INTEGRATED APPROACH TO MONITORING AND CONTROL OF MINERAL GRINDING PROCESSES

Remes A.[1], Karesvuori, J.[2], Pekkarinen, H. [3], Jämsä-Jounela, S-L.[1]

1) Helsinki University of Technology
Department of Chemical Technology
Laboratory of Process Control and Automation
P.O.Box 6100, FIN-02015 HUT, Finland
E-mail: Sirkka-l@hut.fi
2) Outokumpu Technology, P.O.Box 84, FIN-02201 Espoo, Finland
3) Outokumpu Chrome, Kemi Mine P.O.Box 172, FIN-94101 Kemi, Finland

Abstract: To enhance the operation of mineral grinding processes, a greater number of monitoring services and control schemes are nowadays being offered by the equipment manufacturers. In this paper an integrated approach to grinding process monitoring and control is formulated and the components of the integrated automation for typical grinding processes are proposed. Furthermore, the benefits of the process monitoring services are studied on the basis of a specific case study - the Outokumpu Chrome Kemi concentrator. Finally, the results are discussed and a new control scheme is outlined. *Copyright © 2006 IFAC*

Keywords: mineral grinding, particle size analysis, process monitoring, extended product, process control, chromite concentration, gravity separation.

1. INTRODUCTION

In order to enhance the performance of mineral processing equipment, a greater number of intelligent functionalities are being integrated into the equipment. The equipment suppliers can provide advanced operating, maintenance and monitoring methods by adding these functionalities. The concept integrates the equipment, instrumentation and service resources in order to perform the defined operations. Typically, the main parts of the intelligent grinding concept are the process monitoring and control modules.

In the past, several monitoring methods have been developed for the grinding circuit, including monitoring of the feed, product and the mill operating conditions. Mill charge position monitoring has recently gained interest. In this area Valderrama *et al.* (2000), Campbell *et al.* (2001) and Pax (2001) applied signal processing methods to interpret the mill surface vibrations. There are three main industrial measurement techniques for performing the particle size analysis of mill product: mechanical distance detection, ultrasonic attenuation and laser diffraction (Napier-Munn *et al.*, 1999). In addition, the particle size has also been monitored using model-based soft-sensors, see (Casali *et al.*, 1998) and (del Villar *et al.*, 1996). Recently, the main interest in the monitoring of mill feed has centered on the ore type determination, see (Jämsä-Jounela *et al.*, 1998), and on vision-based ore size and texture type determination (Guyot et al., 2004).

A number of authors have presented control strategies for the grinding circuits. Jämsä-Jounela (1990) applied the inverse Nyquist array method in multivariable grinding control. Niemi *et al.* (1997) simulated an industrial process using model predictive control for particle size and slurry density. In addition, a control system based on the mill charge and the particle size on-line estimation in LKAB's Kiruna iron ore concentrator is presented in Herbst *et al.* (1996). Recently, Yianatos *et al.* (2002) showed significant improvements in circuit throughput using particle size rule based control. Laboratory mill grinding simulations have also been carried out in order to compare the PI and MPC control schemes (Ramasasy *et al.*, 2005). Elsewhere, Radhakrishnan *et al.* (1999) applied the ball mill and hydrocyclone models in order to develop a model-based optimizing control. Fuzzy logic has been applied in the control of SAG mill feed size variation in the Ok Tedi Mines, resulting in higher throughput (McCaffery *et al.*, 2002). Hybrid neural network MPC control has been

studied in Mathur *et al.* (1999), where a NN is used for determining the grinding process state. Further, Duarte et al. (2001) tested a combined NN-MPC control in the Codelco Andina grinding plant simulation.

The use of variable rotation speed control in mineral grinding circuits is increasing. In addition, high accuracy on-line particle size distribution measurements enhance the development of the optimizing control for grinding circuits. As an early study, Herbst *et al.* (1983) showed that the mill speed is a major manipulated variable for controlling the circulating load. Recently, discrete element simulations have been used to study different aspects of mill behavior. Cleary (1998) concluded that the lifter wear rates behave nonlinearly when the rotation rate is increased. It has also been proposed that, in order to maintain a steady throughput and to avoid grinding media-liner impacts, the total charge volume should be continuously assessed (Brodie, 2003). The advantages of rotation speed control include better control of product size and downstream processes, power savings and longer liner life, and as a consequence, lower maintenance costs.

In this paper an integrated grinding automation scheme for typical grinding processes is presented and discussed. Furthermore, a case study with a grinding circuit including variable speed control mills and a particle size analyzer is presented in Section 3.

2. DESCRIPTION OF THE FUNCTIONS OF THE INTEGRATED GRINDIGN AUTOMATION

As a concept, integrated grinding automation includes - in addition to the usual process instrumentation and automation - functions that enable the optimization, monitoring and operator support services. The integrated grinding automation utilizes an extended product scheme, in which the additional functionalities and services are a part of the physical product (Thoben *et al.*, 2001). As categorized in Fig. 1, the operating resources for grinding processes are the process equipment itself, and the related instrumentation and available services. Utilizing the integrated intelligence in the equipment, the equipment automation should meet the operating goals. Based on the goals, the equipment automation functions are optimization and control, as well as monitoring and operator support.
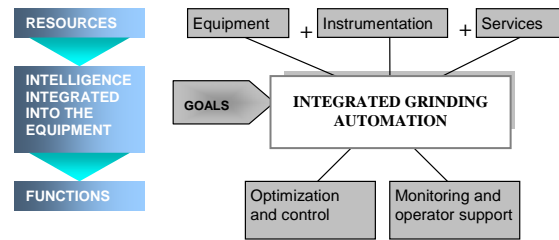

Fig. 1. Structure of the integrated grinding automation.

In this project the first stage was to define the concept components together with the equipment manufacturers and the end-users. Two web-based questionnaires were performed and personal interviews were made worldwide. Based on the results of the questionnaire survey, the main mineral grinding operating goals are described, new aspects for resource development are given and, finally, the main grinding equipment automation functions are summarized in the following.

2.1 Services for monitoring and optimization of the grinding process

In mineral grinding processes the production goals, and thereby the operating strategies, vary in each particular case. However, it is typical of grinding processes that the capacity should be maximized, while keeping the total costs as low as possible. The operating strategy should therefore ensure maximal equipment availability.

It is recommended that the APQ (Availability, Performance and Quality) measure index is utilized to maximize equipment availability and performance (Hagberg, *et al.*, 1998). In a grinding circuit, the availability (A) is calculated for each of equipment, taking into account mill lining wearing, stoppages, and process interruptions. The performance (P) factor is calculated from the basic mill feed and power draw measurements. The quality (Q) is a measure of how accurately the process is kept in the product targets or within the desired constraints.

Hence, in order to monitor the equipment availability, Condition Based Maintenance (CBM) methods are utilized to refine the process and maintenance data, and to predict the remaining availability (Bengtsson, 2003). Furthermore, in order to construct an efficient operator support tool, the equipment life-cycle scale Product Data Management (PDM) or

Enterprise Asset Management (EAM) features will be included in the concept.

In addition, in order to achieve the maximal grinding circuit performance, the mill throughput has to be maximized while, at the same time, minimizing the total operating costs. The constraints to be taken into account in the optimization are typically the degree of mineral liberation and the prevention of over- and under-grinding. The capacity, as well as the target values of the slurry properties, is eventually dictated by the following process stages. The optimization of throughput and operating costs requires estimation of the power curve of the grinding process. Additionally, on-line particle size distribution measurement and ore type information have been found to be beneficial for grinding optimization. Finally, the goal of the intelligent grinding concept is to advise the operators in optimizing the grinding process as a part of the whole mineral processing chain.

As a result, monitoring and optimization are provided as services within the process equipment. Additional services to be offered are data-mining, control loops tuning, circuit/equipment process audit, and maintenance, as well as training and operator support services (Jämsä-Jounela *et al.*, 2005). Finally, as a summary of the defined components of the intelligent grinding concept, the components are categorized according to the desired goals into capacity maximizing, usability and total cost minimizing. These are presented in Fig. 2.

3. CASE STUDY: THE KEMI CONCENTRATOR GRINDING CIRCUIT

The aims of the Kemi concentrator case were, in the first phase, to develop the concept modules with respect to the process monitoring and control strategy. Development was started with process data analysis in accordance with the control strategy design, which is described in the following chapters.

3.1 Description of the Kemi concentrator and the grinding circuit

The Kemi chromium ore deposit is located in northern Finland. The ore reserves are 52 Mt and the annual production of the Kemi concentrator is 1.2 Mt of ore. The products are upgraded lumpy ore with a grade of 35.0 % Cr_2O_3 and lumpy size of 12-100 mm, and the metallurgical grade concentrate with a grade of 45.0 % Cr_2O_3 and average grain size of 0.2 mm. After crushing, separation of the 12-100 mm ore is carried out at the dense medium separation plant. The undersize is further processed in the concentration plant, where the ore is ground in the grinding circuit. Concentration is subsequently carried out using gravity and magnetic separation.

The grinding circuit, shown in Fig. 3, consists of a rod mill and a ball mill, with a maximum power consumption of 560 kW and 220 kW, respectively. The classification is carried out using Derric screens with a 0.8 mm aperture. The mills have variable speed drives, which can be used to control the product particle size distribution, which is measured from the screen underflow using the laser diffraction based PSI500 Particle Size Analyzer (Kongas *et al.*, 2003). The size range of 1…500 µm is measured to a precision of 1-2 %.

Goals and conditions	OPTIMIZATION AND CONTROL					MONITORING AND OPERATOR SUPPORT			
	PROCESS			MAINTENANCE					
	State estimation	Calculation of variables	Control	Availability A	Performance P	Quality Q	Data analysis	indices	Information management
CAPACITY MAXIMIZING									
Degree of mineral liberation		Calculating the degree of mineral liberation							
Costs	Power curve Kwh/ton							Production efficiency	Fault states, common operating manners
Preventing over- and under-grinding			Optimizing expert system						
USABILITY									
Efficiency measurement				Machine-specific utilization rate	Measuring power and input	Quality boundaries, difference from optimum	Monitoring operation situations, auditing	Equipment, control loops, CBM	
Product Data Management									PDM, guiding support system
TOTAL COST MINIMIZING									
Maintaining instrumentation and control				Instrument utilization rate	Cost-efficiency	Quality of functioning		Instrument-specific monitoring	PDM, problem solving system
Optimization		Maintaining control and instrumentation vs. the benefit gained					Equipment- and circuit-specific process improvements		

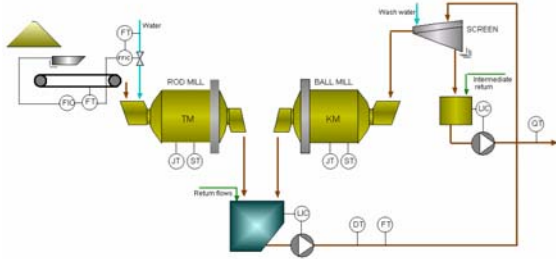Fig. 2. Main functions of the intelligent grinding concept.

Fig. 3. The Kemi grinding circuit with rod and ball mills and screen classification.

3.2 Input variables and training data for the PCA, PLS and SOM models

The aim of the process study was first to determine how the mill operating variables affect the product particle size distribution. This information was subsequently utilized to develop new control strategy for the grinding circuit. The PCA and PLS methods were selected to be tested first. Finally, the SOM method was also applied.

The analyzed process data included the following mill operating variables: circuit feed rate (t/h), mill power draws (kW) and rotation speeds (rpm), and consequently the grinding energy per ton. The -10, -32, -74 and -125 µm particle size fractions where chosen as output variables. A total of six data sequences containing approximately 12 000 rows of minute data were analyzed. The data were median filtered to remove the outliers. The time delays were determined and taken into account by shifting the data appropriately. To describe the ore hardness, a grindability index was calculated, proposed by Tano *et al.* (2005), which takes into account the amount of fine material produced per grinding energy used as follows:

$$GI_1 = (S_D^{32\,\mu m} - S_F^{32\,\mu m}) \cdot \frac{F}{P} \qquad (1)$$

where $S_D^{32\,\mu m}$ and $S_F^{32\,\mu m}$ are the portions of material finer than 32 µm in the circuit discharge and the feed, F is the feed (t/h) and P is the total mill power draw (kW). The amount of fine material is assumed to be negligible and considered as a constant in the feed stream.

3.3 PCA and PLS analyses

The aim of the principal component analysis (PCA) is to reduce the number of variables and detect structures between the variables, and thereby to classify the variables. In this case the goal was to study which process variables are related to the changes in product particle size fractions and, subsequently, which variables are significantly inter-related together. To describe the width of the particle size distribution and thus the amount of fine fractions, the slope of the steepest part of the cumulative size distribution was determined. This variable was also included into the PCA study.

The PCA analysis showed that the mill rotation speed and the ball mill power (indicating the amount of circulating load) have the most significant inverse effect on the size distribution. The greater these variables are, the lower is the cumulative size distribution slope value, meaning a higher production of fines.

The data were further examined using the partial least square analysis. The aim of the partial least squares projections to the latent structures (PLS) is to define a linear multivariate model between the operating variables and the process output variables. In this case, the goal was to study how the particle size distribution is affected by the operating variables, and which variables contribute the most to the product particle size fractions

The PLS model was made for the variables -10, -74 and -125 µm. From those results it was deduced that the rod mill rotation speed and power draw have the most significant effect on the product size fractions. A higher speed produces more fine material, while the higher primary mill power – indicating a higher mill charge – reduces the amount of fine material.

3.4 SOM analysis

Finally the self-organizing map (SOM) was applied to get more insight into the process behavior. The aim of the self-organizing map (SOM) is to classify a high dimensional process data and to compress the information into a two-dimensional plane. In this case the goal was to determine which process operating conditions cause a coarse/fine grinding product. Consequently, the method provides information about the process by classifying the data, especially when the combined PCA-SOM method is applied.

The SOM analysis showed that the process has clearly two clusters, separated mainly according to the milling power. The high milling power is correlated with a high rotation speed and a low grindability, whereas the rod mill feed does not affect the clustering significantly.
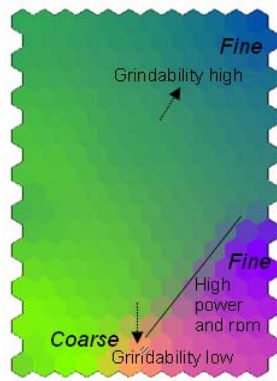
Fig. 4. Combined PCA-SOM, the U-matrix with a PCA similarity coloring.

To visualize the process data and to determine the process conditions causing a fine and a coarse product, the combined PCA-SOM analysis was performed. The data were clustered into two principal components, which where used in the similarity coloring of the U-matrix, resulting from the SOM training. The corresponding process condition were interpreted from the SOM component planes and added to the figure. The resulting graph is shown in Fig. 4. The figure indicates that the production of fine material has occurred when the ore was easily grindable, but also when the ore was harder and too a high rotation speed was applied. This implies that the current control strategy has not reacted to the changing conditions quickly enough.

4. OUTLINE OF THE GRINDING PROCESS CONTROL

Currently the grinding circuit control at the Kemi concentrator is based on visual monitoring of the amount of screen overflow and monitoring of the specific size fraction trends. However, this procedure may lead to a suboptimal operating point, causing excess fines production and thus economic losses.

The aim of the control strategy proposed is to produce the desired product size distribution, while minimizing the energy consumption and the lifter wear. This is obtained by changing the mill rotation speed, thus affecting the material impact forces inside the mill. The circuit feed rate is selected according to the downstream requirements, and the decision to change or accept the off-spec product is an optimization problem beyond this control scheme. Subsequently, the control strategy aims to stabilize the circulating load or, if this is not possible, bypassing the secondary mill is proposed.

5. CONCLUSIONS

Utilization of the integrated grinding automation enables the addition of operational intelligence into the process equipment, thereby increasing the performance of the process. In this paper definitions for the components and functions of the integrated automation were proposed. Furthermore, a case study on the particle size measurement based monitoring of the Kemi concentrator grinding circuit was carried out. In the case study, the mill rotation speed made a significant contribution to the grinding product size distribution. The results encourage further development of the control strategy and monitoring methods for the Kemi process.

REFERENCES

Bascur, O.A. (1982), *Modelling and computer control of a flotation cell*, University of Utah, Salt Lake City, 372 p.

Bengtsson, M., (2003), Standardization Issues in Condition Based Maintenance, *Proceedings of the 16th International Congress of Condition Monitoring and Diagnostic Engineering Management (COMADEM)*, Ed. Shrivastav, O. and Al-Najjar, B., Växjö University Press, Växjö, Sweden.

Brodie, M.N., (2003), Variable speed SAG milling, *CIM Bulletin*, **96**, pp. 67-71.

Campbel, J.,Spencer, S., Sutherland, D., Rowlands T., Weller, K., Cleary, P., Hinde, A., (2001), SAG mill monitoring using surface vibrations, Proceedings of the international conference on autogenous and semiautogenous grinding technology, ed. Barrat, D.J., Allan, M.J., Mular, A.L., University of British Columbia, 2001, Vancouver, Canada, pp. 373-385.

Casali, A., Gonzalez, G., Torres, F., Vallebuona, G., Castelli, L., Gimenez, P., (1998), Particle size distribution soft-sensor for a grinding circuit, Powder Technology, 99, pp. 15-21.

Cleary, P.W., (1998), Predicting charge motion, power draw, segregation and wear in ball mills using discrete element methods, *Minerals Engineering*, **11**, pp.1061-1080.

Del Villar, R. G., Thibaultb, J., Del Villara, R., (1996), Development of a softsensor for particle size monitoring, Minerals Engineering, **9**, pp. 55-72.

Duarte, M., Suarez, A., Bassi, D., (2001), Control of grinding plants using predictive multivariable neural control, *Powder Technology*, **115**, pp 193-206.

Guyot, O., Monredon, T., LaRosa, D., Broussaud, A., (2004), VisioRock, an integrated vision technology for advanced

control of comminution circuits, *Minerals Engineering*, **17**, pp. 1227-1235.

Hagberg, L., et al. Edited, (1998), *Keep it running: industrial asset management*, Scemm, Vantaa Finland, 198 p.

Herbst, J.A., Pate, W.T., 1996, On-line estimation of charge volumes in semiautogenous and autogenous grinding mills, *Proceedings of the international conference on autogenous and semiautogenous grinding technology, ed. Barrat, D.J., Mular, A.L. Knight, D.A., University of British Columbia*, Vancouver, Canada, pp. 817-327.

Herbst, J.A., Robertson, K, Rajamani, K., (1983), Mill speed as a manipulated variables for ball mill grinding control, *Proceedings of the 4th IFAC symposium 22-25 Aug. 1983, ed. T. Westerlund*, Helsinki, Finland, pp. 153-160.

Jämsä-Jounela, S.-L., Laine, S., Ruokonen, E., (1998), Ore type based expert system in mineral processing plants, *Particle & Particle Systems Characterization*, **15**, pp. 200-207.

Jämsä-Jounela, S.-L., (1990) Modern approaches to control of mineral processing, *Acta Polytechnica Scandinavica, Mathematics and Computer Science Series No. 57*, Helsinki.

Jämsä-Jounela, S.-L., Remes, A., Suontaka, V., (2005), Questionnaire on development of the grinding process, *Internal project report - Automin*, Helsinki University of Technology, Espoo, 50 p.

Kongas, M., Saloheimo, K., Pekkarinen, H., Turunen, J. (2003), New particle size analysis system for mineral slurries, *Preprints of IFAC workshop on new technologies for automation of the metallurgical industry*, Shanghai, China, pp. 384-389.

Mathur, A., Parthasarathy, S., Gaikwad, S., (1999), Hybrid neural network multivariable predictive controller for handling abnormal events in processing applications, Control Applications, *Proceedings of the 1999 IEEE International Conference*, Hawai, USA, pp. 13-17.

McCaffery, K.M., Katom, M., Craven, J., (2002), Ongoing evolution of advanced SAG mill control at Ok Tedi, *Minerals & Metallurgical Processing*, **19**, pp. 72-80.

Napier-Munn, T.J., Morrel, S., Morrison, R.D., Kojovic, T., (1999), *Mineral Comminution Circuits: Their Operation and Optimisation*, JKMRC, Queensland.

Niemi, A.J., Tian, L., Ylinen, R., (1997), Model predictive control for grinding system, *Control Engineering Practi*ce, **5**, pp. 271-8.

Pax, R.A., (2001), Non-contact acoustic measurement of in-mill variables of SAG mills, Proceedings of the international

conference on autogenous and semiautogenous grinding technology, ed. Barrat, D.J., Allan, M.J., Mular, A.L., University of British Columbia, 2001, Vancouver, Canada, pp. 386-393.

Radhakrishnan, V.R., (1999), Model based supervisory control of a ball mill grinding circuit, *Journal of Process Control*, **9**, pp. 195-211.

Ramasamy, M., Narayanan, S.S., Rao, Ch.D.P., (2005), Control of ball mill grinding circuit using model predictive control scheme, *Journal of Process Control*, **15**, pp. 273-283.

Tano, K., Pålsson, B.I., Sellgren, A., (2005) On-line lifter deflection measurements showing flow resistance effects in grinding mills, *Minerals Engineering*, **18**, pp.1077-1085.

Thoben, K-D., Jagdev, H., Eschenbaecher, J. (2001), Extended products: evolving traditional product concepts*, Proceedings of the 7th International Conference on Concurrent Enterprising: Engineering the Knowledge Economy Through Co-operation,* Bremen, Germany, pp. 429-439.

Valderrama, W.R., Pontt J.O., Magne, L.O., Hernández, J.S., Salgado, F.I., Valenzuela, J.S. Poze, R.E., (2000), The Impactmeter, e new instrument for monitoring and avoiding harmful high-energy impacts on the mill liners in SAG mills, *Preprints of IFAC workshop on future trend in automation in mineral and metal processing, 2000*, Helsinki, Finland, pp.274-279.

Yianatos, J.B., Lisboa, M.A., Baeza, D.R., (2002), Grinding capacity enhancement by solid concentration control of hydrocyclone underflow, *Minerals Engineering*, **15**, pp. 317-323.