Physicochem. Probl. Miner. Process. 49(1), 2013, 243−253

www.minproc.pwr.wroc.pl/journal/

Physicochemical Problems of Mineral Processing

ISSN 1643-1049 (print)
ISSN 2084-4735 (online)

Received June 15, 2012; reviewed; accepted July 15, 2012

DETERMINATION OF THE NIP ZONE ANGLE IN HIGH-PRESSURE GRINDING ROLLS

Daniel SARAMAK[1], Zdzisław NAZIEMIEC[2]

[1] AGH University of Science and Technology, Faculty of Mining and Geoengineering, Department of Environmental Engineering and Mineral Processing, Mickiewicza 30 Av., 30-059 Krakow, Poland, Fax: +48 12 617 21 98, Mobile: +48 692 597 032, Email:dsaramak@agh.edu.pl

[2] Institute of Glass, Ceramics, Refractory and Building Materials, Department of Mineral Building Materials, Krakow, znaziemiec@immb.com.pl

Abstract: A proposal of the nip zone angle determination in high-pressure grinding rolls (HPGR) crushing process is presented in the paper. Knowledge of the nip zone angle value makes it possible to determine the real maximum pressing force in the high-pressure comminution. Two methods of determination of this maximum pressure were proposed and verified. The first method is based on the roll's geometry and the change of the HPGR chamber's volume together with the roll rotation, while the second one considers the outlet gap width. Results of the nip zone angle calculations according to both methods are similar and show that the nip zone angle is around 3^o. The verification was carried out in a piston-die press and experimental results show that the product size distributions from HPGR and piston-die press are similar. The methodology of the nip zone angle determination presented in the paper has then its practical confirmation. A proper determination of the nip zone border makes it possible to calculate the comminution probability of given type of material and is a basis for the HPGR crushing process modeling and optimization.

Keywords: *HPGR, comminution, nip zone, ore processing*

Introduction

High-pressure comminution becomes more and more popular technology in industrial mineral processing operations, which can be applied both at secondary or tertiary crushing operations, and during the coarse grinding stage (Morell, 2008; Bearman, 2006; Morley, 2006). The HPGR devices are usually implemented into industry as a replacement of conventional tumble and semi-autogenous mills (SAG) due to considerable reduction of energy consumption and size reduction ratio improvement. HPGR presses find applications in many mining and mineral processing industry

http://dx.doi.org/10.5277/ppmp130122

areas like ore processing, cement clinker grinding or limestone flour and fine aggregates production.

The HPGR technology was introduced in the mid-eighties and originally applied in the cement industry (Schoenert, 1988; Maxton et al., 2003). In hard ore processing it was applied in diamond mines for kimberlite crushing. Constant investigations over the HPGR performance benefited in further modernization of technology (Daniel and Morell, 2004; Daniel, 2008; Gruendken et al., 2008; Bailey et al., 2009; Saramak et al., 2010) and since then presses have been gradually applied to harder and more abrasive materials like iron or non-ferrous metal.

The application of HPGR technology results in following advantages:

- lower energy consumption (Fuerstenau et al., 1991; Rule et al., 2008),
- reduced grinding media consumption,
- lower operating costs,
- finer product,
- low dust and noise pollution,
- faster equipment delivery schedules.

The main benefit results from the method of the feed material size reduction: a slow application and the gradual increase of the pressing forces. It causes the damage of the grain structure together with micro-crack formation, and the unfavourable phenomenon of the particle over-grinding is practically eliminated (Fuerstenau et al., 1991; Tromans and Meech, 2002; Morell, 2008; Saramak, 2011a)

The HPGR technology has also some limitations and still need investigations heading towards better understanding of the issue through the development of different HPGR-based flow-sheets (Powell 2010). An introduction of new research programmes significantly increases possibilities of the HPGR-based flow-sheet performance modeling (Daniel, 2004; Morell, 2008; Tumidajski and Saramak, 2009) and optimization (Gruedken et al. 2008; Saramak 2012; 2011b)). Considering the above, an extensive investigation of the wear of linings can be beneficial. Also issues connected with the bath-tub effect (an extensive wear of the central area of rolls) or the edge effect (at very sides of rolls the material breakage is lower than in the central area) are significant.

Principles of high-pressure comminution

The main part of the high-pressure grinding rolls press is a set of two counter-rotating rolls running in bearings and enclosed in the frame. One roll is settled in the frame in the fixed position (fixed roll), while the position of the second one (floating roll) is dynamic allowing the horizontal movement according to the variations in the feed and hydraulic pressure. Both rolls are separated with shims on ends, preventing the contact of the fixed and floating roll. The rolls are driven by two separate motors connected to the roll shafts with the use of gear reducers.

The crushing process in the HPGR crushing chamber is evoked by the pressing force from two rotating rollers. The ore is choke-fed and the material is dragged into the nip zone of working chamber and as the distance between the rolls is decreasing, the pressing force from the floating roller significantly increases, causing the failure of the individual particles structure and formation of micro-cracks. This results in a large reduction of the product particle size, which comes out during the next processes, usually the tertiary grinding in mills. Two zones can be distinguished in the working HPGR chamber: pre-compacting zone and the nip zone (Figure 1)

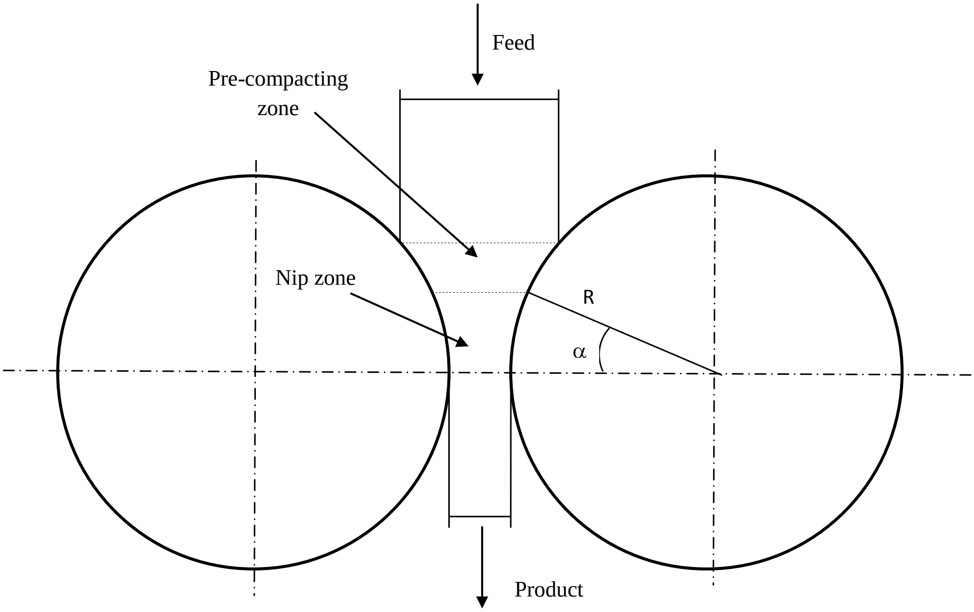

Fig. 1. HPGR crushing scheme

In the first zone the initial thickening of the material can be observed. The pressing force causes that most of inter-particle spaces are eliminated or at least minimized. The proper comminution takes place in the nip zone, because here the maximum pressing force is obtained. The product is usually in a solid sheet form, also referred asflake. The thickness of the flake generally depends on the feed properties and HPGR operating conditions. The micro-crack formation in single particles causes easier size reduction in downstream grinding processes. The Bond work index value in this case is reduced from 20 to 30% for limestone and 15 to 20% for harder minerals.

Methods of pressing force and pressure calculation

The pressing force (F) in HPGR can be calculated from equation (1):

$$F = \frac{D^2 \pi}{4} n\, P_h \tag{1}$$

where: F – pressing force, kN,
D – roll's diameter,
n – number of pistons,
P_h – hydraulic pressure, kPa.

The pressure P is the most significant operating parameter, measured in MPa or N/mm^2:

$$P = \frac{F}{1000\,D l} \tag{2}$$

where: D – roll diameter, m,
l – roll length, m.

The value of P is calculated per total working surface of rolls, but the feed material is comminuted only on certain section of rolls in working chamber, marked in Fig. 1. The real P value calculated from Eq. (2) is then only an approximate. The main crushing process takes part only in the nip zone (Fig. 1) where P_{max} (a maximum pressure value) occurs. Several different formulas can be applied. In order to calculate the maximum operating pressure in press (P_{max}) Schoenert (1988) proposed the following formula:

$$P_{\max} = \frac{P}{k \alpha} \tag{3}$$

where: k – constant,
α – nip zone angle (6–10 degrees).

Neumann (2006), in turn, proposed the following formula for the maximum pressing force:

$$F_{\max} = c \frac{F}{\sqrt{s}} \tag{4}$$

where: c – constant related to the device and the feed material properties,
F – pressing force, kN,
s – gap width, mm.

Formula (4) does not consider the diameter–gap relationship in press. For the various relationship between the gap and roll diameter, the changeable degree of feed material compression is observed. The compression degree is higher for narrow gap s (Fig. 2a) because values of $\frac{s_1}{2R + s_1}$ are smaller than $\frac{s_2}{2R + s_2}$ (Fig. 2). The feed material bed is then more compressed and greater values of pressing force are also expected.

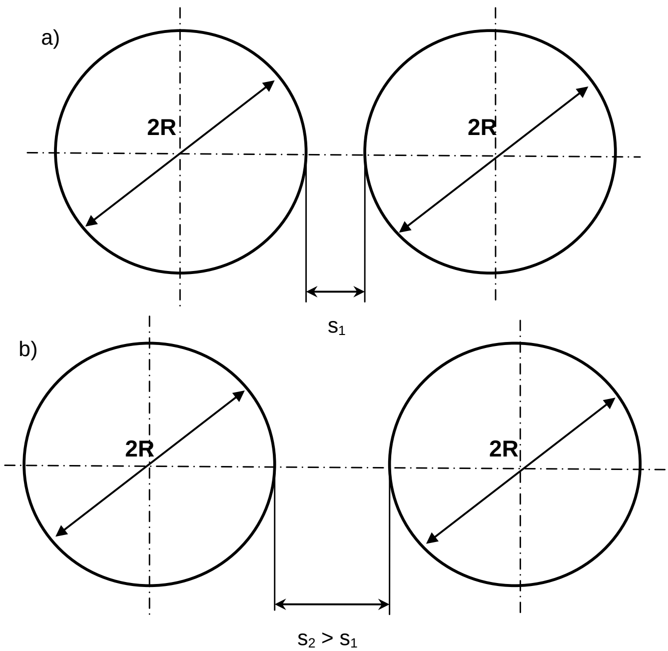

Fig. 2. Influence of relationship between gap *s* and the roller's diameter *2R* on material's compression level in HPGR

Unland and Kleeberg (2006) proposed an empirical formula for P_{max}:

$$P_{\max} = \frac{F}{Dl\sqrt{2\frac{s}{D}\left(\frac{\rho_p}{\rho_n}-1\right)c}} \tag{5}$$

where: F – pressing force,

s – gap width, mm,

ρ_n – feed density, kg/dm^3,

ρ_p – density of compressed product, kg/dm^3,

c – constant,

D – roll diameter,

l – roll length.

Formula (5) allows for determination of the maximum pressure value as a function of the gap width, roll's pressing force and the feed and product densities. For the given type of material the feed density is constant, and only the product density will be a variable.

Other authors (Schwechten, 1987; Smitz, 1993) introduced into the formula for P_{max}, a φ parameter, which describes the feed compression ability:

$$P_{\max} = \frac{F}{D\, l\, \varphi \sqrt{\frac{s}{D}}} \tag{6}$$

where: F – pressing force,
s – gap width,
φ– feed compression ability,
D – roll diameter,
l – roll length.

Feige (1989) run an investigations over the pressing forces in roller crushers. As a result of the above, he proposed the owing formula for calculation the value of maximum pressure:

$$F_{\max} = \frac{2F_r}{l\, L} \cong \frac{2D \int_{\alpha} P(\alpha) d\alpha}{\sqrt{d \;\; 2D + d}} \tag{7}$$

where: F_r – pressing force,
L – a depth of the pressing force penetration into the feed material bed between the rolls, $L \cong \frac{1}{2}\sqrt{d \;\; 2D + d}$,
d – particle size.

Experimental

The real value of maximum pressure can be precisely calculated from the following formula:

$$P_{\max} = \frac{F}{1000\, D\, l\, \pi \frac{\alpha}{360}} = \frac{P}{\pi \frac{\alpha}{360}} \tag{8}$$

where: P_{max} – maximum pressure, MPa
P – pressure, MPa,
α – nip zone angle, [^{o}], which, from the scope of the press geometry, is constant regardless the rolls diameter.

The value of pressure is increasing significantly in the nip zone, and rapidly decreased when the compressed material leaves the press working chamber ($\alpha < 0$). The pressure in nip zone is exerted by the floating roll tighten towards the fixed one with four pistons, and through decreasing the volume of the space between the rolls as the feed material is dragged deeper into the crushing zone. The maximum pressure is expected to occur in the area, where the volume decreases are minimal. In order to find the border value of α, below which these minimal changes in the volume are observed, the nip zone volume should be determined as a function of α.

Considering the situation in the opposite direction to the process run, the lowest value of the space gap between the rolls is on the level zero, for $\alpha = 0$. Together with the increasing of α value, the volume of nip zone increases, but these changes are not large and approximately constant at the beginning. Together with the further increasing of α, the h value and distance between the rolls (see Fig. 2) increase as well and, as a result, the horizontal component of the pressing force F_x (Fig. 4) decreases too. The nip zone border is placed on the height h, where the working chamber volume starts to increase more rapidly. All necessary notations were given in Figure 3, and after suitable calculations, the nip zone value V as a function of α, can be described by the formula (9):

$$V(\alpha) = l R^2 \left(\sin\alpha - \frac{1}{4}\sin 2\alpha - \frac{\pi\alpha}{360} \right) \tag{9}$$

where: l – rolls length, m,
R – rolls diameter, m,
α – angle determining the nip zone border, degrees.

The pressing force value reaches maximum if the first derivative of $V(\alpha)$ heads towards zero:

$$F \to \max, \quad \text{when} \ \frac{\partial V(\alpha)}{\partial \alpha} \to 0. \tag{10}$$

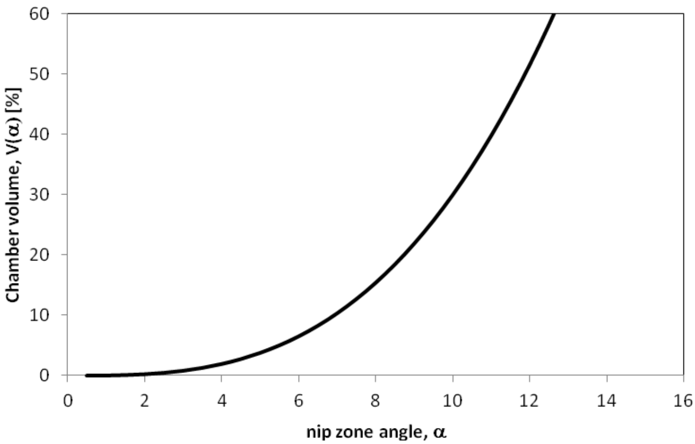

Fig. 3. The press working chamber volume course in relationship to α value

The $V(\alpha)$ function is presented in Fig. 3.

Analyzing Fig. 3, one can notice, that for $\alpha < 3$, chamber volume increases are insignificant. For $\alpha > 4$, in turn, the volume increases more rapidly, what results in decreasing the pressing force on the feed material bed and, in a consequence, the lower comminution intensity. The horizontal component $\vec{F}_x$ of the force F decreases as well (Fig. 4). The curve presented in Fig. 3 can be very well approximated by using the exponential function:

$$\hat{V}(\alpha) = 0.03\alpha^3. \tag{11}$$

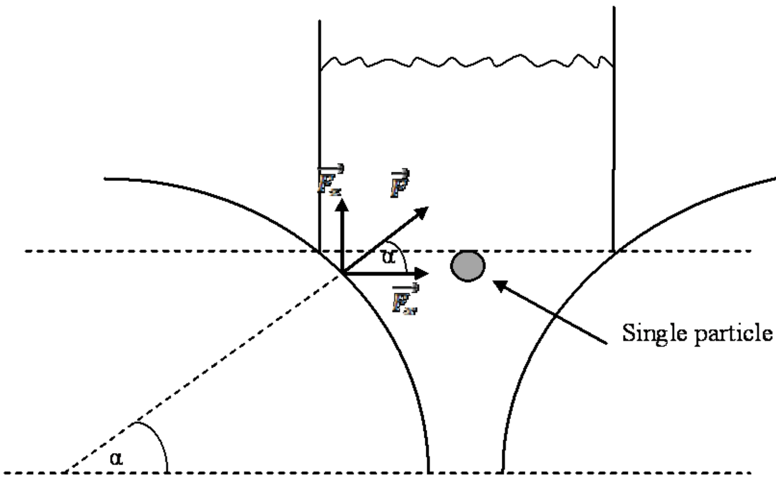

Fig. 4. Forces affecting the feed material between the rolls

The nip zone can be also alternatively determined, taking an advantage of the relationship between the gap and roll diameter. The above relationship is considered as constant, and according to various sources, is determined with following equation for ore processing:

$$s = 0.025R. \tag{12}$$

On the basis of the above, the nip zone is proposed to be described as a space between the rolls, limited by the height equal to s (Fig. 5).

It is possible to calculate the α value for the above nip zone from the formula:

$$\alpha = \arcsin\left(\frac{s}{R}\right). \tag{13}$$

Accepting formula (13) $\alpha = 2.87^{\circ} \approx 3^{\circ}$.

Results of calculations are convergent to those, obtained in the previous paragraph.

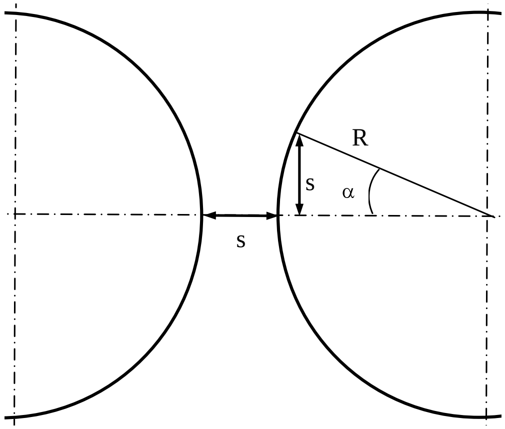

Fig. 5. The nip zone determined by using the gap width *s*

Verification and discussion

A verification covered an experimental programme of limestone crushing in pilot plant press (test 1) and in a laboratory piston-die press (test 2). Test 1 was run for following operating parameters:

- operating pressure $P = 3{,}16$ N/mm^2,
- operating gap width $s = 22$ mm.

The real operating pressure P_{max} for the above parameters was calculated by using formula (9). For accepted angle of the nip zone $\alpha = 3°$ (14), $P_{max} = 120.7$ MPa. For such a pressure value a laboratory test in piston-die press was run. Results of both experiments are presented in Fig. 6.

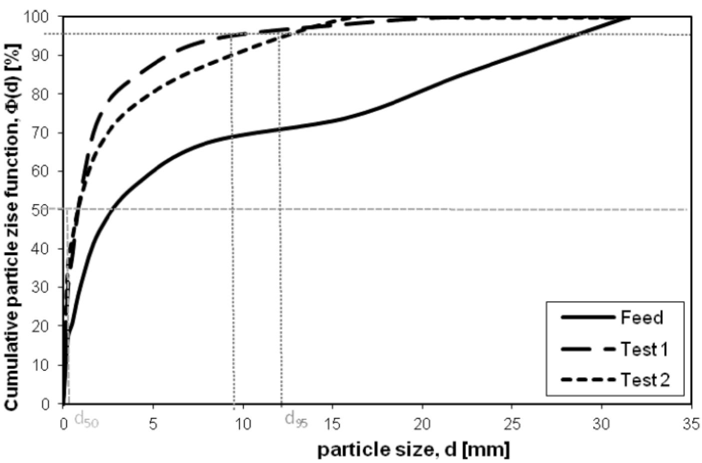

Fig. 6. A comparison of crushing results in plant HPGR (test 1) and piston-die press (test 2)

Average (d_{50}) and maximum (d_{95}) product particle size values were also determined, together with the weight recovery of the fine (i.e. below 0.3 mm) particle fraction $\gamma_{-0.3}$. Results are presented in Table 1.

Table 1. Average and maximum particle size of crushing products from test 1 and test 2

Index	Test 1	Test 2
d_{50} [mm]	0.85	0.83
d_{95} [mm]	10.1	12.7
$\gamma_{-0.3}$ [%]	30.9	36.9

where: d_{50} – average product's particle size, d_{95} – maximum product's particle size, $\gamma_{-0.3}$ – weight recovery of -0.3 mm size fraction

Analyzing the crushing results one can see that an average graining obtained in both tests (d_{50}) is the same for both products, while the maximum particle size of product d_{95} and finest particle contents are quite similar. The greater differences were observed for the product size fractions between 5 and 10 mm, but they do not exceed 10%. This difference can be a result of various dynamics of a product breakage in both devices. In HPGR the particles move together with the rolls' revolution, and may settle down a position which makes easier the breakage. The particle movement in the piston-die test, in turn, occurs only to a limited degree. The content of particles over 3–4 mm is a rather of minor importance, however, because this fraction is anyway recycled to the crushing device.

Comparing the results of both tests, it can be stated, that the reduction ratio value obtained in piston-die test, corresponds to the real high-pressure comminution process. It is also convergent with the methodology of the nip zone angle determination, presented in "Experimental" section. The production of the finest particles is practically identical for both devices. The additional gain of the above verification is the possibility of application the piston-die press as a replacement of laboratory HPGR device, which is more favorable from economic scope.

Conclusions

Apart from the pressure, the high-pressure comminution efficiency is tied with other indices and process parameters, like the roll's surface profile, feeding system, recycle stream volume, device capacity, feed and product particle size and others. However, the real values of pressing force significantly influence not only the feed size reduction ratio, but also the material grindability in downstream grinding processes in ball mills. A determination of real operating pressure value can be helpful for selecting the optimal operating conditions of HPGR and is convergent with the main principle of mechanical processing: do not grind unnecessarily. The excessive pressure values produce more concised flakes, which need to be additionally de-agglomerated. Results presented in the paper have their practical implementation in the optimization investigations, heading towards the improvement of the high-pressure grinding rolls operation efficiency.

Acknowledgments

The article was written within the frames of Ministry of Science research grant N N524 466139.

References

BAILEY C., LANE G., MORELL S., STAPLES P., 2009, *What can go wrong in comminution circuit design?*, Proceedings of the 10th Mill Operatirs' Conference, Adelaide, SA.

BEARMAN R., 2006: *High-Pressure Grinding Rolls – Characterising and defining process performance for engineers*. 3rd International Symposium "Advances in Comminution, Society for Mining, Metallurgy and Exploration (SME).

DANIEL M.J., MORELL S., 2004: *HPGR Model verification and scale-up*, Minerals Engineering, vol. 17.

DANIEL M.J., 2008: *Summary of research outcomes of the P9N project, incorporating mineralogical analyses, particle weakening and micro-cracked HPGR products*, Proceedings of 5th PROCEMIN seminar, Santiago, Chile.

FEIGE F., 1989: *Measurement of pressure acting on layer of particle between two rollers*. Aufbereitungs-Technik 30 (1989), issue 10.

FUERSTENAU D.W., SHUKLA A., KAPUR P.C., 1991: *Energy consumption and product size distribution in choke-fed high-compression roll mills*. Int. Journal of Mineral Processing, vol. 32.

GRUENDKEN A., MATTHIES E., VAN DER MEER F.P., 2008: *Flowsheet confiderations for optimal use of high pressure grinding rolls*, MEI Comminution '08 Conference, Falmouth, Cornwall, UK.

MAXTON D., MORLEY C., BEARMAN R., 2003. *A quantification of the benefits of high pressure rolls crushing in an operating environment*. Minerals Engineering vol. 16.

MORLEY C., 2006: *High-Pressure Grinding Rolls – A technology review*. 3rd International Symposium "Advances in Comminution, Society for Mining, Metallurgy and Exploration (SME).

MORRELL S., 2008: *A method for predicting the specific energy requirement of comminution circuits and assessing their energy utilization efficiency*. Minerals Engineering, vol. 21, issue 3.

NEUMANN E.W., 2006: *Some basics on High-Pressure Grinding Rolls*. 3rd International Symposium "Advances in Comminution, Society for Mining, Metallurgy and Exploration (SME).

POWELL M., 2010: *Enlightened circuit design is essential to the take-up of new equipment*, Draft paper and presentation for Comminution'10 conference, Cape Town, South Africa, 13–16 April 2010.

RULE C.M., MINNARR D.M., SAUREMANN, 2008: *HPGR – revolution in Platinum?* Third International Conference „Platinum in Transformation", The Southern African Institute of Mining and Metallurgy.

SARAMAK D., 2001a: *Technological issues of High-Pressure Grinding Rolls operation in ore comminution processes*, Archives of Mining Sciences, vol. 56, issue 3.

SARAMAK D., 2011b: *The influence of chosen ore properties on efficiency of HPGR-based grinding circuits*, Gospodarka Surowcami Mineralnymi Mineral Resources Management, vol. 27, issue 4.

SARAMAK D., 2012: *De-agglomeration in High-Pressure Grinding Roll based crushing circuits*, Physicochem. Probl. Miner. Process., vol. 48 (1).

SARAMAK D., TUMIDAJSKI T., BROŻEK M., GAWENDA T., NAZIEMIEC Z.: Aspects of comminution flowsheets design in processing of mineral raw materials. Gospodarka Surowcami Mineralnymi Mineral Resources Management, vol.26 issue 4, 2010.

SCHMITZ T.: *Modellierung der Zerkleinerung in der Gutbett-Walzenmuhle und Verknupfung mit dem Schuttgutverhalten zur Voraussage kritischer Betriebszustande*. Dissertation TU Clausthal.

SCHOENERT K., 1993: *A first survey of grinding with high-compression roller mills*. International Journal of Mineral Processing, vol. 22.

SCHWECHTEN D., 1987: *Trocken-und Nassmahlung sproeder Materialien in der Gutbett-Walzenmuhle*. Dissertation TU Clausthal.

TROMANS D., MEECH J.A., 2010: *A fundamental analysis of fracture mechanics of minerals during comminution, research being conducted at The Centre for Environmental Research in Minerals*, Metals and Materials (CERM^3), UBC, July 2010, www.mining.ubc.ca/cerm3/energy%20efficiency.html.

TUMIDAJSKI T., SARAMAK D., 2009: *Methods and models of mathematical statistics in mineral processing* (in Polish), AGH University of Science and Technology Press, Krakow.

UNLAND G., KLEEBERG J., 2006: *The normal load on roll surfaces of high pressure grinding rolls*. Preceedings of XXIII Internetional Mineral Processing Congress, Istanbul.