Factors that influence milling

Grinding large particles into small ones can be a complicated process. Multiple variables in both equipment and particle characteristics can cause some surprising results. In this column, we review basic particle breakage mechanics and how various particle characteristics can affect grinding results.

The principle of particle size reduction follows crack propagation theory. During World War I, engineer A.A. Griffith developed the idea of fracture mechanics of brittle materials. His theory says that minor flaws or cracks occur on a surface. When stress is applied to the surface, the stress concentrates at the flaws and extends them, causing failure or breakage.

A chipped automobile windshield provides an example of crack propagation. The tiny chip is the flaw, and any stress applied to the windshield — a high wind load, thermal expansion in winter, etc. — concentrates on that flaw. The windshield cracks, sometimes into an elaborate spiderweb, and the starting point was the tiny chip.

Particles in grinding mills follow the same crack propagation theory. Microscopic flaws or cracks reside on the particle surface. When stress energy is imparted to the particle, it fails at the point of the microscopic crack. The crack propagates along a failure plane within the particle, and the particle fractures. A crack that travels along the particle edge from one flaw to another causes chipping. A crack that splits through the particle is called breakage or a fracture.

Impacting, crushing, and shearing are three methods that can achieve breakage. Impacting applies force via movement of the particle against another particle or an object or hard surface. Hammermills, jet mills, and pin mills are examples of impact milling equipment. Crushing applies large stresses to a particle and forces cracks to propagate in it. Crushing equipment includes roller mills and jaw crushers. Shearing creates a shear plane within the particle and forces breakage to occur along that plane. Examples of shearing mills are recycle shredders, lump breakers, and food graters. The remainder of this column focuses on factors that affect impact milling, although these same factors can affect crushing and shearing.

Researchers who’ve studied the concepts related to particle breakage have found that the propensity for a particle to break is related to — among other things — its density, diameter, hardness and toughness, impact velocity, and the number of impacts to the particle.

Particle density. The effect of particle density on breakage propensity is simple physics. Density is related to mass; the greater the density for a given particle size, then the greater the mass — and the greater the energy imparted to the particle at impact. More energy increases the propensity for breakage.

Particle diameter. A particle’s diameter affects its propensity for breakage. A large particle is much easier to break than a small one. A rule of thumb is that a particle will only reduce to pieces about 1/10 of its size in one grinding pass. This means that in one pass, a 3,000-micron particle will reduce to about 300 microns; a 300-micron particle will reduce to about 30 microns; and a 30-micron particle will reduce to about 3 microns. A simple hammermill can do the 3,000-to-300-micron grind, but much more energy is needed to reduce a particle from 300 microns to 30 microns, and an even greater amount of energy is needed to reduce a 30-micron particle to 3 microns. This is because a larger particle has more surface area and, thus, more locations for surface flaws, which can propagate into breakage.

Hardness and toughness. Hardness and toughness can be discussed together because they’re inversely proportional. The harder the particle, the less tough it is. Hardness is related to brittleness. A very hard particle, such as a glass bead, can be broken easily because it’s brittle. Toughness relates to elasticity. A tough particle will flex and not fracture along a surface flaw. A harder particle, such as the glass bead, is less tough, so the breakage function goes up, while rubber, a tougher particle, has little hardness so the breakage function goes down. A diamond is extremely hard, but a well-placed strike will split it because it’s not tough. Rubber is tough, and it would take extremely high energy to split a
rubber ball. Many extremely tough or elastic particles require shearing instead of impacting for size reduction. While hardness can be measured with a unit-less value such as the Mohs or Rockwell hardness number, there’s no empirical measurement for toughness.

Cryogenic grinding using an extremely cold gas such as liquid nitrogen is an example of the hardness-versus-toughness concept put into practice. Often, a tough material like rubber can be cryogenically frozen, reducing the particle’s toughness and increasing its hardness, making it easy to grind. Most of us have seen the video of a very soft banana dipped into liquid nitrogen, making it very brittle, before it’s shattered by a hammer.

Although heat can also be used to turn a tough material into a hard material, it can also reduce some materials’ hardness — for example, in a sugar milling operation. A sugar particle has a hard, brittle, crystalline structure at a low temperature, but as its temperature increases the sugar particle’s surface becomes softer and much more difficult to grind. The surface flaws are no longer brittle, and the stresses are no longer concentrated at the flaws. Consequently, more energy is required to grind the warm particle. For materials like this, an airswept hammermill is often used to keep the particle temperature lower during milling.

**Impact velocity.** The breakage function is directly proportional to the impact velocity squared. Each time the velocity is doubled, the propensity for material breakage goes up four times as shown by the equation \( E = mv^2 \). The impact velocity is the relative velocity between the particle and its contact surface. So, there’s minimal breakage in a rolling drum of particles because the particle velocity is simply the particles’ falling speed. Compare that to an airjet mill, where the particles are fired at each other at a very high velocity. The airjet mill produces significant particle breakage because higher velocity equals much greater breakage. This concept explains why it’s important to keep velocities low in a pneumatic conveying system where avoiding particle attrition is important. A high-velocity dilute-phase system will break more particles than a low-velocity dense-phase system.

The particle diameter effect combined with the impact velocity effect demonstrates why a high-velocity airjet mill is needed to reduce 30-micron particles, but a three-arm beater mill might be sufficient to reduce a 3,000-micron particle to 300 microns. This concept also explains why a hammermill can reduce large particles, but a higher rotational speed pin mill or airjet mill is required to reduce small particles.

**Number of impacts.** Finally, the number of impacts has a significant effect on particle milling. While one impact against a particle surface flaw might expand the flaw but not fracture the particle, many impacts on the same flaw will increase the energy input and cause a fracture. To fracture a salt particle with one impact, the velocity between the particle and the impacting surface has to be more than 10,000 fpm. If the particle is impacted 100 or more times, the relative velocity can be reduced to below 1,000 fpm. This is why a pin mill is more aggressive than a simple hammermill: its numerous pins impart more impacts. To add more impacts in a hammermill, you can fit it with a grinding screen or track, which will increase the particles’ residence time in the mill and increase the number of impacts. The number of impacts can also be increased in a ball mill by keeping the particle in the mill for a longer time.

**Applying this information**

So, what does this mean when you’re milling? First, you must test any grinding operation. There’s no model or equation that can help you choose the correct grinder; the key is using what you know about your material particle characteristics and applying these principles. For example, let’s say that you have a large granular material that’s hard and brittle. The starting mean particle size is 2 millimeters, and you want to reduce the material to 200 microns. The principles here would point you to any typical hammermill as long as the rotational speed is high enough to cause breakage. If testing shows that one pass isn’t enough to completely fracture the particles, then perhaps adding a grinding screen will increase residence time and the number of impacts to achieve sufficient grinding.

Now let’s say that you want to introduce a new finished product that uses the same raw material, but you need a particle size that’s only 20 microns. Now you’ll require either significantly more impacts or higher-velocity impacts, so a hammermill won’t work. You’ll need to try a pin mill (more impacts) or an airjet mill (higher velocity) to meet your new product’s grinding requirements. The principles described here can assist in narrowing down your equipment options based on the type of grinding you need to perform.

---

**For further reading**

Find more information on this topic in articles listed under “Size reduction” in Powder and Bulk Engineering’s article index in the December 2018 issue or the Article Archive at PBE’s website, www.powderbulk.com. (All articles listed in the archive are available for free download to registered users.)

**James L. Davis** is president of Powder Processing Solutions (www.powderprocessingsolutions.com) and a consulting engineer specializing in solving difficult powder processing problems and optimizing complex powder systems for efficient operation. He was with Procter & Gamble for 26 years, 15 of them in powder processing. He holds a BS in mechanical engineering from the University of Cincinnati.