SIZE REDUCTION

Size reduction is an extremely important unit operation, whereby materials are subjected to stress in order to reduce the size of individual pieces. The stress is applied by transmitting mechanical force to the solid.

A significant goal of size reduction processes is to improve overall efficiency. This goal of size reduction varies depending on the final application of the product but typically is covered by preparation of naturally occurring raw materials for subsequent separation processes, eg, ore preparation to allow concentration of the valuable fraction; preparation of raw material for subsequent chemically or physically reactive processes, eg, enlargement of the surface area to promote reactivity or to develop the coloring properties of pigments; production of a defined particle-size distribution necessary for a final application, eg, fillers for plastics, rubber, and paint; and preparation of waste materials for recycling, eg, shredding of old tires and waste plastic granulation.

Size reduction of solids is an extremely energy-intensive operation, with estimates of the total U.S. electricity production that is consumed by the process ranging around 2%. Minerals processing accounts for over 50% of this usage, and cement production accounts for about 25%. Only a small fraction, often below 1% of this energy, is used efficiently for size reduction, with the remainder being converted mainly into heat. This article gives an overview of the mechanics of size reduction and the equipment available. However, the science still relies heavily on experience, and it is important that requirements be discussed extensively with equipment manufacturers and large-scale test work carried out prior to decisions being made on the most suitable methods to achieve a given requirement.

1. Particle Breakage and Fracture Mechanics

Size reduction causes particle breakage by subjecting the material to contact forces or stresses. The applied forces cause deformation that generates internal stress in the particles; and when this stress reaches a certain level, particle breakage occurs.

It is important to differentiate between brittle and plastic deformations within materials. With brittle materials, the behavior is predominantly elastic until the yield point is reached, at which breakage occurs. When fracture occurs as a result of a time-dependent strain, the material behaves in an inelastic manner. Most materials tend to be inelastic. Figure 1 shows a typical stress–strain diagram. The section A–B is the elastic region where the material obeys Hooke's law, and the slope of the line is Young's modulus. C is the yield point, where plastic deformation begins. The difference in strain between the yield point C and the ultimate yield point D gives a measure of the brittleness of the material, ie, the less difference in strain, the more brittle the material.

The total area under the curve A–D, shown as shaded in Figure 1, is the strain energy stored in a body. This energy is not uniformly distributed throughout the material, and it is this inequality that gives rise to particle failure. Stress is concentrated around the tips of existing cracks or flaws, and crack propagation is initiated therefrom (Fig. 2) (1).

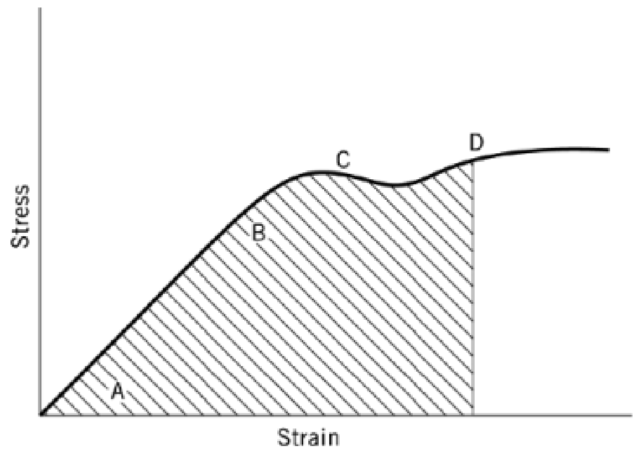


Fig. 1. Typical stress–strain diagram. See text.

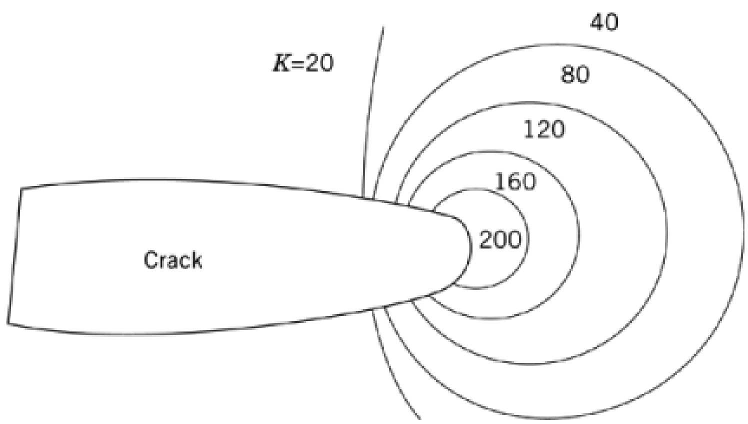


Fig. 2. Stress concentration around a crack. See text.

Stress concentration K is defined (1) as local stress/mean stress in a particle and calculated according to $K = 1 + 2(LR)^{1/2}$, where L is half the crack length and R is the radius of the crack tip.

A subsequent proposal (2) is that for a crack to propagate, the overall stress around the crack must reach a critical value. This critical value depends on crack length, so once stress reaches the critical value and the crack lengthens, it continues to grow. As crack propagation progresses, the strain energy released exceeds the energy associated with new surface and the excess energy concentrates around other cracks in the material, causing a multiple fracture. This is typical behavior for brittle materials.

This theory has been expanded and updated (3). With tough or plastic products the excess strain energy causes internal deformation. With decreasing particle size, materials exhibit increasing plastic behavior (4) and this explains why it is more difficult to break small particles than large particles. In small particles, the crack length is limited by the size of the particle. In practice this is seen where a limit of grindability is reached with many materials and with subjection to further grinding, no decrease in particle size can be observed.

2. Models Predicting Grindability and Energy Requirements

Many attempts have been made to develop models which predict the behavior of materials undergoing size reduction. One proposal is that the energy expended in size reduction is proportional to the new surface formed (5). Another theory is that the energy required to produce a given reduction ratio (feed size ÷ product size) is constant, regardless of initial feed particle size (6). Practical results show, however, that both these theories are limited in their usefulness.

A more practically useful work index based on empirical results from ball milling trials has been developed (7–9) and is expressed by equation 1:

$$E = W_i = \left(\frac{10}{\sqrt{x_p}} - \frac{10}{\sqrt{x_f}}\right) \qquad (1)$$

where E is the energy required, W_i is the Bond work index, and x_f and x_p represent the particle size through which 80% of the feed and products, respectively, pass. A standard grindability test, using a specifically sized ball mill of a given design, is used to measure the work index, and many manufacturers use this to help predict energy requirements, particularly for ball mill applications.

The Hardgrove index (10, 11) is more usually used when predicting energy requirements for pendulum-type roller mills. A standardized test unit is specified in ASTM 409-71 (1978) and BS 1016 Part 20 (1981). The portion of a product passing a 75-μm sieve is measured after a specified test procedure. This is related to the Hardgrove index by reference to a calibration graph. Hardgrove produced a list of indices for comparing the grindability of typical materials.

Although neither the Bond index nor the Hardgrove index can be considered to give absolute values, both are useful in predicting comparative power consumption and output when scaling up from testwork or in estimating the performance of an existing mill if new products are processed. However, in all size reduction applications, accurate prediction by calculation is extremely difficult and it is essential to carry out trials using the proposed type of equipment.

3. Predicting Particle-Size Distribution

The breakage process can be modeled using two basic functions. The specific breakage rate, S_j, is the probability that particles in size class *j* are broken. This probability can be related to either time or energy input, ie, number of mill rotations, to give S_j. The breakage distribution function, b_{ij} is the mass fraction of particles falling into size class *i* that are formed by the breakage of particles in size class *j*. The breakage distribution can also be expressed in a cumulative form B_{ij}, which is the mass fraction of particles below size class *i* that are produced when breaking material of size class *j*.

Table 1 summarizes typical data; the specific breakage rate, S_j, for particles in size class 1 is 0.6, and the breakage product mass in size classes 2–6 is as shown. The corresponding values of b_{ij} and B_{ij} are given.

Using the above concepts, models have been developed to predict size distribution from comminution devices. An assumption is that the rate of breakage of material of a particular size is proportional to the mass of that size present in the comminution zone of a machine. If the mass size distribution in the machine is m_i, where m_i is the mass of particles in size class *i*, then rate of breakage is given by equation 2.

$$\frac{dm_i}{dt} = \sum_{j=1}^{j=i-1} S_j m_j \left(b_{ij}\right) - S_i m_i \qquad (2)$$

The summation term is the mass broken into size interval *i* from all size intervals between *j* and *i*, and $S_i m_i$ is the mass broken from size internal *i*. Thus for a given feed material the product size distribution after

Table 1. Breakage Distribution Function by Product Size Interval Number

Size interval number	Mass	b_{if}[a]	B_{ij}[b]
2	1.2	0.20	1.00
3	1.5	0.25	0.80
4	1.8	0.30	0.55
5	0.9	0.15	0.25
6		0.10	0.10

[a]Basic form.
[b]Cumulative form.

a given time in a mill may be determined. In practice however, both S and b are dependent on particle size, material, and the machine utilized. It is also expected that specific rate of breakage should decrease with decreasing particle size, and this is found to be true. Such an approach has been shown to give reasonably accurate predictions when all conditions are known; however, in practical applications severe limitations are met owing to inadequate data and scale-up uncertainties. Hence it is still the usual practice to carry out tests on equipment to be sure of predictions.

Both the need to reduce experimental costs and increasing reliability of mathematical modeling have led to growing acceptance of computer-aided process analysis and simulation, although modeling should not be considered a substitute for either practical experience or reliable experimental data.

4. Methods for Applying Stress

Equipment for size reduction can be categorized by the method in which the necessary stress is applied to the particles. Figure 3 illustrates the different methods.

4.1. Stressing between Two Solid Surfaces: Crushing

Either single particles (Fig. 3**a**) or a bed of particles (Fig. 3**b**) are crushed between two solid surfaces. The amount of stress that can be applied is governed by the force applied to the solid surfaces.

4.2. Stressing by Impact

Size reduction is achieved by the impact of a particle against a solid surface (Fig. 3**c**) or another particle (Fig. 3**d**). The particle can be accelerated to impact against the surface, or the surface can be accelerated to impact the particle, as in an impact mill. The momentum transferred is limited by the mass of the particle and the achievable impact velocity.

4.3. Stressing by Cutting

This method (Fig. 3**e**) is useful for materials that exhibit plastic behavior.

4.4. Stressing by the Surrounding Medium

Size reduction is effected by shearing forces or pressure waves (Fig. 3**f**). The amount of energy that can be transferred is very limited and this method is used mainly to break agglomerates.

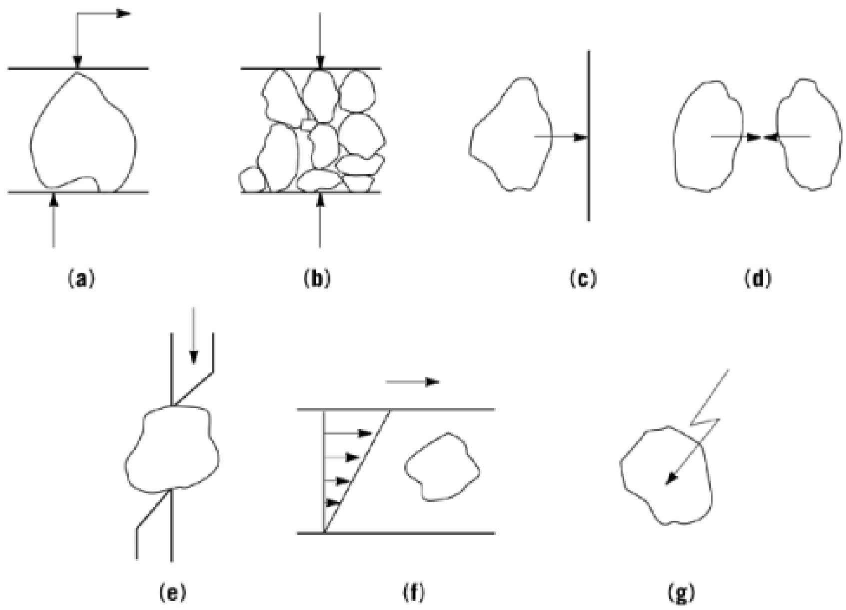


Fig. 3. Stressing mechanisms: (**a**) single particles or (**b**) a bed of particles crushed between two solid surfaces; impact of a particle against (**c**) a solid surface or (**d**) another particle; (**e**) cutting; (**f**) shearing forces or pressure waves; and (**g**) plasma reaction, an example of size reduction by nonmechanical energy.

4.5. Stressing by Nonmechanical Energy

Such processes are not fully developed but examples exist of a plasma reaction (Fig. 3**g**) being used for size reduction. Such cases, however, are specialized and not in general use.

5. Selection Criteria for Size Reduction

Selection of the most suitable machine for a given requirement is an extremely complex process. Added to variations in the properties of the different materials, many of the machines involved have been specifically developed or adapted to perform only particular tasks. The principal factors which must be addressed are toughness/brittleness, hardness, abrasiveness, feed size, cohesity, particle shape and structure, heat sensitivity, toxicity, explodability, and specific surface.

5.1. Toughness/Brittleness

In tough materials the excess strain energy causes plastic deformation, whereas in brittle materials new cracks are propagated. Brittle materials are able to be reduced relatively easily, whereas tough materials present problems. It is sometimes possible to cool a tough material to a temperature low enough to enbrittle it.

5.2. Hardness

There are several hardness (qv) scales. In selecting size reduction equipment generally hardness is expressed according to the Mohs's scale, where a body in one range scratches a body in the immediately previous range:

Mohs's hardness	Material
1	talcum
2	gypsum
3	calcite
4	fluorite
5	apatite
6	feldspar
7	quartz
8	topaz
9	corundum
10	diamond

High speed machines such as impact mills begin to suffer high wear rates when processing materials above Mohs's hardness 3, unless very special wear-resisting measures can be taken.

5.3. Abrasiveness

This property is closely related to hardness in homogenous materials, but can be affected by particle shape, eg, the presence of sharp corners. In many cases a small proportion, as low as 0.5%, of a hard impurity is enough to cause severe wear to many high speed machines.

5.4. Feed Size

The acceptable feed size for a given machine is governed by the type of feed device and physical characteristics of the machine.

5.5. Cohesity

Many materials stick together and adhere to machine parts, depending on their condition, particle size, and temperature.

5.6. Particle Shape and Structure

Some materials exhibit particular properties owing to their particle shape or form, eg, the plate-like minerals talcum and mica or acicular wollastonite. It is often desired to maintain particle shape; in such cases, an impact-type mill is usually chosen rather than a ball mill, as the latter tends to alter the original particle shape.

5.7. Heat Sensitivity

Only 1–2% of applied energy is effectively used for size reduction. The remainder is mainly converted to heat, which is absorbed by the grinding air, product, and equipment.

Materials containing fat can become very sticky, whereas those containing aromatics can lose flavor. In some cases it is possible to cool the process; however, there is an economic penalty. Equipment with a high air throughput is often chosen, as it provides an economical method of dissipating heat and thus limiting the temperature rise of the end product.

5.8. Toxicity

Toxicity has no influence on the actual size reduction, but equipment is often selected for ease of product containment or safe cleaning.

5.9. Explodability

Any material which is flammable in air can potentially support a dust explosion when it is finely divided and dispersed in air. Most organic materials, many metals, and other products fall into this category. Equipment has to be protected by inerting, explosion containment, explosion venting, or suppression. NFPA 68 gives guidelines for venting and VDI 3673 (Germany) and I Chem. E (U.K.) give overall guidance. The ease with which these measures can be applied can affect equipment selection.

5.10. Specific Surface

If a defined specific surface area is required, this can affect the choice of equipment. Machines that apply stress by crushing generally create more ultrafines, and hence higher surface area, than impact mills.

6. Equipment Survey

6.1. Crushers and Roller Mills

In this equipment group, stress is applied by either crushing single particles or a bed of particles between two solid surfaces. In general, most machines are used for coarse and medium-size reduction, with the exception of the high pressure roller mill which can achieve extremely fine particle distributions.

6.2. Jaw Crushers

Both single-toggle (Fig. 4) and double-toggle designs are still widely used. In both, the principle of operation is the same, with feed material being stressed between a stationary jaw and a reciprocating jaw, driven by an eccentric shaft. The end particle-size distribution can be varied by adjusting the width of the outlet gap. Jaw crushers are used in primary size reduction of minerals, and feed openings up to 2.5×2.5 m are available, with outputs of over 1000 t/h possible. The slow speed and absence of rubbing action minimize wear rates, enabling even very hard materials to be processed.

6.3. Gyratory and Cone Crushers

Both of these designs utilize the principle of an eccentrically driven rotor crushing material against a stationary mantle. A typical design is shown in Figure 5. Depending on the particular duty, the rotor is supported by bearings at either one or both of its ends. The size of the end product can be varied by changing the clearance between the rotor and mantle. This is usually achieved by raising or lowering the rotor or mantle. These units are used for medium-coarse size reduction, often following a jaw crusher in minerals-processing plants.

6.4. Roll Crushers

Traditional roll crushers effect size reduction by crushing single particles between two counterrotating rolls; hence they are crushed between the two surfaces. The rolls can either be smooth or profiled to aid feeding of coarser materials. Figure 6 shows a particle of diameter x being reduced between two rolls of diameter D. For

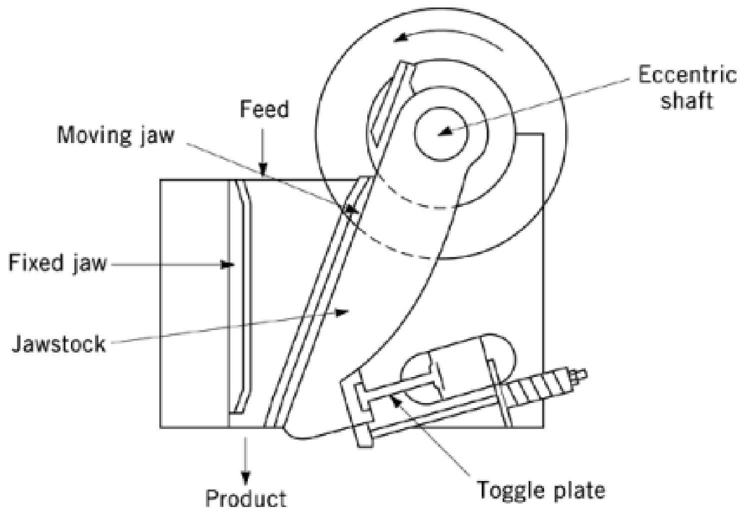


Fig. 4. Single-toggle jaw crusher.

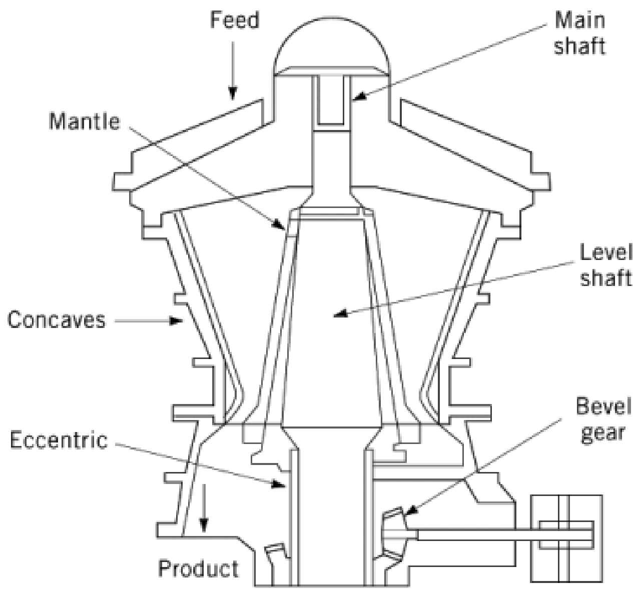


Fig. 5. Cone crusher.

smooth rolls $D/x > 17$ is usually selected, whereas for profiled rolls this can be varied to $D/x < 10$. The feed size-to-gap width ratio is essentially limited to approximately 4.

Roll mills are employed in a wide variety of applications for medium-coarse down to fine size reduction. By far the most prevalent use is in flour milling where banks of roll mills, beginning with coarse profiles and ending with smooth rolls, are used in series with sifting machines to extract the white flour from the associated bran.

In recent years high compression roll mills have become commercially important. In contrast to traditional roll mills, these machines apply stress to a bed of material rather than to single particles (Fig. 7). By applying

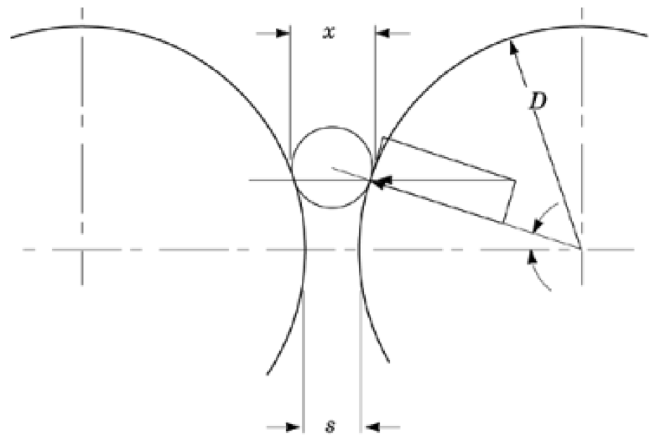


Fig. 6. Roll mill indicating the relationship between roll diameter, D, and feed size, x; s=roll gap width.

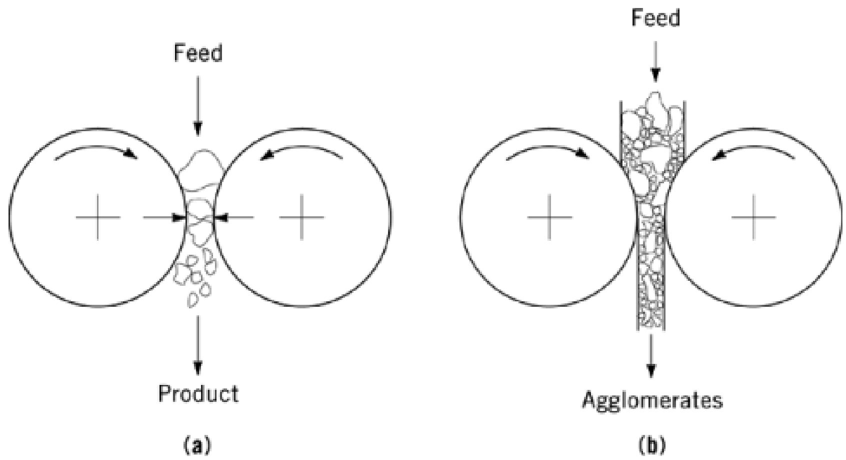


Fig. 7. Comparison between (**a**) roll crusher/mill and (**b**) high compression roller mill.

extremely high pressures to the rolls, ranging from 50 to 500 MPa (7,250–72,500 psi), fine particles can be produced. The end fineness depends on the crushing pressure, and the output is determined by the roll speed.

As only a small proportion of the material is in contact with the rolls and friction on the rollers is low, hard materials can be processed with little wear. The high pressure action creates a slab of ultrafine particles which usually requires a low speed impact milling system to disagglomerate. Used in closed circuit with such a disagglomerator and an air classifier, such machines can reduce the energy requirement for fine grinding many minerals.

6.5. Roller Mills: Pendulum, Table, and Bowl Type

This is a group of machines commonly applied for grinding of mineral powders down to approximately 97% below 75 μm, or even finer in some instances. The mills operate at medium speed, up to approximately 30 m/s, and can handle materials with up to Mohs' hardness 5 before wear rates become prohibitive. Many different

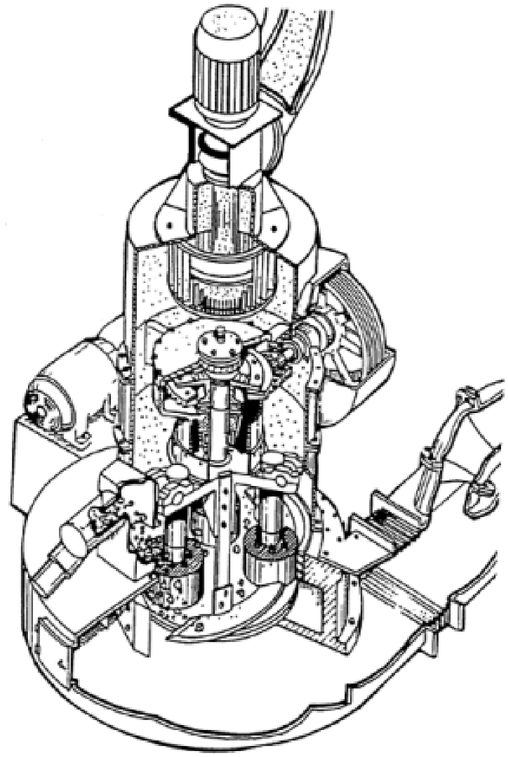


Fig. 8. Pendulum roller mill.(Courtesy of Bradley Pulverizer Company.)

designs are available; the two most commonly encountered variants are pendulum mills and the table roller mill.

Pendulum mills (Fig. 8) have a central, driven shaft. From this shaft several rollers are suspended on pivots. As the central shaft turns, the centrifugal force causes the pivoted rollers to press against the outer, stationary grinding ring. Material is stressed by compression between the roller and the outer ring. The grinding zone is swept by an airstream and the partially ground material is carried to the upper section of the unit, where an air classifier is located. For standard materials a stationary classifier is used, whereas to achieve 97% below 75 μm, a rotating whizzer type is employed. For finest materials possibly down to 30 μm, turbine classifiers have become common in recent years. The table roller mill employs a ring of pivoted rollers which are forced down toward a driven table by either springs or hydraulic pressure. Material is stressed between the rotating table and the rollers to achieve size reduction. Again, the unit is air-swept and the same choice of classifier units is available as for pendulum mills. Both of these roller mill types are widely employed for limestone, barytes, phosphates, dolomite, and many similar minerals.

6.6. Ball Mills and Rod Mills

Ball mills have been utilized since the late 1800s and the construction and principles remain essentially very simple. The machine consists of a cylindrical or conical tube into which loose grinding balls are filled up to a certain level (Fig. 9). Size reduction is achieved by rotating the tube so that the balls either roll against each other or, if the speed is sufficient, they are lifted and fall. In general, the action is a combination of rolling and lifting and this can be influenced by the tube design, eg, using ribs to encourage lifting.

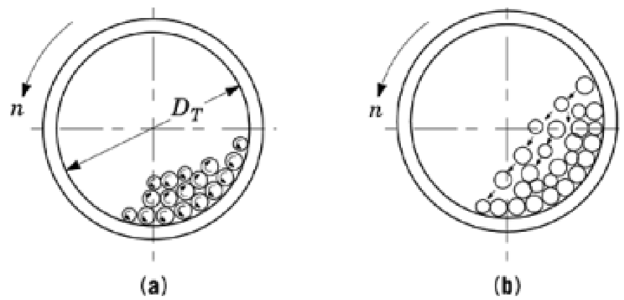


Fig. 9. Size reduction in a ball mill: (**a**) rolling balls and (**b**) tumbling balls.

The formula used to calculate the speed limit, n_c, at which the balls begin to tumble rather than roll, is shown in equation 3, where D_T is the tube diameter and g is the acceleration due to gravity.

$$n_c = \frac{1}{2\,\eta}\left(\frac{2g}{D_T}\right)^{1/2} \qquad (3)$$

The grinding action ensures that a very high stress can be applied to the particles so that a high portion of ultrafine product is produced in a ball mill, compared to impact grinding, for example. Generally, the most economical construction uses a steel shell and balls; however, many products demand iron-free processing, such as ceramic raw materials. In this application the balls are made from flint, aluminium oxide, or similar materials, and the mill is also lined with either one of these or a wear-resistant rubber. Variations employ cylindrical grinding media or rods or use vibration energy to excite the ball charge (Fig. 10) rather than rotate the outer cylinder.

6.7. Impact Mills

In this equipment group, stress is applied by transferring kinetic energy by either particle–particle contact or machine–particle contact. Impact mills can broadly be separated into mechanical types where high speed beaters impact the material to apply stress, and fluid energy mills, where particles are accelerated by the surrounding medium and impact against each other or a target.

6.7.1. Mechanical Impact Mills

The mechanical types include crushers, hammer mills, pin disk mills, turbine mills, and mills with air classifiers.

6.7.1.1. Impact Crusher. Feed material is introduced through a feed opening onto a rotor moving at between 25 and 50 m/s (Fig. 11). The initial impact by the rotor causes some size reduction, and the material is accelerated up to the speed of the rotor and flung against the impact plates, where further size reduction occurs. It is possible to wear-protect these units quite well, so that abrasive materials can be handled. The final end particle size can be varied by the inclusion of an outlet grid to vary the residence time in the machine.

6.7.1.2. Hammer Mills. One of the most versatile, economical, and widely used impact mills is the hammer mill (Fig. 12). Many variations are produced, with special types available for specialized applications, eg, quick screen change for animal feed, heavy duty for minerals, and light constructions for woodchip. The principle employed is similar to that of the impact crusher; however, the rotation speed can vary from 20 up to 100 m/s with high speed fine-grinding versions. The outlet screen is used to vary the residence time, which in turn affects final particle size. The size of the end product is an order of magnitude finer than the size of the perforations in the outlet screen.

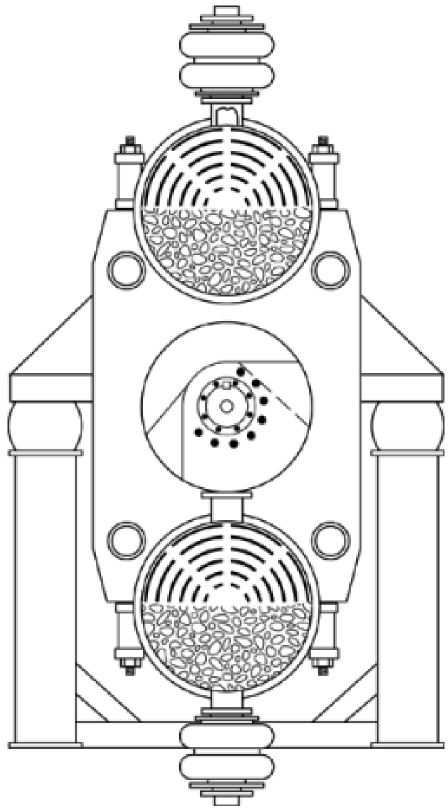


Fig. 10. Vibratory ball mill.(Courtesy of KHD Humboldt Wedag AG.)

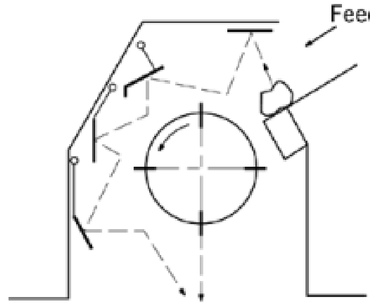


Fig. 11. Impact crusher.

6.7.1.3. Pin Disk Mill. Conventional pin disk mills are equipped with one rotating and one static disk. Each disk has several concentric rows of pins, and when the machine is operating the rows on the rotating disk alternate with the rows of pins on the static disk. Material is fed into the center of the unit through the static disk and is impacted by the rotating pins and the static pins. Air is swept through the machine and this action carries the ground product away to some form of collection, such as a cyclone or dust filter. Pin disk mills are particularly suitable for brittle materials; however, they are very susceptible to wearing of the pins. Owing to

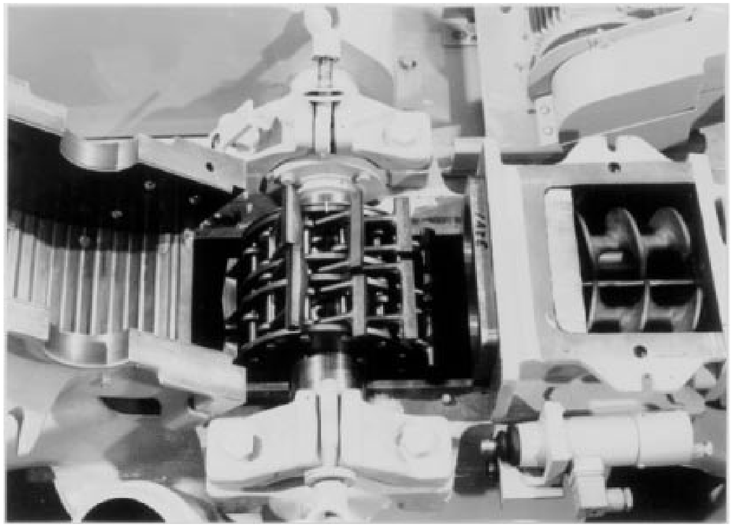


Fig. 12. High speed hammer mill.(Courtesy of Hosokawa Micron Powder Systems N.J.)

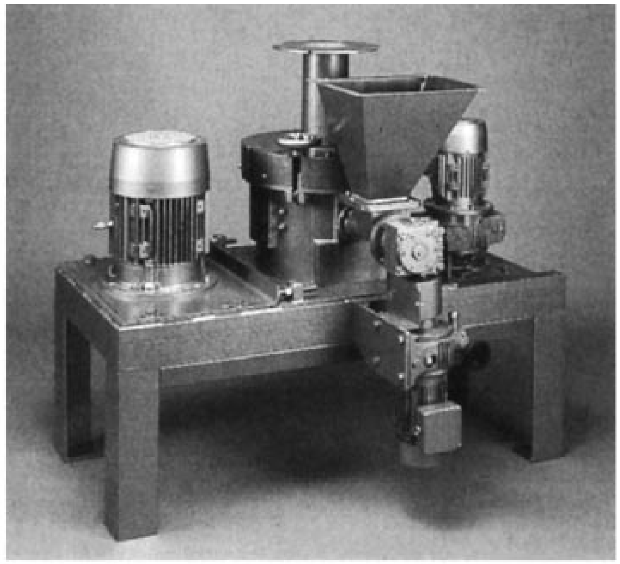
the narrow pin diameter, mechanical strength is quickly lost as the pins wear; hence these machines are best used on material of Mohs' 3 or below. Pin speeds up to 150 m/s are typical. One special variation has pin disks that both rotate. This is an advantage in that it either increases the differential speed by rotating the disks in opposite directions or that it grinds sticky or fatty products, whereas stationary pins in the grinding zone are subject to severe buildup problems which quickly lead to the blocking of the machine.

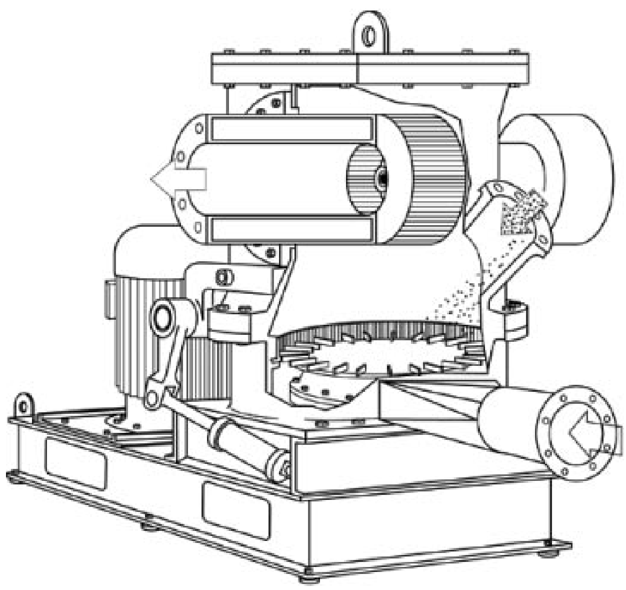
6.7.1.4. Turbine Mills. Probably the most widely used impact mills for fine grinding down to 20 μm are turbine mills with grinding tracks or screens. Various designs of beater systems can be utilized, but all are essentially impact plates that are arranged in either a static grinding track, a perforated screen, or a combination of the two. The turbine-type rotor produces a relatively high air throughput that keeps end-product temperatures relatively cool. Impact speeds at $\sim$120 m/s are a little lower than those of pin disk mills; however, many manufacturers produce Universal-type impact mills that can be fitted with either pin disks or a turbine and track combination, depending on the requirement.

6.7.1.5. Mechanical Mills with Air Classifiers. To improve the end fineness and achieve a sharper topsize cutoff point, many mechanical impact mills are fitted with integral air classifiers (Fig. 13). These can be driven separately from the mill rotor or share a common drive. The material to be ground is introduced into the mill section of the machine, where impact size reduction takes place. The airflow through the machine carries the partially ground product to the air classifier, which is usually some form of rotating turbine. The speed of rotation determines which particle size is internally recycled for further grinding and which is allowed to exit the machine with the airflow. Machines are available up to 375 kW and can achieve products with essentially all material $<$20 μm.

6.7.2. Fluid Energy and Jet Mills

Particles are accelerated rapidly in a high speed gas stream and size reduction is effected either by particle–particle attrition or by impact against a target. Although energy requirements for fluid energy mills are up to 5–10 times higher than for mechanical impact mills, the attainable fineness is much higher, with small residues of 10 μm being common. In most cases air is used as the grinding medium, but superheated steam can provide energy advantages and inert gas can be utilized where appropriate.





(b)

Fig. 13. (**a**) Mikro air classifier mill and (**b**) cutaway of Alpine ZPS unit.(Courtesy of Hosokawa Micron Powder Systems N.J.)

6.7.2.1. Spiral Jet Mill. This is the simplest form of fluid energy mill (Fig. 14) and is still widely used owing to its low cost and ease of cleaning. A flat cylindrical grinding chamber is surrounded by a nozzle ring. Material to be ground is introduced inside the nozzle ring by an injector. The jets of compressed fluid expand through the nozzles and accelerate the particles, causing size reduction by mutual impact. The expanded gas forms a free vortex spiral toward the central outlet of the machine; hence a classification effect forces the

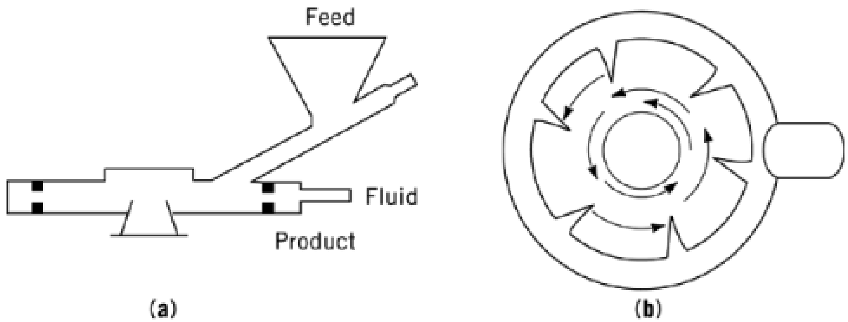


Fig. 14. Spiral jet mill elements (**a**) and grinding chamber (**b**).

coarser particles back outward toward the jet nozzles for further grinding. Finer particles are carried through the outlet orifice with the grinding fluid. Reliance on a free vortex for classification does mean that the end fineness is affected by variations in the feed rate. The shape and size of the outlet orifice affects the final particle size, as does the pressure of the grinding fluid. Impact velocities are around 250 m/s.

6.7.2.2. Fluidized-Bed Jet Mill. To achieve finer products and a better control of final particle size, many fluid energy mills are equipped with mechanical air classifiers. One popular design is the fluidized-bed jet mill (Fig. 15). The lower section of this machine is the grinding zone. The material bed is kept to a predetermined level either by load cell control, level detector, or feedback from the classifier. A ring of grinding nozzles within the material bed is focused toward a central point, and the grinding fluid accelerates the particles. Size reduction takes place within the fluidized bed of material, and this technique can greatly improve energy efficiency. The partially reduced product is carried with the expanded grinding fluid upward toward the turbine air classifier. This unit is rotating at a variable speed that controls the particle size; the oversize part of the product is rejected and goes back to the fluidized bed for further grinding, and the remaining fine product can leave the machine with the expanded fluid.

6.7.2.3. Opposed Jet Mills. These mills are, in some ways, similar to the fluidized-bed machine; however, in this case two opposed nozzles accelerate particles, causing them to collide at a central point (Fig.16). A turbine classifier is again used to separate the product that has achieved the desired fineness from that which must be internally recycled for further grinding.

6.8. Cutting Mills

The machines applying stress by cutting are described in Figure 3**e**. They are usually employed for size reduction of ductile materials such as plastics, vegetables, and animal products.

6.8.1. Granulators or Knife Mills

The usual format of these machines is to have a rotor equipped with several knife blades which cut the product against stationary knife bars. A typical machine is shown in Figure 17, illustrating the size having up to 2-m knife length available. The lower section of the grinding chamber has a semicircular screen which controls the final particle size of the end product. This particular machine was delivered to cut waste electrical cable, freeing the copper conductor from the poly(vinyl chloride) (PVC) insulation for subsequent separation and re-use.

6.9. Wet Grinding

The examples given up to this point all concern size reduction in the dry state, as this is by far the predominant method. However, in certain circumstances it is advantageous to grind in a wet state: (*1*) where a suspension

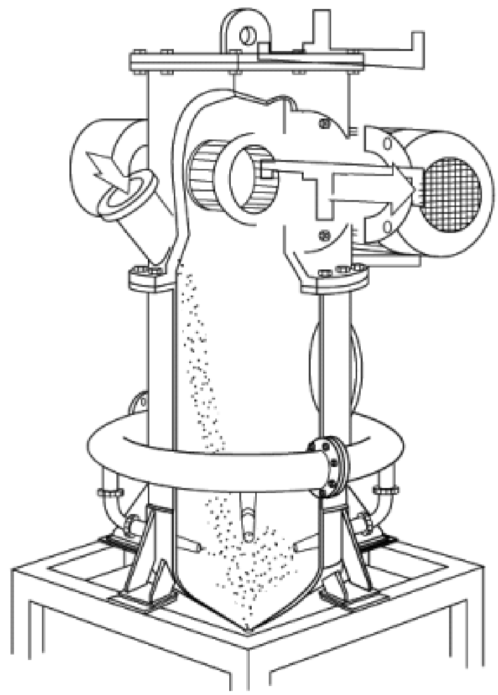


Fig. 15. Fluidized-bed jet mill.(Courtesy of Hosokawa Micron Powder Systems N.J.)

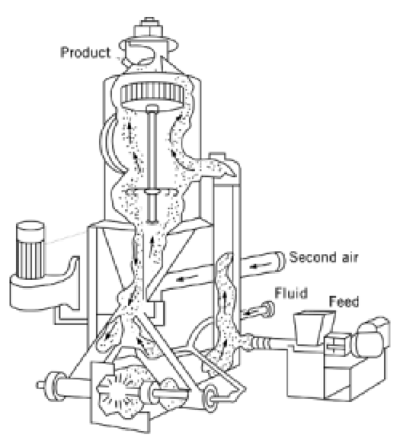


Fig. 16. Opposed jet mill.

is required as an end product; (*2*) where the required particle size cannot be achieved in a dry state; (*3*) where toxic or flammable emissions must be avoided; and (*4*) where chemical or physical surface reactions are desired. Providing the material does not require subsequent drying after grinding, wet milling can give energy savings of ~30%; however, wear rates are usually three to five times higher.

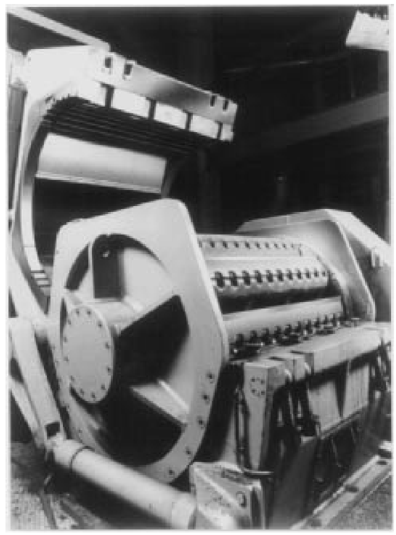


Fig. 17. Granulator or knife mill.(Courtesy of Hosokawa Alpine AG.)

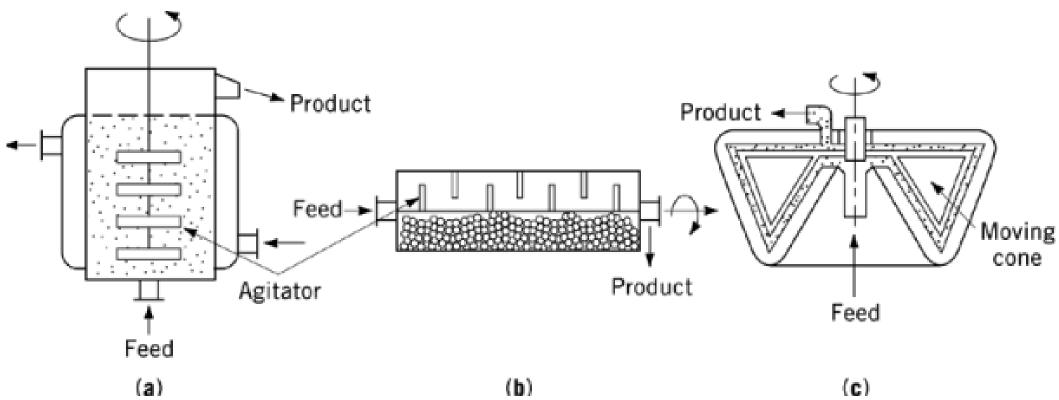


Fig. 18. Stirred wet ball mills: (**a**) vertical and (**b**) horizontal shaft, and (**c**) annular gap.

6.9.1. Stirred Wet Ball Mill

The most commonly applied wet grinding device is the stirred ball mill (Fig. 18) also referred to as sand mill, pearl mill, bead mill, or agitated ball mill. The units also consist essentially of a grinding container which is partially filled with loose grinding media, usually in the size range 0.5–10 mm dia. The chamber is filled with the slurry to be ground, and some form of stirrer accelerates the grinding media. Size reduction takes place as particles are crushed between the media. These units operate either batchwise or as continuous units with a pumped flow once through or recirculated.

Typical stirrer speeds are between 4 and 20 m/s. Uses range from dispersion of pigments and filler for paints, to ceramics and ultrafine minerals such as kaolin. These products usually demand a high percentage of submicrometer particles, which wet grinding can achieve. In many cases the task is to break agglomerates of primary particles that have formed owing to the ultrafine particle size, and the energy requirement for disagglomeration at this size can be considerable.

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