

INVESTIGATION OF ENERGY - TECHNOLOGY DEVELOPMENT IN ULTRA FINE GRINDINGYakup UMUCU^{1*}, Vedat DENİZ², Y. Hakan GÜRSOY³¹ Eskişehir Osmangazi University, Mining Engineering Department, Eskişehir
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ORCID No : <https://orcid.org/0000-0001-8987-7818>**Keywords**Ultra-fine Grinding
Energy
Grindability**Abstract**

Ultra-fine grinding refers to the process of reducing materials to extremely small particle sizes, typically in the micron or submicron range. It is commonly used in various industries such as mining, pharmaceuticals, ceramics, and chemicals, where the production of fine particles with specific properties is required.

Energy plays a significant role in ultra-fine grinding processes. The reduction of materials to such small sizes requires a considerable amount of energy input. The energy consumption in ultra-fine grinding is typically higher compared to conventional grinding methods due to the higher surface area and increased particle-particle interactions.

In the mining sector, with the depletion of high-grade ore deposits, it has become a necessity to operate very low-grade ore deposits with very small particle liberation sizes. In the enrichment of these ores, most of the energy required is spent on grinding. In micronized grinding, conventional mills (such as rod and ball mills) lose their efficiency and become uneconomical.

most of the energy spent in conventional mills is used directly in size reduction, and a significant portion is lost as heat and sound without doing any useful work (size reduction). In addition, for grinding below 75 µm, the efficiency of conventional mills is greatly reduced (energy consumption increases excessively), and grinding becomes uneconomical.

In this study, alternative fine and ultrafine grinding mills for ore dressing plants are introduced, and information about their working principles is presented. Unlike other studies, information on particle and grinding energy calculations is given. The reasons for the lack of a theory or model to perform newly developed calculations for ultrafine grinding theories are tried to be explained.

ULTRA İNCE ÖĞÜTMEDE ENERJİ - TEKNOLOJİ GELİŞİMİNİN İNCELENMESİ**Anahtar Kelimeler**Ultra-İnce Öğütme
Enerji
Öğütülebilirlik**Öz**

Ultra ince öğütme, malzemeleri genellikle mikron veya mikron altı aralığında son derece küçük tane boyutlarına indirme işlemini ifade eder. Madencilik, ilaç, seramik, kimya gibi belirli özelliklere sahip ince tane üretiminin gerekli olduğu çeşitli endüstrilerde yaygın olarak kullanılmaktadır.

Enerji, ultra ince öğütme işlemlerinde önemli bir rol oynar. Malzemelerin bu kadar küçük boyutlara indirgenmesi ciddi miktarda enerji girdisi gerektirmektedir. Ultra ince öğütmede enerji tüketimi, daha yüksek yüzey alanı ve artan tane-tane etkileşimleri nedeniyle geleneksel öğütme yöntemleriyle karşılaştırıldığında genellikle daha yüksektir. Madencilik sektöründe yüksek tenörlü cevher yataklarının tükenmesiyle birlikte, çok küçük tane boyutlarına sahip, çok düşük tenörlü cevher yataklarının işletilmesi bir zorunluluk haline gelmiştir. Bu cevherlerin zenginleştirilmesinde ihtiyaç duyulan enerjinin büyük bir kısmı öğütme işlemine harcanmaktadır. Mikronize öğütmede konvansiyonel değirmenler (çubuk ve bilyalı değirmenler gibi) verimlerini kaybederek ekonomik olmaktan çıkarlar. Bilindiği üzere konvansiyonel değirmenlerde harcanan enerjinin büyük bir kısmı doğrudan boyut küçültmede kullanılmakta, önemli bir kısmı ise herhangi bir faydalı iş yapılmadan (boyut küçültme) ısı ve ses olarak kaybolmaktadır.



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Ayrıca 75 µm'nun altındaki öğütmelerde konvansiyonel değirmenlerin verimi büyük oranda düşer (enerji tüketimi aşırı artar) ve öğütme ekonomik olmaz. Bu çalışmada cevher zenginleştirme tesisleri için alternatif ince ve ultra ince öğütme değirmenleri tanıtılarak, çalışma prensipleri hakkında bilgi verilmiştir. Diğer çalışmalardan farklı olarak tane ve öğütme enerjisi hesaplamalarına ilişkin bilgiler verilmektedir. Ultra ince öğütme teorileri için yeni geliştirilen hesaplamaları gerçekleştirecek bir teori veya modelin bulunmamasının nedenleri açıklanmaya çalışılmaktadır.

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1. Introduction

Grinding operation is a unit operation that needs a significant amount of energy. In this procedure, grinding is responsible for just 2%–20% of the entire energy consumption, according to what has been indicated (Batterham, 2011; Jeswiet and Szekeres, 2016). The remaining energy disappears into the surrounding environment as heat, sound, and vibrations. In engineering projects, researchers are looking at potential solutions that can make mills more energy efficient. In this case, operational variables are used to study both new technologies and ways to improve systems that are already in place.

Important shifts in the technology were used to reduce particle size occurred in the 16th, 19th, and 20th centuries. In each instance, an influx of copious new income prompted an increase in the use of resources, investments in new plants, and the creation of new processes and machinery. As a consequence of this, there was a rise in the need for the size-reduction equipment that had higher levels of both productivity and energy efficiency.

The conventional method of grinding takes place in tumbling mills, in which the ore is fed into a horizontal mill that is then spun by a motor to cause the cylindrical body of the mill to tumble with the mill charge, which consists of the ore and various grinding media. The ore is broken down by the processes of impact, attrition, and abrasion when it is subjected to the free motion of disconnected media like steel rods, steel or ceramic balls, or coarse ore pebbles. This is known as grinding.

Ultrafine grinding, also known as ultrafine milling or ultrafine comminution, is a technique used to reduce materials to extremely small particle sizes. It is commonly used in various industries, including pharmaceuticals, chemicals, minerals, food processing, and materials science.

The primary goal of ultrafine grinding is to produce particles with a specific size distribution or to achieve a

desired level of particle fineness. By reducing the particle size, a larger surface area is exposed, which can enhance the material's reactivity, dissolution rate, and overall performance.

Calculations of the energy consumed in grinding from the past to the present have been made. In addition, models capable of calculating grain size distributions have been developed. However, no equation or model has been developed for fine grinding (-5 µm) that can calculate energy or predict particle size distribution. The main reason for this can be stated as the inability to describe the motion and behavior of very fine grains. Within the scope of this article, research has been carried out on these issues, and solutions have been discussed in detail in the conclusion part.

2. Equipment for Ultra-Fine Grinding

There are several methods employed for ultrafine grinding including:

- **Ball Milling:** Ball mills use rotating cylinders filled with balls as a grinding media. material is fed into the cylinder and subjected to the impact and attrition caused by the balls' movement. By controlling the milling parameters such as rotational speed and ball size, ultrafine particles can be obtained.
- **Vibratory Mills:** Vibratory mills utilize vibrations or oscillations to generate collisions between the grinding media and the material. These mills are particularly suitable for fragile or heat-sensitive materials.
- **Stirred Media Mills:** Stirred media mills, such as the famous "IsaMill," use a series of rotating discs or pins within a chamber to agitate the grinding media. This agitation generates high-energy collisions, resulting in particle size reduction. These mills are well-suited for ultrafine grinding of minerals and ores.

- **Jet Milling:** In jet milling, high-pressure gas or air is used to accelerate particles and cause them to collide with each other, resulting in particle size reduction. Jet mills can achieve particle sizes in the submicron to nanometer range.
- **Fluid Energy Milling:** Fluid energy mills, such as spiral jet mills, utilize compressed gas or superheated steam to create high-velocity streams that impact and disintegrate the particles. The fine particles are carried away by the gas stream, and the oversize particles are recirculated for further grinding.
- **Nano Milling:** Nano milling techniques provide reducing particle size to the nanometer scale, typically below 100 nm. Various methods, including high-energy ball milling and stirred media milling, are used to achieve nano-sized particles.

It is important to note that the choice of ultrafine grinding method depends on factors such as the material being processed, desired particle size, required throughput, and equipment availability. Additionally, it is essential to consider the potential challenges, such as heat generation, particle aggregation, and equipment wear, associated with ultrafine grinding processes.

2.1. Ball Milling

Ball milling is a technique for reducing particle size and mixing materials by grinding them together in a ball mill. The ball mill is a cylindrical device that rotates around its axis and is partially filled with grinding media such as balls made of steel, ceramic, or other materials. The material to be milled is loaded into the ball mill along with the grinding media, and as the mill rotates, the grinding media cascades and collides with the material, reducing its particle size. The process of ball milling involves the following steps:

Loading: The material to be milled and the grinding media are added to the ball mill. The ratio of the material to the grinding media can vary depending on the desired outcome and the properties of the materials involved.

Milling: The ball mill is set into motion, typically by rotating the cylinder. As the mill rotates, the grinding media cascade and impact the material, causing it to break and reduce in size. The collision and friction between the grinding media and the material result in particle size reduction.

Mixing: Ball milling can also be used for mixing or blending materials. In this case, multiple materials with different properties can be loaded into the ball mill together, and the milling process helps in achieving a homogeneous mixture.

Duration: The duration of the ball milling process can vary depending on the desired fineness and the

properties of the materials. It can range from minutes to several hours.

The advantages of ball milling include its versatility, scalability, and relatively simple operation. It can be used for both dry and wet milling processes. Ball milling is widely used in various industries such as pharmaceuticals, chemicals, minerals, paints, ceramics, and more. It is commonly used for grinding and refining materials, producing fine powders, and creating homogeneous mixtures.

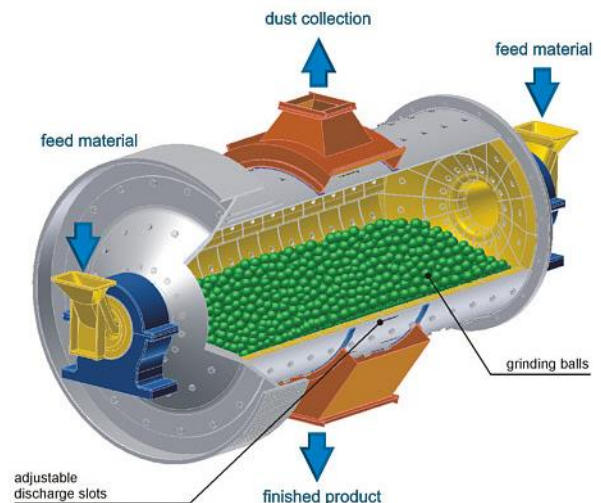


Figure 1. Ball Mills Are Used In Industry (<https://www.hiimac.com/>)

Conversion of energy given when materials undergo size reduction; It was stated by Orr (1966) that it depends on the inter-particle effects of the crushing machine and the crushed material. For inter-particle effects with a crushing machine; While friction, sound, electrical effects and kinetic energy are given, it is stated that the crushed material is due to the rearrangement of the cage structure, surface energy, elastic deformation and plastic deformation. It has been stated that heat arises due to plastic deformation, elastic deformation, friction and kinetic energy. Therefore, electrical effects can be added to the relevant section.

However, it is important to note that ball milling has certain limitations. It may generate heat during the milling process, which can affect heat-sensitive materials. It can also lead to contamination from the grinding media or the mill itself, particularly when milling reactive or abrasive materials. Care should be taken to select appropriate grinding media and milling conditions to achieve the desired results while minimizing any potential drawbacks.

2.2. Vibratory Mills

Vibratory mills also known as vibratory ball mills or vibratory grinding mills, are a type of milling equipment used for fine grinding and mixing of materials. These

mills utilize vibrations or oscillations generated by an eccentrically mounted shaft or an electromagnetic drive to impart energy to the grinding media and the material being processed.

Here's how vibratory mills typically work:

Design: Vibratory mills consist of a cylindrical or conical container that holds the grinding media and the material to be processed. The container is mounted on springs or other vibration-damping elements to isolate the vibrations from the surroundings.

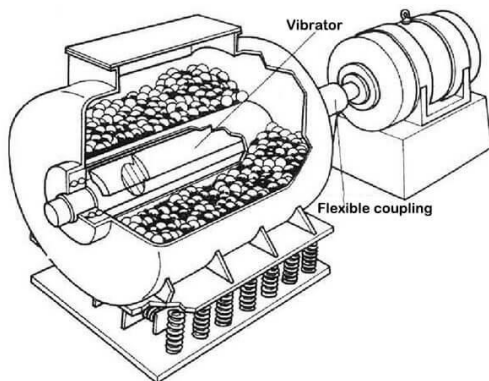


Figure 2. Vibratory Mills Are Used In Industry (<https://ballmillssupplier.com/product-center/vibration-ball-mill/>)

Vibratory Motion: The mill is set into vibration by an eccentrically mounted shaft or an electromagnetic drive system. The vibrations cause the grinding media and the material to move in a circular or elliptical motion within the mill.

Grinding and Mixing: As the mill vibrates, the grinding media, which can be balls, rods, or cylpebs, collide with the material, resulting in impact and attrition. The energy generated by the vibrations fractures and reduces the particle size of the material. The mixing action is also facilitated as the particles and grinding media move around and interact.

Control: The intensity and frequency of the vibrations can be adjusted to control the milling process. This allows for fine-tuning the grinding energy and optimizing the particle size distribution and mixing efficiency.

Vibratory mills offer several advantages, including:

Efficient Grinding: The vibratory motion provides intense and rapid grinding action, resulting in high grinding efficiency and shorter processing times compared to some other milling methods.

Gentle Processing: Vibratory mills are suitable for processing fragile or heat-sensitive materials that may be damaged or undergo unwanted chemical reactions under more aggressive milling conditions.

Scalability: Vibratory mills are available in various sizes and capacities, allowing for scale-up from laboratory-scale mills to industrial production.

Versatility: Vibratory mills can be used for dry or wet grinding and can handle a wide range of materials, including minerals, ores, chemicals, pigments, ceramics, and more.

Despite their advantages, vibratory mills also have some limitations. The high-energy vibrations can lead to increased wear of the mill components, necessitating regular maintenance and replacement of parts. Additionally, controlling the particle size distribution and achieving narrow size ranges can be challenging with vibratory mills.

Overall, vibratory mills are a valuable option for fine grinding and mixing applications, especially when gentle processing and efficient grinding are required.

2.3. Stirred Media Mills

Stirred media mills also known as stirred bead mills or stirred mills, are a type of grinding equipment used for fine and ultrafine grinding of materials. These mills utilize a rotating stirrer, typically composed of discs or pins, to agitate the grinding media and the material being processed.

Here's how stirred media mills typically work:

Design: Stirred media mills consist of a cylindrical or conical container that holds the grinding media and the material to be processed. The container is typically equipped with a central shaft with discs or pins attached to it. The shaft and the grinding media are driven by a motor, causing them to rotate.

Grinding and Mixing: As the shaft and grinding media rotate, the grinding media (beads or cylinders) move in a highly energized and agitated manner. The combination of rotational and radial movements causes intense collisions and shearing forces between the grinding media and the material, resulting in particle breakage and size reduction. The mixing action is also promoted as the particles and grinding media move around and interact.

Size Reduction and Classification: The grinding action in stirred media mills occurs primarily by shear and impact forces rather than by the cascading action found in ball mills. The high-energy collisions and agitation lead to efficient particle size reduction, achieving finer and more uniform product sizes. In some designs, the mills also incorporate a classification system to separate particles of the desired size from the oversized ones.

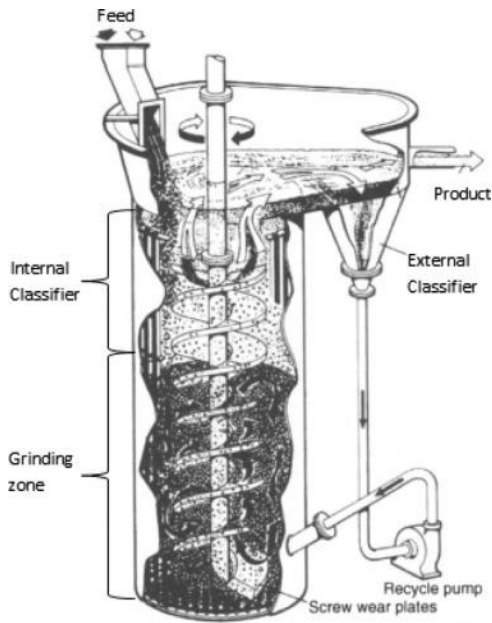


Figure 3. Stirred Media Mills Used in Industry (Mpsi Vertimill).

Control: The rotational speed of the stirrer and the residence time of the material in the mill can be adjusted to control the grinding process. Additionally, the size, shape, and density of the grinding media can be tailored to achieve specific grinding objectives.

Stirred media mills offer several advantages, including:

High Efficiency: The intense agitation and high energy imparted to the grinding media result in efficient grinding, leading to faster processing times and finer particle size distributions.

Versatility: Stirred media mills can handle a wide range of materials, including minerals, ores, chemicals, pigments, ceramics, and nano-sized particles. They can be used for both wet and dry grinding.

Scalability: Stirred media mills are available in various sizes, from laboratory-scale mills to large industrial units, allowing for scale-up and adaptation to different production requirements.

Improved Energy Efficiency: The grinding mechanism in stirred media mills consumes less energy compared to traditional tumbling ball mills, making them more energy-efficient.

Despite their advantages, stirred media mills also have some limitations. High-energy grinding action can lead to increased wear on the mill components, requiring regular maintenance and replacement. Additionally, the selection and optimization of the grinding media and operating parameters can be crucial to achieve the desired product quality and minimize the generation of fines.

Overall, stirred media mills are effective tools for fine and ultrafine grinding, providing efficient size reduction and mixing capabilities across a wide range of materials.

2.4. Jet Milling

Jet milling also known as fluid energy milling, is a method used for reducing the particle size of materials by utilizing high-velocity jets of compressed gas or steam. It is commonly used for micronization and producing fine powders of various materials.

Here's how jet milling typically works:

Feed Material: The material to be milled is introduced into the jet mill through a feed inlet. This can be a dry powder or a suspension of particles in a liquid.

Grinding Chamber: The material enters a grinding chamber, where it encounters a high-velocity stream of gas or steam, typically air or nitrogen. The gas is accelerated to high speeds by passing through a series of nozzles or jets.

Particle Size Reduction: As the high-velocity gas or steam jets collide with the material, they create intense collisions and shearing forces, causing the particles to fracture and reduce in size. The particles are accelerated and dispersed within the grinding chamber, undergoing multiple collisions with each other and the gas jets.

Classification: After the grinding process, the fine particles are carried along with the gas or steam flow out of the grinding chamber. The gas stream containing the fine particles enters a classifier, which separates the particles based on size. The oversized particles are returned to the grinding chamber for further milling, while the fine particles are collected as the desired product.

Collection: The fine particles are typically collected using cyclone separators, bag filters, or other types of collection devices, depending on the application. The collected product can be further processed or used as-is.

Jet milling offers several advantages:

Particle Size Control: Jet milling allows precise control over the particle size distribution of the milled material. By adjusting the gas flow rate, pressure, and nozzle configuration, a wide range of particle sizes can be achieved.

High Efficiency: Jet milling can achieve high grinding efficiencies due to the intense collisions and impact forces generated by the high-velocity gas or steam jets.

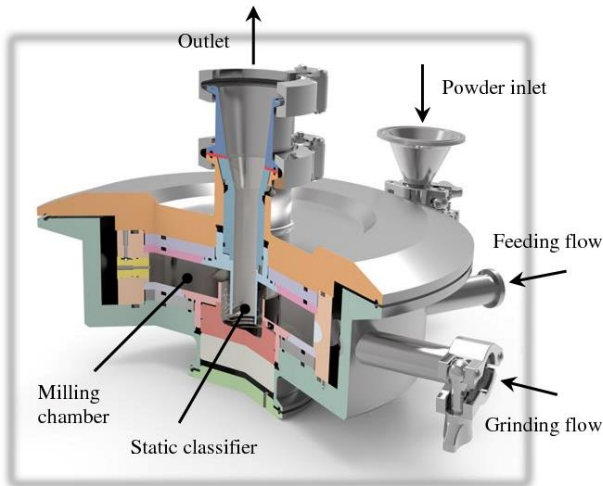


Figure 4. Modular Jet Mill (Lamartino P., Mercuri S., Murdocco A., Crivelli D., Malorgio S. and Joost B., 2018).

Minimal Contamination: Since jet milling does not involve mechanical grinding media, there is minimal risk of contamination from abrasive materials or wearing of grinding media. This makes it suitable for processing sensitive materials such as pharmaceuticals or food products.

Versatility: Jet milling can be used for various materials, including pharmaceuticals, chemicals, pigments, minerals, and ceramics. It can handle both dry and wet materials.

However, jet milling also has some limitations. It may not be suitable for materials that are heat-sensitive or prone to degradation at high temperatures. Additionally, the high-energy collisions in the jet mill can generate heat, potentially requiring cooling systems to maintain product integrity.

Overall, jet milling is a versatile and efficient method for reducing particle size, offering precise control over the final product's characteristics. It finds applications in industries such as pharmaceuticals, chemicals, cosmetics, and materials science.

2.5. Fluid energy milling

Fluid energy milling also known as fluid energy grinding or micronization, is a technique used for reducing the particle size of materials by utilizing high-velocity streams of compressed gas or superheated steam. It is a type of jet milling that employs gas as the grinding medium.

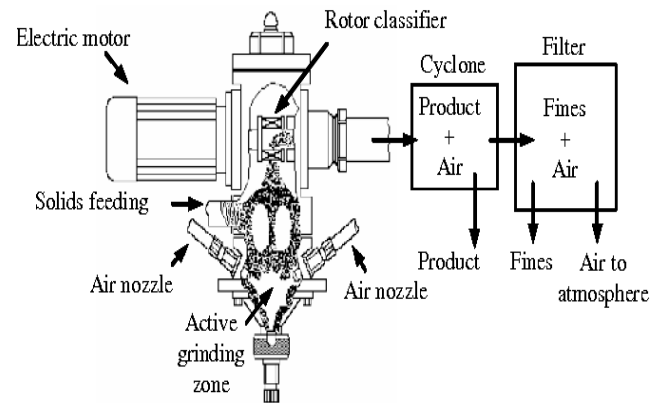


Figure 5. a) Fluid Energy Milling (Coutinho and Embiruçu, 2007).

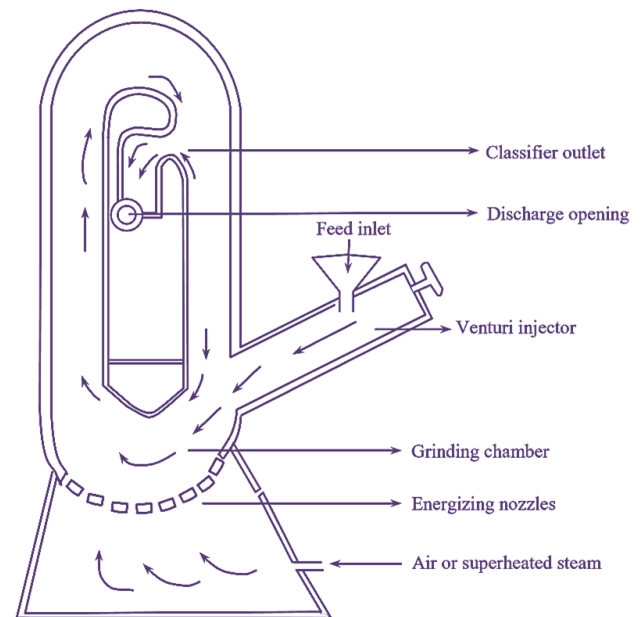


Figure 5. b) Typically Work Shape of Fluid Energy Milling (<https://electricalworkbook.com/fluid-energy-mill/>).

Here's how fluid energy milling typically works:

Feed Material: The material to be milled is introduced into the fluid energy mill through a feed inlet. This can be a dry powder or a suspension of particles in a liquid.

Grinding Chamber: The material enters a grinding chamber, where it encounters a high-velocity stream of gas or steam, typically air or nitrogen. The gas is accelerated to high speeds by passing through a series of nozzles or jets.

Particle Size Reduction: As the high-velocity gas or steam stream collides with the material, it creates intense collisions, impact forces, and shearing actions, causing the particles to fracture and reduce in size. The particles are accelerated and dispersed within the grinding chamber, undergoing multiple collisions with each other and the gas stream.

Classification: After the grinding process, the fine particles are carried along with the gas or steam flow out of the grinding chamber. The gas stream containing the fine particles enters a classifier, which separates the particles based on size. The oversized particles are returned to the grinding chamber for further milling, while the fine particles are collected as the desired product.

Collection: The fine particles are typically collected using cyclone separators, bag filters, or other types of collection devices. The collected product can be further processed or used as-is.

Fluid energy milling offers several advantages:

Particle Size Control: Fluid energy milling allows precise control over the particle size distribution of the milled material. By adjusting the gas flow rate, pressure, and nozzle configuration, a wide range of particle sizes can be achieved.

High Efficiency: Fluid energy milling can achieve high grinding efficiencies due to the intense collisions and impact forces generated by the high-velocity gas or steam streams.

Minimal Contamination: Since fluid energy milling does not involve mechanical grinding media, there is minimal risk of contamination from abrasive materials or wearing of grinding media. This makes it suitable for processing sensitive materials such as pharmaceuticals or food products.

Versatility: Fluid energy milling can be used for various materials, including pharmaceuticals, chemicals, pigments, minerals, and ceramics. It can handle both dry and wet materials.

However, fluid energy milling also has some limitations. It may not be suitable for materials that are heat-sensitive or prone to degradation at high temperatures. Additionally, the high-energy collisions in fluid energy milling can generate heat, potentially requiring cooling systems to maintain product integrity.

Overall, fluid energy milling is a versatile and efficient method for reducing particle size, offering precise control over the final product's characteristics. It finds applications in industries such as pharmaceuticals, chemicals, cosmetics, and materials science.

2.6. Nano milling

Nano milling also known as nano grinding or nanoscale milling is a process used to produce nanoparticles or nanoscale particles from materials by reducing their size to the nanometer range. It is a specialized technique employed to achieve extremely small particle sizes, typically below 100 nm.

Nano milling can be performed using various milling methods, including:

Bead Milling: Bead mills, also called media mills, utilize grinding media, such as beads or balls, to achieve particle size reduction. The material to be milled is suspended in a liquid or a solvent, and the milling beads are agitated within the mill, causing the particles to be ground down to the nanoscale.



Figure 6. a) Nano Milling (<https://www.root-asia.com/root-technology/>).

High-Energy Ball Milling: High-energy ball milling is a mechanical milling technique that utilizes high-energy collisions between balls and the material to be milled. The balls, typically made of metal or ceramics, are impacted and ground against the material, resulting in particle size reduction to the nanoscale.

Jet Milling: Jet milling, as mentioned earlier, can also be used for nano milling by employing high-velocity gas or steam streams to grind the material to the desired particle size. The intense collisions and shearing forces generated by the gas jets facilitate the reduction of particle size to the nanoscale.

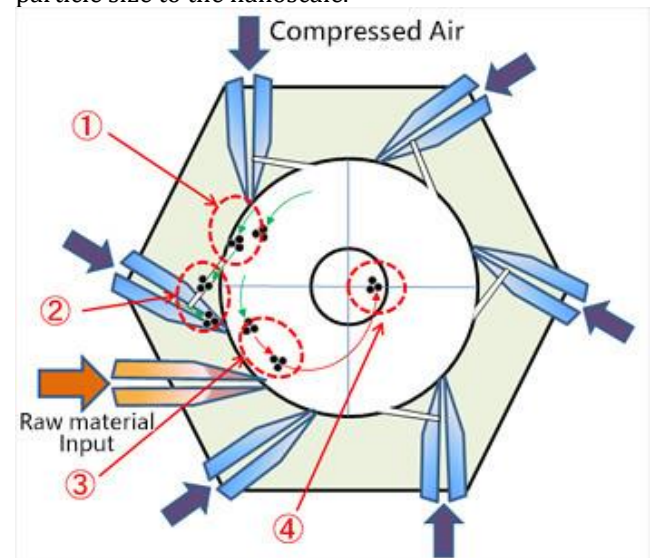


Figure 6. b) Typically Work Shape Of Nano Milling (<https://www.root-asia.com/root-technology/>).

Planetary Ball Milling: Planetary ball mills consist of multiple grinding jars that rotate around their axis while also making planetary motions around a central axis. This combination of rotation and revolution creates high-energy impacts between the grinding balls and the material, leading to size reduction to the nanoscale.

Nano milling offers several advantages and applications:

Enhanced Properties: Nanoscale particles often exhibit unique properties due to their small size and high surface area-to-volume ratio. Nano milling enables the production of nanoparticles with enhanced characteristics, such as improved reactivity, optical properties, mechanical strength, and more.

Nanomaterials Synthesis: Nano milling is used to produce nanomaterials for various applications, including electronics, catalysis, energy storage, coatings, pharmaceuticals, and advanced materials.

Nanocomposites: Nano milling is employed to disperse nanoparticles or nanofillers into a matrix material to create nanocomposites with tailored properties. This is particularly relevant in industries like polymer composites and coatings.

Drug Delivery Systems: Nano milling plays a crucial role in the formulation of nanoscale drug delivery systems, such as nanoparticles, liposomes, and nano emulsions. The reduced particle size allows for improved drug dissolution, bioavailability, and targeted delivery.

It is important to note that nano milling can be a challenging process due to the increased tendency of particles to agglomerate at the nanoscale. Proper milling conditions, such as appropriate milling time, speed, media size, and stabilizers, are essential to achieve well-dispersed nanoparticles.

Overall, nano milling is a vital technique for producing nanoparticles and nanoscale materials with unique properties and diverse applications in various industries.

Today, grinding mills use about 2% of the electricity generated in the world, and dry-grinding processes consume about 75% of this energy. Note that some of the major size-reduction processes that consume a great deal of energy, such as the grinding of trees to produce wood pulp cellulose, are beyond the scope of this article.

3. Energy Equations Used in Comminution

Scientists and inventors have long worked to develop and improve size-reduction processes and machines to solve the engineering challenges associated with grinding. Size reduction—used in every mineral-processing operation—has been a continuing field for scientific inquiry and has contributed to more efficient size-reduction processes in many areas (Beke, 1981):

- Design of better machines

- Modeling and simulation techniques to optimize circuits
- Control techniques to ensure that products meet tight specifications
- Laboratory techniques to measure material and process characteristics.

Grinding presents several difficult technical problems, and researchers and inventors have spent a significant amount of time and effort trying to design and enhance size-reduction techniques and equipment. The process of size reduction, which is used at every stage of mineral processing, has been studied for a long time. This has led to the development of more effective size-reduction methods in some fields, including (Beke, 1981):

- Development of more efficient mechanisms
- Modeling and simulation methods for optimizing circuits
- Control strategies for ensuring that products fulfill stringent standards
- Laboratory procedures for measuring the properties of materials and processes

There are several models used to estimate the energy consumed in grinding processes. Here are some commonly used models (Rhymer, Ingram, Sadler and Windows- Yule, 2022).

3.1. Bond's Law

Bond's Law developed by F.C. Bond (1961) is a model used to estimate the energy required for size reduction in grinding processes, particularly in ball and rod mill grinding circuits. It is based on the concept of work index, which is a parameter that characterizes the material's grindability.

According to Bond's Law, the energy consumption (E) in kilowatt-hours per ton (kWh/ton) can be calculated using Eq. 1:

$$E = 10 \sqrt{\frac{W_i}{P_{80} - P_0}} \quad (1)$$

Where:

E is the energy consumption (kWh/ton)

W_i is the work index of the material being ground (kWh/ton)

P₀ is the size of the product (µm) corresponding to 80% passing the feed size.

P₈₀ is the size of the product (µm) corresponding to 80% passing the final desired product size.

The work index (W_i) is determined through laboratory testing using a standardized procedure. It represents

the energy required to reduce a unit mass of the material from a reference size to the desired size. The work index values for different materials can be found in reference tables or determined experimentally.

Bond's Law provides an estimate of the energy consumption based on the work index and the particle size distribution. However, it does not consider other factors that may affect energy consumption, such as mill design, operating conditions, and specific material properties. Therefore, it is important to consider the limitations of Bond's Law and validate the estimated energy consumption through experimental data or use more sophisticated models when necessary (Beke, 1981).

3.2. Hukki's Law

Finland's R.T. Hukki reviewed data from many industrial operations and concluded that the three energy-size reduction theories referred to different regions on the curve relating energy used to particle size produced, as shown in Figure 7 (Hukki 1961).

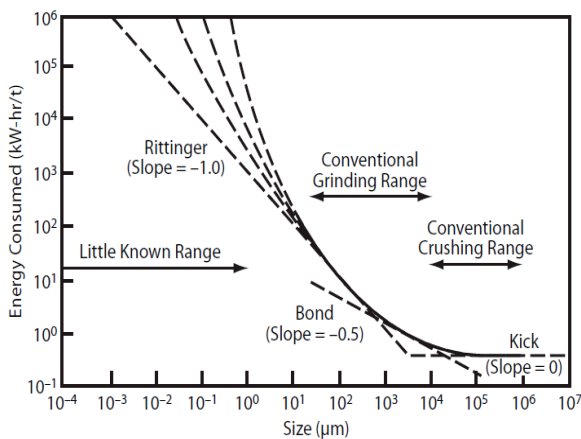


Figure 7. Relationship In The Process Of Breaking Between The Amount Of Energy And The Particle Size (Hukki 1961)

Figure 7 makes it clear why Bond's work was so successful and why it will continue to be used to design circuits that grind to about 200 µm. His work covered a product range of 25,000 to 20 µm, and most applications will continue to fall in this range. However, extending this work to products less than 5 µm is incomplete.

After Bond retired in 1964, the engineers at Allis-Chalmers continued to develop the Bond equation and publish their results. The book *Design and Installation of Comminution Circuits*, published by the Society of Mining Engineers in 1982, was dedicated to Bond.

In the days before digital computers, sizing distributions were often simplified to a single value, typically the size in microns through which 50% or 80% of the material passed.

This was good enough for Bond's work on circuit design but not good enough for understanding breakage mechanisms or identifying how problems in breakage occurred. Complete size distributions were needed, and it was Paul Rosin and Erich Rammler in Germany who showed that sieve analyses of pulverized coal could be fitted by a simple negative exponential equation (Morrell, 2004).

In a talk that he gave to the Fine Particle Society in England in 1976, Rumpf discussed some of the work that had been done at the laboratory (Rumpf 1977). During the lesson, he remarked the lines of, "In comminution, the particles will respond individually in a bigger amount than in any other process." The reason for this is because the defect and dislocation structures play a crucial role in the creation of the fracture. As a consequence of this, the behavior of breaking, for instance, will change a great deal depending on the kind of material and the particle size, but it may also change a significant amount even when using the same material and the same particle size. Only by conducting methodical testing with single particles will it be possible to ascertain the actual amount of energy that may be saved.

In his research, Rumpf and Müller (1962) studied the amounts of specific energy used by materials when they were crushed into single particles and when they were fractured in industrial comminution operations. Figure 8 illustrates his findings, which suggest that there is theoretical potential for a tenfold increase in energy efficiency (although it would be less in practice). One of the results of Rumpf's work was the invention of high-pressure grinding rollers (HPGRs), which is considered one of the most significant achievements in the creation of new grinding equipment throughout the 20th century.

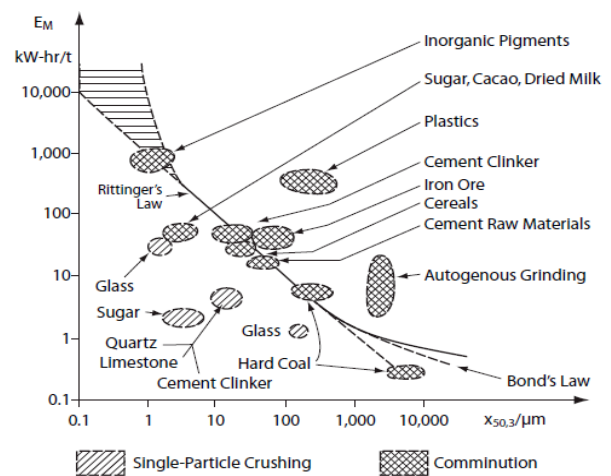


Figure 8. Specific Energy Consumption In Comminution And Single-Particle Crushing (Rumpf 1977)

3.3. Population Balance Models (PBM)

Population Balance Models are mathematical models used to describe and simulate the behavior of particulate systems, particularly in grinding and other particle size reduction processes. These models consider the distribution of particle sizes within a system and track the evolution of this size distribution over time.

In the context of grinding, population balance models aim to predict the changes in particle size distribution as particles are subjected to grinding forces and break into smaller sizes. These models provide insights into important parameters such as particle size distribution, residence time distribution, and breakage rates.

The general form of a population balance equation (PBE) is as follows:

$$\partial N/\partial t = \partial(B[N])/ \partial x - \partial(S[N])/ \partial x \quad (2)$$

Where:

$N(x, t)$ is the number density of particles with size x at time t .

$B[N]$ represents the breakage term, which describes the rate of particles breaking into smaller sizes.

$S[N]$ represents the source term, which describes the rate of particles being generated by breakage.

The breakage term ($B[N]$) and source term ($S[N]$) depend on various factors, including the properties of the material being ground, the grinding mechanism, and the specific grinding equipment employed. These terms can be defined using empirical relationships, experimental data, or theoretical models.

Solving the population balance equation provides information on how the particle size distribution changes over time during the grinding process. The PBE can be solved using numerical methods, such as finite difference or finite element techniques, to obtain the evolution of the particle size distribution.

Population balance models allow for the prediction and optimization of grinding processes, aiding in the design of more efficient grinding systems and the development of grinding circuits. They provide insights into the effects of operating parameters, such as feed rate, grinding media size and distribution, and mill residence time, on the resulting particle size distribution.

It's worth noting that population balance models can be computationally demanding, and their accuracy relies on the quality of the model parameters and assumptions. Experimental validation and calibration are often necessary to ensure the reliability of the model predictions.

3.4. Discrete Element Method (DEM)

Discrete Element Method (DEM) is a numerical simulation technique used to model and analyze the behavior of a collection of discrete particles. It is particularly useful for studying granular materials and particle systems in various engineering and scientific applications, including grinding, milling, powder mixing, and particle-fluid interactions (Mhadhbi, 2021; Rhymer et al., 2022).

In the context of grinding, DEM is employed to simulate the motion, interactions, and collisions of individual particles within a grinding mill. By considering the behavior of each discrete particle, DEM provides insights into the dynamic aspects of grinding, such as particle breakage, energy transfer, and the resulting particle size distribution.

Here's an overview of how DEM works in the context of grinding:

Particle Representation: In DEM, each particle is represented as a discrete entity with its own set of properties, such as size, shape, mass, and material characteristics. These particles interact with each other and with the surrounding environment.

Contact Detection: DEM algorithms determine the contacts between particles based on their positions and shapes. Contact detection algorithms consider factors such as particle overlap, shape matching, and interparticle forces to identify the interactions between particles.

Force Calculation: Once the contacts between particles are identified, the forces acting on each particle are calculated. These forces include normal forces (due to particle-particle contact) and tangential forces (frictional forces).

Integration of Equations of Motion: Using Newton's laws of motion, the equations of motion for each particle are integrated over time. This integration accounts for the forces acting on the particles and updates their positions and velocities.

Time Stepping: DEM simulations progress through small time steps, where the positions, velocities, and forces of the particles are updated at each time step. The simulation continues until a specified endpoint is reached or until a desired level of convergence is achieved.

By simulating the motion and interactions of individual particles, DEM provides valuable information about particle trajectories, energy transfer, and particle breakage during grinding processes. It can help optimize mill design, study the effects of operating parameters, and understand the mechanisms of particle breakage.

However, it's important to note that DEM simulations can be computationally intensive and require substantial computational resources. The accuracy of the results depends on the accuracy of input parameters, including particle properties, contact models, and material properties. Validating the DEM results with experimental data is essential to ensure the reliability of the simulations.

Overall, DEM is a powerful tool for studying the behavior of particulate systems, including grinding processes, and provides detailed insights into particle motion, interactions, and breakage that are difficult to obtain through experimental means alone (Mhadhbi, 2021; Rhymer et al., 2022).

4. Grindability of Materials

As a property of the material, grindability needs to indicate whether or not it is appropriate for size reduction. The outcome of the grinding process must be reflected in its value in terms of the amount of energy that was expended per unit. Here is where we run into a problem: the procedure produces a new particle size distribution that cannot be characterized by a single value. As a result, grindability cannot be expressed as the difference between two numbers or as the quotient of two numbers. In the industrial world, however, grindability is defined as the relationship between specific surface increase (measured by the Blaine test in cm^2/g) and energy use (measured in kWh/g by the Jig). This standard was developed by Lehmann and Haese (1975).

The use of industrial experience consequently significantly simplifies the situation. The grindability of a material is measured in kWh/t , whereas the grinding resistance of a material is characterized in kg/j for a known grinding process (for example, grinding cement in a ball mill to a grinding fineness of $3000 \text{ cm}^2/\text{g}$ Blaine). It is hardly unnecessary to point out that the grinding equipment also affects these figures since it is so obvious. Therefore, to grind raw cement meal, various values will be achieved depending on whether the grinding takes place in a ball mill, an autogenous mill, or a roller mill (Menéndez-Aguado, Dzioba and Coello-Velázquez, 2005; Menéndez-Aguado, Coello-Velázquez, Dzioba and Diaz, 2006).

Grindability tests are standardized laboratory tests used to quantify the grindability or ease of grinding of a material. These tests provide valuable information for process optimization, equipment selection, and energy consumption estimation in grinding operations. In order to assess the kWh/t material properties, many test procedures are used in industrial practice, considering the aforementioned restrictions. All of these methodologies include the process of grinding under carefully controlled laboratory circumstances to replicate real-world commercial scenarios. The

obtained outcomes often need adjustments based on empirical evidence. The existence of three commonly used approaches in industrial practice, namely Hardgrove, Zeisel, and Bond, is well acknowledged (Beke, 1981; Deniz, 1996).

Bond Work Index (BWI) Test: The Bond Work Index test (1961) is widely used for determining the grindability of brittle materials, such as ores and minerals. It measures the energy required to grind a material from a specified feed size to a target product size. The test involves grinding a specified amount of material in a laboratory ball mill for a specified duration. The resulting product size distribution is measured, and the Bond Work Index is calculated based on the energy input and the size reduction achieved (Tavares, L.M., R.M., D.C., Guerrero, J.C., 2012).

Hardgrove Grindability Index (HGI) Test: The HGI test (Remenyi, 1966) is primarily used for assessing the grindability of coal. It measures the energy required to grind a coal sample in a standardized grinding machine, called the Hardgrove Grindability Index tester. The test involves grinding a fixed-weight of coal sample under specified conditions of grinding speed, grinding duration, and air flow. The resulting product fineness and HGI value are determined, with higher HGI values indicating better grindability.

Zeisel Grindability Test: The Zeisel grindability test (1953) is used for evaluating the grindability of various materials, including cement, raw materials, and solid fuels. It measures the energy required to grind a material in a tumbling mill under specified conditions. The test involves grinding a fixed amount of material for a set grinding time, followed by sieving to determine the amount of material finer than a specified size. The Zeisel index is calculated based on the energy input and the amount of fine material produced.

SAG Grindability Index (SGI) Test: The SAG Grindability Index test (Amelunxena, Berriosb and Rodriguezb, 2014) is specific to assessing the grindability of ores in semi-autogenous grinding (SAG) mills. It measures the energy required to grind an ore sample in a laboratory SAG mill to a specific size distribution. The test involves grinding the ore sample in a small-scale SAG mill under controlled conditions, and the resulting product size distribution is measured to determine the SGI value.

These are just a few examples of grindability tests commonly used in the industry. The specific test used depends on the material being tested and the grinding application of interest. It's important to note that grindability tests provide relative measures of grindability and are typically used for comparative purposes or as a guide in process design. The actual energy consumption and performance in industrial grinding operations may vary due to differences in equipment, scale, and operating conditions.

4.1. Hardgrove grindability test

The Hardgrove Grindability Index (HGI) test (Deniz, 1996; Bilen, 2021) is a standard method used to assess the grindability of coal and lignite, particularly for pulverized coal-fired boilers. The HGI test measures the relative grindability or ease of grinding of a coal sample compared to a standard coal reference.

Here's an overview of how the HGI test is conducted:

Sample Preparation: A representative coal sample is collected and prepared for testing. The sample is typically crushed and sieved to obtain a particle size range suitable for testing.

Test Equipment: The HGI test requires a specialized grinding machine called the Hardgrove Grindability Index tester. This machine consists of a grinding bowl and a set of grinding balls. The grinding machine is designed to simulate the grinding of coal in a pulverizer.

Grinding Procedure: A weighed coal sample is placed in the grinding bowl of the HGI tester. A specified number of grinding balls are added to the bowl. The bowl is then rotated at a set speed for a specified duration.

Grinding Duration: The coal sample is ground for a predetermined period, typically 60 revolutions, to achieve the desired level of grinding.

Sieve Analysis: After grinding, the ground coal is sieved through a set of standard sieves to determine the particle size distribution. The sieves used typically have mesh sizes ranging from 75 to 200 mesh (200 to 75 µm).

Calculation of HGI: The HGI is calculated using formula Eq. 3:

$$HGI = 13 + 6.93 \times G \quad (3)$$

where: HGI is the Hardgrove Grindability Index,

G is the weight of the ground coal sample passing through a 200-mesh sieve, expressed as a percentage of the total sample weight.

The HGI represents the relative grindability of the coal sample, with higher HGI values indicating easier grinding. A standard reference coal with an HGI of 100 is often used for comparison.

It's important to note that the HGI test is specific to coal and cannot be directly applied to other materials. The actual grinding performance in industrial coal pulverizers may differ from the HGI results due to differences in equipment design, coal properties, and operating conditions.

The Hardgrove method can characterize only a very coarse grinding. This means that Hardgrove test results can be applied to commercial fine grinding operations only based on experimental data related to similar

materials and similar fineness. But it should not be forgotten that the Hardgrove test is a simpler and quicker method than the two others (Beke, 1981).

4.2. Zeisel test

The Hardgrove mill was first designed to grind coal (Zeisel 1953). Zeisel made modifications to the equipment to accommodate hard materials, and also implemented the use of the metric system. However, the primary characteristic of his actions was that he did not cease the rotation of the mill after 60 revolutions; rather, he persisted in operating the grinding unit until the desired level of fineness was achieved. The power usage was evaluated by the measurement of torque.

The grinding of coal was the initial purpose for the creation of the Hardgrove mill. In addition to introducing the metric system, Zeisel altered the machinery to work with hard materials. The most essential thing to note, however, is that he did not stop the mill when it reached 60 revolutions; rather, he prolonged the grinding unit until it reached the desired fineness. The measurement of the torque served as the basis for calculating the power usage (Beke, 1981).

According to Zeisel, the quantity of energy required for commercial operation is twice as much as the amount indicated by the laboratory test. This conclusion was reached after extensive research was conducted using a broad variety of materials. This assertion was correct for the dry grinding that was done in ball mills back in the early 1950s.

Recent research conducted by Ellerbrock (1975) suggests that the technique was carried out using a semi-technical 0.63 m × 0.63 m laboratory ball mill rather than the Zeisel.

4.3. Bond Tests

The aforementioned two approaches replicate the open grinding process. Contrary to popular belief, Bond created his system to model closed-circuit processes in conformity with the solely used business practice in the United States. The experiment is conducted using a laboratory ball mill with dimensions of 12 inches by 12 inches (305 mm × 305 mm). The procedure involves a series of phases, whereby the undersized fractions obtained through sieving are consistently replaced with an equivalent number of fresh original feed. The condition of steady equilibrium is achieved when the replacement of mass G occurs consistently throughout the subsequent phases. The substitution of the mass in question may be regarded as indicative of the grindability under actual circumstances. The work index may be determined using the empirical formula (Kannewurf, 1957; Bond, 1961; Wasmuth, 1969).

$$W_{iw} = \frac{16}{G^{0.82}} \sqrt{\frac{h}{100}} \text{ kWh/sht} \quad (4)$$

h is the mesh size in microns of the test sieve.

The energy demand of the commercial operation can be calculated according to Eq. 5:

$$W = 10W_i \left(\sqrt{\frac{1}{P}} - \sqrt{\frac{1}{F}} \right) \text{ kWh/sht} \quad (5)$$

where P is the undersized 80% of the product, F is that of the feed. Bond later modified somewhat the above formulae and recommended Eq. 6:

$$W_i = 44.5/h^{0.23} G^{0.82} \left(\sqrt{\frac{10}{P}} - \sqrt{\frac{10}{F}} \right) \text{ kWh/t} \quad (6)$$

Here P is the value in microns which 80% of the last cycle sieve undersized product passes, and F is the size which 80% of the new ball mill feed passes.

Eq. 6 is equivalent to (5/2) in the case of sieve mesh 150 ($h = 105 \mu\text{m}$).

The Bond test is widely regarded as the most effective method for simulating contemporary closed-circuit grinding operations in ball mills, with the size of the mill playing a crucial role in determining outcomes. Nevertheless, moving beyond contemplation. The recommended circuit coefficient of Eq. 6 corresponds to a screen oversize of around 70% in the mill, indicating a very coarse grinding fineness, particularly in closed circuit processes such as cement grinding.

The conversion of Hardgrove grindabilities to Bond's work indices may be achieved with a sufficient level of approximation by using the empirical formula proposed by Bond in 1961:

$$W_i = 435/H^{0.91} \quad (7)$$

In conclusion, it may be said that there is no singular, definitive value that can fully characterize grindability. The estimation of energy requirements for commercial grinding processes often relies on laboratory testing, which must be supplemented by adjustment factors derived from extensive practical knowledge. The feasibility of three testing procedures for the grinding of raw cement material was examined by Haese, Scheffler and Fasbender (1975).

4.4. Bond Mill Used Fast Methods

4.4.1. Smith and Lee Method (1968)

In 1968, Smith and Lee determined the grindability of different materials of different sizes in a standard closed-circuit Bond grindability test. Using the same Bond mill and the same grinding conditions, they determined appropriate batch grindability values for different sizes. A direct correlation between the two grindability values was found for the finer sizes of the grind, and the batch tests were performed for less than 300 revolutions of the mill. Using this form of correlation, it is possible to estimate the Bond grindability very simply. In reality, the correlation curve thus determined can be usefully used for a particular type of similar material. If an unknown sample has a different mineralogical structure or different grain size, another reference curve is needed. In addition, it requires the use of a Bond mill and similar preparation of the material as in the standard test. Therefore, the method is considered impractical (Deniz, 1996).

4.4.2. Kapur Method (1970)

In 1970, Kapur created a general algorithm for the simulation of the Bond grindability test that was based on linear grinding kinetics. It is a method of estimating the Bond work index and Bond grindability in the first two cycles of a Bond test.

In addition to the disadvantage that this method requires the use of a Bond mill, which is not available in some laboratories and especially not in most plants, it is also impractical to use separate experimental equations for the determined work indices. The help of a skilled technician is needed rather than complex calculations that are not easily understood (Deniz, 1996).

As a result of Kapur's research on 19 ores, the average error between experimental and calculated work indices was found to be 9.37.

4.4.3. Karra Method (1981)

In 1981, Karra modified the Kapur method. Here, a quantity of material much finer than the grinding size is fed for grindability testing. This material is discarded and replaced with the same amount of fresh feed. This mixed feed is used for the first cycle of grindability tests. Kapur's demonstration has been modified to take this special case into account. In addition, Karra is a new representation, and this representation, which takes into account the effect of the cyclic load, can also represent difficult meals of the feed material. Therefore, there is a very low rate of grinding. In this new representation, a statistical fitting method is also used to determine the value of the work index.

This method also guides for the first two periods of Bond's standard grindability in determining the values of the grinding parameters needed in the simulation.

After determining the grindability values for the first and second experimental periods, the calculation of the Bond grindability for the subsequent grinding periods up to the equilibrium state is performed according to the assumptions of the demonstration.

This method follows a similar approach to Kapur's method but also inherits the disadvantages of this method, as mentioned earlier (Deniz, 1996).

As a result of Karra's research on 15 ores, the average error value between experimental and calculated work indices was found to be 4.77.

4.4.4. Magdalinovic Method (1989)

This method is based on linear grinding kinetics. It differs from the other methods in that the two-period grinding experiments are performed with a specially prepared feed material, which aims to simulate the Bond test experimentally.

The work index is calculated by substituting the grindability value (G) directly into the Bond work index equation. The fact that the calculation of the work index requires the use of an empirical equation specific to the method is another feature that distinguishes this method from others. It has also been suggested that the standard method can be shortened by using the number of cycles in the second period of this method, N_c , as the initial cycle of the standard Bond method (Deniz, 1996).

In a study conducted by Ersayın and Kırşan (1995), it was suggested that the Magdalinovic method gave the best result in the comparison of Kapur, Karra, and Magdalinovic methods.

The average error value between the experimental and calculated work indices obtained as a result of Magdalinovic's research (2012) for 4 different sizes of 3 ores was determined as 4.77.

4.4.5. Köse and Koç Method (1990)

The method developed by Köse and Koç (1990) is based on the principle that determining the number of turns for the first period of the standard test based on the proportion of material finer than the test sieve in the feed can shorten the total number of periods.

As a result of the research conducted by Köse and Koç on 4 ores, the average error value between the experimental and calculated grindability was determined to be 1.22.

4.4.6. Sönmez and Demirel Method (1992)

Sönmez and Demirel (1992) used a cumulative base kinetic model. In this model, there are two methods for calculating the breakage rate values. The first is to determine the particle size distributions of the product by performing batch grinding experiments at varying

grinding times, plotting the cumulative sieve top values for each particle size against time, and determining the breakage rate values from the slope of the lines obtained. The second method is the linear regression method.

The advantage of this method is that it takes much less time than the standard Bond method in terms of the number of experiments and the results that can be obtained for different size values. However, the disadvantage of this method is the need for a Bond mill.

As a result of the research conducted by Sönmez and Demirel on 3 ores, the average error value between the experimental and calculated work indices was determined to be 2.7.

4.5. Methods to Determine the Work Index Without a Mill

4.5.1. Yashima et al. (1970-1977)

Yashima, Morohashi, Awano, and Kanda presented a completely unique, non-standard method of work index determination in 1970. Using dimensional analysis, Yashima and Fujita (1977) developed an empirical correlation relationship between work index and mechanical properties of materials with seven different hardnesses.

The method of Yashima et al. can be applied to brittle materials with hardnesses ranging from 2 to 6 mohs.

Although this method is an approach that takes into account the mechanical properties of the material, its applicability does not seem to be very practical. This is because a large part of the work goes into determining the properties needed for the correlation. This is particularly true for inhomogeneous materials such as ores. These properties, which differ from sample to sample, need to be determined for each ore.

As a result of the research conducted by Yashima et al. on seven ores, the average error value between the experimental and calculated work indices was determined to be 7.27.

4.5.2. Deniz and Ozdag Approach (2003)

The method developed by Deniz and Ozdağ (2003) is a new approach that can eliminate the difficulties in determining Bond grindability and work index values, which are important parameters in the selection of crushing and grinding equipment.

The basic element of this approach is to determine the physicomaterial parameters that are thought to affect the grinding of a material and that is determined by static methods by dynamic methods, which can be obtained more easily, and to reveal the relationship with grindability.

It has been determined that the dynamic bulk modulus gives the best result between dynamic parameters and grindability. When the grindability and work index values determined experimentally and calculated from the dynamic bulk modulus are compared, the general average error value is around 9%. The most important result of this study is that, for the first time, a relationship between grindability and seismic velocities has been established.

4.5.3. Deniz et al.'s Approach (1996)

The method developed by Deniz, Balta, and Yamık (1996) is an approach based on the excavation mechanics parameters in determining the Bond grindability and work index values, which are important factors in the selection of transfer media type grinding elements.

The basis of the study was to determine the relationship between Bond grindability and work index and Point Load Index (Is), Impact Strength Index (ISI), and Friability Index (FD) values obtained from point loading, impact strength, and drop tests.

These relationships show that it is possible to determine Bond grindability and work index approximately by point loading, impact strength, and drop tests used in excavating.

When the experimentally determined grindability values calculated by point loading, impact strength, and drop tests were compared, the average error values were determined as 11.46% for ISI, 6.01% for Is, and 9.27% for FD. These error values are acceptable in terms of obtaining quick and easy results from point loading, impact strength, and drop tests.

The most important result of this study is that, for the first time, a relationship between coal grindability and work index and the point loading, impact strength, and drop tests used in coal excavation has been demonstrated.

5. Conclusion and Suggestions

While very fine grinding cannot be realized in conventional milling equipment due to the use of coarser grinding media, the mills developed in recent years make it possible to grind economically even below 10 µm due to the very high amount of energy released per unit time and volume.

Considering that the need for very fine-sized materials in different branches of industry such as ore dressing, plastics, ceramics, paint, food, and cosmetics will increase in the future, it is seen that the use of the latest mills will increase even more with lower energy consumption compared to conventional mills.

Grinding, one of the mineral processes, is still the most energy-intensive process stage; more than half of the

total energy used is in this area. This is why facilities must be improved, equipped with the right equipment, and implemented with energy-saving methods. In this context, the selection of an unsuitable mill is based on the properties of the ore. It is certain to increase operating costs even more. Today, depending on the properties of the ore and the desired alternative mills depending on particle size, mills have been designed and continue to be designed.

For example, with a classic ball mill, it takes both time to make milling to a micron level and an excessive increase in costs, which leads to a lot of problems. Instead, it should be stirred for a very short time in a mill to lower the cost of grinding to the level of a few microns. Similarly, for dry ingredients with a crunchy texture, such as the classic higher capacity, instead of drum mills, the use of roller mills for the operation will be in your best interest. Also, after grinding, the beneficiation method to be applied to the ore plays an important role in mill selection.

According to the findings of Mosher and Tague (2001), it was determined that enhancing the repeatability and reproducibility of Bond's grindability test could be achieved by closed-loop criteria and accurately establishing the size distributions of the feed and product.

Energy calculations can be made for very fine grinding, just as they can be made for coarser grinding processes. However, there may be specific challenges or complexities associated with energy calculations for very fine grinding that make them more difficult or less accurate compared to coarser grinding processes. Here are some reasons why energy calculations for very fine grinding may be challenging:

Particle Size Distribution: In very fine grinding, the particle size distribution may be close to the particle sizes of similar-sized particles. Measuring the energy required to grind particles in this size range accurately can be challenging due to the small size of particles.

High Surface Area: Very fine grinding often results in a high surface area of the ground material. This increased surface area can lead to increased energy consumption because of the additional surface energy that needs to be overcome during grinding.

Particle Interactions: Fine particles may exhibit different behaviors, such as agglomeration or surface interactions, which can affect the energy required for grinding. These interactions may not be accounted for in simplistic energy calculations.

Equipment Limitations: The instrumentation and equipment used to measure energy consumption during grinding may have limitations in accurately capturing fine grinding processes, especially when dealing with small quantities of material.

Heat Generation: Fine grinding can generate more heat due to increased friction and energy input. This heat generation needs to be accurately accounted for in energy calculations.

Adaptive Grinding: In some fine grinding processes, the grinding conditions may change dynamically based on the material properties and desired particle size. This adaptability makes it challenging to define a single energy consumption value.

Data Variability: Fine grinding can exhibit more variability in terms of energy consumption because of the sensitivity to factors like particle size, hardness, and moisture content. Gathering accurate and representative data may require more effort.

Specific Models: Fine grinding may require more complex and specific models to accurately predict and calculate energy consumption. These models can be computationally intensive.

Despite these challenges, energy calculations for very fine grinding are conducted in research and industrial settings. Researchers and engineers use various techniques and instruments, such as grinding mills equipped with power meters or calorimeters, to measure energy consumption accurately.

It's essential to acknowledge that while energy calculations for very fine grinding are possible, they may require more specialized methods and equipment compared to coarser grinding processes. Additionally, practical experience and empirical data from similar processes or materials can complement energy calculations to optimize very fine grinding operations.

Conflict of Interest

There is no conflict of interest.

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