SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

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EFFECT OF OPERATING PARAMETERS IN STIRRED MILL FOR FILLER PRODUCTION

By

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DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled **"Effect of Operating Parameters in Stirred Mill for Filler Production".** I also declare that it has not been previously submitted for the award of any degree or diploma or other similar title of this for any other examining body or university.

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Date : 4 July 2017

Witness by

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KESAN PARAMETER OPERASI TERHADAP MESIN PENGISARAN BERKACAU DALAM PENGHASILAN PENGISI

ABSTRAK

Mesin pengisar berkacau kini telah dikenali dalam pengisaran halus kerana lebih cekap berbanding pengisar bebola konvensional. Penganalisis saiz Sympatec telah digunakan untuk mengenal pasti pengedaran saiz partikel batu kapur selepas pengisaran oleh mesin pengisar berkacau. Tujuan kerja ini adalah untuk mengenal pasti kesan parameter operasi terhadap kadar pengisaran dan saiz produk yang terhasil. Parameter operasi yang telah disiasat ialah kelajuan pengacau, kepekatan dan nisbah pengisian. Kejayaan dan prestasi pengisaran dinilai daripada kadar pengurangan saiz produk dan saiz produk yang terhasil. Kadar pengisaran dan kecekapan pengisaran meningkat apabila kelajuan pengacau dan kepekatan meningkat. Manakala, kadar pengisaran dan kecekapan pengisaran meningkat dengan meningkatnya nisbah pengisian sehingga pada tahap optimum. Jika nisbah pengisian melebihi tahap optimum, kadar pengisaran dan kecekapan pengisaran akan menurun. Daripada kerja yang telah saya lakukan, kadar pengisaran dan kecekapan pengisaran paling tinggi dicatatkan apabila kelajuan pengacau pada 160 revolusi per minit (rpm) dan kepekatan pada 70%. Manakala, kadar pengisaran dan kecekapan pengisaran dicatat paling tinggi apabila nisbah pengisian pada 0.9 untuk saiz diatas 8.60 µm. Bagi saiz dibawah 8.60 µm, nisbah pengisian dicatat memberi kadar pengisaran dan kecekapan pengisaran paling rendah.

EFFECT OF OPERATING PARAMETER IN STIRRED MILL FOR FILLER PRODUCTION

ABSTRACT

Stirred mill has becomes popular recently for fine grinding as it is more efficient than conventional ball mill. Sympatec particle size analyser was used to identify the size distribution of the limestone after grinding by stirred mill. The aim of this work is to investigate the effects of the operating parameters on grinding rate and the size of products. The operating parameters had been investigated in this work were stirrer speed, solids concentration and media filling. Grinding performance was assessed by analysing the particle size reduction and the size of the products. The grinding rate and grinding efficiency increases when the stirrer speed and solids concentration were increases. Meanwhile, for media filling ratio, the grinding efficiency and grinding rate increases if the media filling increases until an optimum level which the media filling increases passes the optimum level, the grinding efficiency and grinding rate decreases. In my study, stirrer speed of 160 revolutions per minute (rpm) and solids concentration of 70% had higher grinding efficiency and higher grinding rate. Meanwhile, media filling of 0.9 had higher grinding efficiency and higher grinding rate for size higher than 8.60 μm and lower grinding efficiency and lower grinding rate for size lower than 8.60 μm.

CHAPTER 1

INTRODUCTION

1.1 Overview

Most minerals are finely dispersed and associated with the gangue, liberation process must be taken place to separate them from the gangue. This liberation can be done by comminution. Comminution is physical process of reducing the particle size of ore to liberate the precious minerals from unwanted gangue minerals. In earliest stages of comminution in mineral processing industry, the purpose is to reduce the size of ore so that the ore can be easily handled and transported by scraper, conveyor and other ore carriers. The first stage of comminution is always blasting.

The next step in comminution is crushing. The purpose of crushing is to reduce the size of the run – of – mine ore by crushing equipment to the size needed for grinding process to take place. The mechanisms of crushing are the compression of ore towards hard surfaces or impaction against hard surfaces in constrained motion path. The last step in comminution is grinding. The purpose of grinding is to reduce the size of crushed ore until the size where the precious minerals and unwanted gangue minerals are separated. The mechanisms of grinding are abrasion and impaction by free movement of media such as rods, pebbles, and balls towards the ore which differ from the mechanisms of crushing.

Tumbling mills with either balls, steel rods or sized ore as grinding media are usually used in either coarser or finer grinding because of its value in process large throughputs. However, tumbling mill is in disadvantage when it comes to fine grinding. Tumbling mill becomes energy intensive and energy inefficient at fine and ultrafine grinding. Thus, advanced technology to ball mills was developed and basically adapted from other industries into the mineral processing industry.

Nowadays, stirred mills are widely used in mineral processing industry and it actually have been used in other industries for many years (Stehr and Schwedes, 1983). Stirred mills have been used as it is more energy efficient compared to tumbling mill. The mills are from the group of mills which use a stirrer to give movement to the media. The stirred mills are classified into two types which are vertical stirred mills and horizontal stirred mills.

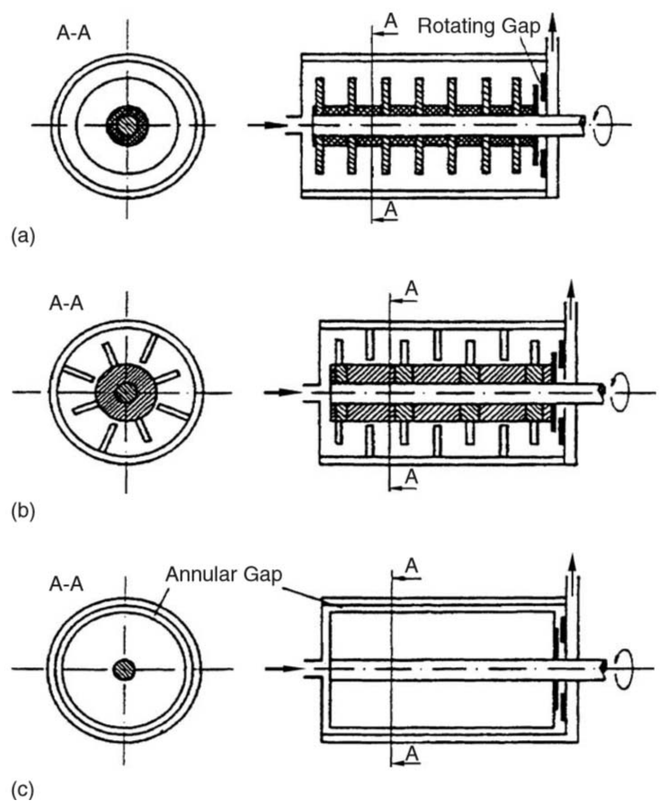

Figure 1.1: The geometry of three types of agitators. (a) Disc agitator, (b) pin agitator, (c) annular gap agitator (Kwade and Schwedes, 2007).

Stirred mills can be classified according to the agitators used as well. There are three types of agitators which are disc agitator, pin agitator and annular gap agitator. Figure 1.1 shows the geometry of three types of agitators.

1.2 Problem statement

Stirred mills have been widely used in mineral processing industry especially for fine grinding and ultrafine grinding due to its high energy efficiency than tumbling mills as well as conventional ball mills. It is important to identify the parameters which can be manipulated to optimise the efficiency of the stirred mills in grinding operation. Molls and Hornle (1972) have found 44 parameters which affect the efficiency of grinding in stirred mills. However, only several of them which are really important parameters have been investigated in past works.

The most important parameters regardless of the design of the stirred mills are stirrer speed, media size, media filling, solids concentration and media density. In this work, three of the parameters are investigated which are stirrer speed, media filling and solids concentration as the past works about these parameters are a little bit confusing.

1.3 Objectives

The purpose of this thesis is to investigate the effect of operating parameters on the grinding rate and the product size of vertical stirred mill in fine grinding. The operating parameters investigated in this thesis are:

- Stirrer speed
- Media filling ratio

- Solids concentration

The specific objectives of this study are:

- Determine the relationship between operating parameters on the product size and grinding rates of vertical stirred mill.
- Determine the best parameters condition in producing finer products.

1.4 Scope of work

Grinding process with vertical stirred mill with the pin – type agitator is used in the size reduction of limestone. The media used is 5 mm ceramic beads. Jones Riffle Splitter is used in the sampling process before the sample being ground by the stirred mill so that homogeneity of the sample for the grinding work is achieved and accurate data and results can be achieved. Three operating parameters are manipulated in this study which are stirrer speed, media filling ratio and solids concentration. The stirrer speed used are 100 rpm, 120 rpm, 140 rpm and 160 rpm. The media filling ratio used are 0.5, 0.7 and 0.9. The solids concentration used and investigated are 30%, 50% and 70%. The product of the grinding is introduced to particle size analyser for the particle size distribution analysis. The pattern of the particle size distribution is investigated to determine the size of the products and grinding rate. In this experiment, the operating parameter which produce finer products and have a faster grinding rate is determined.

1.5 Thesis outline

In chapter 2, literature reviews are about past works and literatures on stirred mill operation in fine grinding including the most operating parameters affecting the efficiency of stirred mill, mechanisms of breakage in stirred mill and the advantages of stirred mills over conventional ball mills.

In chapter 3, detailed procedures of work tests are presented from sample preparation and sampling, grinding conditions until the procedures of the samples analysis.

In chapter 4, the results and analysis of the results which are particle size distribution are reviewed from the work tests done by manipulating the operating parameters.

Finally, the main findings and the conclusions of this research are presented as well as the recommendations for future works in chapter 5.

CHAPTER 2

LITERATURE REVIEW

The literature review covers the past researches and studies including stirred mill operation, breakage mechanisms involve in the stirred mill, usefulness of stirred mill in mineral processing industry and advantages of stirred mill over conventional ball mill. Stirred mill operation and its parameters affecting the stirred mill operation are important to be able to be listed out and understood. In order to simulate the grinding action in the stirred mill, mechanisms of breakage in stirred mill is studied. Other than that, the reasons of stirred mill being widely used for mineral processing industry especially in fine grinding purposes and its advantages for those purposes over conventional ball mill also crucial to be understood first.

2.1 Stirred mill operation

Stirred mills are categorised under the group of mills with free movable grinding media (Kwade and Schwedes, 1997). The mill's chamber is filled with grinding media. The grinding media could be natural sand, steel slag or ceramic beads. The stationary grinding chamber of a stirred mill equipped by a grinding agitator which rotating in order to give necessary energy for the grinding media. The rotating agitator lift the grinding media and give potential energy which then transferred into kinetic energy. The feed material in form of slurry is ground by the act of pressure between layers of media or by impact of cascading media.

Stirred mills are positively contributed in fine and ultrafine grinding because of its high energy efficiency compared to other type of ball mills. Mainly, the high energy efficiency of stirred mills is achieved by the use of smaller media and at high filling ratios which stirred at high tip speeds. This advantage of stirred mills has been proved by many researchers (Keith, 1990 ; Corrans and Angove, 1991 ; Shi et al., 2009 ; Jankovic, 2003). Other than that, stirred media mills are better than other ball mills because of it is easily controlled, low capital cost, low installation cost, low maintenance cost, less space required, less noise, few moving parts and highly safe (Lofthouse and John, 1999).

There are several types of most commonly used stirred mills in the minerals processing industry which are Tower mill, Verti mill, ISAMILL and Stirred media detritor (SMD). Tower mill is the first stirred mill with low speed used in minerals industry. The mill was invented by a chemical engineer, Iwasaki Iskoichi, and introduced by the Nichitsu Mining Industry Co., Ltd in 1953. The technology of tower mill change its owner from time to time and the latest owner is Nippon-Eirich. The Verti mills come from its predecessor, Tower mill. In the 80's, Tower mill was manufactured by MPSI in America with an agreement from with the Japanese. However, the agreement expired in 1991 and Svedala Industries, Inc obtained the technology with the name changed to Verti mill.

Tower mill and Verti mill have basically the same design. The mills consist of internal double start helical screws agitator, stationary vertical grinding chamber, settling classifier and pebble port as grinding media remover. The agitator helps to improve grinding media movement and provide more energy to the media in grinding action. The double start helical screws agitator that attached around central shaft increase the screw density and this assembly design helps the screws protected from abrasion.

The Tower mill have strong swirling flow as well as strong axial recirculation with the movement of grinding media follow the direction of the screw towards central core (Clearly *et al*., 2006). Then, the media move slowly downward in a thin ring-shaped area next to the mill chamber. The outer screw edge can operate in large speed and gives high pressure as well as media energy absorption rates which decrease whether by increasing or decreasing radii. This mill has a good media participation rate and the media can contribute to the material size reduction simultaneously.

The rotating helical screw push the feed material upward which produce high forces which transmitted upward and radially outward. The particles are either in strong load bearing chains, weak secondary chains or in free motion which do not participate in any force chain. There is an anisotropic and coherent directional stress field condition in the particle bed produced by the screw agitator that create strong upward and swirling motion of the bed. The cylindrical layer of balls slides downward over layer of balls which uplifted by the screws agitator.

In 1990s, Mt Isa Mines Limited and Netszch-Feinmahltechnik GmbH developed Isamill. Isamill is basically a huge version of the Netszch horizontal mill which was used in chemical processing industries for ultrafine grinding applications. The volume of the mill was expanded by a factor of 6 to make it fit for mining industry applications. Isamill is recognised by its ability to let the grinding media remain in the mill while enabling slurry to exit the mill (Enderle *et al*., 1997). This mill has been used in many mining applications and has gone further development over the time to fit with the applications. The latest is installed in the Merensky Platinum Tailings that has gone adjustment to 2.6 MW, 10 m^3 for retreatment process (Buys *et al*., 2005).

Isamill is low throughput device and in order to produce particles with the size below 15µm, high energy input is required. The particles breakage mechanisms involved in this mill are attrition or abrasion with low power consumption. These mechanisms are powered by high disc rotation speed which give sufficient energy to the media in order to break the particles. This high rotation disc also give a homogenous grinding condition inside the mill which the grinding event is evenly distributed in the mill. This homogeneous help in producing very fine particles.

The rotating disc mounted on a shaft which is coupled to a motor and gearbox. This design make it easy to remove the chamber and the agitator as well for maintenance. The shaft is counter levelled at the feed inlet. The feed particles are being fed into the mill continuously through the feed port and being ground by the disc agitator. The products being separated from the grinding media by product separator where the media remain in the mill chamber. This helps to produce particles with constant target size based on power draw.

English China Clays is the one responsible on the development of the first Stirred Media Detritor (SMD) in 1960s. In 1969, first SMD in production scale was installed in a kaolin plant. Currently, around 200 mills used in calcium carbonate and kaolin processing plants (Lofthouse and Johns, 1999). Australia had its first SMD installation at the Elura lead/zinc mine where two mills are in operation. Meanwhile, 18 ECC mills were operated at Century zinc mine concentrator for zinc rougher concentrate grinding to P_{80} = 7µm (Burgess *et al.*, 2001).

SMD is a pin type mills. The distance between pins are far enough so that their effects are independent and the theories on compression intersection or shear from adjacent pins are not supported. The particles are flowing in circular trajectories and more concentrated in the middle and upper area of the mill chamber. Energy absorption by the media will be decreased with high localized to the particular part of the pins. Small area surrounding the two pins closest to the base plate has the highest energy contribution in the grinding. Furthermore, SMD has a very poor media participation rate with most of the charge volume little to be reduced in size.

2.2 Fine grinding in mineral processing industry

Stirred milling technology is basically adopted from the stirred mill technology which has been extensively used in the ceramic, paint and pharmaceutical industries. Therefore, this technology is new in minerals processing industry. This technology has gone many development to suit with the mineral processing industry. The latest development is nano-grinding which the ability of the stirred mill to grind down to nano-sizes.

Fine grinding has been used in both mineral and paint industry. The definition of fine grinding for mineral industry is differ from paint industry. For paint industry, 1µm is considered fine particles. Meanwhile, in mineral industry, fine particles mean particles that are very hard to be recovered in separation process. Usually, the particles are in the size range of 1mm to below 10µm regarding to the type of separation process.

There are four types grinding stages in mineral processing industry which are conventional grinding, regrinding, fine grinding and very fine grinding. Conventional grinding is grinding to 80% passing 75µm while regrinding is grinding of particles as fine as 75 µm down to the size as fine as 30µm. Fine grinding refers to the grinding of particles in the size below 30 µm down to roughly 10µm. Lastly, very fine grinding is frequently used in the grinding of particles in the size below 10µm.

There is a problem in regrinding as well as fine grinding using ball mill because its consume too much energy and makes the process uneconomical. From the graphical illustration of the relationship between particle size and energy consumption shown in Figure 2.1, it can be seen that the energy consumption rises steeply for grinding particles below 75µm and 30µm. Thus, stirred mill is better in fine grinding and regrinding compared to ball mills. The stirred mills help in economically fine grinding and there are a few base metal concentrators nowadays operate grinding to as low as 10µm (Underle *et al.*, 1997; Burgess *et al.*, 2001; Ellis and Gao, 2002).

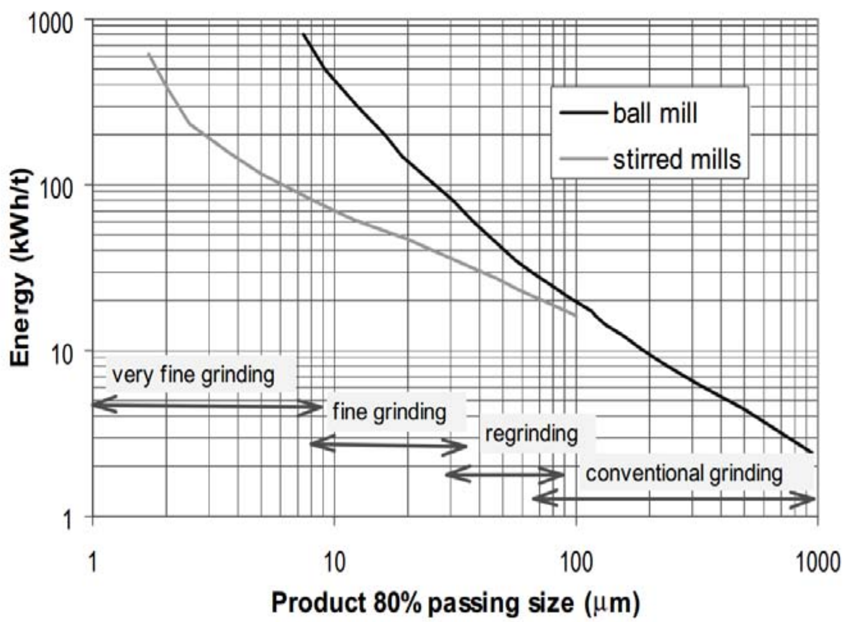

Figure 2.1: Graphical illustration of the relationship between particles size and energy consumption (Jankovic A, 2002).

2.3 Most important operating parameters of stirred mill

There are so many parameters which can affect the grinding in stirred mills. 44 parameters which can affect the grinding have been found by Molls and Hornle (1972). The large number of that parameters may be less important. There are few parameters that give a huge effect on grinding of stirred mill and considered as the most important operating parameters of the stirred mill which are stirrer speed, media size, density and solids concentration. The energy usage in stirred media mills can be controlled by the complex interaction between the variables. The significant variables is classified as mill configuration or process state (Rahal *et al.*, 2011). The critical operating variables in stirred mills is shown in Figure 2.2.

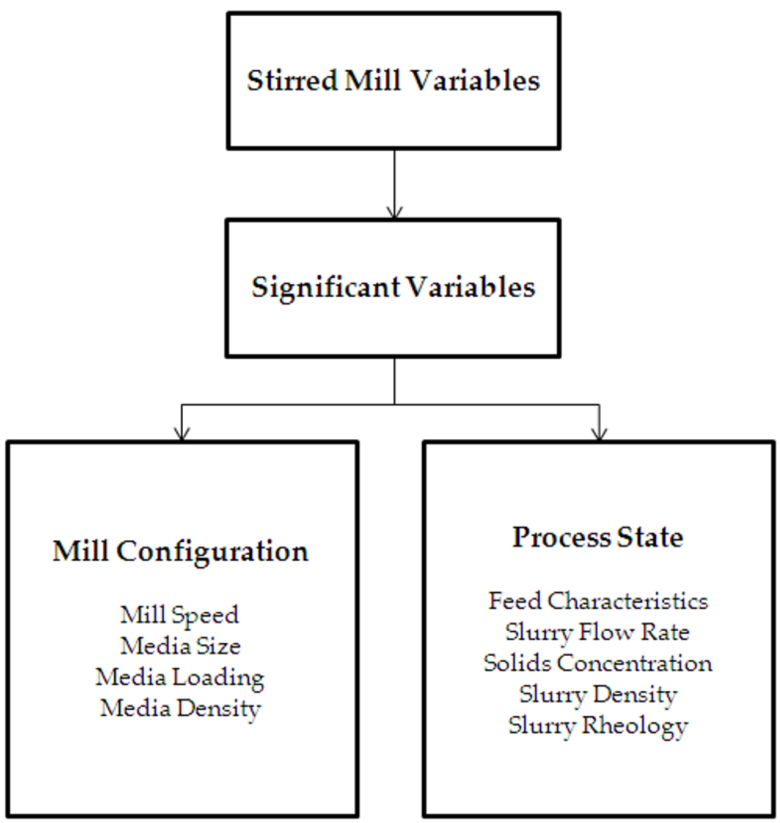

Figure 2.2: Critical operating variables in stirred mills (Rahal *et al.*, 2011).

2.3.1 Stirrer speed and media motion

Stirrer speed is found as one of the most important operating parameter which affects the energy efficiency and energy input of a stirred mill. In order for the stirred mill to work with optimum efficiency, optimum stirrer speed is needed. There are few literatures of study on stirrer speed of stirred mill depending on design of stirred mill and the agitators used. The range of stirrer speeds of vertical mill speeds studied using pin-type agitators are 200 – 300 rpm (Mankosa *et al*., 1986), 200 – 1350 rpm (Mankosa *et al.*, 1989), 260 – 1000 rpm (Zheng *et al*., 1996), and 450, 1000 – 1500 rpm (Jankovic, 2003). There are studies on the stirrer speed of horizontal stirred mill as well and the speed used is higher than vertical stirred mill. The stirrer speeds studied are 2130 – 4370 rpm (Bel Fadhel and Frances, 2001) and 1500 – 2500 rpm (Outtara and Frances, 2003).

The energy input and product fineness are increases with the stirrer speed increases but these result in the decreasing of energy efficiency (Zheng *et al*., 1996). This study supports the past study which found that the product fineness is decreases with decreases stirrer speed at constant energy input and high stirrer speeds are less energy efficient than low stirrer speeds (Mankosa *et al*., 1989). Jankovic (2003) found that high energy efficiency can be achieved by using low stirrer speeds as well. Furthermore, Bel Fadhel and Frances (2001), in their study of horizontal stirred mills, lower stirrer speeds give more efficient in terms of energy compared to high stirrer speeds. Outtara and Frances (2003) also found the same thing which low stirrer speeds give high energy efficiency compared to high stirrer speeds. The low stirrer speeds always give high energy efficiency compared to high stirrer speeds whether it is horizontal or vertical stirred mill.

The media motion and flow fields are affected by stirrer speed and agitator type. The media motion and flow fields are complicated and few methods used such as CFD (computational fluid dynamics), PEPT (position emission particle tracking) and DEM (discrete element method). Blecher *et al.* (1996) has investigated the flow fields in a horizontal stirred mill for a laminar stirred and homogenous Newtonian fluid. The effects of flow fields on motion and trajectories of single grinding beads also has been studied in the literature. Blecher *et al.* (1996) has simplified the model of complicated flow fields in stirred mills.

From the work, two high intensive energy zones are identified which the zones where the grinding action is occur. The zones are a zone around the stirred discs with high tangential and radial velocity gradients and a zone close to the mill chamber wall with a high axial fluid transport gradient. This model and zones are shown in Figure 2.3. Through this model, a single bead motion in horizontal stirred mills is identified as well as the mean ratio between centrifugal and inertial forces of a single bead.

With more advanced technology in computers, better simulation results for the media motion in stirred mills can be achieved. DEM simulation has been used by Sinnot *et al*. (2006) in the study of media motion, energy efficiency and collision environment in vertical stirred mills. Meanwhile, the combination of DEM – CFD models are used by Jayasundra *et al*. (2006, 2008, 2009, 2010, and 2011) in the study of the effects of various parameters on media and slurry motion in horizontal stirred mill with PEPT as validation (van der Westhuizen *et al.*, 2011). This complicated media motion models will be investigated from time to time to study all the interactions between parameters for both horizontal and vertical stirred mill as well as different types of agitator.

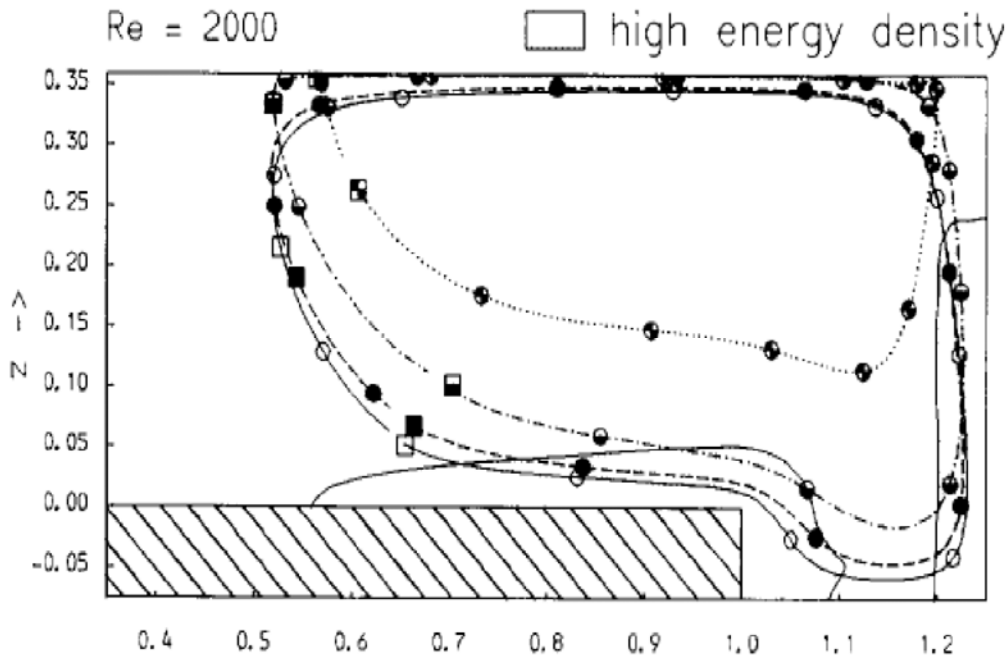

Figure 2.3: Zones of the high energy density in horizontal stirred mill (Blecher *et al*., 1996).

2.3.2 Size of media

Size media also one of the important operating parameters in stirred mills. Many literatures and studies show that fine grinding is greatly affected by media size. The effects of media size in a low speed pin type stirrer of vertical stirred mill on coal has been studied by Mankosa *et al*. (1986). It is found that when the media/particle size was 20:1, an optimum energy – specific breakage rate (tons/kWh) is achieved in monosized feed condition. From this study, it was found that media size selection is depending on feed size.

Blecher *et al*. (1996) found that when small size media used in grinding, there are high possibilities for the media to enter the high energy density zones as in Figure 2.3.

This is because of higher drag forces by smaller size media compared to larger size media which have a higher inertial force. Meanwhile, a study of comminution of limestone in horizontal stirred mill with a perforated disc stirrer has been done by Kwade *et al*. (1996). From the study, it is found that at low specific energies, grinding by using larger media gives finer product (d50) while at higher specific energies, grinding by using smaller media gives finer product (d50).

This results is also supported by another work by Bel Fadhel and Frances (2001) which studied the comminution of gibbsite in a horizontal stirred mill with a disc agitator. This work also stated that smaller media is better in producing finer product at higher specific energies while larger media is better in producing finer product at lower specific energies. However, this work contradicts with the work by Mankosa *et al*. (1986) which the mean ratio of media/feed size was found to be 20 and 200 compared to 20 and 1 by Mankosa *et al*. (1986). This may because of the different feed conditions and different stirred mill designs used. From the literatures, it can be concluded that to choose the best grinding media size, the factors of feed size, desired product size and specific energy input must be taken into account.

2.3.3 Density of media and elasticity

Media density plays important role in determining the efficiency of grinding in stirred mill. Media is the medium used to transfer energy to the feed particles in order to break the particles to smaller size. The density and elasticity of the media is important for that transfer of energy to the particles. Denser media have higher stored energy than less dense media because of its higher mass and less elastic media can transfer more energy to the particles than more elastic media.

This statement is supported by the work by Zheng *et al.* (1996). From the work, it was found that finer product was produced by more dense media which is steel at density of 7.8 g/cm^3 but have low energy efficiency than less dense media which is glass at density of 2.5 g/cm^3. The denser media consume higher energy than less dense media. The work on the effects of media density and elasticity on specific energy is done by Becker *et al.* (2001) in a horizontal stirred mill with discs agitator. The media used is limestone and fused corundum was used as feed.

In the work, it was found that Young's Modulus which is a measure of stiffness of an elastic material affect the energy supplied to the stirred mill. Media with high Young's Modulus can transfer more energy compared with the media with lower Young's Modulus. For further research on grinding media in high energy stirred mills, it was recommended that media used have the following structural and physical combinations (Graves and Boehm, 2007):

- High hardness and fracture toughness
- High surface stability and fine grain structure
- Low friction coefficient

The selection of media is crucial for the effectiveness of the grinding and the combination of media size and media density is important for this selection. For the recommendations by Graves and Boehm, 2007), zirconia based ceramic grinding media is the one which meet the recommendations and often used in mineral processing industry.

2.3.4 Concentration of solids and slurry rheology

Concentration of solids and particle size distribution greatly affect the slurry rheology in fine grinding. When the particles are ultrafine and the concentration of solids is high, the surface properties affect the system the most (He *et al.*, 2004). The concentration of solids is basically amount of water in the solids and can be adjusted by addition or removal of water. There are higher possibilities for the particles to be trapped between media at high solids concentration while at lower solids concentration, there are low possibilities for the particles to be trapped between media. In a work by Zheng *et al.* (1996), energy efficiency of a stirred mill can be maximised with optimum concentration of solids. The work found that the energy efficiency increases with increased concentration of solids up until it reach its optimum level. The energy efficiency decreases when the concentration of solids is higher than the optimum level.

The work done by Jankovic (2003) also states that the stirred mill efficiency increases when the concentration of solids is increased. Jankovic (2003) also theoretically stated that maximum efficiency happens as the range of concentration of solids used in the work was not sufficiently enough. Meanwhile, a work by Mankosa *et al*. (1989) found that the torque increases when the concentration of solids is increased. The result is actually is an expected result because power and torque is proportional to the slurry concentration when the power number of the system is constant. However, the power draw and torque of the system are controlled by the viscosity at very high concentration of solids and when the sizes are too fine (Zheng *et al*., 1996).

2.3.5 Media filling ratio

Media filling ratio is defined as the bulk volume fraction of grinding media in the stirred mill. Media filling is able to affect the power draw in the stirred mill. Van der

Westhuizen *et al*. (2010) found the optimum mill filling in horizontal stirred mills. Meanwhile, in a study of vertical stirred mill by Weller and Gao (1999), they found that when the media filling is increased, the grinding volume also increases as long as the media covers the number of stirrers but the efficiency in the grinding volume will remain not increase. There is a limit on media filling in vertical stirred mills and the limit is determined by the minimum height of the media separation zone at the top of the mill or the top stirrer position to the product outlet (Weller and Gao, 1999).

2.4 Introduction of particle breakage

The main aim of comminution in mineral processing is particle breakage. According to failure analysis, particle can be broken into smaller sizes by several types of breakage depending on the size of material and the grinding equipment being used. There are three types of breakage that can be occur in comminution process:

- Impact (cleavage) – the force acting on the particle and produce a very wide size distribution.
- Compression (fracture) – application of steady opposing normal forces in size reduction.
- Abrasion – Size reduction of particles by shear forces

The mechanisms of breakage is shown in the Figure 2.4. All the mechanisms above occur in grinding process but normally only one mechanism is dominant in the process. There are a theoretical model made by Hogg (1999) which states that abrasion is the dominant mechanism in ultrafine grinding and a mixed abrasion – fracture model has been made to explain the particle breakage in stirred mill. From the work by Hogg (1999), it found that abrasion increases the grinding process and abrasion causes the non – first order breakage function in ultrafine grinding.

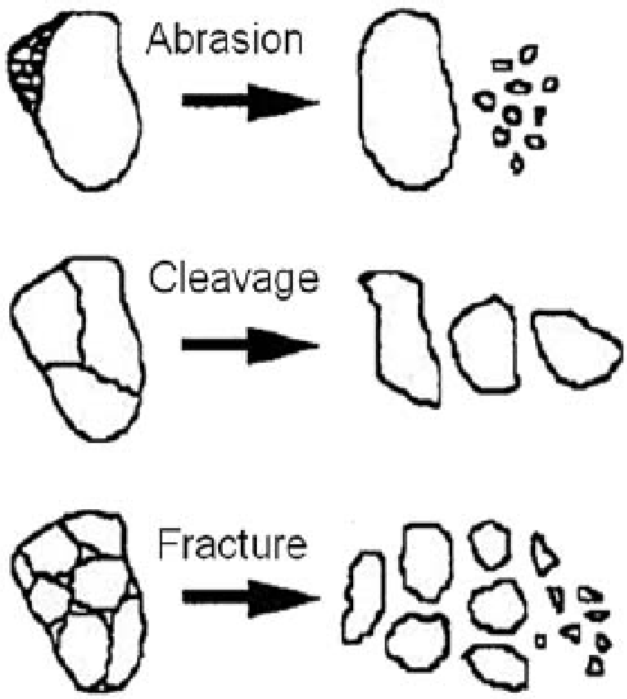

Figure 2.4: Types of breakage mechanisms (Hennart *et al*., 2009).

Meanwhile, Tuzun *et al*. (1995), in a study of vertical stirred mill, they found that first order breakage happens when the feed used is 100% passing 100µm and be ground to median size of 2µm. The first order breakage also is discovered in the work of Yue and Klein (2005). However, a non-linear relationship which promotes a change in the grinding mechanism is noticed below P_{80} of 10µm.

Failure analysis is defined as the study of various breakage mechanisms in a work piece that made of various materials such as metal, ceramic, rubber polymer, and other materials. Failure fracture is happening by the static overloading and it can be ductile or brittle. Fatigue fractures are often hardly physically shown and it is caused by the multiple impacts loadings. The stress of the fracture can be calculated by quantitatively determine the fracture strength of the component. There are always crack for a material to fail and in order to propagate the crack, sufficient energy to exceed the material plastic deformation energy is needed. The fracture toughness of a material is proportional to the energy consumed in plastic deformation such as stress intensity factor (K_I).

The stress intensity factor is defined as the stress level at the tip of the crack and as a function of crack geometry. Unstable fractures can occur when the stress intensity exceeds beyond the limit of the material, and it is called as critical intensity factor value (K_C). The K_C is decreases when the thickness of material is increases. The value of K_C is decreases until the minimum value is reached as the fracture toughness value of a material (K_{IC}) shown the Figure 2.5. The fracture toughness of a material is defined as the total energy needed for material fracture and it is shown in Figure 2.6.

From Figure 2.6, it shows that ductile material absorbs more energy before fracture compared to brittle material. The high fracture toughness value represents high energy being absorbed by the material before fracture happens. Ductile and brittle fracture also can be defined by macroscopic or microscopic plastic deformation. The mode of breakage can be determined by analysing the morphology.

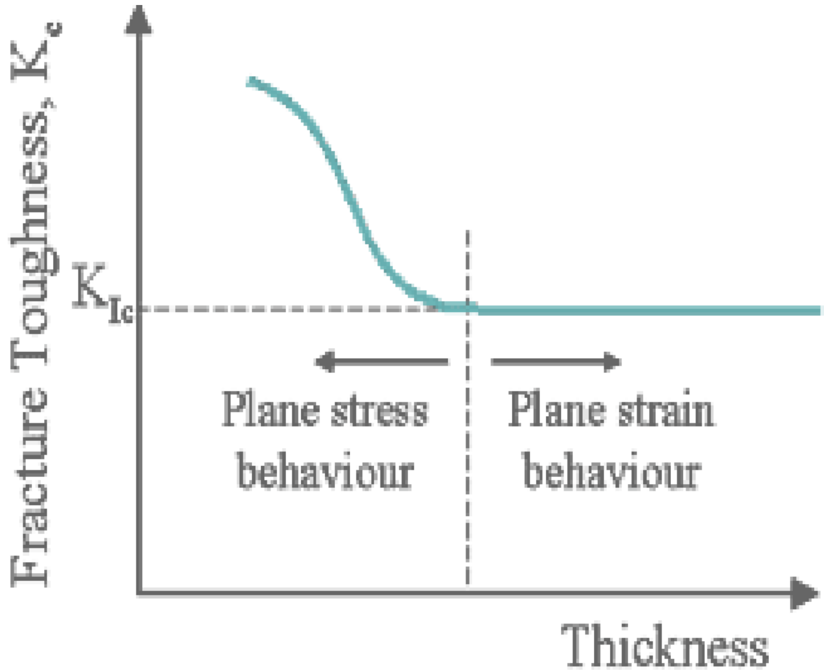

Figure 2.5: Fracture toughness, K_C against material thickness (Farag, 1989).

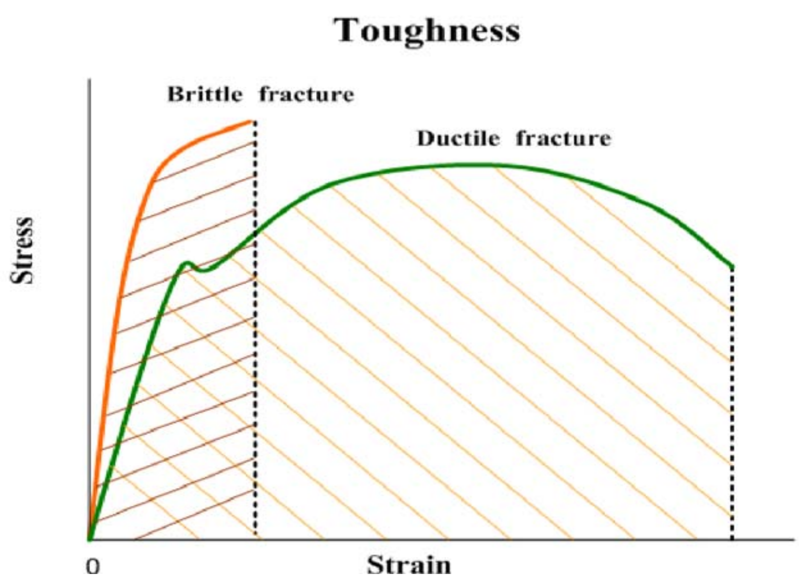

Figure 2.6: Fracture toughness of ductile and brittle material (Farag, 1989).

Particle shape is one of the variables which can affect the performance of the grinding. From Figure 2.7 (a) below, the shape of the particles are not perfectly round, there are existence of high stress concentration zones and internal hair cracks probably exist as well. At the high stress concentration zones, the fracture is propagated with minimum loading when the stress intensity factor (K_I) reaches its critical value. Meanwhile, high critical stress factor value (K_C) is happening when the thickness of the small particles facing the propagation direction of the crack. As a result, the energy needed for the fracture to propagate is lesser. When large size particles facing crack propagation direction, this is the event where the fracture toughness of the material (K_{IC}) is identified (Whitney *et al*., 2007).

Meanwhile, in Figure 2.7 (b), the particles have perfectly round shape. This round shape particles will have permanent flaws which can cause micro cracks which then lead to fracture by multi impact or multi compression loading. Particle size also greatly affects type of stress that causes initiation and propagation and fractures.

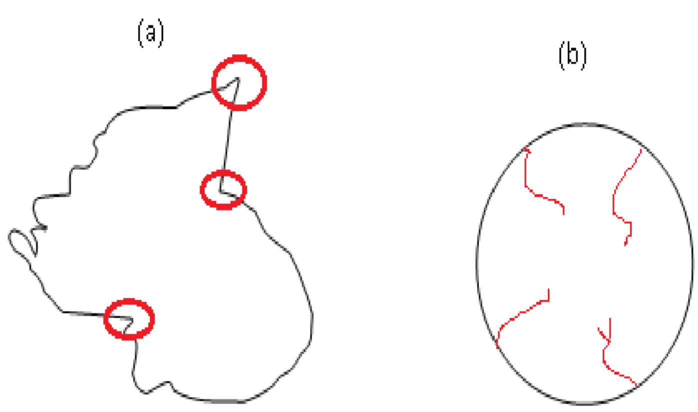

Figure 2.7: (a) Typical particles shape **(b)** Perfectly round shape.

Density of media affecting the shearing force of particles. Media with high density creates high shearing force compared to media with low density. The stirring action of the agitator also helps in creating shearing action by the media to the particles and leads to the size reduction of the media. Figure 2.8 (a) and Figure 2.8 (b) shows the shearing forces that might happen in stirred mill.

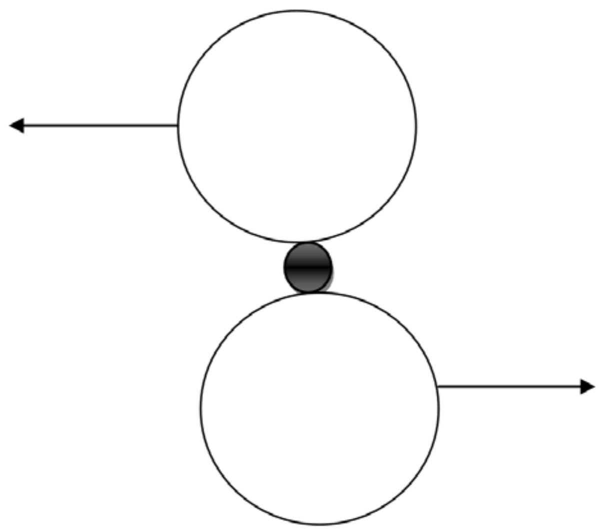

Figure 2.8 (a): Particle in between the media.

In SMD with pin type agitators, the pressure acting on the chamber wall as well as agitator shaft and stress increasing with bed depth. High normal stress zones occur in facing surface of the pins, on the shaft and below each pin. These are caused by the compressed zone of particles that has been pushed and compressed by the pin which give high pressure towards the shaft and pin surfaces. The zones of the low normal stress occur on the backs of the pins and areas close to shaft.