Abstract

High pressure roller mills have been used successfully for grinding brittle materials since 1985. The advantages of this new technology are, less energy consumption, less wear and noise emission and a smaller mill size compared with ball mills. The HP-roller mill achieves comminution in a particle bed stressed by a high pressure. The performance of this mill differs from that of a ball mill with respect to the decoupling of throughput and comminution action. To operate a HP-roller mill, one has to understand the features of interparticle breakage, the interdependence of milling force and energy absorption, the capacity issue and the wear problem.

1. Introduction

High pressure roller mills are capable to comminute finely brittle materials with remarkably less energy and at a higher specific throughput than ball or roller-table mills. The first units were installed in 1985, and as of now about 200 mills are in operation, most of them for cement clinker and raw materials but also for slags, burnt lime, coal, limestone, diamond ore, silicium carbide and other brittle materials.

The principle design is shown in fig. 1. Two rollers are mounted within a strong frame. The bearing beocks of one roller are fixed and those of the other roller are movable and pressed against the material bed within the gap by a hydraulic force system. The maximum pressure on the bed can be adjusted with respect to the material properties, the feed size and the wanted fineness. In most applications a pressure between 100 and 200 MPa is advantageous.

Most of the primary particles are broken, fragments are rebroken and the bed is compacted up to relative bulk density of 75 to 85 percent regardless to a possible agglomeration, which can be enhanced up to the formation of flakes. The agglomerates are disintegrated in a following hammer-, impact- or ball mill. Then the material is sent to a classifier, and the coarse portion is recirculated.

The high pressure roller mill and the procedure meet the three criteria for an effective grinding process: (1) the direct tran-
sport of the material into the active volume in which it is stressed, (2) the possibility to adjust the stressing intensity at an optimum value, and (3) the direct discharge of the fine material after being produced /1/.

2. Characteristics of interparticle breakage

The term “interparticle stressing” describes the situation in which particles are stressed by other ones as happens in a material bed between two plates, if all particles are smaller than the bed height. The result is called “interparticle breakage”. The stress field in a particle and its breakage depend on the number of neighbours, which varies with respect to the size distribution and the packing structure. As long as the average stressing intensity is the same everywhere, the situation is called “homogeneous interparticle stressing”.

Actual interparticle stressing often differs from the homogeneous case by edge effects and material motion as the bed is unconfined. The edge particles contact the compressing plates and are stressed, therefore, with a somewhat higher intensity. This effect becomes negligible as the bed height exceeds the maximum particle size by a factor of four and the bed diameter the height by a factor of three /2/. In an unconfined bed the outer particles will be pushed away sidewards. The energy absorption and also the portion of broken particles depend strongly on geometrical configuration /3/.

In practical applications HP-roller mills often are operated with a feed size distribution of up to twice the gap width. Then the rollers nip the coarse particles, stress and break them, and the bed consisting of the smaller particles and those fragments are formed below the nipping area; fig. 2 demonstrates this situation.

To understand the phenomena of interparticle stressing and breakage it is reasonable to study a confined bed under the condition mentioned above. The general features are as follows /4,5,6/:

(1) The compaction diagram can be approximated by the equation:

\[
\theta = \frac{\delta - \delta_0}{(1 - \delta_0)} = 1 - \exp \left\{ -\left( \frac{\rho}{\rho_p} \right)^n \right\}
\]  

(1)

\(\delta_0, \delta =\) the initial and final relative bulk density, \(\rho =\) the pressure, \(\rho_p =\) the characteristic pressure depending on the material and feed size distribution, characterizing the resistance of the bed against compaction, and \(n =\) the curve shape factor depending mainly on the material. The value of \(\rho_p\) and \(n\) have to be determined experimentally.

(2) Using the above equation the energy absorption \(E_{\omega}^{\text{abs}}\) can be expressed by an equation such as,

\[
E_{\omega}^{\text{abs}} = P \cdot H\left( \frac{\rho}{\rho_p}, \delta_0, n \right)
\]

(2)
as long as the energy regain due to the relaxation of the bed is negligible, which normally gives an overestimation of some percentage.

(3) It is not possible to break all particles by one stressing. The fraction of broken particles \(S\) can be approximated by the equation:

\[
S/S_\infty = 1 - \exp \left\{ -\left( \frac{E_{\omega}^\theta}{E_{\omega}^{\text{abs}}} \right)^\beta \right\}
\]

(3)

\(E_{\omega}^\theta = \) energy absorption, \(E_{\omega}^{\text{abs}} =\) the characteristic value of \(E_{\omega}^\theta\) characterizing the particle strength and depends on the material and particle size, \(S_\infty =\) the limiting value of \(S\) also depending on material and particle size, \(\beta =\) the curve shape factor; \(S_\infty, E_{\omega}^{\text{abs}}\) and \(\beta\) have to
be determined experimentally.

(4) The product size distribution becomes finer with increasing pressure and increasing energy absorption, respectively, but converges against a limiting distribution.

(5) The breakage function can be approximated with a truncated logarithmic normal distribution

\[ B = \int_{\infty}^{\xi_{\text{50}}} h(\tau) d\tau \]

\[ h(\tau) = (2\pi)^{-1/2} \exp \left\{ -\tau^2/2 \right\} \]

\[ t = (1/\sigma) \left( \ln \eta - \ln \eta_0 \right) \]

\[ \eta = \xi_{\text{50}}^2 (1 - \xi) \]

\[ \sigma = (1/2) \left( \ln \eta_{\text{50}} - \ln \eta_{\text{50}}^* \right) \]

\[ \xi = x / x^* \]

The measures \( \xi_{\text{50}} \) and \( \sigma \) depends on the material and also on particle size and energy absorption. The breakage functions are not normalizable; an example is shown in fig.3.

It is possible to express the influence of particle size and energy absorption by power functions:

\[ \left( \xi_{\text{50}} / \xi_{\text{50}}^* \right) = \left( x / x^* \right)^a \left( E_m / E_m^* \right)^b \]

\[ \left( \sigma / \sigma^* \right) = \left( x / x^* \right)^c \left( E_m / E_m^* \right)^d \]

So the breakage function of one material is given by ten parameters; for quartz, as an example, it was evaluated:

\[ \xi_{\text{50}} = 0.36, \quad x^* = 650 \mu m, \quad E_m^* = 10.5 \text{ J/g}, \quad a = -0.27, \quad b = -0.34, \]

\[ \sigma^* = 2.23, \quad x^* = 770 \mu m, \quad E_m^* = 8.75 \text{ J/g}, \quad c = 0.05, \quad d = 0.12 \]

(6) The breakage is mainly determined by the absorbed energy, the stressing velocity and the moisture only show a minor influence with the following tendencies: the velocity effect decreases with increasing hardness (no effect with quartz); the moisture influences the breakage positively, but this effect decreases with decreasing hardness at slow velocities.

(7) The material hardness influences the breakage effects as expected; the fraction of broken particles and the breakage functions converge against their limiting values at lower energy levels as the hardness decreases.

3. Operation of HP-roller mills

Three major aspects have to be considered in operating a mill: power draft, capacity and wear. These three factors can be controlled generally by one or more operational parameters and are also related to each other, but it depends on the type of mill, which operational parameters influence them and to what. The size reduction in one passage through a mill is mainly determined by the specific...
energy $E^*$, which is related to the power draft $P$ and the mass flow through the mill $M$:

$$E^* = P / M$$  \hspace{1cm} (6)

In a closed-circuit operation with a classifier, the throughput of the circuit $M_c$ and the recirculating load $M_r$ defines the circuit factor $k$:

$$k = (M_c + M_r) / M_c$$  \hspace{1cm} (7)

Eq. 6 can be rewritten as:

$$E^* = P / k M_c$$  \hspace{1cm} (8)

and the specific energy for comminution in a circuit is given by:

$$E_s = k E^*$$  \hspace{1cm} (9)

The capacity of a ball mill can be varied within a fairly wide range without any change in the power draft. The power draft is adjustable by changing the ball filling ratio or the liner shape, the speed normally cannot be adjusted. The capacity, therefore, determines the specific energy. The situation with HP-roller mills is quite different.

### 3.1 Energy absorption in a HP-roller mill

The energy absorption $E^*$ of the material at one passage follows from the torque $T$, the number of revolutions $n$ and the mass throughput $M$:

$$E^* = 2 \pi n T / M$$  \hspace{1cm} (10)

The mass throughput also depends on $n$ and is given by the following equation if the material does not slip at the exit of the compression zone,

$$M = \delta \cdot \rho \cdot \sigma \cdot D \cdot L \cdot n = \pi \cdot \delta \cdot \rho \cdot \sigma \cdot n \cdot D^2 \cdot L$$  \hspace{1cm} (11)

$\delta$ = the relative bulk density in the gap clearance, $\zeta$ = the material density, $\sigma$ = $(s/D)$ = the relative gap width, $D$ and $L$ the diameter and length of the roller.

After introducing eq. 7 into eq. 6, the speed can be cancelled, so it does not influence the energy absorption directly. The torque is caused by the milling force $F$; both are related to each other according to:

$$T = \beta F \cdot D$$  \hspace{1cm} (12)

$\beta$ = force acting angle. Now, eq. 6 can be rewritten as:

$$E^* = (2/\delta \cdot \sigma) \cdot (F / \rho \cdot D^2)$$  \hspace{1cm} (13)

Experiments have shown that $\beta$ and also the term $(\delta \cdot \sigma)$ are almost independent of the force. Equation 9, therefore, indicates the proportionality between the energy absorption and the milling force, which always can be adjusted to achieve the energy absorption which is desired for the actual process.

### 3.2 Capacity of a HP-roller mill

The capacity is given by eq. 10. The proportionality to the speed cannot be valid up to infinity, so the relative gap width $\sigma$ must depend on it.

Fig. 5 shows some throughput characteristics of a lab-scale mill ($D = 200 \text{ mm}, L = 100 \text{ mm}$) /7/; this type of curves is always found. In general, the throughput of plane rollers decreases with increasing hardness of the material, but the material influences are reduced with corrugated rollers. Some values are shown in the table:

| Quartz Feed | Throughput $\dot{M}$ in t/h |
|-------------|-----------------------------|
| 0.1/6.3     | 1.6/6.3                     |
| 0.1/6.3     | 1.6/6.3                     |
| 0.1/6.3     | 1.6/6.3                     |

Fig. 5 shows throughput $\dot{M}$ over roller speed $u$ of a lab-scale mill ($D = 200 \text{ mm}, L = 100 \text{ mm}$), plane and corrugated rollers (height 1 mm, width 2 mm, distance 6 mm), quartz feed 0.25/1.00, 1.6/6.3, 0.1/6.3 mm.
ues of the capacity index $v_o$ (see eq. 15) are listed in Table 1 to give a first impression on the influence of material, feed size and roller surface structure /7/.

The throughput is almost independent of the milling force, thus, the capacity, is controlled by mechanisms acting in the region above the compaction zone; this region should be called the "acceleration zone". Inside it, two processes are performed: first the narrowing of the material stream width, and second the acceleration of the particles. The energy for these processes is caused by the friction forces acting from the roller surface on the particles and is transmitted into the material stream by the particle-particle friction. As a result, the wall and the internal friction influences the throughput. The first one is the most important because it enables the energy to be created.

The normal force and the coefficient of friction determine the friction force. The normal force is given by the difference in the normal component of the gravity minus the centrifugal force arising as the particles move along the curved surface of the rollers. With velocity $u_p$ and the size $x$ of the particle, the centrifugal acceleration is given by:

$$a_c = 2 u_p^2 / (D + x) = 2 u_p^2 / D \leq 2 u^2 / D$$ (14)

In the lab-scale mill with $D = 200$ mm and at $u = 1$ m/s the maximum centrifugal acceleration of $10$ m/s$^2 = g$ occurs. The normal component of the gravity is less than $g$, so the centrifugal effect can be expected to influence the throughput. High speed films have shown some particles moving off the roller as the speed exceeds about $1$ m/s. Fig. 6 are sketches from two films taken at 1000 frames per second. One shows the situation with plane rollers at $3.3$ m/s. The particles (limestone $6.0 / 8.0$ mm) have much slip and a tangential velocity of only $0.6$ m/s. The corrugated rollers run with $1.1$ m/s, and the tangential particle velocity reaches $0.5$ m/s. The time between the two frames is about $20$ ms. The radial movement of the dotted particles can only be caused by the centrifugal force and is only possible if the bed around them is loosened. The centrifugal force also acts on the other particles, which are kept on the rollers by their neighbours, and reduces the friction force.

It seems to be reasonable to try an approximation of the throughput characteristic by the following expression,

$$\dot{M} = Au - Bu^2$$

$$v = \dot{M} / DL = v_o - kz$$

$$z = u / u_o = u / \sqrt{gD / 2}$$ (15)

The throughput index $v_o$ is the key value in the capacity issue. Fig. 7 shows a $(v, z)$-plot for quartz; the results can be expressed by eq. 15; more detailed informations are given in /7/.

Production mills have rollers of 1 to 2 m diameter and are operated with a speed up to 2 m/s, so $z$ ranges between about 0.6 and 1.0; the centrifugal effect may be less than in the lab mill. It seems to be reasonable to attend to the characteristic speed $u_o$ in sizing the capacity of roller mills.

Beside the centrifugal effect, the throughput can be reduced by the fluidization effect since

| Feed          | Plane Rollers | Corrugated Rollers |
|---------------|---------------|--------------------|
|               | Quartz        | Limestone          | Quartz | Limestone |
| 0.25 / 1.00 mm| 1.20          | 1.65               | 1.70   | 2.40      |
| 0.8 / 3.2 mm  | ---           | ---                | 2.10   | 2.70      |
| 1.6 / 6.3 mm  | 1.10          | 2.00               | 2.90   | 2.85      |
| 0.4 / 6.3 mm  | ---           | ---                | 3.05   | 2.90      |
| 0.1 / 6.3 mm  | 1.40          | 2.20               | 3.55   | 3.10      |
The feed contains fine material. The compaction of the bed squeezes off the air, which mostly flows upwards into the acceleration zone. The volumetric flow $V_L$ and the average air velocity $v_0$ through the entry cross-section of the compression zone follows from the equations:

$$V_L = \gamma \left( \frac{M}{\zeta} \right) \left( \delta_e - \delta_i \right) / \delta_e.$$

$$v_0 = \gamma w_e \left( \delta - \delta_i \right) / \delta_e \leq \gamma u (\delta - \delta_i) / \delta_e.$$

$\gamma$ = the portion of the upwards flow, $\delta_e$ = the relative bulk density at the entrance, $w_e$ = the material velocity at the entrance, $u$ = the roller speed. For an estimation it should be assumed that $\gamma = 0.5$, $\delta_e = 0.55$, $\delta_e = 0.8$, resulting in $v_0 = 0.16 u_e$. The settling velocity $c$ of a 100 $\mu$m
Quartz particle in air is about \( c = 1 \text{ m/s} \). The fluidization velocity of a particle bed is given by \( v_\text{f} = c(1-\delta)^n \); with \( n = 5 \) follows \( v_\text{f} = 0.018 \). These figures show the possibility of partial fluidization, which also reduces the throughput if the feed contains fine particles.

For a better understanding of the throughput characteristic more fundamental research is needed.

### 3.3 Wear of rollers

The specific wear of a mill is expressed normally in terms of worn-off mass \( M_\text{w} \), related either to the ground mass \( M_\text{g} \), or to the consumed energy \( E \).

\[
\frac{w_\text{m}}{M_\text{g}} = \frac{w_\text{t}}{M_\text{g}} = \frac{w_\text{t}}{M_\text{g}} = \frac{k}{M_\text{g}} \quad (18)
\]

Although these terms are useful for describing technical operations, the average thickness \( d_\text{s} \) of the layer worn off one roller in one revolution represents a more reasonable figure for fundamental considerations and comparing different materials and mills. This is because the wear is caused on the roller surface and the throughput due to the gap width. Using the denotations already introduced, \( d_\text{s} \) can be calculated from \( w_\text{m} \) or \( w_\text{t} \), the throughput number \( v \), the density of the ground material \( \rho \) and that of the wear material \( \rho_1 \) as follows:

\[
d_\text{s} / D = (\rho / \rho_1) (\nu / 2k) w_\text{m} \quad (19)
\]

These equations show that the specific wear decreases with increasing roller diameter as long as \( d_\text{s} \) and the throughput number remain constant.

The operation time \( t_\text{op} \) is limited by the thickness \( d_\text{s} \) of the material layer, which can be worn off before rewelding.

\[
t_\text{op} = \pi (d_\text{s} / d_\text{a}) (D / u) \quad (20)
\]

Experiences with limestone and cement clinkers have shown that \( d_\text{s} \) is in the order of \( 10^{-9} \text{ m} = 10^{-7} \text{ mm} / 8 \). Assuming \( d_\text{s} = 0.01 \text{ m}, D = 1.5 \text{ m}, (\rho_1 / \rho) = 2.6, u = 1.5 \text{ m/s}, \nu = 0.015 \) and \( k = 1 \) for pre-milling and \( k = 4 \) for fine-milling, it follows that \( w_\text{m} = 0.23-0.92 \times 10^6 \) and \( t_\text{op} = 8700 \text{ h}. \) The specific wear is very low even with a value of \( d_\text{s} \), that is ten times higher. The operation time arises as the real problem because it is inversely proportional to \( d_\text{s} \).

The wear mechanisms are not fully understood, although hard work is going on at this issue. Recently, a paper was published containing many data /9/. The particles in the acceleration zone slip greatly on the roller surface, but the normal forces are very low. The pressure on the surface increases steeply in the compression zone; fig.8 shows an example for limestone 0.5/0.8mm measured with a 2mm pin inserted in the roller. The compaction also causes some tangential movement of the material at the surface. Both facts together, the high pressure and the small amount of slip, are probably the main reasons for the wear. Because high pressure is needed for the comminution and cannot be avoided, one has to try to reduce the slip inside the compression zone. One important fact is that the slip increases at high compaction above a relative bulk density of 85%.

### 4. Selection of mill size

The selection of the proper mill size has to consider the mass throughput, the maximum particle size in the feed and the investment costs. The throughput is given by eq. 11. Introducing the relative speed \( z \), the characteristic speed \( u_\text{n} \), the throughput number \( \nu \) and the length-diameter ratio \( \lambda = L / D \), mill size \( M \) reads:

\[
M = (\nu z \lambda / \sqrt{2}) \sqrt{g} \rho D^3 \quad (21)
\]

At a fish approximation, the investment costs are proportional to the mill volume \( V_\text{m} \), which can be characterized as:

\[
V_\text{m} \sim D^2 L = \lambda D^3 \quad (22)
\]

with eq. 21 one rewrites:
\[ V_n \sim (\frac{1}{\lambda})^{0.3} (\frac{M}{\nu})^{1.2} \]  

(23)

As long as \( \lambda \) varies in the usual range of about 0.5 to 1.2 the length-diameter ratio has only a small influence on the mill volume, if \( M \) is given, \( \nu \) kept constant and \( \nu \) does not change as \( \lambda \) is varied. A decrease of \( \lambda \) from 1.2 to 0.5 increases \( V_n \) by about 12%, so the value of \( \lambda \) can be chosen with respect to desing problems.

The mill size selection has to be focussed on the roller diameter \( D \) to satisfy the demand of the throughput, and again the question arises as to how the throughput number \( \nu \) depends on the operating conditions, the surface structure and the roller diameter itself. The diameter should be chosen with respect to the maximum feed particle size \( x_{\text{max}} \) if it exceeds the gap width \( s \). A large \( (x_{\text{max}}/s) \)-ratio can cause local pressure peaks, so it should be smaller than 2 to 3. With the relative gap width \( \sigma = (s/D) \) it follows that:

\[ \left( \frac{D}{x_{\text{max}}} \right) = \left( \sigma (x_{\text{max}}/s) \right)^{-1} \]  

(24)

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(24)

5. Flow sheets

A HP-roller mill can be used in different modes, some possible flow sheets are shown in fig.9.

In the first applications the mill was installed ahead an already existing ball mill-classifier circuit, see fig.9a. This premilling mode had the advantage of minimizing the risk at the introduction of this new technology. The HP-roller mill increases the throughput by 15 to 30%, in some case even more, and reduces the total specific energy consumption by 10 to 20%. These results are achieved if the HP-roller mill produces at least 10% of fine material, and the ball charge is modified.

The potential of energy saving can be used better as the comminution action in the HP-roller mill is enhanced by partially recirculating the classifier coarse to it; fig. 9b shows this hybrid-milling mode. Many instal-
lations for cement clinker grinding are working successfully according fig. 9a and 9b/10-13/. In the fine-milling mode, fig. 9c, all classifier coarse is sent back to the HP-roller mill, which then is followed by a hammer or impact mill to deagglomerate the flakes. New classifiers are developed which have integrated a deagglomeration system, so the circuit only consists of two parts. The energy saving increases up to 50% compared with a ball mill circuit. With decreasing classifier cut and sharpness, the mill feed contains more and more fine material, which may worsen the introduction into the compression zone. The quiet running of the mill is disturbed by shattering of the rollers; a recirculation of a portion of flakes reduces the shattering and improves the mill performance. This is indicated with the dashed line in fig. 9c. HP-roller mills in the fine milling mode are used successfully for cement raw material (−200/μm), burnt lime (−100/μm), cement clinker (−80/μm), limestone (−20/μm and even −10/μm) and other brittle materials/10, 14-18/.

Fine and very fine milling should not be done in one step, a two step flow sheet seems to be more reasonable. One possibility is shown in fig. 9d consisting of two HP-roller mills, one deagglomerator and two classifiers. In this way the recirculating load to each mill is reduced, and furthermore, each mill can be adjusted better to the optimum condition.

6. Outlook

The quick introduction of HP-roller mills into technical operations during the last years proves the advantage of this new grinding technology for brittle materials. Some problems have appeared with respect to design details and wear, but this is normal in establishing a new system especially as it happens so fast. The behaviour of this mill differs from the well-known ball mill, so one has to learn and get accustomed to it. The application will be broadened in the future, especially in the area of ores and fine materials/17, 18/.

Until now only a small amount of fundamental research and modelling has been done, and more is needed. Although this mill and its operation looks very simple, many questions are still unanswered. The most important issues are: (1) the capacity in general and especially with fine feed, (2) wear mechanisms and wear materials, (3) microcrack forming, (4) profiled roller surfaces, influences on capacity and wear, (5) rewelding techniques, (6) segmented roller liners, (7) modelling, and (8) influences on down-stream processes as flotation and leaching. One should compare the situation with the enormous research and development efforts in ball milling.

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