Dynamics in double roll crushers

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**Article Info**

**Abstract**

Double roll crushers (DRC) have the highest throughputs among primary crushers. In the oil sands, the hourly capacity may exceed 14,000 t/h. They are preferably used to comminute medium-hard rock or sticky materials. An unusual tough particle or unbreakable object may effect substantial dynamic forces in a DRC. Considering the large amount of energy stored in the flywheels and the fact that the mass of the floating rolls of the largest machines exceeds 60 t, any unexpected dynamic behavior can be an issue for a safe and reliable operation.

Research is conducted on a small industrial scale smooth DRC at the Institute of Mineral Processing Machines. Results of the crushing force dynamics under extreme conditions, as well as the related product particle size distribution and the influence of the mineral structure of a variety of rocks on the nipping behavior are presented.

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**1. Introduction**

Rolls have been used in comminution since ancient times. Rolls were easy to manufacture, to install and to operate in a wide range of applications. A robust and reliable design, low machine height and an excellent ratio of capacity versus machine mass make double-roll crushers (DRC) still today the preferred choice for many soft to medium-hard rock applications in quarries and ore mines. The principle is particularly suitable for the comminution of wet, sticky or frozen feed material (Höffl, 1984; Wills and Napier-Munn, 2006). With maximum throughputs of up to 14,000 t/h achieved in primary comminution of oil sands in Canada, DRC are among the primary comminution machines with the highest capacities. This draws renewed interest to the technology since a rising world population, coupled with an even faster growing demand for raw materials (BP, 2015) and a tendency towards smaller head grades in ore deposits (Schodde, 2010; Mills, 2015) require technologies capable to efficiently process high throughputs.

Research on DRC conducted so far covers a wide range of topics such as throughput, power consumption, wear, geometry and material of crushing tools, and product particle size distribution. Models derived range from empirical equations (Höffl, 1984) via population balance considerations (Austin et al., 1980, 1981) to simulations based on the Discrete Element Method (DEM) (Schmidt, 2011; Weerasekara et al., 2013; Cleary and Sinnott, 2015). Dynamic conditions of the comminution process in a DRC have rarely been in the specific focus of investigations.

Knowledge on realistic magnitude and dynamic characteristics of those forces is essential to improve the design of machine components such as rolls, shafts, casings and retraction hydraulics and to expand the DRC application into new areas. Moreover, relief systems are usually installed to withdraw the floating roll in case of an overload. Also for the proper design of those systems, knowledge on magnitude and duration of peak-loads in normal operation is essential. The paper presents initial results of investigations on the influence of nip conditions, rotation speed and certain feed material characteristics onto the crushing and bearing forces.

**2. NIP condition**

**2.1. Nip angle and friction factor**

The investigations were conducted on a smooth DRC to exclude influences of the crushing tools (profile, tooth shape, etc.) design on the measurements at this stage. In order to grab a particle between the rolls, the intaking force $F_{in}$ has to be larger than the outpushing force $F_{out}$ (Fig. 1).

The horizontal components of the forces acting from both rolls onto the particle are balanced. Hence, only the vertical components have to be considered. Due to the symmetry, the calculation of these forces shall be shown only for the contact point on one side. The vertical forces mainly consist of forces resulting from compression...
sion and friction. The outpushing force $F_{\text{out}}$ consists of the vertical component $F_{\text{out}}$ of the normal force $F_n$, which is a reaction force (therefore marked with $\perp$) due to the support of the rolls for the particle in point P. The intaking force $F_{\text{in}}$ consists of the vertical component $F_{\text{in}}$ of the friction force $F_f$, which develops as a result of the normal force $F_n$ and the coefficient of friction $\mu$. The weight force $F_G$ can be neglected, since it is substantially smaller than the normal force. The following equations show the relationship

$$F_{\text{out}} = F_n \cdot \sin \left( \frac{\alpha}{2} \right)$$  

(1)

$$F_{\text{in}} = F_f \cdot \cos \left( \frac{\alpha}{2} \right) = \mu F_n \cdot \cos \left( \frac{\alpha}{2} \right)$$  

(2)

where $\alpha$ is the nip angle (Höffl, 1984).

If a particle shall be grabbed, the following condition has to be met.

$$F_{\text{in}} > F_{\text{out}}$$  

(3)

The insertion of Eqs. (1) and (2) in (3) and conversion to $\mu$ results in:

$$\mu > \tan \left( \frac{\alpha}{2} \right)$$  

(4)

In principle, two different friction conditions might be considered: the static friction, characterized by the coefficient $\mu_S$ and the kinetic friction, characterized by $\mu_C$. The static friction defines the case that the particle touches the roll surface with synchronized speed and is taken in instantly. This condition can only be met if the vectors of circumferential speed $v_\theta$ and particle speed $v_m$ point into the same direction (Fig. 2). This is only the case in the crushing gap exactly on the line between the roll rotation centers. The particle comminution itself, however, starts much earlier depending on the particle size, and is already finished at the point of the smallest crushing gap.

In all other cases, the particle hits the roll surface with differential speed. It is sliding over the surface until it has eventually synchronized its speed. In this case, the kinetic friction factor $\mu_k$ has to be considered in calculations. Often, however, only the static coefficient of friction between the particle and the roll surface is given in literature, e.g. for the combination dry rock-steel $\mu_S = 0.3 \ldots 0.35$ (Höffl, 1984), for limestone-steel $\mu_S = 0.24$ or for marble-steel $\mu_S = 0.17$ (Stieß, 1994). With $\mu_S = 0.3$ the resulting nip angle as per (4) would be $\alpha = 33.4^\circ$.

There are only a very few sources to be found in literature for the kinetic coefficient of friction, e.g. for hard abrasive material-steel $\mu_C = 0.22 \ldots 0.24$ (Mölling, 1967) or for rock-steel $\mu_C = 0.22$ (Motek, 1972). Moreover, $\mu_C$ depends on the relative speed of the friction partners. It decreases with increasing peripheral speed of the rolls. The number of publications at least touching speed dependency of the kinetic friction factor in comminution is rather limited (Wills and Napier-Munn, 2006; Schmidt, 2011).

2.2. Feed particle size

The maximum equivalent feed particle size $d_{a,\text{max}}$ can be derived from the following geometric relationship which is obtained from the triangle ABC in Fig. 1:

$$\cos \left( \frac{\alpha}{2} \right) = \frac{R_W + \frac{s}{2}}{R_W + \frac{d_A}{2}}$$  

(5)

With the radius $R_W$ of the roll, the gap $s$ between the rolls, the particle size $d_A$, the trigonometric relation (6) and $R_W = D_W/2$ with $D_W$ as the roll diameter inserted in (5) the maximum equivalent feed particle size $d_{a,\text{max}}$ can be derived with inclusion of (4) from (7).

$$\cos \left( \frac{\alpha}{2} \right) = \frac{1}{\sqrt{1 + \tan^2 \left( \frac{\theta}{2} \right)}}$$  

(6)

$$d_{a,\text{max}} < \left( D_W + s \cdot \sqrt{1 + \mu^2} \right) - D_W$$  

(7)

2.3. Product particle size distribution

With focus on the question of self-similarity in comminution, investigations were conducted with a Dolomite (Ostrauer Kalkwerke GmbH; $\sigma_0 = 94$ MPa; compressive strength values marked with “w” are derived from Point-Load-Tests) (Kichowicz, 2013). In this investigation, next to the Dolomite also Granite and Quartz particles in three different size fractions ($\sim 300$ mm, $\sim 30$ mm, $\sim 3$ mm) were comminuted on various machines to identify similarities in the PSD patterns of the comminution products. The cumulative passing particle size distribution (PSD) from comminution tests in a DRC, a piston-die press (DP) and a jaw crusher (JC)
are normalized to the particle size at 50% passing of the PSD. They revealed that normalized PSD of a smooth DRC product is similar to a single particle comminution product generated by a DP, but not similar to the one of the JC product (Klichowicz, 2013) despite all products are generated by compression loads. The JC product of the Dolomite showed a much sharper PSD (Fig. 3). Thereby, the system reduction ratio was further investigated in a piston die press. It was found that at reduction ratios of 10% the material passes the crushing chamber, with pressure release and reorganization of the material after each compression. In contrast, the comminution in a DRC occurs in one single step. Finally, the influence of the material and the reduction ratio was further investigated in a piston die press. It was found that at reduction ratios of ε = 2.3 the Dolomite did already cake. This is low compared to typical reduction ratios of DRC ranging between 4 and 6 (Höffl, 1984). Thereby, the system reduction ratio εs of the comminution system shall be defined as follows:

\[ \varepsilon_s = \frac{d_{m,\text{in}}}{s} \]  \hfill (8)

with \( d_{m,\text{in}} \) being the average particle size of the particle fraction and \( s \) being the indicated gap.

Fig. 4 shows the results of the test with 4 irregular shaped samples of the size fraction ~300 mm with the caking areas marked. The tests were repeated with Granodiorite (Kindisch, \( \sigma_u = 212 \text{ MPa} \)) and Quartz (Ottenendorf-Okrilla, \( \sigma_u = 190 \text{ MPa} \)). It was found that the caking behavior is material specific. With Quartz, almost no caking could be monitored at the same testing parameter settings. The significantly larger crack release-energy converts into kinetic energy of the fragments. This leads to a long-range, more uniform distribution of the fragments under the piston and complicates the caking.

The forming of the cake even at low reduction ratios explains why the cumulative PSD curve of a DRC is more similar to the one of a piston-die press than to the one of a jaw crusher even in single particle comminution. An agglomerated material bed may resist much higher forces as a single particle of comparable size and of the same material. As a result, the forces acting in a double roller crusher could be much higher, at least locally, as one would expect for normal single particle comminution. This should be true even if the DRC is, as usual, starvation fed with just about 15 per cent of the crushing gap filled with solids.

3. Crushing and bearing forces

For sizing a DRC and its components, the knowledge of the acting forces is essential. There are different ways to predict the forces, in particular the maximum ones. Most commonly, one of the following methods is applied:

– consideration of the maximum transmitted torque,
– consideration of the material’s compressive strength.

The first approach shall be investigated in further detail.

3.1. Forces derived from maximum transmitted torque

The calculation starts with the maximum drive torque, which can be transmitted in the static friction case. The crushing force \( F_{zh} \) and accordingly the horizontal bearing force \( F_{bh} \) are obtained from the equilibrium of moments in the roll center (Fig. 5) (Höffl, 1984):

\[ F_{bh} = F_{zh} = -\frac{M_d}{R_w \cdot \sin \delta} \]  \hfill (9)

with the assumption of \( \delta = \frac{\pi}{4} \) for the angle of resulting crushing force acting on the rolls. For a nip angle of 33.4° this would lead to \( \delta = 8.3^\circ \). The maximum drive torque \( M_{d,\text{max}} \) is obtained from:

\[ M_{d,\text{max}} = \frac{P_{\text{max}} \cdot \omega}{\phi W} = \frac{P_{\text{max}} \cdot \omega}{2 \pi n_W} \]  \hfill (10)

where \( n_W \) is the roll speed.

The power at the roll shaft is \( P_W = \eta_{\text{friction}} \cdot P_{\text{motor}} \) with \( \eta_{\text{friction}} \) as the efficiency factor accounting for the power loss of the drive train and \( P_{\text{motor}} \) as installed power.

\[ P_{\text{max}} = \frac{\eta_{\text{friction}} \cdot P_{\text{motor}} + P_{\text{block}}}{2} \]  \hfill (11)

The blockade power results from the released energy of inertia \( E_{\text{rot}} \) when the rolls stalled in the time \( t_{\text{stop}} \). The literature values for \( t_{\text{stop}} \) range from 0.05 to 0.1 s (Höffl, 1984).

\[ P_{\text{block}} = E_{\text{rot}} \cdot t_{\text{stop}} = \frac{J_{\text{ges}} \cdot (2\pi n_W)^2}{2 \cdot t_{\text{stop}}} \]  \hfill (13)

Other power losses, caused by bearing friction for instance, are neglected to simplify the calculation. Eqs. (12) and (10) are inserted in (9) and \( P_W \) is substituted to get the equation for the maximum bearing force \( F_{bh,\text{max}} \):

\[ F_{bh,\text{max}} = \left( \frac{\eta_{\text{friction}} \cdot P_{\text{motor}} + P_{\text{block}}}{\eta \cdot P_{\text{motor}}} \right) \cdot \frac{1}{\pi n_W \cdot D_w \cdot \sin \delta} \]  \hfill (14)

3.2. Forces derived from material compressive strength

Another method to calculate the crushing force and, accordingly, the bearing force for single particle comminution, is the use of the material compressive strength. Since the PLT-index \( I_{\text{PLT}} \), generated with the point load test (PLT), shows a good correlation to the unconfined compressive strength (UCS) this value is often used to describe the material strength. In this paper compressive strength values derived from PLT results are marked with "\( w \)".

![Fig. 3. Normalized cumulative passing PSD of Dolomite (colored graphs: piston-die press product (DP) with remaining gap indication, feed particle size ~300 mm (red), ~30 mm (blue), ~3 mm (green); black graphs: DRC product (DRC) and jaw crusher product with crushing gap indication (feed size 25–30 mm)); (Klichowicz, 2013).](http://dx.doi.org/10.1016/j.mineng.2016.08.009)
The force at the PLT is introduced between two round tipped cones, so there is a point to point load condition. The load conditions in the roll crusher, however, are usually point to face or face to face load conditions, which cause a larger contact area and therefore a slightly higher breaking force to be considered by a conversion factor (Schmidt, 2011). The method shows good results, however, for single particle crushing and low comminution ratios.

The breaking force $F$ can be estimated using the following equation after conversion (Popov, 2007):

$$I_{S(50)} = \frac{F}{D_e} \left( \frac{D_e}{50} \right)^{2(1-m)} \text{ in MPa}$$

(15)

$F$ is the breaking force in [kN], $D_e$ is the equivalent diameter of a fracture surface equal circle in [mm] and the parameter $m$ is the gradient of the regression line $\lg F = m \cdot \lg D_e^2 + b$. The parameters $m$ and $b$ are material specific. The maximum force can be calculated with the known material parameters and the particle size taken into account by $D_e$.

4. Experimental investigations

The aim of the investigations is to determine the magnitude and dynamics of the bearing forces and their dependencies on the crushing gap, the feed particle size and the material properties.

4.1. Experimental setup

Fig. 6 illustrates the smooth DRC of the Institute of Mineral Processing Machines at the TU Bergakademie Freiberg which is used for the experimental investigations. The housing consists of a central and two lateral parts per side, which hold the bearings of the rolls. The central part (2) is mounted to the base frame (1). Two pull rods (5) on each side brace the lateral parts (3) and (4). The two rolls (6) and (7) are both configured as solidly mounted rolls. There is no floating roll (Fig. 7), as it is in a common DRC. The gap between the rolls can be adjusted by two worm gears (9). A scraper (10) at each roll removes material, if it sticks on the rolls. The basic technical parameters of the machine are presented in Table 1.

The forces $F$, which occur due to the comminution process (Fig. 7), are transmitted via the rolls, the bearings and the housing parts (3) and (4) to the pull rods (5). Their straight geometry results in a simple linear stress field with a linear strain correlation. Strain gauges (6) are applied in the middle of the rods to measure these strains. Two T-rosettes with grids, perpendicular to each other, are bonded on each pull rod on the upper and lower side. They are connected to a full bridge to compensate interference factors and bending. All four pull rods are equipped with strain gauges to measure the total crushing force.

4.2. Test program

The initial trial tests were conducted with various mineral materials (see Table 2) and a narrow gap of $s = 0.5$ mm. The aim was to identify the test material with the best nipping behavior, allowing the widest range of reduction ratios for the following investigations.

Four size fractions (5.6/6.3 mm; 11.2/12.5 mm; 16.0/20.0 mm and 20.0/22.4 mm) were tested at three different rotation speeds (85; 113 and 127 RPM). With each parameter set, 50 particles of each material were comminuted separately one by one. The best nipping behavior could be documented for the limestone with even the largest size fraction being drawn in at the highest speed.
at once. The flakes produced are shown at Fig. 8. The thickness of the flakes was between 2.5 and 3.0 mm.

The other materials showed a worse nipping behavior. Granodiorite particles up to 20.0 mm size were nipped at speeds of up to 113 RPM. Greywacke particles were nipped immediately only with the lowest rotation speed. With Amphibolite even at the lowest speed only particles up to 12.5 mm size were nipped at all. The crushing forces for the different materials showed quite a different behavior, which cannot hardly be related to the compressive strength. The highest crushing forces were determined for the Limestone, the material with the least strength. An explanation is agglomeration, which generates particularly high local forces when the flakes are formed. The other three materials showed different, in general less, tendency to cake. Therefore, also the crushing forces were smaller.

According to the results from the first test series, the following tests were conducted with limestone from the quarry Bad Kösen, Germany, at a peripheral speed of both rolls was 3.0 m/s (at 127 rpm). The gap $s$ was varied in the range of 0.2–6.9 mm. The feed particle size $d_A$ ranged from 5.6 mm to 31.5 mm (Table 3). In order to further reduce influences from particle size differences the particles within the fractions were weighted. Only those within the indicated mass limits were used for the tests. The reduction ratios $e$ varied from 4.1 to 26.5. At least 50 single particles were comminuted for each parameter setting. The tensile force of all four pull rods was measured with Wheatstone bridges in parallel and recorded in 0.5 ms increments.

### 4.3. Results and discussion

The tensile forces from the four pull rods were summarized to get the total horizontal force $F_{\text{max}}$ of each comminuted particle. Furthermore, for each parameter setting the average value $F_{\text{max},m}$ of the total horizontal forces from all respective particles was calculated.

### 4.4. Correlation between maximum average total force $F_{\text{max},m}$ and gap $s$

The correlation between $F_{\text{max},m}$ and the gap $s$ between the rolls is shown in Fig. 9 for four different feed particle sizes. $F_{\text{max},m}$ increases in a logarithmic scaling linearly with increasing gap $s$. Respectively, for a given feed particle size the crushing force increases exponentially with the narrowing of the gap. The smaller the feed particle size the steeper is the increase of the forces for the reduction to the same gap size. This may be related to the known size dependency of compressive strength.

### 4.5. Maximum total force $F_{\text{max}}$

The maximum average total force $F_{\text{max},m}$ of the tests reaches 200 kN in the particle size fraction 20.0/22.4 mm at a gap of 0.8 mm. Maximum total forces $F_{\text{max}}$, however, peaked in specific cases at more than 300 kN. These large forces can be explained...
with the generation of a material bed due to the large reduction ratios \( e = 26 \) and the material specifics of the limestone. Contrary to choke fed HPGR with a solids content of 85% in the gap and a respective wide particle bed, the caking with the starvation fed DRC (single particle breakage) happens only in narrow localized spots. As shown, the forces acting onto these spots may be substantial, however.

The maximum bearing forces measured shall be compared with respective values occurring during roll blockage as per Eq. (14). With \( n_W = 124 \text{ min}^{-1} \), \( t_{\text{stop}} = 0.05 \text{ s} \), \( J_{\text{ges}} = 12 \text{ kg m}^2 \), \( \eta_g = 0.9 \), \( P_{\text{motor}} = 15 \text{ kW} \) for each drive, \( D_W = 449.5 \text{ mm} \) and \( \delta = \pi/4 = 8.4^\circ \), the maximum bearing force would be calculated according to the literature to 79 kN. This value makes up about one quarter only of the maximum force \( F_{\text{max}} \) from the experimental tests, despite during the tests roll blockage never occurred.

The angle \( \delta \) of the resulting crushing force \( F_{\text{Zn}} \), besides the assumed time for the blockage \( t_{\text{stop}} \) the most uncertain variable in Eq. (8), is recommended in literature with \( \delta = \pi/4 \) (Höffl, 1984). The angle of resulting crushing force during confined particle bed comminution on HPGR is given in literature with a range of 1.7–2.9° (Kleeberg, 2007).

Tests were conducted with the drive uncoupled from the crusher just before the crushing event to measure the slight deceleration during crushing. This allows the calculation of the energy consumption for comminution. 50 samples of limestone (Bad Kösen, as per Table 2) were tested at a nominal speed of 124 RPM and \( s = 2.0 \text{ mm} \) gap width. Samples were again narrow fractioned (by size and weight) in the 20.0/22.4 mm fraction (see Table 3 and Fig. 10). Forces and roll rotation speeds were recorded in increments of 0.5 ms.

Fig. 11 shows a typical graph with data recorded during the comminution of one of the particles. It indicates the total pull rod force (blue line) and the roll rotation speed (orange line) versus the rotation angle \( \delta \). As often applied when showing the comminution forces in an HPGR, also in this graph the y-axis represents the independent variable (angle \( \delta \)), while the total pull rod force \( F \) and the roll speed \( n_1 \) are shown on the x-axis. Thereby, a positive \( \delta \) is above the horizontal line between the roll rotation centers and a negative \( \delta \) below this line. Despite the nipping of the particles as per particle size, gap and roll diameter should start at an angle of \( \delta = 11.3^\circ \), see Eq. (5), forces were hardly measurable until the angle falls below \( \delta = 5^\circ \). The force sharply spikes below \( 5^\circ \) to reach its maximum at around \( \delta = 2.5^\circ \). This figure for \( \delta \) is far below the values indicated for DRC and falls well into the range of HPGRs.

When considering the peak force acting at \( \delta = 2.5^\circ \), the sharp slowing down of rolls in the last 0.5 ms prior to the peak (in this case from \( n_{1.1} = 95.3 \text{ min}^{-1} \) to \( n_{1.2} = 94.0 \text{ min}^{-1} \)) as a measure for

![Fig. 11](https://example.com/figure11.png)

**Fig. 9.** Correlation between maximum average total force \( F_{\text{max},\text{a}} \) with standard deviation and the gap \( s \) for several particle size fractions; particle size fractions given in mm (Hillmann et al., 2015).

Table 3

<table>
<thead>
<tr>
<th>Particle size fraction [mm]</th>
<th>5.6/6.3</th>
<th>11.2/12.5</th>
<th>20.0/22.4</th>
<th>25.0/31.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle mass [g]</td>
<td>0.3–0.4</td>
<td>2.3–2.8</td>
<td>15.6–17.9</td>
<td>22.3–26.7</td>
</tr>
</tbody>
</table>

![Table 3](https://example.com/table3.png)

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the modified Eq. (14) can be calculated to \( F_{th} = 314 \text{ kN} \). This value almost matches the measured maximum total force shown in the graph of Fig. 11. It can be considered as another hint to similarities in the comminution between DRC and HPGR.

5. Conclusion and outlook

The development of the peak forces close to the crushing gap center similar to the HPGR as well as the local formation of a particle bed due to caking is seen as the reason for peak loads in DRC. These peak loads may even occur in case of very local agglomerating events and may cause high loads on respective spots of the crushing roll. That is why it may be recommendable to consider local agglomerating also in the case of designing other DRC than just the smooth faced ones. As already described by Klichowicz et al. (2014) formation of a particle bed substantially depends on the characteristics of the material to be comminuted, of course, and may occur for certain materials even at rather low comminution ratios.

The peak forces on the DRC are extremely short time events. In the investigated case, they usually lasted for just around 20–35 ms. This issue should be further investigated for larger toothed DRC. The time measured in the investigations is certainly substantially shorter than considered for the roll relieve devices in most of today’s larger DRC.

The nipping behavior not only depends on geometrical data of the rolls, the particles and the commonly used static friction factor. The kinetic friction factor considering the influence of relative speed of the friction partners will have to be used. Further investigation on kinetic friction factors of various mineral materials is recommended.

References