not fully developed yet therefore it is excluded from the group of quality index determination.

2.5.3 Measurement method (M_7) (not developed yet) [16], [17] is an electro magnetic method with open transformers placed on the rubber liner. If an AC electromagnetic coil is moved closer or further away from a conductive target, a current, commonly referred to as an eddy current, is induced in the target. The electromagnetic field induced within the target opposes and reduces the magnetic field in the sensing coil. This loss of field strength due to the eddy current is detected by an inductance bridge circuit and the resulting current output is converted to linear voltage which is proportional to the distance between the coil and the conductive target.

However, the ore is often more or less magnetic which probably will dramatically reduce the accuracy below the demand limits, thus this measurement principle is not further examined in the present study.

2.5.4. Measurement principle (M_8) [11], [17] is based on the principle of X-Ray thickness gauges. Thickness can be determined by measuring the amount of X-ray energy absorbed by a material as it passes between an emitter and a receiver. An X-ray sensor uses the same principle as a nuclear sensor, i.e. a radiation source and a radiation detector arranged in either a transmission or backscatter configuration. In the case of an X-ray source, however, no dangerous radioisotope is used. Instead, the measuring radiation is generated electrically from an X-ray tube.

However, the present method can provide x-ray devices which are capable of measuring thin film rubber sheet with a thickness far less than 1 mm which is far less than the demand 400 mm. therefore it is excluded from the group of quality index determination.

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2.5.5 Measurement principle (M_9) [17] is based on infrared sensors. Normally the method is associated with temperature measurements, but can also be used for measuring thin layers. When measuring thin layers, this principle is based on absorption of infrared radiation into the material whose thickness is to be measured. The absorption is non-linear dependent on the thickness. The principle can be configured with the infrared source and detector on the same side of the product to be measured.

Infrared sensors are extremely sensitive to compositional variations in the product to be measured [17]. This in combination with that the present authors not have found any supplier that can provide infrared devices which are capable of measuring rubber of significant thickness. The other properties are not examined in the present study since the thickness demands not are fulfilled.

Other possible methods, close to No 10, can eventually be based on using cameras with traditional optics. By using a number of cameras it will be theoretical possible to take pictures of the liners at several angles and occasions and then achieve the wear by means of subtracting the photos form each other. This technique can eventually also being solved by means of using infra red cameras by subtracting temperature pictures from each other, but then the accuracy will be drastically reduced since infrared temperature cameras not are optimized for geometric accuracy.

2.6 Category C: Experiments on the methods for indirect measurements

Under this category a brief description is given for some of the proposed methods which can be used for indirect measurements. The main objective of indirect measurements is to reduce the downtime cost during the inspection as the mill not needs to be stopped during the measurements.
Also the charge dynamics in tumbling mills can be predicted by means of vibration signature technique [18, 19] therefore the present authors also address this method to be of eventual use in order to predict the abrasive wear of the rubber lifters.

2.6.1 Measurement method (M_{10}) (not developed yet): An experiment was carried out to develop an indirect method based on power signature diagnosis. The power consumption and angular velocity of the mill will increase or decrease, if there are any changes in the mechanical process. This small change (typically less than 0.00001%) is measured by means of current and voltage sensors, and collected by measurement computers with A/D converters. Next step was to filter the collected data and analyzing it with respect to time and frequencies. Today, the method is in use for measurement of damages in gears, fans and bearings, etc. These signals can then be compared with the actual dimensions of the liners, resulting in an indirect measurement method for predicting the wear of liners.

The obtained signals from the frequency converter, aimed for controlling the speed of the electric motor of the mill. These signals can be transported to a computer via fibre optical cable for analyzing within excel sheet. Both the variation in speed and power supply of the electric motor can be obtained. The present case study this technique has been tested. The power was measured within +/- 0.00001 % and the angular speed of the electric motor was measured within +/- 0.0001 rpm. The time difference between each measurement is approximately 0.03seconds and the accuracy of the time measurements is +/-0.0000001 s.

For a typical case of average angular velocity of the electric motor, 600.8 rpm, this corresponds to 8.380 rpm of the mill (gear ratio of the gearbox is equal to 5.647 and 23 gear teeth on the pinion gear of the mill and 292 teeth on the ring gear of the mill). This corresponds to 7.16 seconds/revolution on the mill. With 18 large lifters and 18 small lifters this corresponds to 0.398 seconds between each contact between the large lifter and the charge and 0.199 seconds between the small and the large lifters. Random fall of the ore in the mill will cause scatter in the measurement curves but in spite of this, the test results clearly indicate peaks when both the small and the large lifters are approaching the charge, see figure 10 and 11.

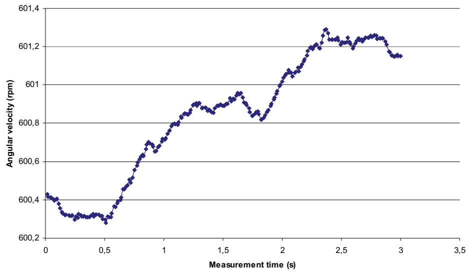

Figure 10 Angular velocity of electric motor as a function of measured time

Figure 10 shows a small variation of the angular velocity which coincides with the time between each contact between the large lifters and the charge. A reasonable explanation is that when the lifters hit the charge, the speed of the mill will be somewhat decreased because of the extra torque needed to move the charge which is hitting the lifter. The main increase of the angular velocity is because of the speed controlling of the mill due to the processing. However, as showed in Figure 10, the influence of the lifters on the speed of the mill is not very significant since it is not possible to recognize the small influence of the small lifters.

By means of studying the influence of the lifters on the power supply to the mill, more significant results was achieved, see Figure 11

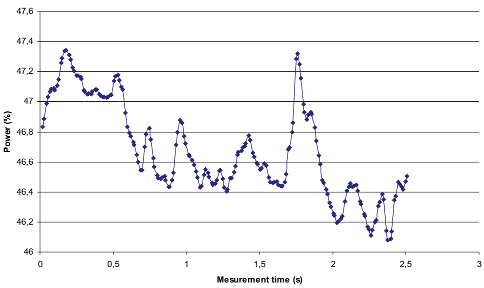

Figure 11 Percent of full power of the electric motor as a function of time

Figure 11 shows a significant dependence between the power and the time when the lifters approach the charge. There is a clear possibility that the large peaks corresponds the large lifters and the small peaks corresponds to the small lifters. The height of the lifters will decrease as a function of time due to wear and this will probably affect the amplitude of the peaks. By means of calibrating the average amplitudes measured with this method, with real measured values of the height of the lifters, this can be a useable method for estimating the average size of the liners without stopping the mill. This information can be of use concerning remaining life time of the liners and also for optimum process control of the mill.

The effect of the lifter wear cycle on the charge behaviour and power draw wear on a ball mill was also studied by means of using discrete element methods, DEM, [20]. He found that at sub-critical speeds, the wear induces increases in lifter face angle and reductions in lifter height lead to steadily decreasing amounts of cataracting material thrown shorter distances and higher toe positions. At low speeds, the steepest lifters produce the highest power draw. With increasing mill speed, the highest power draw is expected in the first half of the lifter life and then declines slowly. At higher speeds, the power draw initially increases as the lifters wear and then decreases. The face angle producing the highest power draw decreases steadily with increasing mill speed.

Measurement method No. (not developed yet)

No. 12 (Wijaya, 2009) is an indirect method based on multivariate data analysis of measured process parameter. This approach is based on the statistical principle of multivariate statistics that deal with the observation and analysis of more than one statistical variable at a time [21]. In this study, the technique is used to reveal the internal structure of the data in a way which best explains the variance in the data and their effect on the response of interest.

As mill operation is governed by Programmable Logic Controller (PLC) that adjusts all process parameters to keep a constant torque, torque can be expressed as a function of process parameters and volume inside the mill as follow,

$$\tau = f(P, \omega, w, mf, wf, \delta) \bullet f(V)$$

where τ is torque, P is power consumption, ω is angular velocity, w is total weight of mill, mf is mass flow, δ is density of ore, and V is volume inside the mill. Since torque is maintained constant, expression is altered as

$$f(P, \omega, w, mf, wf, \delta) \approx k / f(V)$$

and can be rewritten as

$$f(P, \omega, w, mf, wf, \delta) \approx g(V)$$

This relation indicates that volume inside the mill could possibly be predicted by taking into account of the variation of other process parameter. Due to the fact that process parameters correlated each other, approach is developed by utilizing multivariate data analysis [22]. Preliminary study shows that different mine has different ore properties (e.g. density) and from Partial Least Squares (PLS) and Principle Component Analysis (PCA), it indicates that different type of ore has a great contribution to the model, see figure 12.

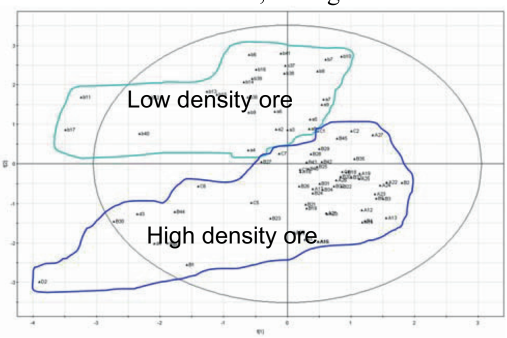

Figure 12 Scores plot t_1 vs t_2 for PLS model of Torque

Thus Principle Component Regression (PCR) model is developed for each type of ore. In case of type of ore with low density (type I), model can accurately predict the change of volume inside the mill, see figure 12. It gives MAPE (Mean Absolute Percentage Error) value of less than 5%. However model can not perform a good prediction for type of ore with high density (type II). Possible explanation for this behaviour is due to the fact that variation of density within the type II ore is quite big.

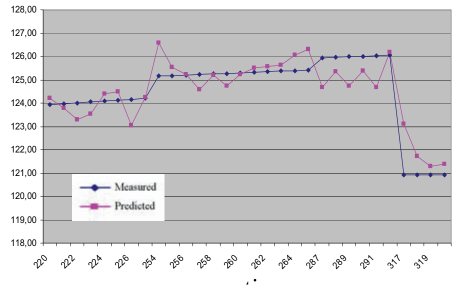

Figure 13 Comparison of measured volume and predicted volume

To overcome the limitation of the model, other parameters that can explain variation within type of ore and can represent variation of density in different way, such as retention time, fraction of ore as a function of volume, shape of ore, etc. should be considered.

3. EVALUATION APPROACH

A systematic approach [23] is used as a basis in order to determine the quality index. The key objective of using the approach is to incorporate the quantitative and qualitative inputs together taking internal weightings of the quality attributes based on its importance into account. The qualitative inputs from the expert group are used for giving weights to qualitative attributes such as cost, reliability, accuracy and accessibility. The demand limits for each quality attributes are also determined from the expert group. The quantitative inputs i.e. cost, reliability and accuracy were achieved by means of a combination of the opinion from expert group and experiments by the authors used to make the evaluation more robust.

3.1 Selection of measurement equipments for determining quality index using demand limits

Since each measurement equipment needs to fulfil the minimum requirements of each quality attributes, therefore a screening is done based on these quality attributes. The screening process of demand limits is shown in figure 14. As described earlier some of the methods are not selected due to feasibility criteria as they are not used in the real mills. A selection process mentioned in the figure deals with the measurement equipments which are existing and usable in real mills.

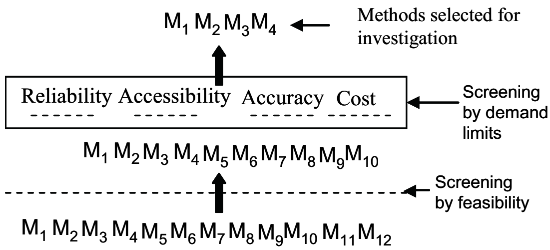

Figure14: Methods selection process for quality index (QI) quality index determination

3.2 Qualitative comparison of different measurement devices

A survey is designed in order to collect data for determining the importance of quality attributes of a measurement device for both supplier (liner manufacturer) and user (mining industry) perspective. The survey was conducted and among the experts in the field of mill process and characteristics of rubber liners and researchers at operation and maintenance division, Luleå University of Technology.

A pairwise comparison matrix [24] has been developed among the quality attributes and the results have been obtained which are given in Table 2. An example of pairwise comparison between O_i and O_j is shown in table 1. For comparison between two attributes a preference ratio are used (ratio w_i/w_j indicates how much attribute i is preferred to relative to attribute j);

– $w_{ij} = 1$ if the two objectives (O_i, O_j) are equal in importance
– $w_{ij} = 3$ if O_i is more important than O_j

– w_{ij} = 5 if O_i is very much important than O_j

Table2: A sample of pairwise comparison between quality dimensions

Attribute	Very Imp (5)	More Imp (3)	Equal (1)	more Imp (3)	Very Imp (5)	Attribute
O_i	☐	☐	☐	☐	☒	O_j

The information for qualitative comparison has been provided by 5 experts from company M. Relative importance of quality attributes was calculated based on pairwise comparison. See table 3

Table 3: Pairwise comparison for four quality attributes

	W_c	W_R	W_{Au}	W_{Ac}		Relative weight
Cost (W_c)	1	3	1	5		0,375
Reliability (W_R)	1/3	1	1/5	1/3	➔	0,082
Accuracy (W_{Au})	1	5	1	5		0,417
Accessibility (W_{Ac})	1/5	3	1/5	1		0,125

3.3 Linear interpolation: A linear interpolation method [25] was used for giving grades to various measurement methods for different attributes. The limits for the linear interpolation were set based on the minimum needs or demand limits provided by the expert group.

The main reason of selecting linear scale was due to unavailability of required data to obtain the precise correlation function.

The grade scale was defined as in the table below. The minimum grade '1' is given to a method when it just fulfils the minimum requirement and the highest grade'5' is given if it is theoretically perfect. See table 4

Table 4: Theoretical definition of grades

Grade	Definition
1	Identical with the demand
2	Slightly better than the demand
3	Above the demand
4	Certainly above the demand
5	Theoretically perfect

Table 5: Liner interpolation for quality dimensions

Grade	Total Cost ($) per measurement	Relia--bility (%)	Acc-uracy (+/-mm)	Accessibility
1	14860	95.00	20	Just possible to carry into the mill
2	11145	96.25	15	-
3	7430	97.50	10	Possible to carry into the mill without significant problems
4	3715	98.75	5	-
5	0	100	0	Possible to carry as hand luggage

3.4 Total cost calculation: The cost calculation for each method is calculated according to the cost structure mentioned in figure 2. As described earlier the major cost component of the equipment is due to downtime cost. Thus a breakdown of downtime and cost calculation is shown in table 6.

Table 6: Down time cost calculation per measurement

Methods	Down time (Minutes)		Total downtime cost ($)
	Prepa-ration	Measurement	Total time (hr) × downtime cost ($/hr)
1	30	5	((30+5)/60) × 10000 = 5833
2	30	50	((30+50)/60) × 10000 = 13333
3	30	25	((30+25)/60) × 10000 = 9166
4	30	60	((30+60)/60) × 10000 = 15000

Preparation time represents the time taken to stop the mill, entering into the mill and come out from the mill. Measurement time represents the actual time during the measurement.

Since the service cost for method M_1 is not known therefore a variable (X) is taken as a service cost.

Table 7: Total cost calculation for each measurement instruments

Methods	Downtime cost ($)	Equipment cost ($)	Service cost ($)	Total cost ($)
1	5833		X	5833+X
2	13333	20	-	13353
3	9166	236	-	9402
4	15000	694	-	15694

In this investigation the equipment cost is distributed over a period of ten years. Since the company policy is assuming that the life time of all measurement equipment is to be a period of 10 years. Therefore, in order to incorporate the equipment cost, these costs are normalized over 10 year period. On an average in a year 5 inspections are needed, hence in 10 years the total number of inspection will be 50. The equipment cost per measurement is calculated in table 7.

Cost per measurement = (Equipment cost/50)

The value of other quality attributes is determined from expert opinion and supplier. The value of reliability and accuracy attributes are obtained from the equipment suppliers. Since, accessibility is a subjective attribute therefore after using expert opinion and discussion among researchers in the operation and maintenance division it is categorized into three categories as shown in table 5. An average values of mentioned quality attributes each method are mentioned in table 8. Thereafter by using table 5 and liner interpolation the values of interpolated grades of each quality attributes for corresponding methods are determined.

Table 8: Interpolated grades for different quality dimensions

Meth-od	**Cost** ($)		**Reliability** (%)		**Accu-racy** (+/- mm)		**Accessibility**
M	*AV* *	IG_c **	*AV*	IG_R	*AV*	IG_{Au}	IG_{Ac}
1	5833+X	-	99	4.2	1	4.8	1
2	13353	1.59	100	5	13	2.4	5
3	9402	2.61	100	5	20	1	5
4	15694	1	99	4.2	5	4	3

** AV: Average value*

***IG: Interpolated grade value*

C: Cost, R: Reliability, Au: Accuracy, Ac: Accessibility

3.5 Quality index determination

The quality index was determined by using Table 7 and 8. The formula for the quality index is defined as

$$QI = IG_C \times W_C + IG_R \times W_R + IG_{Au} \times W_{Au} + IG_{Ac} \times W_{Ac}$$

Table 9: Liner interpolation for quality dimensions

Met-hods (M)		**Quality Index**
1	$f(X)$ $+4.2\times 0.082$ $+4.8\times 0.417+1\times 0.125$	**f(X)+2.47**
2	$1.59\times 0.375+5\times 0.082$ $+2.4\times 0.417+5\times 0.125$	= **2.63**
3	$2.61\times 0.375+5\times 0.082$ $+1\times 0.417+5\times 0.125$	**= 2.48**
4	$1\times 0.375+5\times 0.082$ $+4\times 0.417+3\times 0.125$	**= 2.82**

*

An affordable service cost for the industry for 3d laser equipment is estimated by putting quality index of method 1 to the quality index of method 4.

From table (6) the total cost of method 1 is the function of service cost (X). The value of f(X) is determined by using liner interpolation for the cost parameter.

The cost component is linearly interpolated between (1, 14860) and (5, 0) i.e. (grade, cost). The grade for cost element for the 3D laser equipment is then estimated from the liner interpolation.

$$f(X) = ((13575 - X)/3715) \times 0.414$$

If we equate the quality index of 3D laser equipment equal to the highest value of quality index as given in table 6 then the value of X will be

$f(X) + 2.47 = 2.82$
$((13575 - X)/3715) \times 0.414 + 2.47 = 2.82$

$\Rightarrow X = \text{USD } 10434$

When only down time cost is considered then the affordable service cost for each measurement will be
$5000 + X = 14860$

$\Rightarrow X = \text{USD } 9860$

Table 9 shows that method no. 4 is the most preferable measurement method since it has the highest quality index among the three methods investigated for quality index determination.

On the other hand, the service cost, Today the mining company, M, is using method no. 2, and if they prefer to change to method no. 1, as this method has better measurement accuracy (see Table 8), then the maximum acceptable service cost for method no. 1 can be estimated as US $ 9860 per measurement provided only the cost aspect is considered. On other hand if all quality dimensions are considered together the maximum acceptable service cost will be US $ 10434 per measurement. However these are the maximum additional cost that company can bear for getting the similar monetary benefits what they are currently getting. Therefore, for taking a decision of using service based method a negotiation should to be carried out between company using the service and service provider.

The limitations of the present study are as follows:

- Liner interpolation was carried out for each quality dimension for defining grades.
- The liner interpolation for the different quality dimensions was defined between two boundaries. The first boundary limit was defined using theoretical perfect values and the other limit was defined using the minimum requirement for each quality dimension provided by the companies involved in the project [23].
- The grade for the accessibility dimension was defined as per an expert opinion based on the weight, volume and height of the equipment.
- It is assumed that grades and weighting can be multiplied.
- The delay due to unavailability of equipment is not considered.

The most important advantages and disadvantages of the analyzed measurement principles are summarized in Table 10.

Table 10: Advantages and Disadvantages of measurement devices

Category	Method No.	Advantages	Disadvantages
Method selected for determining QI	1	• The only existing method which provides a complete profile based on all the measures of the liners • Only 5 minutes of pure measurement time for a whole mill, useful for overall mill volume calculation	• Available only as a service and the service cost is not known to the authors • The mill needs to be stopped. • The accuracy is unknown in humid conditions.
Method selected for determining QI	2	• Reliable method, very often used today. • Delivers the complete profile of the liner at the measurement points • No problem under moisture and temperature inside the mill	• The mill needs to be stopped. • Relatively long measurement time compared with method no. 1 • Does not provide good accuracy in complete liner volume calculation
Method selected for determining QI	3	• Relatively faster and more accurate for spot measurement than method 2	• The mill needs to be stopped. • Does not provide the complete profile
Method selected for determining QI	4	• Provide complete profile of all liners and rubber plate at measurement location	• Relative measurement i.e. two measurements are required to know the liner thickness • Imperfect orientation of the instrument leads to inaccuracy
Method developed as prototype but not used in real mill	5	• The mill does not need to be stopped, provided that electronics and software have been developed to make it possible to deliver data.	• The sensor will be destroyed when the liner is worn out. • Sensitive to mechanical damage • The device must be fastened to the liner before assembly in the mill. • Does not provide complete profile of the liner
Method developed as prototype but not used in real mill	6	• The mill does not need to be stopped, provided that electronics and software have been developed to make it possible to deliver data.	• No existing fully-developed product on the market • Does not provide a complete profile
Method developed as prototype but not used in real mill	7	• The mill is not needed to be stopped provided that electronics and software are developed in order to make it possible to deliver data.	• Not possible to use since magnetic properties of the ore will reduce the accuracy significantly
Method developed as prototype but not used in real mill	8	• Not investigated in the present study	• Can not measure thickness more than 1 mm hence not fulfilling the demand limits for thickness of 400 mm
Method developed as prototype but not used in real mill	9	--do--	--do--
Method developed as prototype but not used in real mill	10	--do--	• Not possible due to accuracy which is significantly affected by variation of compositional variations in the liner
Indirect Measurement Methods	11	• Continuous measurement without stopping the mill which can be used to determine economic performance of mill and cost effective decision making for liner replacement • The measurement data can eventually be used for continuously optimizing the process	• Not fully-developed • Provides only approximate value of overall wear of liners • Does not provide full profile of liner wear
Indirect Measurement Methods	12	--do--	--do--

4. CONCLUSIONS

An overall evaluation process for abrasive measurement devices is described in the paper. Various types of data were collected from the industries of the case study and corresponding results have been obtained from the evaluation method. Based on overall study, following conclusions have been made.

- A systematic evaluation method is proposed for evaluating the optimum choice of equipment for measuring the wear of liners. The output from the method is highly dependent on the values of the input variables. Therefore, a careful assessment is needed while doing objective analysis.
- Quality index of investigated measurement devices gives an overall idea of equipment effectiveness with respect to all quality attributes described in the paper.
- Significant economic savings can be achieved if suitable measurement devices are developed so that measurements of the liners can be performed without stopping the mill.
- Concerning complete measurements of all the dimensions of the liner, the useable method today is laser scanning.
- In this study ultrasonic technique is identified as a promising method capable of measuring rubber liner with a thickness of 400 mm. Due to fast measurement process it is more preferable than a mechanical device if only the height of the liner are of interest.
- Power signature diagnosis is identified as a promising method which should be developed further, since the mill does not need to be stopped and the signals can be used for optimizing the process and for checking the average condition of the liners.
- A possible future setup for measuring the liners is the use of signature power diagnosis for the information concerning the average size of the liners and for process control in combination with ultrasonic devices equipped with wireless transmitters sending data for the measurement of critical spots.

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