Design, Fabrication and Testing of a Double Roll Crusher

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Abstract- A developing nation like Nigeria, with huge deposit of different solid minerals and rocks, needs to explore the processing of these solid minerals to reduce dependence on petroleum. The old ways of stone crushing by hand is still being practiced in several villages and towns in Nigeria. Design and production of an indigenous roll crusher from locally available materials for low hardness rocks was carried out in this work. The throughput capacity of the machine was 1.43tonnes/hour. The theoretical efficiency of the double roll crusher when crushing limestone was 60% while that of kaolin was 80%.

Keywords: *Double roll, crushing, Particle size, design analysis, solid mineral.*

1. Introduction

Crushing" and "grinding" have been in use since the beginning of human existence.

The old ways of crushing is stressful, less efficient, and less productive, leading to poor size reduction and non uniformity of products [1]. Various modern crushing techniques have their applications in many areas such as food processing, cement production, metallurgy applications, chemical industries, electric power generation and construction [2]. A developing nation like Nigeria, with huge deposit of different solid minerals and rocks, needs to explore the processing of these solid minerals to reduce dependence on petroleum [3]. Design and production of an indigenous roll crusher for low hardness rocks provides impetus for industrial growth.

Size reduction equipment are classified into crushers and grinders. Crushers are used for reducing large solid materials into feed sizes for grinding. The input and output particle sizes distinguish crushing from grinding rather than mechanism of size reduction [4]. There are primary and secondary crushers. A primary crusher reduces large particles into smaller sizes for further crushing by the secondary crusher. Examples of crushers include jaw crusher, gyratory crusher and roll crusher. A double roll crusher consists of two rolls. Crushing takes place between two cylindrical rolls with each rotating about a concentric horizontal shaft in opposite directions. This is the most common of all roll crushers.

Grinding machines are used for reducing crushed particles into their smallest functional sizes. Examples of grinders include attrition mills, roll-compression mill, fluid energy mill and ball mills [5].

The crushing of any particle takes place when the applied external forces are greater than the cohesion among molecules of a particle. The force of cohesion is decided by property and structure of the material's own crystal, the cohesion inside crystal can be calculated in theory according to crystal's structure and property of particles' mutual force. Size reduction is measured by a reduction ratio, defined as,

$$r = \frac{\text{Seive size through which 80\% particles passes before crushing}}{\text{Seive size through which 80\% particles passes after crushing}}$$

The energy consumption for crushing an ore is a function of its hardness, feed sizes and product sizes. The standard measure of energy demand is Bond work index. The work index, w_i, represents the kilowatt hours per tonne required to reduce the material from theoretically infinite feed size to 80 percent passing 100μm [4].

2. Design Analysis and Calculations

2.1 Roll Crusher Geometry

It is necessary to estimate the maximum size of the mineral particles that can be fed into the machine for a known roll diameter, roll length and roll gap. It is convenient to assume that the particle is spherical and the roll surfaces are smooth when calculating for the maximum size of the particle feed.

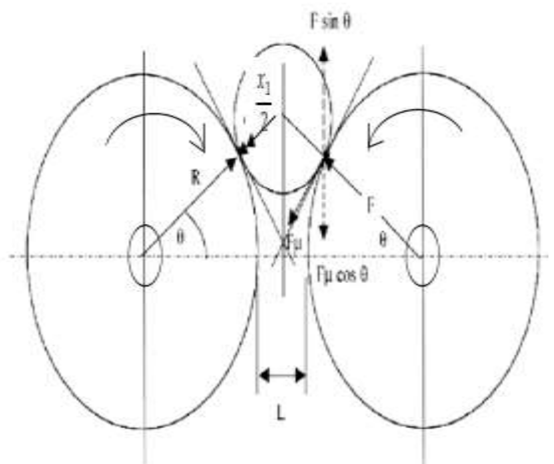

Figure 1: Double roll crusher geometry

Figure 1 is the geometry of a double roll crusher with a spherical particle about to enter the crushing zone of a roll crusher and is about to be nipped [4], [5]. For rolls that have equal radii and length, tangents drawn at the point of contact of the particle and the two rolls meet to form the nip angle (2θ). By simple geometry the nip angle (2θ) between two rolls of radius R, the size of the particle to be crushed i.e. size of the feed (x_1) and the distance between the two rolls (L) is given by,

$$\text{Cos } \theta = \frac{\left(R+\frac{L}{2}\right)}{\left(R+\frac{x_1}{2}\right)} \quad (2)$$

where, x_1 =diameter of feed particle, R = radius of the rolls, L =distance between the two rolls (roll gap). Thus x_1 becomes,

$$x_1 = 2\left(\frac{\left(R+{}^{L}/_{2}\right)}{\cos\theta} - R\right) \quad (3)$$

Equation 2 indicates that to estimate the diameter of the feed x_1 , the nip angle is required. The nip angle (2θ) on its part depends on the coefficient of friction μ between the roll surface and the particle surface. The relationship between compressive force, F, coefficient of friction, μ and nip angle is given by,

$$F \sin\theta = F \mu \cos\theta \quad (4)$$

Dividing both sides by F

$$\sin\theta = \mu \cos\theta$$

$$\mu = \tan\theta$$

$$\theta = \tan^{-1}\mu \quad (5)$$

Average coefficient of friction μ of low hardness rocks (hardness number 1 to 4 on the moh's hardness scale) in contact with steel is between 0.2 and 0.3 [5]. Adopting, the lower limit,

$\theta = \tan^{-1}\mu$ = 11.31degrees.

The nip angle 2θ = 2 × 11.31 = 22.62 deg.

2.1.2 The Diameter of Rolls, Width of Rolls and the maximum Roll Gap

These dimensions are design decisions which depend on desired input particle size, the feed rate and maximum output particle size. The specification for *D* is 120mm, width, W, of each roll is 150mm, and the maximum roll gap, l, is 5mm.

2.1.3 Maximum Size of the Particle that can be Fed into the Roll Crusher

The maximum size of the particle that can be fed into the roll crusher is determined by the radius of the roll R, roll gap, L and the angle of nip 2θ.
From Equation (3), the maximum size of the particle (x_1) that can be fed into the machine is,

$$x_1 = 2\left(\left(\frac{60+{}^{5}/_{2}}{\cos 11.31}\right) - 60\right) = 7.5\text{mm}$$

2.1.5 Thickness of the Roll

A hollow cylindrical shaft is used to build the roll, this hollow shaft's thickness must be calculated to check for its ability to withstand the compressive strength of the hardest of all the rocks [6].

$$\sigma_t = \frac{P \times d}{2t} = \quad (7)$$

$$t = \frac{p \times d}{2\sigma_t} \quad (8)$$

where, t = thickness of the roll
σ_t = tensile strength of the roll
p = Roll pressure

Substituting into Equation (8)

p = 20MPa [4], $d = 120mm$, σ_t = 410MPa and a design factor of 1.4 to account for the wide range of rock harness, yields,

$$t = \frac{20 \times 120}{2 \times 410} \text{x}1.4$$

t = 6.74mm, say 8mm plate.

2.1.6 Weight of the Roll

The weight of the roll can be calculated as follow

$$W_{ROLL} = \rho.V.g = m \quad (8)$$

$$V = \left(\frac{\pi D^2}{4} - \frac{\pi {d_i}^2}{4}\right) l + 2\left(\frac{\pi d^2}{4}\right)t \text{ and } m = \rho\left(\left(\frac{\pi D^2}{4} - \frac{\pi {d_i}^2}{4}\right) l + 2\left(\frac{\pi {d_i}^2}{4}\right)t\right)$$

$$W_{ROLL} = \rho\left(\left(\frac{\pi d^2}{4} - \frac{\pi {d_i}^2}{4}\right) l + 2\left(\frac{\pi {d_i}^2}{4}\right)t\right) \times g \quad (9)$$

where, W_{ROLL} = Weight of the roll, N; m = Mass of the roll, kg; ρ =Density of the roll, kg/m^3; D=Outer diameter of roll; d_i = inner diameter of roll; V= Volume of the roll, m^3; g= Acceleration due to gravity, m/s^2. Substituting yields,

$$W_{ROLL} = 7850\left(\left(\frac{\pi \times 0.12^2}{4} - \frac{\pi \times 0.10^2}{4}\right) 0.15 + 2\left(\frac{\pi \times 0.10^2}{4}\right) 0.01\right) \times 9.81$$

$$W_{ROLL} = 105.24N$$

2.1.7 Rotating Speed of the Rolls

The choice of roll speed affects the production rate [5]. Low speed is required for large diameter rolls, while for smaller rolls high speed is required. Wills and Napier Munn, [4] indicated that peripheral speed of rolls range from 1m/s for small rolls to 15m/s for the largest rolls. Also chain drive to be used has maximum reduction ratio of 5:1 [7]. Since low speed motor to be used runs at 1400 rpm, an initial speed of 280 rpm corresponding to this ratio was used. The peripheral speed was checked for closeness to the lower boundary of the range since the roll diameter is small. Angular speed of rolls is,

$$\omega = \frac{2\pi N}{60} = \frac{2\pi 280}{60} = 29.322\text{rad/s}$$

Therefore the peripheral speed of rolls (v= rω) equals 1.76m/s. This was considered close enough for a prototype roll crusher.

2.1.8 Capacity of the Roll Crusher

The capacity Q, of roll crushers is directly proportional to its width, W, diameter, D and the speed of revolution of rolls. Under continuous and steady feeding conditions the capacity is given by the following [4], [5].

$Q = \pi\ 60\ D\ W\ N\ L\ \rho$

$Q = 188.5\ D\ W\ N\ L\ \rho\ \ (t/h)$ 11

where, $D = 0.120$m, W = Width = 0.15m

N =angular speed of the roll, rpm = 280 rpm

L = Distance between rolls (roll gap), m, 0.005 m

ρ = Bulk specific gravity of the mineral, $^{kg}/_{m^3}$

Gupta and Yan [5] indicated that the operating density of roll crushers are low (0.15– 0.3)

Substituting yields a capacity, Q = 1.430 t/hr.

The actual capacity of roll crushers is only about 25% of the theoretical value due to voids between particles and loss of speed in gripping the feed particle [4], [5]. Thus the actual capacity, Q = .356 t/hr

2.1.9 Crushing Power

The required crushing power is a function of Bond work index, capacity and the reduction ratio. Adopting Gupta and Yan [5] the power is given by,

$P = Q.R_d.w_i$

where Q = crushing capacity, Rd = reduction ratio (x_1/x_2) and wi = work index. In this work Q = .356 t/hr and x_1 = 7.5mm. A roll gap of 5mm had already been specified and x_2 is less than or equal to this value. Maximum power is drawn for x_2 = 5mm Thus Maximum power requirement for limestone, with w_i of 7 kWh/t [8] becomes,

P = .356 x 1.5x 7 = 3.74kW.

Electric motors are rated in horsepower. Thus motor power required becomes 5hp.

2.1.10 Torque on the Shaft

The shaft power is product of shaft torque and speed. That is,

$P = T\omega$ and

$$T = \frac{P}{\omega} \qquad (12)$$

where P = Power required, T = Torque on the shaft and w = Angular speed of the shaft.

Substituting, P = 3.74kW, w = 29.322rad/s, torque was found to be 127.55 Nm.

2.1.11 Selection of the Chain Drive

The speed ratio is 5:1, and a sprocket teeth should not be less than 21 on the small sprocket for moderate speed [7], [9]. The sprocket on the motor shaft must be larger than 5hp motor shaft. Thus a first design size of 50mm was used. The pitch p is given by

p = d(Sin {180/N})

where N is the number of sprocket teeth. Substituting N=21 and d= 50mm yielded a pitch value of 7.5mm. This is greater the pitch of number 25 standard chain but less than number 35 chain. However the 35 Number chain is not readily available and hence the number 40 ANSI chain with a pitch of 12.5mm was used. Mott [7] indicates that a number 40 chain on a sprocket of 21 teeth has a rated power of 9.31hp at a speed of 1400rpm. Accounting for the usual shock load associated with milling, the actual load designed for was obtained by multiplying 5hp with 1.5 [7]. Thus the anticipated service load on chain is 7.5hp. Since the rated power is greater than the service load the selected chain is adequate.

2.1.12 Design Calculation of Shaft Diameter Design based on Strength

The shaft diameter according to standard practice [7], [6], [9] is,

$$D^3 = \frac{16}{\pi S_s}\sqrt{(k_b M_{max})^2 + (k_t M_t)^2}$$

Data

$K_b = 1.5,\ K_t = 1.0$

$S_s = 40MN/m^2$(Shear stress for mild steel)

$M_{max} = 43.7Nm,\ M_t = 137.21Nm$

$D^3 = \frac{16}{\pi\times40\times10^6}\sqrt{(1.5\times43.7)^2 + (1\times137.21)^2}$

$D^3 = 1.273X10^{-7}\sqrt{4296.80 + 18826.58}$

$D^3 = 1.94\times10^{-5}$

$D = \sqrt[3]{1.94\times10^{-5}}$

$D = 0.02686m$

$\therefore D = 26.9mm$

Design Calculation of Shaft Diameter based on Torsional Rigidity

From Equation 3.26

$$D^4 = \frac{584\,M_t L}{G\theta}$$

Data

$M_t = 137.21Nm$

$l = 500mm = 0.5m$
$\theta = 0.5$
$G = 80 \times 10^9 Nm^{-2}$
$D^4 = \frac{584 \times 137.21 \times 0.5}{80 \times 10^9 \times 0.5}$
$D^4 = 1.002 \times 10^{-6}$
$D = \sqrt[4]{1.002 \times 10^{-6}}$
$D = 0.0316m$
$\therefore D = 31.6mm$
Hence a shaft diameter of 32mm is selected for this design.

3. Fabrication and Testing

The crushing chamber was fabricated from a mild steel sheet of uniform thickness 3mm. The mild steel sheet was cut to shape and all the parts were joined together using electric-arc-welding. The bottom of the crushing chamber is connected to the spout by bolts and nuts to make the rolls easily accessible for maintenance while the top of the crushing chamber was attached to the feed hopper through electric arc-welding. Various welding positions were used depending on the parts to be joined together.
The two rolls were fabricated using a 10mm metal steel, that was rolled into the desired diameter of 120mm. Eight metal rods of 3mm were welded to the circumference of the roll to increase the grip between the rocks and the roll.

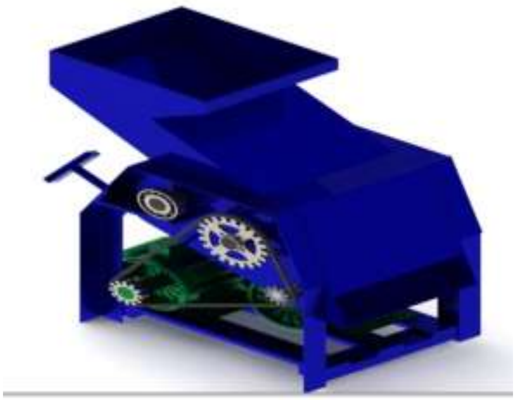

Figure 1: The fabricated double roll crusher.

4. Results and Discussion

After the completion of the fabrication of the machine, the machine was tested to check for its workability and efficiency. The conformability of the machine to the design was also checked and the results were noted.

The roll crusher was tested with limestone and kaolin, the feed and product size was compared with the theoretical feed and product size.
When an average feed size of $55mm$ was fed into the hopper of the roll crusher, the particle size analysis of the products is presented in Table 1

Table 1: Random particle size of products

CRUSHED LIMESTONE SIZES (mm)	CRUSHED KAOLIN SIZES (mm)
43.2	40.2
39.1	38.9
38.2	34.6
48.4	38.9
47.6	24.5
23.4	26.7
46.7	37.5
37.5	44.5
39.1	46.7
38.4	39.2

Average Product size of Limestone = was found to be 38.16mm while that of kaolin was 37.17

4.1 Efficiency of the Roll Crusher

The theoretical efficiency of the crusher was based on the ratio of actual size reduction to the total number of particles that passed through the sieve,
Efficiency of Crushing
$= \frac{\text{Total number of particles that passed through the sieve}}{\text{Total number of particles expeted to pass}} \times 100\%$
Efficiency in Crushing limestone was found to 60% while that of kaolin was 80%.

5. Conclusion

The design, fabrication and testing of a double roll crusher from locally available materials for low hardness rocks was successfully carried out in this work. The throughput capacity of the machine was 1.43tonnes/hour. The theoretical efficiency of the double roll crusher when crushing limestone was 60% while that of kaolin was 80%.
A further development on this work is required to open up the solid mineral sector for affordable processing.

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