CHAPTER 11

SIZE REDUCTION

Raw materials often occur in sizes that are too large to be used and, therefore, they must be reduced in size. This size reduction operation can be divided into two major categories depending on whether the material is a solid or a liquid. If it is solid, the operations are called grinding and cutting, if it is liquid, emulsification or atomization. All depend on the reaction to shearing forces within solids and liquids.

GRINDING AND CUTTING

Grinding and cutting reduce the size of solid materials by mechanical action, dividing them into smaller particles. Perhaps the most extensive application of grinding in the food industry is in the milling of grains to make flour. But it is used in many other processes, such as in the grinding of corn for manufacture of corn starch, the grinding of sugar and the milling of dried foods, such as vegetables. Cutting is used to break down large pieces of food into smaller pieces suitable for further processing, such as in the preparation of meat for retail sales and in the preparation of processed meats and processed vegetables.

In the grinding process, materials are reduced in size by fracturing them. The mechanism of fracture is not fully understood, but in the process, the material is stressed by the action of mechanical parts of the grinding machine and initially the stress is absorbed internally by the material as strain energy. When the local strain energy exceeds a critical level, which is a function of the material, fracture occurs along lines of weakness and the stored energy is released. Some of the energy is taken up in the creation of new surface, but the greater part of it is dissipated as heat.

Time also plays a part in the fracturing process and it appears that material will fracture at lower stress concentrations if these can be maintained for longer periods. Grinding is, therefore, achieved by mechanical stress followed by rupture and the energy required depends upon the hardness of the material and also upon the tendency of the material to crack - its friability.

The force applied may be compression, impact, or shear, and both the magnitude of the force and the time of application affect the extent of grinding achieved. For efficient grinding, the energy applied to the material should exceed, by as small a margin as possible, the minimum energy needed to rupture the material. Excess energy is lost as heat and this loss should be kept as low as practicable.

The important factors to be studied in the grinding process are the amount of energy used and the amount of new surface formed by grinding.

Energy Used in Grinding

Grinding is a very inefficient process and it is important to use energy as efficiently as possible. Unfortunately, it is not easy to calculate the minimum energy required for a given reduction process, but some theories have been advanced which are useful.

These theories depend upon the basic assumption that the energy required to produce a change dL in a particle of a typical size dimension L is a simple power function of L:

$$dE/dL = KL^n \qquad\qquad (11.1)$$

where dE is the differential energy required, dL is the change in a typical dimension, L is the magnitude of a typical length dimension and K, n, are constants.

Kick assumed that the energy required to reduce a material in size was directly proportional to the size reduction ratio dL/L. This implies that n in eqn. (11.1) is equal to -1. If

$$K = K_K f_c$$

where K_K is called Kick's constant and f_c is called the crushing strength of the material, we have:

$$dE/dL = K_K f_c L^{-1}$$

which, on integration gives:

$$E = K_K f_c \ln(L_1/L_2) \qquad\qquad (11.2)$$

Equation (11.2) is a statement of Kick's Law. It implies that the specific energy required to crush a material, for example from 10cm down to 5cm, is the same as the energy required to crush the same material from 5mm to 2.5 mm.

Rittinger, on the other hand, assumed that the energy required for size reduction is directly proportional, not to the change in length dimensions, but to the change in surface area. This leads to a value of -2 for n in eqn. (11.1, as area is proportional to length squared. If we put:

$$K = K_R f_c$$

And so;

$$dE/dL = K_R f_c L^{-2}$$

where K_R is called Rittinger's constant, and integrate the resulting form of eqn. (11.1), we obtain:

$$E = K_R f_c (1/L_2 - 1/L_1) \qquad\qquad (11.3)$$

Equation (11.3) is known as Rittinger's Law. As the specific surface of a particle (the surface area per unit mass) is proportional to $1/L$, eqn. (11.3) postulates that the energy required to reduce L for a mass of particles from 10cm to 5cm would be the same as that required to reduce, for example, the same mass of 5mm particles down to 4.7mm. This is a very much smaller reduction, in terms of of energy per unit mass for the smaller particles, than that predicted by Kick's Law.

It has been found, experimentally, that for the grinding of coarse particles in which the increase in surface area per unit mass is relatively small, Kick's Law is a reasonable approximation. For the size reduction of fine powders, on the other hand, in which large areas of new surface are being created, Rittinger's Law fits the experimental data better.

Bond has suggested an intermediate course, in which he postulates that n is (-3/2) and this leads to:

$$E = E_i (100/L_2)^{1/2}[1 - (1/q)^{1/2}] \qquad\qquad (11.4)$$

Bond defines the quantity E_i by this equation. L is measured in microns in eqn. (11.4) and so E_i is the amount of energy required to reduce unit mass of the material from an infinitely large particle size down to a particle size of 100μm. It is expressed in terms of q, the reduction ratio where $q = L_1/L_2$.

Note that all of these equations [eqns. (11.2), (11.3), and (11.4)] are dimensional equations and so if quoted values are to be used for the various constants, the dimensions must be expressed in appropriate units. In Bond's equation, if L is expressed in microns, this defines E_i and Bond calls this the Work Index.

The greatest use of these equations is in making comparisons between power requirements for various degrees of reduction.

EXAMPLE 11.1. Grinding of sugar
Sugar is ground from crystals of which it is acceptable that 80% pass a 500μm sieve (US Sieve No.35), down to a size in which it is acceptable that 80% passes a 88μm sieve (No.170), and a 5horsepower motor is found just sufficient for the required throughput. If the requirements are changed such that the grinding is only down to 80% through a 125μm sieve (No 120) but the throughput is to be increased by 50% would the existing motor have sufficient power to operate the grinder? Assume Bond's equation.

Using the subscripts 1 for the first condition and 2 for the second, and letting m kgh^{-1} be the initial throughput, then if x is the required power
   88μm = 88x10^{-6}m, 125μm = 125x10^{-6}m, 500μm= 500x10^{-6}m

$$E_1 \quad = 5/m \quad = E_i(100/88 \times 10^{-6})^{1/2}[1 - (88/500)^{1/2}]$$

$$E_2 \quad = x/1.5m \quad = E_i(100/125 \times 10^{-6})^{1/2}[1 - (125/500)^{1/2}]$$

$$E_2/E_1 \quad = x/(1.5 \times 5) = \frac{(88 \times 10^{-6})^{1/2}[1 - (125/500)^{1/2}]}{(125 \times 10^{-6})^{1/2}[1 - (88/500)^{1/2}]}$$

$$x/(7.5) \quad = 0.84 \times (0.500/0.58)$$
$$= 0.72$$

$$x \qquad = \underline{5.4 \text{ horsepower}}.$$

So the motor would be expected to have insufficient power to pass the 50% increased throughput, though it should be able to handle an increase of 40%.

New Surface Formed by Grinding

When a uniform particle is crushed, after the first crushing the size of the particles produced will vary a great deal from relatively coarse to fine and even to dust. As the grinding continues, the coarser particles will be further reduced but there will be less change in the size of the fine particles. Careful analysis has shown that there tends to be a certain size that increases in its relative proportions in the mixture and which soon becomes the predominant size fraction. For example, wheat after first crushing gives a wide range of particle sizes in the coarse flour, but after further grinding the predominant fraction soon becomes that passing a 250μm sieve and being retained on a 125μm sieve. This fraction tends to build up, however long the grinding continues, so long as the same type of machinery, rolls in this case, is employed.

The surface area of a fine particulate material is large and can be important. Most reactions are related to the surface area available, so the surface area can have a considerable bearing on the properties of the material. For example, wheat in the form of grains is relatively stable so long as it is kept dry, but if ground to a fine flour has such a large surface per unit mass that it becomes liable to explosive oxidation, as is all too well known in the milling industry. The surface area per unit mass is called the specific surface. To calculate this in a known mass of material it is necessary to know both the particle size distribution and also the shape factor of the particles. The particle size gives one dimension that can be called the typical dimension, D_p, of a particle. This has now to be related to the surface area.

We can write, arbitrarily:

$$V_p = pD_p^3$$

and

$$A_p = 6qD_p^2$$

where V_p is the volume of the particle, A_p is the area of the particle surface, D_p is the typical dimension of the particle and p, q are factors which connect the particle geometries.(Note subscript p and factor p.)

For example, for a cube, the volume is D_p^3 and the surface area is $6D_p^2$; for a sphere the volume is $(\pi/6)D_p^3$ and the surface area is πD_p^2 In each case the ratio of surface area to volume is $6/D_p$.

A shape factor is now defined as $q/p = \lambda$, (lambda), so that for a cube or a sphere $\lambda = 1$. It has been found, experimentally, that for many materials when ground, the shape factor of the resulting particles is approximately 1.75, which means that their surface area to volume ratio is nearly twice that for a cube or a sphere.

The ratio of surface area to volume is:

$$A_p /V_p = 6q/pD_p = 6\lambda/D_p \qquad (11.5)$$

and so
$$A_p = 6q \, V_p /pD_p$$
$$= 6\lambda V_p /D_p$$

If there is a mass m of particles of density ρ_p the number of particles is $m/\rho_p V_p$ each of area A_p
So total area

$$A_t = (m/\rho_p V_p)(6qV_p/pD_p) = (6qm/\rho_p\, pD_p)$$
$$= 6\lambda m/\rho_p D_p \qquad\qquad\qquad (11.6)$$

where A_t is the total area of the mass of particles. Equation (11.6) can be combined with the results of sieve analysis to estimate the total surface area of a powder.

EXAMPLE 11.2. Surface area of salt crystals
In an analysis of ground salt using Tyler sieves, it was found that 38% of the total salt passed through a 7mesh sieve and was caught on a 9mesh sieve. For one of the finer fractions, 5% passed an 80mesh sieve but was retained on a 115mesh sieve. Estimate the surface areas of these two fractions in a 5kg sample of the salt, if the density of salt is 1050kgm^{-3} and the shape factor (λ) is 1.75.

Aperture of Tyler sieves, 7 mesh = 2.83mm, 9 mesh = 2.00mm, 80 mesh = 0.177mm, 115 mesh = 0.125mm.
Mean aperture 7 and 9 mesh = 2.41mm = 2.41 x10^{-3}m
Mean aperture 80 and 115 mesh = 0.151 mm = 0.151 x10^{-3}m.
Now from equn.(11.6)

$\quad\quad\quad\quad A_1 \quad$ = (6 x 1.75 x 0.38 x 5)/(1050 x 2.41 x 10^{-3})
$\quad\quad\quad\quad\quad\quad\quad$ = $\underline{7.88\text{m}^2}$
$\quad\quad\quad\quad A_2 \quad$ = (6 x 1.75 x 0.05 x 5)/(1050 x 0.151 x 10^{-3})
$\quad\quad\quad\quad\quad\quad\quad$ = $\underline{16.6\text{m}^2}$

Grinding Equipment

Grinding equipment can be divided into two classes - crushers and grinders. In the first class the major action is compressive, whereas grinders combine shear and impact with compressive forces.

Crushers

Jaw and gyratory crushers are heavy equipment and are not used extensively in the food industry.

In the jaw crusher, the material is feed between two heavy jaws, one fixed and the other reciprocating, so as to work the material down into a narrower and narrower space, crushing it as it goes.

The gyratory crusher consists of a truncated conical casing, inside which a crushing head rotates eccentrically. The crushing head is shaped as an inverted cone and the material being crushed is trapped between the outer fixed, and the inner gyrating, cones, and it is again forced into a narrower and narrower space during which time it is crushed.

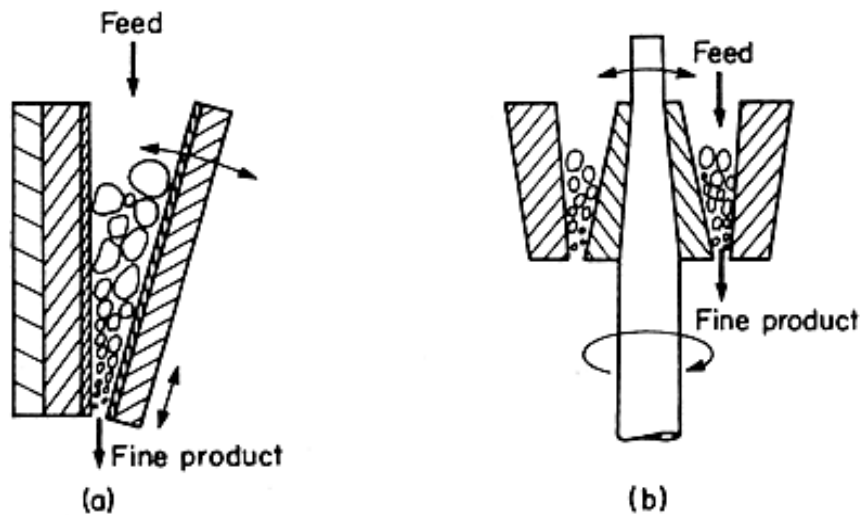Jaw and gyratory crusher actions are illustrated in Fig 11.1 (a) and (b).

Figure 11.1 Crushers: (a) jaw (b) gyratory

Crushing rolls consist of two heavy horizontal cylinders, mounted parallel to each other and close together. They rotate in the opposite direction and the material to be crushed is trapped and nipped between them, being crushed as it passes through. In some case, the rolls are both driven at the same speed. In other cases, they may be driven at differential speeds, or only one roll is driven. A major application is in the cane sugar industry, where several stages of rolls are used to crush the cane

Hammer mills

In a hammer mill, swinging hammerheads are attached to a rotor that rotates at high speed inside a hardened casing. The principle is illustrated in Fig. 11.2(a).
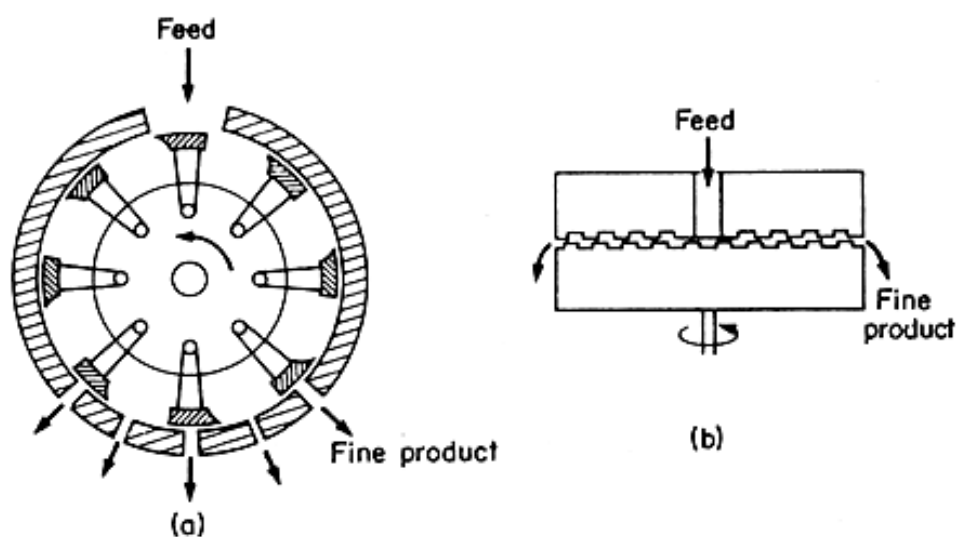

Figure 11.2 Grinders: (a) hammer mill, (b) plate mill

The material is crushed and pulverized between the hammers and the casing and remains in the mill until it is fine enough to pass through a screen which forms the bottom of the casing. Both brittle and fibrous materials can be handled in hammer mills, though with fibrous material, projecting sections on the casing may be used to give a cutting action.

Plate mills

In plate mills the material is fed between two circular plates, one of them fixed and the other rotating. The feed comes in near the axis of rotation and is sheared and crushed as it makes its way to the edge of the plates, see Fig. 11.2(b). The plates can be mounted horizontally as in the traditional Buhr stone used for grinding corn, which has a fluted surface on the plates. The plates can be mounted vertically also. Developments of the plate mill have led to the colloid mill, which uses very fine clearances and very high speeds to produce particles of colloidal dimensions.

Fixed head mills

Various forms of mills are used in which the material is sheared between a fixed casing and a rotating head, often with only fine clearances between them. One type is a pin mill in which both the static and the moving plates have pins attached on the surface and the powder is sheared between the pins.

Roller mills

Roller mills are similar to roller crushers, but they have smooth or finely fluted rolls, and rotate at differential speeds. They are used very widely to grind flour. Because of their simple geometry, the maximum size of the particle that can pass between the rolls can be regulated. If the friction coefficient between the rolls and the feed material is known, the largest particle that will be nipped between the rolls can be calculated, knowing the geometry of the particles.

Miscellaneous milling equipment

The range of milling equipment is very wide. It includes ball mills, in which the material to be ground is enclosed in a horizontal cylinder or a cone and tumbled with a large number of steel balls, natural pebbles or artificial stones, which crush and break the material. Ball mills have limited applications in the food industry, but they are used for grinding food colouring materials. The edge-runner mill, which is basically a heavy broad wheel running round a circular trough, is used for grinding chocolate and confectionery. Many types of milling equipment have come to be traditional in various industries and it is often claimed that they provide characteristic actions that are peculiarly suited to, and necessary for, the product.

Cutters

Cutting machinery is generally simple, consisting of rotating knives in various arrangements. A major problem often is to keep the knives sharp so that they cut rather than tear. An example is the bowl chopper in which a flat bowl containing the material revolves beneath a vertical rotating cutting knife.

EMULSIFICATION

Emulsions are stable suspensions of one liquid in another, the liquids being immiscible. Stability of the emulsion is obtained by dispersion of very fine droplets of one liquid, called the *disperse phase*, through the other liquid, which is called the *continuous phase*. The emulsion is stable when it can persist without change, for long periods of time, without the droplets of the disperse phase coalescing with each other, or rising or settling. The *stability of an emulsion* is controlled by

- interfacial surface forces,
- size of the disperse phase droplets,
- viscous properties of the continuous phase and
- density difference between the two phases.

The dispersed particles in the emulsion have a very large surface area, which is created in the process of emulsification. Surface effects depend upon the properties of the materials of the two phases, but very often a third component is added which is absorbed at the interface and which helps to prevent the droplets from coalescing. These added materials are called emulsifying agents and examples are phosphates and glycerol monostearate.

The size of the disperse phase droplets is important and these are commonly of the order 1-10 μm diameter. Below 0.1μm droplet diameter, the dispersion is often spoken of as colloidal. Coalescence of the disperse phase droplets is hindered by increased viscosity in the continuous liquid phase. The nearer the densities of the components are to each other, the less will be the separating effect of gravitational forces. Stokes' Law gives a qualitative indication of the physical factors that influence the stability of an emulsion. This is because the relative flow of the particles under gravitational forces may break the emulsion, so stability is enhanced by small settling velocities. From eqn. (10.2):

$$V_m = D^2 g(\rho_p - \rho_f)/18\mu$$

the critical importance of particle size, occurring as a squared term, can be seen. Also it shows why emulsions are more stable when density differences are small and when the viscosity of the continuous phase is high.

Preparation of Emulsions

The essential feature of an emulsion is the small size of the disperse phase droplets. This can be achieved by imposing very high shearing stresses upon the liquid that is to be dispersed and the shearing forces break the material into the multitude of fine particles.

Shearing is, generally, attained by passing the liquid through a high pressure pump, to bring it up to pressures of the order of 7×10^3kPa, and then discharging this pressure suddenly by expansion of the liquid through a small gap or nozzle; the equipment is often called a homogenizer. In passing through the nozzle, very large shear forces are exerted on the liquid, disrupting cohesion and dispersing it into the very small particles.

Centrifugal orifices may also be used to obtain the shearing action. Discs spinning at high velocities give rise to high shearing forces in liquids flowing over them. Flow between

contra-rotating discs, which may have pegs on the disc faces, can be used to produce emulsions. Designs in which small clearances are used between a stationary disc and a high speed flat or conical rotating disc are called colloid mills. Another source of energy for shearing is from ultrasonic vibrations induced in the liquid.

Existing emulsions can be given increased stability by decreasing the size of the droplets either by impact or shearing the emulsion still further; the process is called homogenization. Homogenizing results in smaller and more uniform droplet sizes and a practical example is the homogenizing of milk.

Examples of emulsions met with frequently in the food industry are - milk (fat dispersed in water), butter (water dispersed in fat), mayonnaise (oil in water) and ice cream (fat in water which is then frozen).

Milk is an emulsion of fat in water, which is not stable indefinitely as it separates on standing, into skim milk and cream. This is caused by the density differences between the fat and the water, the fat globules rising as predicted by Stokes' Law and coalescing at the surface to form a layer of cream. After homogenizing, this separation does not occur as the globules are much reduced in size. Homogenizing is also used with ice cream mixes, which are dispersions of fat and air in sugar solutions, and in the manufacture of margarine.

The same surface effects that govern liquid emulsions also apply to dispersions of solids in liquids and of liquids or solids in gases. Colloidal solutions of solids can be produced if the particle size is of the necessary order, below about $0.1\mu m$, and again stability depends upon the surface properties of the materials. Aerosols, for example, fine mists in the atmosphere, can also be quite stable.

SUMMARY

1. Size reduction is accomplished by shearing forces that cause the material to fracture releasing most of the applied energy as heat.

2. A general equation giving the power required for size reduction is:

$$dE/dL = KL^n$$

and from this can be derived

   (a) Kick's Law in which $n = 1$ and which may be integrated to give:

   $$E = K_K f_c \ln(L_1/L_2)$$

   (b) Rittinger's Law in which $n = -2$, integrated to give:

   $$E = K_R f_c(1/L_2 - 1/L_1)$$

   (c) Bond's equation in which $n = -3/2$, integrated to give:

   $$E = E_i (100/L_2)^{1/2}[1 - (1/q)^{1/2}]$$

It appears that Kick's results apply better to coarser particles, Rittinger's to fine ones with Bond's being intermediate.

3. The total surface area of a powder is important and can be estimated from

$$A_t = 6\lambda m/\rho_p D_p$$

4. An emulsion is produced by shearing forces, which reduce the size of droplets of the dispersed phase to diameters of the order of 0.1-10μm, with a large specific surface area. Application of Stokes' Law gives an indication of emulsion stability.

PROBLEMS

1. From measurements on a uniformly sized material from a dryer, it is inferred that the surface area of the material is 1200m^2. If the density of the material is 1450kgm^{-3} and the total weight is 360kg, calculate the equivalent diameter of the particles if their value of λ is 1.75.

   (2200microns)

2. Calculate the shape factor (λ) for model systems in which the particles are:

   (a) cylinders with $L = 2D$,

   (b) tetrahedra with their sides being equilateral triangles; the volume of a tetrahedron being the area of the base x 1/3 of the vertical height.

(c) Estimate the specific surface area of a powder consisting of equal numbers, of equal total weight, of the above two shapes in which there are 4×10^3 particles kg^{-1}. The cylinders have a density of 1330kgm^{-3} and the tetrahedra a density of 1500kgm^{-3}.

((a) 0.83, (b) 2.4 (c) 0.81m^2 kg^{-1})

3. It is found that the energy required to reduce particles from a mean diameter of 1cm to 0.3cm is 11 kJ kg^{-1}. Estimate the energy requirement to reduce the same particles from a diameter of 0.1 cm to 0.01 cm assuming:

(a) Kick's Law,
(b) Rittinger's Law,
(c) Bond's Equation.

((a) 21kJkg^{-1} (b) 423 kJkg^{-1} (c) 91 kJkg^{-1})

4. It is suspected that for a product of interest the oxidation reactions, which create off-flavours, are surface reactions, which proceed at a rate that is uniform with time. If the shelf life of the product is directly related to the percentage of the off-flavours that have been produced, estimate the reduction in shelf life consequent upon the size reductions of example 3, that is (a) from 1cm to 0.3cm and (b) from 0.1cm to 0.01cm in diameter, assuming $\lambda = 1.5$.

((a) 10:1 (b) 100:1)

5. If it is desired to reduce the separation time for milk to at least one week (before cream will rise to the top), what maximum diameter of cream droplet would Stokes' Law predict to be necessary for the homogenization to achieve?

(0.0567 microns)