

where E_p is the energy required to form unit area of double surface.

It can therefore be seen that the ease of comminution depends on the brittleness or plasticity of the material because of their relationship with crack initiation and crack propagation.

Surface hardness

In addition to the toughness of the material described above, size reduction may also be influenced by the hardness of the material. Hardness can be described empirically by its position in a scale devised by a German mineralogist called Mohs. Mohs' scale is a table of minerals; at the top of the table is diamond, with Mohs hardness >7 , and this has a surface that is so hard that it can scratch anything below it. At the bottom of the table is talc, with Mohs hardness <3 , and this is soft enough to be scratched by anything above it.

A quantitative measurement of surface hardness was devised by Brinell. This involves placing a hard spherical indenter (e.g. hardened steel or sapphire) in contact with the test surface and applying a known constant load to the sphere. The indenter will penetrate into the surface until and when the sphere is removed, the permanent deformation of the sample is measured. From this, the hardness of the material can be calculated. Hardness has the dimensions of stress (force applied to the indenter divided by the area of test material that will support the load, example units are MPa). A similar Vickers hardness test employs a square-pyramidal diamond as the indenter tip.

Such determinations of hardness are useful as a guide to the ease with which size reduction can be carried out because, while it appears to be a surface assessment, the test actually quantifies the deformation characteristics of the bulk solid. In general, harder materials are more difficult to comminute and can lead to abrasive wear of metal mill parts, which can then result in product contamination. Conversely, materials with a large elastic component, such as rubber, are extremely soft yet difficult to size reduce.

Materials such as rubber that are soft under ambient conditions, waxy substances such as stearic acid that soften when heated, and 'sticky' materials such as gums are capable of absorbing large amounts of energy through elastic and plastic deformation without crack initiation and propagation. This type

of material, which resists comminution at ambient or elevated temperatures, can be more easily size reduced when temperatures are lowered below the glass transition point of the material. At these lower temperatures the material undergoes a transition from plastic to brittle behaviour and crack propagation is facilitated.

Other factors that influence the process of size reduction include the moisture content of the material. In general, a material with a moisture content below 5% is suitable for dry grinding and one with greater than 50% will generally require wet grinding to be carried out.

Energy requirements of size reduction process

Only a very small amount of the energy put into a comminution operation actually effects size reduction. This has been estimated to be as little as 2% of the total energy consumption, the remainder being lost in many ways, including:

- elastic deformation of particles
- plastic deformation of particles without fracture
- deformation to initiate cracks that cause fracture
- deformation of metal machine parts
- interparticulate friction
- particle-machine wall friction
- heat
- sound
- vibration.

A number of hypotheses and theories have been proposed in an attempt to relate energy input to the degree of size reduction produced.

Rittinger's hypothesis relates the energy, E , used in a size reduction process to the new surface area produced, S_n , or:

$$E = \kappa_R(S_n - S_i) \quad (10.3)$$

where S_i is the initial surface area and κ_R is Rittinger's constant, expressing energy per unit area.

Kick's theory states that the energy used in deforming or fracturing a set of particles of equivalent shape is proportional to the ratio of the change in size, or: