PROC 5071:
Process Equipment Design I

Size Reduction

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1 Size Reduction

- Size reduction is the process of reducing the particle size of a substance to a finer state of subdivision to smaller pieces to coarse particles or to powder.
- All ways in which particles of solids are cut or broken into pieces are applicable to size reduction.
- Size reduction process is also referred to as comminution and grinding.
- When the particle size of solids is reduced by mechanical means it is known as milling.

1.1 Why is size reduction needed?

- Raw materials often occur in sizes that are too large to be used and, therefore, they must be reduced in size.
  - Chunks of crushed crude ore are crushed to workable size.

- Commercial products must often meet stringent specifications regarding the size and sometimes the shape of the particles they may contain
  - Synthetic chemicals are ground into powder.
  - Sheets of plastics are cut into tiny cubes or diamonds.
- Particles size is often reduced to increase specific surface area.
  - to increase adsorption.
  - to increase reactivity
- The mixing of several solid ingredients is easier and more uniform if the ingredients are reduced to same particle size.
- Particle size is sometimes reduced to permit separation of unwanted ingredients by mechanical methods.
- Size reduction reduces the bulk of fibrous materials for easier handling and waste disposal.

1.2 Why is size reduction important?

- For particulate solids, size of the particles affects the material properties
  - flow properties
  - compactness
  - dissolution and suspension
  - aerosol
- Often particle size is used as a quality indicator
- Industry specific examples
  - appearance and gloss of paint
  - flavor of cocoa powder
  - reflectivity of highway paint
  - hydration rate and strength of cement
  - properties of die filling powder
  - absorption rates of pharmaceuticals
  - appearances of cosmetics

2 Factors affecting size reduction

2.1 Hardness

- Hardness is a measure of how resistant solid matter is to localized plastic deformation when a force is applied
- A material's ability to withstand friction, essentially abrasion resistance, is known as hardness
- Graphite is soft, diamond is hard; metals are hard, wood and plastics are soft
- It's a surface property
- A material can be hard but brittle
- The harder the material the more difficult it is to reduce in size
- Harness is often described in the so called Mohr's scale

2.2 Toughness

- Toughness is the ability of a material to absorb energy and plastically deform without fracturing

- A soft but tough material may present more problems in size reduction than a hard but brittle substance
- It is difficult to break rubber than a stick of blacboard chalk
- Diamond can be very hard, however, you can easily break it with a hammer

2.3 Abrasiveness

- Abrasiveness is a property of hard materials that allows it to go into the makeup of other objects
- An abrasive grain contains many sharp projection cutting edges or points
- This property is important for the use of abrasive material to shape or finish a workpiece through rubbing, which leads to part of the workpiece being worn away by friction
- For size reduction this property is important because an abrasive material can abrade the

size reduction equipment and thus get contaminated

- Also it may limit the use of certain type of machinery

2.4 Stickiness

- Stickiness is a property of soft materials that results in its sticking to other things
- Stickiness causes considerable difficulty in size reduction, for material may adhere to the grinding surfaces, or the meshes of the screen may become choked
- However, lack of stickiness can cause slipperiness which can also be problematic in size reduction by lowering the efficiency of grinding surfaces

2.5 Softening temperature

- For some materials, softening can happen beyond certain temperature
- Waxy or substance with oil and fat contents may have significant softening
- Softening can affect the size reduction operation
- Cooling of the equipment may be required for proper operation

3 Commonly used mechanisms of size reduction

Four commonly used mechanisms are used in size reduction equipment

3.1 Compression

- the material is crushed by application of pressure

- Example: a nutcracker
- used for coarse reduction of hard solids
- gives relatively few fines

3.2 Impact

- Example: a hammer
- impact occurs when the material is more or less stationary and is hit by an object moving at high speed
- or when the moving particle strikes a stationary surface. In either case, the material shatters to smaller pieces.
- Usually both will take place, since the substance is hit by a moving hammer and the particles formed are then thrown against the casing of the machine.
- gives coarse, medium and fine products

3.3 Attrition

- the material is subjected to pressure as in compression, but the surfaces are moving relative to each other, resulting in shear forces which break the particles.
- example: a file
- attrition yields very fine particles from soft, non-abrasive materials

3.4 Cutting

- Cutting machinery is simple, consisting of rotating knives in various arrangements.
- The knives are kept sharp so that they cut rather than tear.
- example: a pair shears, bowl chopper in which a flat bowl containing the material revolves beneath a vertical rotating cutting knife.
- gives a definite particle size and sometimes a definite shape with few or no fines

- the material is cut by means of a sharp blade or blades

4 Equipment for size reduction

Size reduction equipment are broadly classified into four categories. However, this classification not based on the size reduction mechanisms discussed previously. Some equipment use a combination of these mechanisms for size reduction.

4.1 Crushers

- Crushers are low speed machines to do the heavy work of breaking large pieces of solid materials into small lumps.
- The characteristic mechanism of crushers is compression.
- Widely used in mining, cement production and similar large-scale operations.
- Examples

- ○ Jaw crusher
- ○ Gyratory crusher
- ○ Smooth-roll crusher
- ○ Toothed-roll crusher

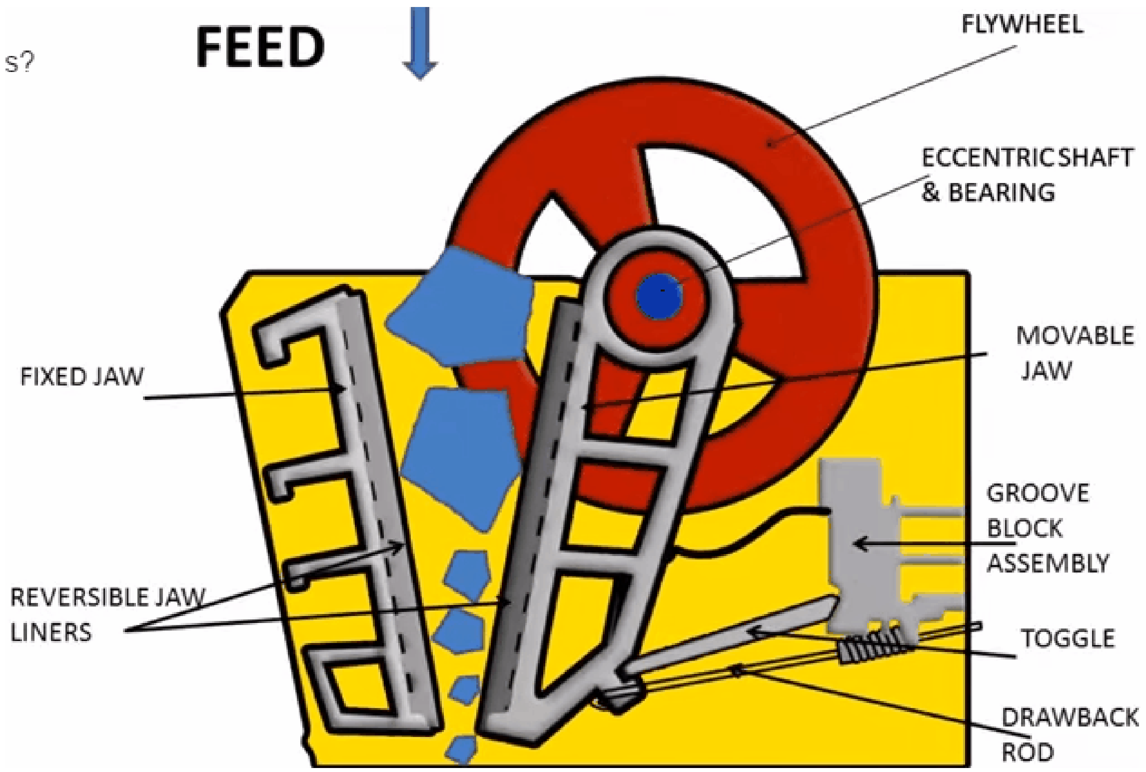

Figure 1: SChematic of a jaw crusher.

4.2 Grinders

- Grinders reduce crushed feed to powder.
- Grinders employ impact and attrition, sometimes combined with compression.
- Examples

- Hammer mill
- Roller mill
- Attrition mill
- Tumbling mill

4.3 Ultrafine grinders

- Ultrafine grinders operate primarily by attrition.
- Specially configured grinders e.g. hammer mills with classifier can act as ultrafine grinders that reduce solids to that fines.
- Examples
  - Classifying hammer mill
  - Fluid energy mill
  - Agitated mill
  - Colloid mill

4.4 Cutters

- Some materials are too resilient to be broken by compression, impact or attrition

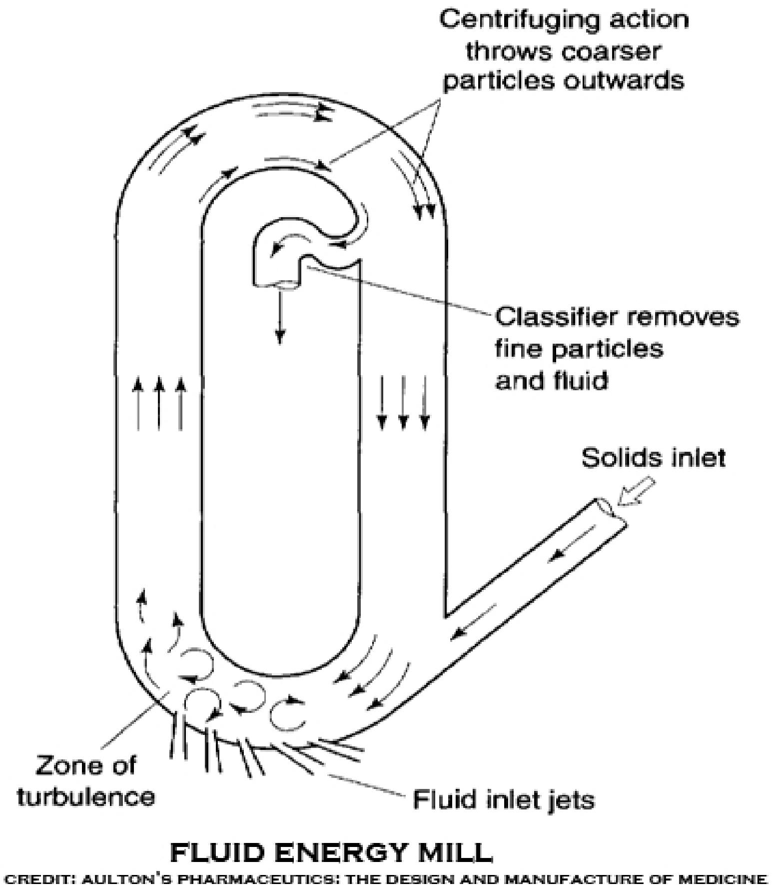

Figure 2: Schematic of a Fluid Energy Mill.

- For some products, precise size and shape need to be maintained.
- Cutting equipment are most suitable for the above cases
- Examples
  - Granulator
  - Cutter
  - dicer
  - slitter

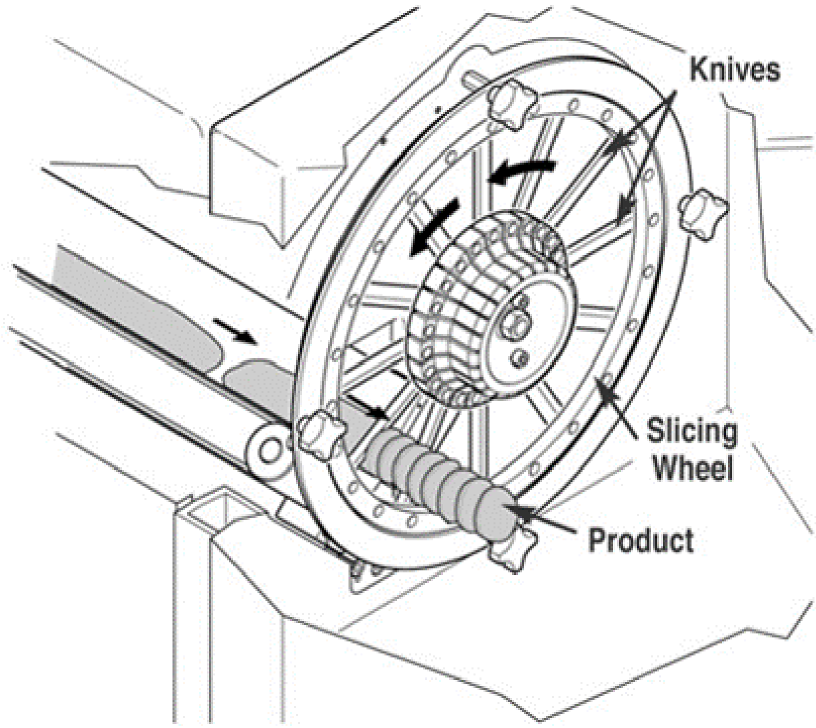

Figure 3: Schematic of a Rotary Knief Cutter.

4.5 Typical product size from different equipment

5 The ball mill

- The ball mill is a type of tumbling mill.
- Tumbling mills are specially preferred for intermediate and fine grinding.
- Tumbling mills are classified based on the grinding medium.
- In a rod mill the medium is rods; in a pebble mill the medium is flint pebbles or porcelain or

Table 1: Product size from different equipment

Equipment	Size ranges
Crushers	
Primary crusher	$150 - 200mm$
Secondary crusher	$\sim 6mm$
Grinders	
Intermediate grinder	40-mesh
Fine grinder	200-mesh
Ultrafine grinders	$1 - 50\mu m$
Cutters	$2 - 10mm$

zircon spheres.

5.1 Operational procedure

- In a typical ball mill, a cylindrical shell slowly turns about a horizontal axis.
- The shell is filled to about one-half of its volume with balls, the grinding medium.
- The shell is usually steel, lined with high-carbon steel plate, porcelain, silica rock or rubber.
- The balls are of metal, rubber or wood.

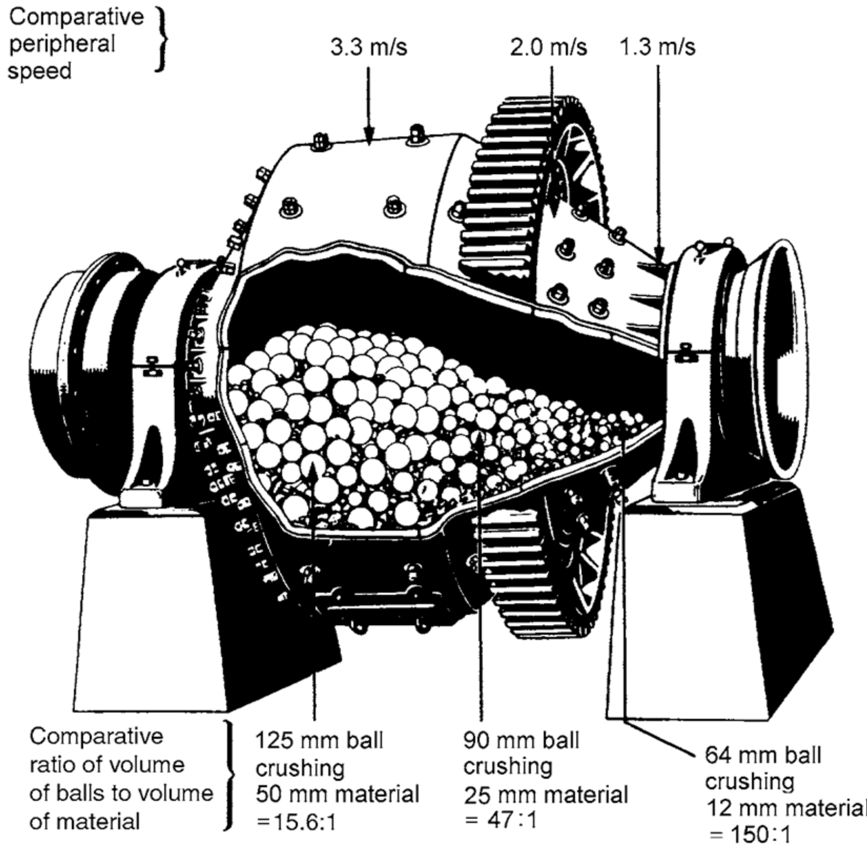

Figure 4: A conical ball mill.

5.2 Mode of operation

- Ball mills and other tumbling mills can be operated both in continuous and batch mode.
- In a batch mode a measured quantity of the solid to be ground is loaded into the mill through an opening, the opening is then closed and the mill is turned for several hours; it is then stopped and product is discharged.
- In a continuous operation, the solid flows steadily

through the revolving shell.

5.3 Mill size

- In a large ball mill, the shell might be $3\ m$ in diameter and $4.25\ m$ long.
- The balls are 25 to $125\ mm$.

5.4 Mechanism of size reduction

- When the mill is rotated, the balls are picked up by the mill wall and carried nearly to the top.
- Centrifugal force keeps the balls in contact with the wall and with one another during the upward movement.
- While in contact with the wall, the balls do some grinding by slipping and rolling over one another.
- When they break the contact with the wall, the balls fall to the bottom.

- Most of the grinding occurs due to the impact resulting from the fall of the balls.
- In a rod mill, much of the reduction is done by compression and attrition as the rods slide downwards and roll over one another.

5.5 Operational limit and the critical speed

- The faster the mill is rotated, the further the balls are carried up inside the mill and the greater the power consumption and the capacity.
- If the speed is too high, the balls are carried over and the mill is said to be centrifuging.
- The speed at which centrifuging occurs is called the critical speed.
- The critical speed, n_c, may be found from the equation

$$n_c = \frac{1}{2\pi}\sqrt{\frac{g}{R-r}} \tag{1}$$

where, g is the acceleration of gravity, R is the radius of the mill, and r is the radius of the grinding elements.

5.6 Factors affecting ball mill operation

- Mill speed: Mill speed between 65 and 75% are suitable
- Ball load: Typical ball load is between 30% and 50% of the mill volume
- Ball size: Minimum-size balls capable of grinding the feed give maximum efficiency. Ball size with a distribution based on feed size distribution is found to be effective.
- Feed rate: Material filling equal to ball-void volume is optimum
- Ball properties: heavier balls result in finer product

6 Energy and power requirement in comminution

- During size reduction particles are first distorted and strained
- The work necessary to strain particles is stored temporarily as mechanical energy of stress

- With additional force, particles distort beyond their ultimate strength and suddenly rupture into fragments
- The rupture creates new surface
- A unit area of solid has a definite surface energy
- The energy required to create new surface is supplied by the release of energy of stress during rupture
- The excess energy is converted into heat

6.1 Energy efficiency

- Size reduction is very inefficient in terms of energy
- In crushing less than 1% of the energy delivered to the solid is converted into surface energy; the rest is dissipated as heat
- The energy delivered to the solids is between 25 to 60% of the total energy supplied to the machine

7 Laws for comminution energy

7.1 General formulation

- Walker et al. [1] proposed that the energy required for size reduction is
  - directly proportional to the differential decrease in size and
  - inversely proportional to the size to some power
- Mathematically this is stated as

$$d\tilde{E} \propto -dD$$
$$d\tilde{E} \propto \frac{1}{D^n}$$

- Here, $\tilde{E}$ is the specific energy, i.e. energy required per unit mass, $\tilde{E} = \frac{E}{m}$, D is the characteristic dimension of the particles, and n is a constant.
- Note the negative sign before dD; this is due to reduction in size making dD itself to be negative.

[1] Walker, W. H.; Lewis, W.K.; McAdams, W.H.; Gilliand, E.R. (1937) Principles of Chemical Engineering. McGraw-Hill, NY, USA.

- Putting the above two relations together, we get

$$\frac{d\tilde{E}}{dD} = -\frac{C}{D^n} \tag{2}$$

where, C is a constant.

- Note that this general formulation is based on the laws proposed earlier, namely, Rittinger's law, Kick's law and Bond's law.

7.2 Rittinger's law

- With $n = 2$ we get the Rittinger's law, giving the energy required to produce particles with size D_p from a feed with size D_f as

$$\tilde{E} = C_R \left(\frac{C}{D_p} - \frac{C}{D_f} \right) \tag{3}$$

- Rittinger [2] stated that stated that the energy required for size reduction is proportional to the new surface area generated. Specific surface

[2] Rittinger, R.P.(1867) Lehrbuch der Aufbereitungskunde. Ernst and Korn, Berlin, Germany.

area is inversely proportional to the particle size and hence we get eq. 3.

7.3 Kick's law

- For $n = 1$, we get the Kick's law

$$\tilde{E} = C_K \log \frac{D_f}{D_p} \tag{4}$$

- Kick [3] proposed the above based on the theory that the equivalent relative reductions in sizes require equal energy.

7.4 Bond's law

- Bond [4] proposed that the energy required is proportional to the square root of the surface

[3] Kick, F. (1885) Das Gesetz der proportionalen Widerstande und seine anwendung felix. Leipzig, Germany.
[4] Bond, F.C. (1952) The third theory of comminution. Trans. AIME, vol. 193. pp. 484–494.

area to volume ratio. With $\sqrt{\frac{s}{v}} \propto \frac{1}{\sqrt{D}}$, we get

$$\tilde{E} = C_B \left(\frac{1}{\sqrt{D_p}} - \frac{1}{\sqrt{D_f}} \right) \quad (5)$$

- The Bond's law can be obtained from eq. 2 by putting $n = 1.5$ which is in between the values for Rittinger's law and Kick's law.
- Bonds law or the so called the 'Third Law' of grinding is based on the theory that the net energy required in comminution is proportional to the total length of the new cracks formed.

7.5 The work index

- For practical applications, Bond used the term work index, W_i, which is defined as the energy required in kWh per ton of very large feed to produce a product 80% of which will pass through a $100\mu m$ screen.
- So with $\frac{1}{\sqrt{D_p}} = \frac{1}{\sqrt{100}}$ and $\frac{1}{\sqrt{D_p}} >> \frac{1}{\sqrt{D_f}}$, one

gets

$$K_B = \sqrt{100}W_i = 10W_i \tag{6}$$

- If D_p has the unit of mm, one gets

$$K_B = \sqrt{100 \times 10^{-3}}W_i = 0.3162W_i \tag{7}$$

- In terms of total energy required

$$\frac{E}{m} = 0.3162W_i \left(\frac{1}{\sqrt{D_p}} - \frac{1}{\sqrt{D_f}} \right) \tag{8}$$

- Finally, in terms of power P and mass rate of feed, $\dot{m}$

$$\frac{P}{\dot{m}} = 0.3162W_i \left(\frac{1}{\sqrt{D_p}} - \frac{1}{\sqrt{D_f}} \right) \tag{9}$$

Note that in this equation D_f and D_p are in millimeters, $\dot{m}$ is in ton/h and P is in kW

8 Workbook: Calculation of power requirement in crushing

Power requirements for grinding is often calculated using experimental data from prior operations as the work index for materials and ores are often unknown. In grinding a feed materials for which 80% passes through a 4-mesh screen, the power requirement was 5.9kW to produce a product 80% of which passes through a 48-mesh screen. What will be required power to produce a finer product 80% of which passes through a 200-mesh screen?

8.1 Solution

8.2 Problem analysis

- Here we are given two cases where the product and feed sizes are given for both cases.
- The power requirement for one case is given;

you need to calculate the power requirement for the other case.

- Note that no information on $\dot{m}$ or W_i is given. However, we can assume that W_i is the same; also we can assume that the same amount of particles are considered for both cases.
- So we can write

$$\frac{P_1}{\dot{m}} = 0.3162W_i \left(\frac{1}{\sqrt{D_{p_1}}} - \frac{1}{\sqrt{D_f}} \right)$$
$$\frac{P_2}{\dot{m}} = 0.3162W_i \left(\frac{1}{\sqrt{D_{p_2}}} - \frac{1}{\sqrt{D_f}} \right)$$

- Where the subscripts 1 and 2 are for the two cases.
- The above two equations will allow you to calculate P_2 directly.
- Now **just do it**.
- You should get an answer $P_2 = 13.75kW$

References

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