Chapter 2

Particle Size Reduction and Enlargement

2.1. Introduction

Materials are rarely found in the size range required, and it is often necessary either to decrease or to increase the particle size. When, for example, the starting material is too coarse, and possibly in the form of large rocks, and the final product needs to be a fine powder, the particle size will have to be progressively reduced in stages. The most appropriate type of machine at each stage depends, not only on the size of the feed and of the product, but also on such properties as compressive strength, brittleness and stickiness. For example, the first stage in the process may require the use of a large jaw crusher and the final stage a sand grinder, two machines of very different characters.

At the other end of the spectrum, many very fine powders are frequently to difficult handle, and may also give rise to hazardous dust clouds when they are transported. It may therefore be necessary to increase the particle size. Examples of size enlargement processes include granulation for the preparation of fertilisers, and compaction using compressive forces to form the tablets required for the administration of pharmaceuticals.

In this Chapter, the two processes of size reduction and size enlargement are considered in Sections 2.2 and 2.4, respectively.

2.2. Size Reduction of Solids

2.2.1. Introduction

In the materials processing industry, size reduction or *comminution* is usually carried out in order to increase the surface area because, in most reactions involving solid particles, the rate of reactions is directly proportional to the area of contact with a second phase. Thus the rate of combustion of solid particles is proportional to the area presented to the gas, though a number of secondary factors may also be involved. For example, the free flow of gas may be impeded because of the higher resistance to flow of a bed of small particles. In leaching, not only is the rate of extraction increased by virtue of the increased area of contact between the solvent and the solid, but the distance the solvent has to penetrate into the particles in order to gain access to the more remote pockets of solute is also reduced. This factor is also important in the drying of porous solids, where reduction in size causes both an increase in area and a reduction in the distance
the moisture must travel within the particles in order to reach the surface. In this case, the capillary forces acting on the moisture are also affected.

There are a number of other reasons for carrying out size reduction. It may, for example, be necessary to break a material into very small particles in order to separate two constituents, especially where one is dispersed in small isolated pockets. In addition, the properties of a material may be considerably influenced by the particle size and, for example, the chemical reactivity of fine particles is greater than that of coarse particles, and the colour and covering power of a pigment is considerably affected by the size of the particles. In addition, far more intimate mixing of solids can be achieved if the particle size is small.

2.2.2. Mechanism of size reduction

Whilst the mechanism of the process of size reduction is extremely complex, in recent years a number of attempts have been made at a more detailed analysis of the problem. If a single lump of material is subjected to a sudden impact, it will generally break so as to yield a few relatively large particles and a number of fine particles, with relatively few particles of intermediate size. If the energy in the blow is increased, the larger particles will be of a rather smaller size and more numerous and, whereas the number of fine particles will be appreciably increased, their size will not be much altered. It therefore appears that the size of the fine particles is closely connected with the internal structure of the material, and the size of the larger particles is more closely connected with the process by which the size reduction is effected.

This effect is well illustrated by a series of experiments on the grinding of coal in a small mill, carried out by Heywood(1). The results are shown in Figure 2.1, in which the distribution of particle size in the product is shown as a function of the number of

Figure 2.1. Effect of progressive grinding on size distribution
revolutions of the mill. The initial size distribution shows a single mode corresponding to a relatively coarse size, but as the degree of crushing is gradually increased this mode progressively decreases in magnitude and a second mode develops at a particular size. This process continues until the first mode has completely disappeared. Here the second mode is characteristic of the material and is known as the persistent mode, and the first is known as the transitory mode. There appears to be a grind limit for a particular material and machine. After some time there seems to be little change in particle size if grinding is continued, though the particles may show some irreversible plastic deformation which results in a change in shape rather than in size.

The energy required to effect size reduction is related to the internal structure of the material and the process consists of two parts, first opening up any small fissures which are already present, and secondly forming new surface. A material such as coal contains a number of small cracks and tends first to break along these, and therefore the large pieces are broken up more readily than the small ones. Since a very much greater increase in surface results from crushing a given quantity of fine as opposed to coarse material, fine grinding requires very much more power. Very fine grinding can be impeded by the tendency of some relatively soft materials, including gypsum and some limestones, to form aggregates. These are groups of relatively weakly adhering particles held together by cohesive and van der Waals forces. Materials, such as quartz and clinker, form agglomerates in which the forces causing adhesion may be chemical in nature, and the bonds are then very much stronger.

In considering energy utilisation, size reduction is a very inefficient process and only between 0.1 and 2.0 per cent of the energy supplied to the machine appears as increased surface energy in the solids. The efficiency of the process is very much influenced by the manner in which the load is applied and its magnitude. In addition the nature of the force exerted is also very important depending, for example, on whether it is predominantly a compressive, an impact or a shearing force. If the applied force is insufficient for the elastic limit to be exceeded, and the material is compressed, energy is stored in the particle. When the load is removed, the particle expands again to its original condition without doing useful work. The energy appears as heat and no size reduction is effected. A somewhat greater force will cause the particle to fracture, however, and in order to obtain the most effective utilisation of energy the force should be only slightly in excess of the crushing strength of the material. The surface of the particles will generally be of a very irregular nature so that the force is initially taken on the high spots, with the result that very high stresses and temperatures may be set up locally in the material. As soon as a small amount of breakdown of material takes place, the point of application of the force alters. BEMROSE and BRIDGEMATER(2) and HESS and SCHÖNERT(3) have studied the breakage of single particles. All large lumps of material contain cracks and size reduction occurs as a result of crack propagation that occurs above a critical parameter, $F$, where:

$$ F = \frac{\tau^2 a}{Y} $$

where: $a =$ crack length,  
$\tau =$ stress, and  
$Y =$ Young's modulus.
Hess\(^{(3)}\) suggests that at lower values of \(F\), elastic deformation occurs without fracture and the energy input is completely ineffective in achieving size reduction. Fundamental studies of the application of fracture mechanics to particle size reduction have been carried out, by Schönhert\(^{(4)}\). In essence, an energy balance is applied to the process of crack extension within a particle by equating the loss of energy from the strain field within the particle to the increase in surface energy when the crack propagates. Because of plastic deformation near the tip of the crack, however, the energy requirement is at least ten times greater and, in addition kinetic energy is associated with the sudden acceleration of material as the crack passes through it. Orders of magnitude of the surface fracture energy per unit volume are:

<table>
<thead>
<tr>
<th>Material</th>
<th>Surface Fracture Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>1 - 10 J/m(^2)</td>
</tr>
<tr>
<td>Plastics</td>
<td>10 - 10(^3) J/m(^2)</td>
</tr>
<tr>
<td>Metals</td>
<td>10(^3) - 10(^5) J/m(^2)</td>
</tr>
</tbody>
</table>

All of these values are several orders of magnitude higher than the thermodynamic surface energy which is about 10\(^{-1}\) J/m\(^2\). Where a crack is initially present in a material, the stresses near the tip of the crack are considerably greater than those in the bulk of the material. Calculation of the actual value is well nigh impossible as the crack surfaces are usually steeply curved and rough. The presence of a crack modifies the stress field in its immediate location, with the increase in energy being approximately proportional to \(\sqrt{a/l}\) where \(a\) is the crack length and \(l\) is the distance from the crack tip. Changes in crack length are accompanied by modifications in stress distribution in the surrounding material and hence in its energy content.

During the course of the size reduction processes, much energy is expended in causing plastic deformation and this energy may be regarded as a waste as it does not result in fracture. Only part of it is retained in the system as a result of elastic recovery. It is not possible, however, to achieve the stress levels necessary for fracture to occur without first passing through the condition of plastic deformation and, in this sense, this must be regarded as a necessary state which must be achieved before fracture can possibly occur.

The nature of the flaws in the particles changes with their size. If, as is customary, fine particles are produced by crushing large particles, the weakest flaws will be progressively eliminated as the size is reduced, and thus small particles tend to be stronger and to require more energy for fracture to occur. In addition, as the capacity of the particle for storing energy is proportional to its volume (\(\propto d^3\)) and the energy requirement for propagating geometrically similar cracks is proportional to the surface area (\(\propto d^2\)), the energy available per unit crack area increases linearly with particle size \(d\). Thus, breakage will occur at lower levels of stress in large particles. This is illustrated in Figure 2.2 which shows the results of experimental measurements of the compressive strengths for shearing two types of glass. It may be noted from Figure 2.2 that, for quartz glass, the compressive strength of 2 \(\mu\)m particles is about three times that of 100 \(\mu\)m particles.

The exact method by which fracture occurs is not known, although it is suggested by Piret\(^{(5)}\) that the compressive force produces small flaws in the material. If the energy concentration exceeds a certain critical value, these flaws will grow rapidly and will generally branch, and the particles will break up. The probability of fracture of a particle
in an assembly of particles increases with the number of contact points, up to a number of around ten, although the probability then decreases for further increase in number. The rate of application of the force is important because there is generally a time lag between attainment of maximum load and fracture. Thus, a rather smaller force will cause fracture provided it is maintained for a sufficient time. This is a phenomenon similar to the ignition lag which is obtained with a combustible gas–oxidant mixture. Here the interval between introducing the ignition source and the occurrence of ignition is a function of the temperature of the source, and when it is near the minimum ignition temperature delays of several seconds may be encountered. The greater the rate at which the load is applied, the less effectively is the energy utilised and the higher is the proportion of fine material which is produced. If the particle shows any viscoelastic behaviour, a high rate of application of the force is needed for fracture to occur. The efficiency of utilisation of energy as supplied by a falling mass has been compared with that of energy applied slowly by means of hydraulic pressure. Up to three or four times more surface can be produced per unit of energy if it is applied by the latter method. Piret(5) suggests that there is a close similarity between the crushing operation and a chemical reaction. In both cases a critical energy level must be exceeded before the process will start, and in both cases time is an important variable.

The method of application of the force to the particles may affect the breakage pattern. Prasher(6) suggests that four basic patterns may be identified, though it is sometimes difficult to identify the dominant mode in any given machine. The four basic patterns are:

(a) Impact — particle concussion by a single rigid force.
(b) Compression — particle disintegration by two rigid forces.
(c) Shear — produced by a fluid or by particle–particle interaction.
(d) Attrition — arising from particles scraping against one another or against a rigid surface.
2.2.3. Energy for size reduction

Energy requirements

Although it is impossible to estimate accurately the amount of energy required in order to effect a size reduction of a given material, a number of empirical laws have been proposed. The two earliest laws are due to Kick\(^{(7)}\) and von Rittinger\(^{(8)}\), and a third law due to Bond\(^{(9,10)}\) has also been proposed. These three laws may all be derived from the basic differential equation:

$$\frac{dE}{dL} = -CL^p$$

which states that the energy \(dE\) required to effect a small change \(dL\) in the size of unit mass of material is a simple power function of the size. If \(p = -2\), then integration gives:

$$E = C \left( \frac{1}{L_2} - \frac{1}{L_1} \right)$$

Writing \(C = K_R f_c\), where \(f_c\) is the crushing strength of the material, then Rittinger’s law, first postulated in 1867, is obtained as:

$$E = K_R f_c \left( \frac{1}{L_2} - \frac{1}{L_1} \right)$$

(2.3)

Since the surface of unit mass of material is proportional to \(1/L\), the interpretation of this law is that the energy required for size reduction is directly proportional to the increase in surface.

If \(p = -1\), then:

$$E = C \ln \frac{L_1}{L_2}$$

and, writing \(C = K_K f_c\):

$$E = K_K f_c \ln \frac{L_1}{L_2}$$

(2.4)

which is known as Kick’s law. This supposes that the energy required is directly related to the reduction ratio \(L_1/L_2\) which means that the energy required to crush a given amount of material from a 50 mm to a 25 mm size is the same as that required to reduce the size from 12 mm to 6 mm. In equations 2.3 and 2.4, \(K_R\) and \(K_K\) are known respectively as Rittinger’s constant and Kick’s constant. It may be noted that neither of these constants is dimensionless.

Neither of these two laws permits an accurate calculation of the energy requirements. Rittinger’s law is applicable mainly to that part of the process where new surface is being created and holds most accurately for fine grinding where the increase in surface per unit mass of material is large. Kick’s law, more closely relates to the energy required to effect elastic deformation before fracture occurs, and is more accurate than Rittinger’s law for coarse crushing where the amount of surface produced is considerably less.
Bond has suggested a law intermediate between Rittinger's and Kick's laws, by putting \( p = -3/2 \) in equation 2.1. Thus:

\[
E = 2C \left( \frac{1}{L_{1}^{1/2}} - \frac{1}{L_{2}^{1/2}} \right) 
\]

\[
= 2C \sqrt{\left( \frac{1}{L_{2}} \right) \left( 1 - \frac{1}{q^{1/2}} \right)} 
\]

where:

\[
q = \frac{L_{1}}{L_{2}}
\]

the reduction ratio. Writing \( C = 5E_{i} \), then:

\[
E = E_{i} \sqrt{\left( \frac{100}{L_{2}} \right) \left( 1 - \frac{1}{q^{1/2}} \right)} 
\]

Bond terms \( E_{i} \) the work index, and expresses it as the amount of energy required to reduce unit mass of material from an infinite particle size to a size \( L_{2} \) of 100 \( \mu \)m, that is \( q = \infty \). The size of material is taken as the size of the square hole through which 80 per cent of the material will pass. Expressions for the work index are given in the original papers\(^{(8,9)}\) for various types of materials and various forms of size reduction equipment.

Austen and Klimpel\(^{(11)}\) have reviewed these three laws and their applicability, and Cutting\(^{(12)}\) has described laboratory work to assess grindability using rod mill tests.

**Example 2.1**

A material is crushed in a Blake jaw crusher such that the average size of particle is reduced from 50 mm to 10 mm with the consumption of energy of 13.0 kW/(kg/s). What would be the consumption of energy needed to crush the same material of average size 75 mm to an average size of 25 mm:

a) assuming Rittinger's law applies?

b) assuming Kick's law applies?

Which of these results would be regarded as being more reliable and why?

**Solution**

a) *Rittinger's law.*

This is given by:

\[
E = K_R f_c [(1/L_2) - (1/L_1)]
\]

Thus:

\[
13.0 \times K_R f_c [(1/10) - (1/50)]
\]

and:

\[
K_R f_c = (13.0 \times 50/4) = 162.5 \text{ kW/(kg mm)}
\]
Thus the energy required to crush 75 mm material to 25 mm is:

\[ E = 162.5[(1/25) - (1/75)] = 4.33 \text{ kJ/kg} \]

b) Kick's law.

This is given by:

\[ E = K_K f_c \ln(L_1/L_2) \]  

(equation 2.4)

Thus:

\[ 13.0 = K_K f_c \ln(50/10) \]

and:

\[ K_K f_c = \frac{13.0}{1.609} = 8.08 \text{ kW/(kg/s)} \]

Thus the energy required to crush 75 mm material to 25 mm is given by:

\[ E = 8.08 \ln(75/25) = 8.88 \text{ kJ/kg} \]

The size range involved by be considered as that for coarse crushing and, because Kick's law more closely relates the energy required to effect elastic deformation before fracture occurs, this would be taken as given the more reliable result.

**Energy utilisation**

One of the first important investigations into the distribution of the energy fed into a crusher was carried out by Owens\(^{(13)}\) who concluded that energy was utilised as follows:

(a) In producing elastic deformation of the particles before fracture occurs.
(b) In producing inelastic deformation which results in size reduction.
(c) In causing elastic distortion of the equipment.
(d) In friction between particles, and between particles and the machine.
(e) In noise, heat and vibration in the plant, and
(f) In friction losses in the plant itself.

Owens estimated that only about 10 per cent of the total power is usefully employed.

In an investigation by the U.S. Bureau of Mines\(^{(14)}\), in which a drop weight type of crusher was used, it was found that the increase in surface was directly proportional to the input of energy and that the rate of application of the load was an important factor.

This conclusion was substantiated in a more recent investigation of the power consumption in a size reduction process which is reported in three papers by Kwong et al.\(^{(15)}\), Adams et al.\(^{(16)}\) and Johnson et al.\(^{(17)}\). A sample of material was crushed by placing it in a cavity in a steel mortar, placing a steel plunger over the sample and dropping a steel ball of known weight on the plunger over the sample from a measured height. Any bouncing of the ball was prevented by three soft aluminium cushion wires under the mortar, and these wires were calibrated so that the energy absorbed by the system could be determined from their deformation. Losses in the plunger and ball were assumed to be proportional to the energy absorbed by the wires, and the energy actually used for size reduction was then obtained as the difference between the energy of the ball on striking the plunger and the energy absorbed. Surfaces were measured by a water or air permeability method or by gas adsorption. The latter method gave a value approximately
double that obtained from the former indicating that, in these experiments, the internal surface was approximately the same as the external surface. The experimental results showed that, provided the new surface did not exceed about 40 m$^2$/kg, the new surface produced was directly proportional to the energy input. For a given energy input the new surface produced was independent of:

(a) The velocity of impact,
(b) The mass and arrangement of the sample,
(c) The initial particle size, and
(d) The moisture content of the sample.

Between 30 and 50 per cent of the energy of the ball on impact was absorbed by the material, although no indication was obtained of how this was utilised. An extension of the range of the experiments, in which up to 120 m$^2$ of new surface was produced per kilogram of material, showed that the linear relationship between energy and new surface no longer held rigidly. In further tests in which the crushing was effected slowly, using a hydraulic press, it was found, however, that the linear relationship still held for the larger increases in surface.

In order to determine the efficiency of the surface production process, tests were carried out with sodium chloride and it was found that 90 J was required to produce 1 m$^2$ of new surface. As the theoretical value of the surface energy of sodium chloride is only 0.08 J/m$^2$, the efficiency of the process is about 0.1 per cent. ZELENY and PIRET$^{(18)}$ have reported calorimetric studies on the crushing of glass and quartz. It was found that a fairly constant energy was required of 77 J/m$^2$ of new surface created, compared with a surface-energy value of less than 5 J/m$^2$. In some cases over 50 per cent of the energy supplied was used to produce plastic deformation of the steel crusher surfaces.

The apparent efficiency of the size reduction operation depends on the type of equipment used. Thus, for instance, a ball mill is rather less efficient than a drop weight type of crusher because of the ineffective collisions that take place in the ball mill.

Further work$^{(5)}$ on the crushing of quartz showed that more surface was created per unit of energy with single particles than with a collection of particles. This appears to be attributable to the fact that the crushing strength of apparently identical particles may vary by a factor as large as 20, and it is necessary to provide a sufficient energy concentration to crush the strongest particle. Some recent developments, including research and mathematical modelling, are described by PRASHER$^{(6)}$.

### 2.2.4. Methods of operating crushers

There are two distinct methods of feeding material to a crusher. The first, known as *free crushing*, involves feeding the material at a comparatively low rate so that the product can readily escape. Its residence time in the machine is therefore short and the production of appreciable quantities of undersize material is avoided. The second method is known as *choke feeding*. In this case, the machine is kept full of material and discharge of the product is impeded so that the material remains in the crusher for a longer period. This results in a higher degree of crushing, although the capacity of the machine is
reduced and energy consumption is high because of the cushioning action produced by
the accumulated product. This method is therefore used only when a comparatively small
amount of materials is to be crushed and when it is desired to complete the whole of the
size reduction in one operation.

If the plant is operated, as in choke feeding, so that the material is passed only once
through the equipment, the process is known as open circuit grinding. If, on the other
hand, the product contains material which is insufficiently crushed, it may be necessary to
separate the product and return the oversize material for a second crushing. This system
which is generally to be preferred, is known as closed circuit grinding. A flow-sheet
for a typical closed circuit grinding process, in which a coarse crusher, an intermediate
crusher and a fine grinder are used, is shown in Figure 2.3. In many plants, the product
is continuously removed, either by allowing the material to fall on to a screen or by
subjecting it to the action of a stream of fluid, such that the small particles are carried
away and the oversize material falls back to be crushed again.

![Figure 2.3. Flow diagram for closed circuit grinding system](image)

The desirability of using a number of size reduction units when the particle size is to
be considerably reduced arises from the fact that it is not generally economical to effect
a large reduction ratio in a single machine. The equipment used is usually divided into
classes as given in Table 2.1, according to the size of the feed and the product.

A greater size reduction ratio can be obtained in fine crushers than in coarse crushers.

<table>
<thead>
<tr>
<th>Feed size</th>
<th>Product size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse crushers</td>
<td>1500–40 mm</td>
</tr>
<tr>
<td>Intermediate crushers</td>
<td>50–5 mm</td>
</tr>
<tr>
<td>Fine crushers</td>
<td>5–2 mm</td>
</tr>
<tr>
<td>Colloid mills</td>
<td>0.2 mm</td>
</tr>
</tbody>
</table>
PARTICLE SIZE REDUCTION AND ENLARGEMENT

The equipment may also be classified, to some extent, according to the nature of the force which is applied though, as a number of forces are generally involved, it is a less convenient basis.

Grinding may be carried out either wet or dry, although wet grinding is generally applicable only with low speed mills. The advantages of wet grinding are:

(a) The power consumption is reduced by about 20–30 per cent.
(b) The capacity of the plant is increased.
(c) The removal of the product is facilitated and the amount of fines is reduced.
(d) Dust formation is eliminated.
(e) The solids are more easily handled.

Against this, the wear on the grinding medium is generally about 20 per cent greater, and it may be necessary to dry the product.

The separators in Figure 2.3 may be either a cyclone type, as typified by the Bradley microsizer or a mechanical air separator. Cyclone separators, the theory of operation and application of which are fully discussed in Chapter 1, may be used. Alternatively, a whizzer type of air separator such as the NEI air separator shown in Figures 1.29 and 1.30 is often included as an integral part of the mill, as shown in the examples of the NEI pendulum mill in Figure 2.21. Oversize particles drop down the inner case and are returned directly to the mill, whilst the fine material is removed as a separate product stream.

2.2.5. Nature of the material to be crushed

The choice of a machine for a given crushing operation is influenced by the nature of the product required and the quantity and size of material to be handled. The more important properties of the feed apart from its size are as follows:

**Hardness.** The hardness of the material affects the power consumption and the wear on the machine. With hard and abrasive materials it is necessary to use a low-speed machine and to protect the bearings from the abrasive dusts that are produced. Pressure lubrication is recommended. Materials are arranged in order of increasing hardness in the Mohr scale in which the first four items rank as soft and the remainder as hard. The Mohr Scale of Hardness is:

1. Talc
2. Rock salt or gypsum
3. Calcite
4. Fluorspar
5. Apatite
6. Felspar
7. Quartz
8. Topaz
9. Carborundum
10. Diamond.

**Structure.** Normal granular materials such as coal, ores and rocks can be effectively crushed employing the normal forces of compression, impact, and so on. With fibrous materials a tearing action is required.

**Moisture content.** It is found that materials do not flow well if they contain between about 5 and 50 per cent of moisture. Under these conditions the material tends to cake together in the form of balls. In general, grinding can be carried out satisfactorily outside these limits.
Crushing strength. The power required for crushing is almost directly proportional to the crushing strength of the material.

Friability. The friability of the material is its tendency to fracture during normal handling. In general, a crystalline material will break along well-defined planes and the power required for crushing will increase as the particle size is reduced.

Stickiness. A sticky material will tend to clog the grinding equipment and it should therefore be ground in a plant that can be cleaned easily.

Soapiness. In general, this is a measure of the coefficient of friction of the surface of the material. If the coefficient of friction is low, the crushing may be more difficult.

Explosive materials must be ground wet or in the presence of an inert atmosphere. Materials yielding dusts that are harmful to the health must be ground under conditions where the dust is not allowed to escape.

Work has presented a guide to equipment selection based on size and abrasiveness of material.

### 2.3. TYPES OF CRUSHING EQUIPMENT

The most important coarse, intermediate and fine crushers may be classified as in Table 2.2.

<table>
<thead>
<tr>
<th>Coarse crushers</th>
<th>Intermediate crushers</th>
<th>Fine crushers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stag jaw crusher</td>
<td>Crushing rolls</td>
<td>Buhrstone mill</td>
</tr>
<tr>
<td>Dodge jaw crusher</td>
<td>Disc crusher</td>
<td>Roller mill</td>
</tr>
<tr>
<td>Gyratory crusher</td>
<td>Edge runner mill</td>
<td>NEI pendulum mill</td>
</tr>
<tr>
<td>Other coarse crushers</td>
<td>Hammer mill</td>
<td>Griffin mill</td>
</tr>
<tr>
<td></td>
<td>Single roll crusher</td>
<td>Ring roller mill (Lopulco)</td>
</tr>
<tr>
<td></td>
<td>Pin mill</td>
<td>Ball mill</td>
</tr>
<tr>
<td></td>
<td>Symons disc crusher</td>
<td>Tube mill</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hardinge mill</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Babcock mill</td>
</tr>
</tbody>
</table>

The features of these crushers are now considered in detail.

#### 2.3.1. Coarse crushers

The Stag jaw crusher shown in Figure 2.4, has a fixed jaw and a moving jaw pivoted at the top with the crushing faces formed of manganese steel. Since the maximum movement of the jaw is at the bottom, there is little tendency for the machine to clog, though some uncrushed material may fall through and have to be returned to the crusher. The maximum pressure is exerted on the large material which is introduced at the top. The machine is usually protected so that it is not damaged if lumps of metal inadvertently enter, by making one of the toggle plates in the driving mechanism relatively weak so that, if any large stresses are set up, this is the first part to fail. Easy renewal of the damaged part is then possible.
1. Fixed Jaw Face  
2. Swing Jaw Face  
3. Swing Jaw Stock  
4. Toggle Seating  
5. Front Toggle Plate  
6. Toggle Seating  
7. Back Toggle Plate  
8. Springs and Cups  
9. Swing Jaw Shaft  
10. Eccentric Shaft  
11. Pitman Bush  
12. Pitman  
13. Flywheel grooved for V rope drive  
14. Flywheel  
15. Toggle Block  
16. Wedge Block  
17. Flywheel  
18. Tension Rods.  
19. Cheek Plates (top)  
19A. Cheek Plates (bottom)  
20. Body  
21. Swing Jaw Shaft Bearing Caps  
22. Eccentric Shaft Bearing Caps  
23. Wedge for Swing Jaw Face  
24. Bolts of Wedge  
25. Bolts for Toggle Block  
26. Bolts for Wedge Block  
27. Eccentric Shaft Bearing Bush (bottom)  
28. Eccentric Shaft Bearing Bush (top)  
29. Swing Stock Bush  

Figure 2.4. Typical cross-section of Stag jaw crusher
Stag crushers are made with jaw widths varying from about 150 mm to 1.0 m and the running speed is about 4 Hz (240 rpm) with the smaller machines running at the higher speeds. The speed of operation should not be so high that a large quantity of fines is produced as a result of material being repeatedly crushed because it cannot escape sufficiently quickly. The angle of nip, the angle between the jaws, is usually about 30°.

Because the crushing action is intermittent, the loading on the machine is uneven and the crusher therefore incorporates a heavy flywheel. The power requirements of the crusher depend upon size and capacity and vary from 7 to about 70 kW, the latter figure corresponding to a feed rate of 10 kg/s.

**The Dodge jaw crusher**

In the Dodge crusher, shown in Figure 2.5, the moving jaw is pivoted at the bottom. The minimum movement is thus at the bottom and a more uniform product is obtained, although the crusher is less widely used because of its tendency to choke. The large opening at the top enables it to take very large feed and to effect a large size reduction. This crusher is usually made in smaller sizes than the Stag crusher, because of the high fluctuating stresses that are produced in the members of the machine.

![Figure 2.5. Dodge crusher](image)

**The gyratory crusher**

The gyratory crusher shown in Figure 2.6 employs a crushing head, in the form of a truncated cone, mounted on a shaft, the upper end of which is held in a flexible bearing, whilst the lower end is driven eccentrically so as to describe a circle. The crushing action takes place round the whole of the cone and, since the maximum movement is at the
bottom, the characteristics of the machine are similar to those of the Stag crusher. As the crusher is continuous in action, the fluctuations in the stresses are smaller than in jaw crushers and the power consumption is lower. This unit has a large capacity per unit area of grinding surface, particularly if it is used to produce a small size reduction. It does not, however, take such a large size of feed as a jaw crusher, although it gives a rather finer and more uniform product. Because the capital cost is high, the crusher is suitable only where large quantities of material are to be handled.

The jaw crushers and the gyratory crusher all employ a predominantly compressive force.

**Other coarse crushers**

Friable materials, such as coal, may be broken up without the application of large forces, and therefore less robust plant may be used. A common form of coal breaker consists of a large hollow cylinder with perforated walls. The axis is at a small angle to the horizontal and the feed is introduced at the top. The cylinder is rotated and the coal is lifted by means of arms attached to the inner surface and then falls against the cylindrical surface. The coal breaks by impact and passes through the perforations as soon as the size has been sufficiently reduced. This type of equipment is less expensive and has a higher throughput than the jaw or gyratory crusher. Another coarse rotary breaker, the rotary coal breaker, is similar in action to the hammer mill described later, and is shown in Figure 2.7. The crushing action depends upon the transference of kinetic energy from hammers to the material and these pulverisers are essentially high speed machines with a speed of rotation of about 10 Hz (600 rpm) giving hammer tip velocities of about 40 m/s.
2.3.2. Intermediate crushers

The edge runner mill

In the edge runner mill shown in Figure 2.8 a heavy cast iron or granite wheel, or muller as it is called, is mounted on a horizontal shaft which is rotated in a horizontal plane in
a heavy pan. Alternatively, the muller remains stationary and the pan is rotated, and in some cases the mill incorporates two mullers. Material is fed to the centre of the pan and is worked outwards by the action of the muller, whilst a scraper continuously removes material that has adhered to the sides of the pan, and returns it to the crushing zone. In many models the outer rim of the bottom of the pan is perforated, so that the product may be removed continuously as soon as its size has been sufficiently reduced. The mill may be operated wet or dry and it is used extensively for the grinding of paints, clays and sticky materials.

**The hammer mill**

The hammer mill is an impact mill employing a high speed rotating disc, to which are fixed a number of hammer bars which are swung outwards by centrifugal force. An industrial model is illustrated in Figure 2.9 and a laboratory model in Figure 2.10. Material is fed in, either at the top or at the centre, and it is thrown out centrifugally and crushed by being beaten between the hammer bars, or against breaker plates fixed around the periphery of the cylindrical casing. The material is beaten until it is small enough to fall through the screen which forms the lower portion of the casing. Since the hammer bars are hinged, the presence of any hard material does not cause damage to the equipment. The bars are readily replaced when they are worn out. The machine is suitable for the crushing of both brittle and fibrous materials, and, in the latter case, it is usual to employ a screen.
with cutting edges. The hammer mill is suitable for hard materials although, since a large amount of fines is produced, it is advisable to employ positive pressure lubrication to the bearings in order to prevent the entry of dust. The size of the product is regulated by the size of the screen and the speed of rotation.

A number of similar machines are available, and in some the hammer bars are rigidly fixed in position. Since a large current of air is produced, the dust must be separated in a cyclone separator or a bag filter.

The pin-type mill

The Alpine pin disc mill shown in Figure 2.11 is a form of pin mill and consists of two vertical steel plates with horizontal projections on their near faces. One disc may be stationary whilst the other disc is rotated at high speed; sometimes, the two discs may be rotated in opposite directions. The material is gravity fed in through a hopper or air conveyed to the centre of the discs, and is thrown outwards by centrifugal action and broken against of the projections before it is discharged to the outer body of the mill and
falls under gravity from the bottom of the casing. Alternatively, the pins may be replaced by swing beaters or plate beaters, depending on the setup and application. The mill gives a fairly uniform fine product with little dust and is extensively used with chemicals, fertilisers and other materials that are non-abrasive, brittle or crystalline. Control of the size of the product is effected by means of the speed and the spacing of the projections and a product size of 20 μm is readily attainable.

The Alpine universal mill with turbine beater and grinding track shown in Figure 2.12 is suitable for both brittle and tough materials. The high airflow from the turbine keeps the temperature rise to a minimum.