Development of a rapid particle breakage characterisation device – The JKRBT

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Ore breakage characterisation plays an essential role in the design and optimization of comminution circuits. Recently, the JKMRC comminution research team has developed a Rotary Breakage Tester (JKRBT) for rapid particle breakage characterisation tests. The JKRBT uses a rotor–stator impacting system, in which particles gain a controlled kinetic energy while they are spun in the rotor and are then ejected and impacted against the stator, causing particle breakage. The first industrialised JKRBT was installed at Anglo Research in Johannesburg in March 2007, and six more JKRBTs were deployed in 2008 around the world. This paper discusses the major design and calibration issues encountered in the JKRBT development and findings from detailed experimental studies.

1. Introduction

Mining companies have long recognized that the performance of a comminution machine such as a crusher or an autogenous/semi-autogenous grinding (AG/SAG) mill depends not only on the machine operating conditions, but also on the “hardness” of the feed material to be broken. This is very much exemplified at the OK Tedi Mine in Papua New Guinea, where the SAG mill throughput varied from 700 t/h to 3000 t/h due to variations in feed ore hardness (Bond work index 5–16 kWh/t) and in feed size distributions (Sloan et al., 2001).

Particle breakage characterisation aims to quantify the product size distribution which results from the application of energy to a selected feed size via a specific breakage mechanism. Specifically it aims to establish the relationship between specific energy input and resultant product through some type of laboratory test on a given ore (Napier-Munn et al., 1996). The outcomes from particle breakage characterisation may be in the form of a single hardness or strength parameter, or a relationship describing the level of size reduction with respect to the applied energy or other test conditions. The result of breakage characterisation is useful in assisting in comminution equipment specification, circuit design, machine modelling, and process optimization.

Recently, the Julius Kruttschnitt Mineral Research Centre (JKMRC) comminution research team has developed a Rotary Breakage Tester (JKRBT) for rapid particle breakage characterisation tests. The major issues encountered in design, calibration and development of this breakage characterisation machine are discussed in this paper.

2. Background

The laboratory breakage characterisation tests can be roughly classified in two broad groups based on their primary breakage modes: tumbling and impact/compression. The Bond ball/rod mill tests (Bond, 1952, 1961) represent the typical tumbling test, which have become the industry standard for estimating the specific energy (kWh/t) of rod and ball mills. However, as the energy application and particle stressing conditions in the single particle impact tests can be well defined and controlled, the latter have received significant attention in the last 30 years. It was estimated that mining companies worldwide spent over three million US dollars on single particle impact breakage characterisation testing in 2006.

A number of impact breakage testing devices have been developed at the JKMRC for comminution research and commercial service:

- Twin pendulum (Narayanan, 1985).
- Drop Weight Tester (DWT) (Napier-Munn et al., 1996).
- Mini-Drop Weight Tester (Man, 1999).
- Short Impact Load Cell (SILC) (Bourgeois and Banini, 2002).

Since all tests using the Twin pendulum, DWT, Mini-Drop Weight Tester, ALICE, or SILC are conducted on single rock specimens positioned manually on the anvil or flat surface, they are both time-consuming and expensive. For the test to remain practical the rock samples being tested are limited to 10–30 pieces for each size fraction, which inevitably throws into question the statistical validity of the derived ore characteristics. This was a significant limitation in meeting the emerging needs of comminution research.
DEM simulations of the impact energy distribution pattern in an AG mill operation have revealed that small energy impacts occur much more frequently than high energy impacts (Djordjevic et al., 2004). As such it appears a new requirement in breakage testing will be the characterisation of incremental breakage at small impact energies. However, testing of repetitive impacts at small energies using the DW tester is very time-consuming and hence impractical. Research into finding a rapid breakage characterisation device was clearly warranted in an effort to overcome these limitations.

The concept of using kinetic energy to crush rocks seemed like a viable alternative for rapid breakage characterisation, since it no longer requires the positioning of rock specimens manually on the anvil. Industrial applications of this concept are found in Vertical Shaft Impact (VSI) crushers and laboratory pulverizers, which employ a rotor–stator impacting system. However, both of these devices are employed merely for particle size reduction, not for breakage characterisation, as the exact amount of energy applied in the process is not well controlled or measured.

In the past it was often regarded as difficult to impact particles at predetermined conditions using kinetic energy. Questions were raised regarding the influences of the rotor–stator design on the actual impact velocity, the influence of particle properties on impact energy determination, the effect of secondary breakage of particle fragments, etc. So it was suggested that any machines using the kinetic energy concept may work in a chaotic way and may generate uncertain results (van der Zanden et al., 2002).

Work in modelling hammer mills (Shi, 2002; Shi et al., 2003) and VSI crushers (Kojovic, 1996; Djordjevic et al., 2003) at the JKMRC found that these machines can be modelled from first principles, allowing useful simulations (e.g. effect of rotor speed) to be carried out with only the basic design data on the machine and rock characteristics required. This suggests that the rock characteristics may be inferred from the products if the amount of energy applied in the process can be precisely controlled and measured. A paper published by Vogel and Peukert (2004) discusses a single particle breakage device based on the kinetic energy concept, originally developed by Marktscheffel and Schönert (1986). In their apparatus, the impact velocity was calculated assuming that both radial and tangential components equalling to the circumferential speed of the rotor.

The SynchroCrusher development, also based on the kinetic energy concept (van Muijen, 1998; van der Zanden and van der Zanden, 2004), demonstrates that the particle motions can be well controlled in the device. Since the SynchroCrusher employs multiple impacts to increase comminution intensity for size reduction, it is unclear whether or not the energy application during these impacts can be accurately quantified for breakage characterisation.

In response to the body of evidence supporting the use of kinetic energy, the JKMRC research team led by Shi and Kojovic decided to investigate in detail the feasibility of using the kinetic energy concept for particle impact breakage characterisation. The investigations were focused on:

- What factors affect the particle impact velocity in the device?
- How to precisely control impact energy using the kinetic energy concept?
- Can the breakage device be used for rapid ore characterisation?
- How reproducible are the breakage characterisation results?

This paper highlights the investigations and analysis undertaken to address these questions.

### 3. From concept to the industrialised JKRBT

In 2005 a prototype JKRBT (Fig. 1), with a rotor diameter of 360 mm, was designed and manufactured by the JKMRC pilot plant workshop team. The prototype JKRBT provides a useful means to conduct detailed investigations on the suitability using the concept of kinetic energy for particle breakage characterisation.

The operating system consists of a vibrating feeder, a rotor–stator impacting device with its drive system, and an operation control unit. In the rotor there are four guiding radial channels. Particles of the selected size are fed into the rotor–stator impacting system via a vibrating feeder, and are randomly distributed into one of the guiding channels. The particles are accelerated in the channel and ejected from the circumference of the rotor. The particles impact the surrounding anvils with a velocity which combines the tangential and radial velocity components. After impact breakage, the product is collected from a container underneath the rotor.

Twelve months of detailed investigation were undertaken using a high speed video camera to study the prototype JKRBT under various operational conditions and treating different ore samples. The findings confirmed that the JKRBT kinetic energy approach may be applied for rapid particle breakage characterisation.

The outcomes of the prototype JKRBT study was reported to the sponsors of AMIRA (Australia Mining Industry Research Association) P9N project in June 2006. The positive feedback received from mining companies has prompted the JKMRC to validate the device and a new breakage model (Shi and Kojovic, 2007) that can be used to derive the breakage characteristic parameters from the experimental data obtained by the JKRBT or DWT through a formalized experimental test program. The first unit of industrialised JKRBT was designed and manufactured by Russell Mineral Equipment (RME). RME is a specialist mining equipment designer with its manufacturing plant based in Toowoomba, Queensland in Australia. Fig. 2 shows a photograph of the first unit of industrialised JKRBT installed at Anglo Research Pilot Plant in Johannesburg, South Africa in March 2007.

The industrialised JKRBT employs a rotor 450 mm in diameter. The rotor is direct driven by a 3 Phase, 7.5 kW, 5000 rpm electric motor. The motor is controlled by a VFD unit via a Human Machine Interface (HMI) in the control panel. One of the major differences from the prototype JKRBT is that the lid of the industrialised JKRBT can be opened for easy access to clean the breakage chamber. The lid is operated by an electronically driven linear actuator. The counter-weight at the back of the lid is designed to prevent the lid from falling down by gravity should the electronic system fail while the lid is opening or closing. The rotor and anvils are inclined.

![Video camera viewing window](image)

**Fig. 1.** The prototype JKRBT.
at 30° to allow operator easy access and are fully enclosed in a robust chamber. Samples are recovered by an integral vacuum system that collects the crushed rock in a removable bin.

The base frame incorporates several proximity switches to ensure that the machine cannot be operated unless all sub-systems are ‘control healthy’ and the lid is securely latched. A spring-loaded safety rail is mounted to the Base Frame and surrounds the Anvil. Any foreign objects which may prevent the lid from closing correctly or present a hazard to the operator will depress this safety rail and cause the lid to reopen.

This unit can treat particles up to a size of 45 mm. Thus four of the five particle size fractions that are tested in the standard DWT can be treated in the industrialised JKRBT (37.5–45 mm, 26.5–31.5 mm, 19–22.4 mm and 13.2–16 mm). The smallest particle size fraction tested to date was 2.36–3.35 mm. The industrialised JKRBT has a wide specific impact energy range, 0.001–3.8 kWh/t.

A couple of teething problems were encountered during the commissioning of the first industrialised JKRBT, related to the vibrating feeder jamming and a small leak in the hydraulic fluid system. No safety concerns were reported by Anglo Research. The operating issues were evaluated by RME resulting in some design changes in the March 2008 release. These changes include the:

- hydraulic fluid re-circulation system,
- particle feeding system, and
- number of rotor guide channels.

Fig. 3 shows the second version of the JKRBT. A crank-style rotary feeder has replaced the vibrating feeder. The feeder design has minimised the operating noise levels through improved air flow control. It also limits the length of rocks that can be fed into the JKRBT. The crank-style feeder has compartments which are manually filled with rocks; these compartments empty into the JKRBT feed tube as the crank is turned. The number of guide channels has increased from two to three to mitigate the risk of particles being held-up in the rotor hub due to centrifugal forces. This design change is discussed in the next section.

Six units of the V2 design JKRBT were deployed around the world, including:

- Anglo Platinum (Mogalakwena, formerly PPL Mine, South Africa).
- Barrick Gold (installed at KJMRC for one year until final site selected).
- BHP Billiton (Newcastle, Australia).
- JKMRC (Brisbane, Australia).
- Rio Tinto (KUCC Utah, USA).
- Teck Cominco (ART Trail, Canada).

The validation project is expected to be completed in June 2009, with commercial release expected in the second half of 2009.

The developing journey from the concept to the industrialised JKRBT including its design, testing and validation has taken four years. The positive response from the mining companies reflects their need for rapid ore testing, and confidence in the fundamental research underpinning the JKRBT. The following sections elucidate some of the major findings during this research period.

4. Machine calibration

4.1. Basic principle

As the JKRBT is used for particle breakage characterisation, rather than size reduction as in the VSI crusher, it was necessary to know exactly the amount of specific energy applied in the breakage of each rock.

The specific energy of each impact in the JKRBT, \( E_{si} \), is defined as the kinetic energy \( E_k \) per particle mass \( m \):

\[
E_{si} = \frac{E_k}{m} = \frac{0.5 \times m \times V_i^2}{m} = 0.5 \times V_i^2
\]

Hence the particle mass no longer affects the specific energy as is the case with the DWT. The specific energy is dependent solely on the impact velocity \( V_i \), which results from the rotor tangential velocity \( V_t \) and the radial velocity \( V_r \) (Fig. 4):

\[
V_i^2 = V_t^2 + V_r^2
\]

If the two velocity components are equal, as assumed by theory, then the impact velocity can be expressed as:
The accuracy of the camera clock system and the velocities calculated by the Photron Motion software were carefully examined prior to the detailed test program. To check the camera clock system, the rotor revolutions were manually counted (e.g. to a total of 80 revolutions), and the number of frames observed for the 80 revolutions were noted. Together with the camera recording rate (frame per second), the rotor speed (rpm) could be calculated. This figure was compared with the speed indicated by an electronic revolution counting system installed in the JKRBT. Tests were repeated at various rotor speeds. Results show that the two systems produce almost identical rotor speeds, with an averaged relative difference of only 0.04%, i.e. ±0.8 rpm at a nominal speed 2000 rpm. It was concluded that both the rotor speed counting system of the device and the camera clock system are accurate. The same procedures were applied to the industrialised JKRBT as well.

In order to check if the velocity calculated by the Photron Motion software from the recorded movie scripts was correct, an independent analysis of the frame-by-frame particle trajectory motion was carried out using Excel. This method was used to determine the impact angle from the particle trajectory, which can then be used to calculate the impact velocity given the known tangential velocity. This analysis is different from the calculation by Photron Motion software, in which the impact velocity was directly measured using a pair of reference calibration points in the image. Though the manual tracking of the impact angle was time consuming, it was successful in identifying a problem associated with the initial calibration points in the Photron Motion software calculations. The calibration has since been rectified. Comparison between the manual tracking and the Photron Motion software calculations for eight sets of test data showed that there was only 0.16% difference between the two methods. Statistical analysis based on a t-test paired comparison suggests that the difference was not significant, and the velocities calculated by the Photron Motion software were deemed to be reliable.

Extensive tests to determine the particle impact velocities at various machine operating conditions were conducted using the high speed video camera. The following operating conditions and their ranges were investigated:

- Rock type – various ore samples were used: gold ore, copper/gold ore, hornfels aggregate, coal and ceramic balls.
- Particle size – particles in various narrow size fractions were selected for testing: 6.7–9.5 mm, 13.2–16.0 mm for the prototype JKRBT, 11.2–13.2 mm, 19–22.5 mm, 26.5–31.5 mm, 37.5–45 mm for the full scale JKRBT.
- Particle shape: the ratio of particle length to width from 1.0 (spherical balls) to 2.8 (elongated).
- Particle surface: varied from very smooth (balls) to rough/angular.
- Particle moisture: comparison of dry particles with moist particles.
- Solids density: varied from 1.3 (coal) to 4.5 (chromite).
- Rotor speed: varied from 300 rpm to 5000 rpm.
- Feed rate: varied from less than one particle per second to more than 10 particles per second.
- Feed location: gravity dropping particles from the vibrating feeder compared with releasing particles at bottom of the rotor hub using a mechanical holding/releasing tool. This was carried out to investigate the effect of initial velocity on the particle final impact velocity.

The recorded movie scripts were processed by the Photron Motion Tools software (Fig. 5) to determine the impact velocity of the particle.
4.3. The velocity constant $C$

During the 12 month experimental program using the high speed camera, more than 500 video scripts were recorded and analysed. The measured particle velocities at the moment of impacting the anvil were compared with the theoretical impact velocities to determine the velocity constant $C$. The following conclusions were noted:

- The velocity constant $C$ in Eq. (4) is not equal to unity. It varies between approximately 0.85 and 0.95. This indicates that the efficiency of the machine in transferring the kinetic energy from the rotor to the particle is not 100%. From Eq. (5) a velocity constant $C$ = 0.85 means that the actual specific energy at impact is only 72.3% of that expected from theory.
- Among all variables investigated, the rotor speed exerts the most significant influence on the velocity constant $C$. Increasing rotor speed will increase the velocity constant $C$, yet the trend is not linear. Hence $C$ essentially accounts for the friction which is proportional to mass and the velocity of the rotor.
- Particle size also exerts an influence on the velocity constant $C$: large particles have higher $C$. This trend was not as originally expected. From the viewpoint of particle contact friction with the guiding channel, the opposite trend was initially expected. This has been resolved through the effective rotor radius explanation in the next section.
- The constant $C$ is machine-dependant. For example, the prototype and the industrialised JKRBT have different $C$ values (all other conditions being the same) due to the differences in machine design such as the number of ports in the rotor, geometry of the channel, channel roughness, material, etc. This implies that every JKRBT needs to be calibrated before it can be accurately applied to ore testing.
- At the current level of the velocity measurement accuracy, the rock properties investigated (other than the particle size) do not exert a statistically significant influence on the velocity constant $C$. This conclusion is significant, as it provides for easy control of the specific energy in testing various types of rock samples.

A relationship to describe the $C$ and the influencing factors was established. It has been calibrated for each individual JKRBT using the high speed video camera data. Once calibrated, the Perspex viewing window was replaced with a steel cover, and the high speed video camera is no longer required in the JKRBT operation except in future calibration. This relationship can be programmed in the HMI control system to run the rotor at the correct speed (rpm) to achieve the desired specific energy values, or can be employed off-line to calculate the true specific energy from the machine operating conditions.

5. Design factors investigated

A number of design issues have been carefully examined by means of theoretical calculations, numerical simulation software, Visual Nastran software, and/or experimental testing in the JKRBT development stages. This section summarises some major factors investigated.

5.1. Particle entrance to the rotor guide channels

Particles are fed into the guiding channels one after another via a vertical feeding tube at the centre of the rotor through a vibrating feeder (the prototype and version 1 industrialised JKRBT) or a rotary feeder operated manually (version 2 JKRBT). The particles move at an initial velocity $V_1$ towards one of the radial guiding channels (typically $V_1 < 5$ m/s; see Fig. 4). The particle entry port has a 15 mm radius in the prototype JKRBT, 35 mm in the version 1 JKRBT, and 50 mm in the version 2 machine. During collection the particle is simultaneously loaded by impact and accelerated. The initial impact velocity ($V_3$) is determined by the inner channel tip velocity ($V_2$), the initial particle velocity ($V_1$) and by the angle of collection ($\alpha_1$). The particle needs to be move sufficiently deep into the channel to be collected or will otherwise be collected by the next port. This is a rather complicated process, which the JKRBT version 1 design attempted to resolve by simply having a straight two-channel design, instead of the 4-channel design employed in the prototype. However the two-channel design had some shortcomings as explained below.
Two major design variables affect the movement of particles in the rotor entry port: the radius of the port and the number of guide channels. The port velocity $V_2$, and hence the impact loading velocity $V_3$, is affected by the port radius – the larger the port, the higher velocity at a given rotor rotational speed. There is a possibility that a rock particle may be held-up by centrifugal force. Fig. 6 shows a rock hung up against the side wall of the entry port at a rotor speed 2641 rpm in the version 1 JKRBT with two guide channels. The hung-up particle typically releases at a reduced rotor speed before the rotor completely stops, and reports to the product collection bin. This creates a problem as the operator may be not aware how to deal with the unbroken particles, particularly at low impact energy tests. In the version 1 JKRBT, on average three rock hang-ups could be expected in every 100 pieces of rock tested. Clearly this situation was not acceptable and a design solution was warranted.

Increasing the number of the guide channels was expected to eliminate the rock hang-up problem. For example, in the prototype JKRBT where there were four guide channels, no rock hang-up issues were observed. However, the impact loading can be sufficient to cause significant initial breakage at the intersections of the channels during collection.

Visual Nastran simulations indicated that for a particle of 45 × 45 × 80 mm, the design top size for the industrialised JKRBT, the diameter of the guide channels should be 100 mm to avoid any particle jams in the entry port and channel. For an entry port radius of 50 mm and version 2 JKRBT rotor running at the maximum speed of 5000 rpm, the linear velocity of the intersection of the channels is 26 m/s. This is equivalent to a 0.1 kWh/t specific energy, which means about 3% of extra pre-breakage energy may be added to the target specific breakage energy if any particle is caught by the intersection of two channels. In the 3-channel design (version 2 JKRBT), the area of the intersections is about 15% of the total guide channel area, i.e. about 15% of the particles may receive a further 3% of the target energy in the rotor entry port. In the 4-channel design, the proportion of particles that may receive the additional pre-breakage energy will increase significantly.

Decreasing the number of channels will decrease the amount of particles receiving extra pre-breakage energy, but may increase the probability of particles hanging up in the rotor entry port, and vice versa. As a compromise between minimising the rock hang-up and minimising the pre-breakage, three-channel ports were selected for the version 2 JKRBT design. Statistical experiments indicate a rock hang-up event may happen once in every 500 particles tested, a significant reduction from the 3% using the two-channel design in version 1 JKRBT. The extra pre-breakage energy in the three-channel ports may be corrected through the energy calibration constant $C$.

The rotor hub in the version 2 JKRBT was fitted with a conical plug (see Fig. 7) designed to deflect the rocks towards one of the three rotor channels. This helped minimise the path and time the rocks took to move towards the guide channels. Visual Nastran software was used to evaluate the effect of the plug on the start and final velocity. The program showed that the start velocity ($V_3$) had very little effect, which was confirmed subsequently through controlled release testing using the prototype JKRBT. These tests were designed to compare the effect of releasing the rock at the base of the rotor hub using a remote mechanical release tool, with the rocks released from the standard feed height of approximately 250 mm.

5.2. Effective rotor radius

The high speed video camera data consistently demonstrated that higher impact velocity constants $C$ were associated with larger particles. This was puzzling at the beginning as one would expect the opposite since larger particles experience higher friction forces due to their larger contact area in the guide channels.

Slowly playing back the movie scripts taken by the camera showed that the particle remained in contact with the guide channel until the particle completely emerged from the channel. The implication from this observation is that the effective rotor radius should be increased by at least half of the particle diameter (to the centre of gravity of the particle, refer to Fig. 8) in calculating the tangential component of the impact velocity. For example the tangential velocity for the maximum design particle size (37.5–45.0 mm) will increase by 9% which represents an increase of 19% in the expected specific energy. Similarly, for the smallest size
to be tested in the JKRBT validation project (13.2–16.0 mm), the tangential velocity and specific energy increase by 3% and 6%, respectively.

The tangential velocity and hence the theoretical impact velocity were re-calculated using the effective rotor radius concept. The velocity constants $C$ were determined based on the new theoretical impact velocities. These velocity constants were regressed for each individual JKRBT, and used to calculate the corrected specific energy (Eq. (6)):

$$E_{cs} = 3.046 \times 10^{-4} C^2 N^2 \left( r + \frac{x}{2} \right)^2$$  \hspace{1cm} (6)$$

where $x$ is geometric mean particle size ($m$).

The measured high speed video camera data and the breakage characterisation results appear to support the effective rotor radius concept.

5.3. The influence of inclined rotor surface

The rotor and anvils are inclined at 30° in the industrialised JKRBT, different from the prototype JKRBT which employed a horizontal rotor–stator arrangement. This design feature allows fragments to move into the product collection bin so as to prevent fragments from building up and interfering with subsequent impacts during the tests, and to allow operator easy access when the lid is opened after testing is complete.

Concerns have been raised about the angled rotor suggesting that the particles are preferentially collected at the lower edge of the collection area (refer to Figs. 2 and 3). Additionally, the location where the particle is collected by the guide channels determines the location where the particle collides with the anvil, which means that impact concentrates at certain specific anvils.

The potentially adverse effect of the angled rotor has been taken into account in the JKRBT design stage. For an entrance port of radius 50 mm, the particle velocity ($V_p$, refer to Fig. 4) entering the guiding channel is 26.7 m/s when the rotor runs at 5000 rpm, or 5.8 m/s running at 1000 rpm. On the vertical coordinates, the 30° inclined rotor will raise the height at the upper most edge of the entry port circumference by 25 mm. The difference in vertical velocity due to gravity for the 25 mm height is 0.7 m/s. When the rotor runs at 5000 rpm, the inclined surface only causes a 0.1% higher velocity for a particle preferentially entering a channel in the lower edge of the collection area, and 0.9% higher velocity when the rotor is running at 1000 rpm. The influence of the angled rotor on particle preferential collection is therefore insignificant. This is also evident from the impact markings on the anvils which, after a long period of testing, show no significant difference between the lower and higher anvils (see Fig. 9).

5.4. The influence of protruding anvils

The JKRBT employs 12 curved anvils with protruding corners (Figs. 2 and 5). The profile was designed to ensure impact angles higher than 70°, necessary to maintain high impact efficiency for accurate breakage characterisation tests. The high speed camera data suggests that the lowest angle of impact, expected at the minimum operating speed of 100 rpm, is approximately 70°. At the more typical test speeds of 800–4000 rpm, the impact angles range from 78 to 85° depending on machine design.

The anvils can be supplied in two forms, depending on wear life expectations: (1) fitted with twelve hardened steel plates, or (2) four Bisalloy 400 steel segments (see Fig. 10). The anvil plates are interchangeable and can be rotated should uneven wear be detected. The 4-piece anvil sections are less expensive and easily replaceable if worn. To date the hardened anvil liners appear to be the best choice, with minimal wear evident after significant testing at Anglo Research.

The protruding corners may cause disturbance when particles impact on the corners. The influence is more significant for large particles. For the top size fraction (37.5–45 mm), approximately one third of the particles may be affected by the protruding corners. For small size fractions (e.g. 13.2–16 mm), the probability decreases to about 16%.

Since the standard breakage characterisation uses the same particle size fractions for testing, the influence of the protruding corners would be similar for different ore samples. Hence if different
ore samples are characterised at the identical testing conditions, the resultant ore hardness parameters should be consistent and comparable. Therefore the influence of the protruding anvils is mitigated when using the JKRBT for breakage characterisation tests.

The principle used in the SynchroCrusher (van der Zanden and van der Zanden, 2004) may provide a more precise way to control the impact point on the anvils. However further research is required to understand how this concept can be integrated in the JKRBT design.

5.5. The influence of fragment rebound

Undoubtedly some fragments will rebound and impact the moving rotor surface after collision with the anvils. This is called secondary breakage. Impact marks on the rotor edge give evidence of the rebound of fragments (see Fig. 11). Concerns have been raised that the secondary breakage may negatively impact the accuracy of rock breakage characterisation. Analyses carried out suggest this effect is negligible as explained below.

The key issue in the secondary breakage is the additional energy imparted to rebound particles after contacting the moving rotor. The initial rebound impact into the rotor is considered to be part of the parent particle energy dissipation and main breakage event. However, the rebound fragment may gain energy from the moving rotor and this constitutes secondary breakage energy. The movie scripts show two types of secondary breakage:

1. The rebound fragments hit the rotating outer rotor surface and receive a glancing blow, causing particle surface chipping.
2. The rebound fragments are directly impacted by the inside surface of the trailing edge of the open guide channels, causing secondary breakage.

For the first type of secondary breakage event, the rebound velocity can be calculated from the coefficient of restitution and consideration of radial and tangential impulse on the rock as it rebounds into the moving rotor. Assuming the coefficient of restitution for rock–steel contact is 0.3 (e), and coefficient of friction for rock–steel is 0.4 (μ), the rebound velocity of a fragment, \( V_{reb} = \frac{1}{\mu} \left[ e^{2} + \frac{1 - e^{2}}{2} \right] V_{i} \approx 0.18 V_{i} \), where \( V_{i} \) is the primary impact velocity. The kinetic energy of the rebound fragment is therefore

\[
E_k = 0.5 m_f V_{reb}^2
\]

where \( m_f \) is the fragment mass (kg).

In high energy breakage tests (e.g. \( E_{cs} = 2.5 \text{ kWh/t} \)), the size reduction is significant, resulting in small product fragments. Assuming the fragment mass \( m_f = 0.1 m_i \), where \( m_i \) is the parent particle mass before impacting the anvil, Eq. (7) suggests the kinetic energy of the rebound fragment post impacting the rotor will be only 0.3% of the original parent particle impact energy. In a low energy breakage test (e.g. 0.25 kWh/t), the fragments may be larger, say 0.8 of the parent mass, increasing their kinetic energy to 2.6% of the parent particle. Such small kinetic energies would not be expected to generate substantial damage in the subsequent collisions. Type 1 secondary breakage was observed to cause minor particle chipping.
The option to line the outside of the rotor with rubber was considered, but discounted as the analysis suggests this would result in a longer residence time during impact and a greater impulse to the rock leading to the rock having more kinetic energy after impact and more secondary breakage when it strikes the next steel surface.

For the second type of the secondary breakage, the trailing edges of the open guide channels act like rotating hammers if they happen to collide with the rebound fragments. This additional energy would result in particle breakage, particularly at high rotational speeds. However, only a small fraction of the fragments would be expected to rebound towards rotor, say less than 10%. The probability of a rebound particle being caught by a guide channel is only 11.6%, based on the ratio between the total open area of the guide channels and the total rotor circumference area. As a result, less than 1.2% of the rebound particles would be expected to sustain this type of secondary particle breakage in the JKRBT (i.e. 10% rebound towards the rotor × 11.6% probability to be caught by the open guide channel).

The movie scripts recorded by the high speed video camera appear to agree with the above analysis. It also showed evidence that some fragments after impacting the anvil are suspended in the air before dropping into the collection chamber. This is probably due to the air flow directed from the rotor channels towards the anvils counteracting the velocity of the rebound fragments. It is therefore assumed that the influence of rebound fragments does not significantly affect the accuracy of the characterisation tests and the secondary breakage resulting from fragment rebound can be corrected. It should be noted that the airstream in the JKRBT is throttled by the new rotary feeder.

In summary, the research team have studied various issues over the last four years to progressively improve the JKRBT design and operation. Aspects such as the rock entry into the guide channels, effect of the angled rotor and protruding anvils, and secondary breakage have been noted and known to contribute to the uncertainty in the breakage data generated, but are minor in the context of the intended application. The use of a high speed video camera provided a powerful tool to understand the mechanisms inside the JKRBT and to calibrate the specific energy required for breakage characterisation tests. The development team is confident that the specific energy can be well controlled in the JKRBT, and results to date support this assertion (refer to the next section).

6. Features of the JKRBT

The results from extensive trials using the prototype and ongoing validation project using the industrialised JKRBT machines are summarised below.

1. The JKRBT allows rapid characterisation of particle impact breakage properties. The feedback from Anglo Research indicated that one JKRBT test (equivalent to one standard DWT) can be completed in approximately 1/8th–1/10th of the time it takes to complete a DWT test.
2. The ability to test a large number of particles offers statistically more valid results. For example, the system is able to break 1200 particles in 20 min. This is particularly useful when the breakage probability has to be determined, which requires 2500 particles to be broken in order to obtain a statistically valid result (Vogel and Peukert, 2004). In comparison, the DWT normally tests 10–30 particles in each size fraction to determine $f_{10}$ values. It is not physically and economically practical to test more than a 1000 particles with a DWT.
3. The required specific energy can be accurately and precisely controlled since the impact specific energy in the new system is independent of the particle mass (Eq. (1)). In the DWT, the particle mass affects the specific energy of each breakage event, resulting in an unmeasured distribution of specific energies for each size fraction tested. Adjusting the drop mass or height for each particle mass could prevent this problem, but would extend the testing time significantly, making the DWT impractical for routine breakage characterisation. Similarly, the JKRBT eliminates the need for tight particle mass control in the SMC tests on sized broken fragments.
4. High specific energies can be delivered to both small and large rock particles since the specific energy is independent of the particle mass. This enables the characterisation results to cover a wide range of specific energy levels for all particle sizes. This is not currently possible with the DWT, as high specific energy tests on large particles require a heavier drop head and higher drop height than are practically possible (e.g. high SG iron ore samples).
5. Repeatability of the JKRBT tests is higher than the traditional DWT, as illustrated in Fig. 12, even with the same number of

![Fig. 12. Comparison of repeatability of DWT and JKRBT on same ore and particle size.](image-url)
particles in each test (30 particles per size–energy test for both JKRBT and DWT). This is largely attributed to the benefit of improved specific energy control.

6. Comparative breakage tests using the JKRBT and traditional Drop Weight Tester show that the two devices generate similar breakage–energy relationships, after correcting for the applied specific energy and the single versus two point fracture mechanisms. Statistical analysis indicates that the two testing methods can generate statistically similar breakage parameter $A_{xb}$ values, as illustrated in Fig. 13 which compares the $A_{xb}$ values of 16 ore types determined by the version 1 JKRBT and DWT installed at Anglo Research, respectively.

Given the benefits outlined above, the JKRBT may find many prospective applications into the future that are currently either difficult or impossible with existing equipment. One of the niche applications is in geomechanical testing where the JKRBT device offers a rapid and consistent method for determining the hardness of drill core samples (Walters and Kojovic, 2006). Other potential applications of the JKRBT have been discussed elsewhere (Kojovic et al., 2008, 2009; Shi et al., 2008).

The JKMRC recognized that rocks in industrial crushers and mills rarely experience impacts at velocities that were envisaged in the JKRBT device, but the focus was on testing the ore hardness at set specific energies, not necessarily the direct replication of the breakage mode in mills. As the breakage modes in a mill include both single and two point impact breakage, there is no clear choice as to which device is more appropriate. According to Gildemeister and Albers, the comminution of particles may be regarded as a quasi-static process up to impact velocities of 200 m/s (refer to Tomas et al., 1999). Therefore, the JKRBT tests even at the highest energy 3.8 kWh/t (150 m/s) are still in a similar quasi-static breakage status as in the comminution devices, and the JKRBT characterisation tests are relevant to the crushing and grinding processes.

7. Conclusions

A new rapid breakage characterisation testing device, called the JKRBT, has been developed by the JKMRC for rapid impact breakage characterisation. A detailed study using a prototype machine confirmed the concept of using controlled kinetic energy to characterise ore particle breakage, prompting a comprehensive validation using an industrialised JKRBT, designed and fabricated by RME.

Seven industrialised JKRBT units have been deployed at various locations around the world, including Australia, North America and South Africa. The JKMRC and some of the world’s major mining companies (Anglo American, Barrick, BHP Billiton, Rio Tinto and Teck), are participating in a formal validation project expected to close in June 2009.

A detailed study using a high speed video camera has resulted in better understanding of breakage mechanisms in the JKRBT. This study has recognized that each machine needs to be calibrated to provide accurate control of the breakage energy necessary for characterisation tests. A detailed review of the design looking at the rock entry into the guide channels, effect of the angled rotor and protruding anvils, and secondary breakage has identified areas which contribute to the uncertainty in the breakage data generated, but all were found to be minor in the context of the intended application.

Investigations to date have shown that the JKRBT can generate statistically similar breakage parameters to the traditional DWT, but with significant advantages over its predecessor. The limitations of the DWT, specifically its lack of precision in the energy input, the lengthy time required to run individual tests and the challenges encountered in testing small particles have all been overcome by the JKRBT.

Despite the uncertainties in the impact energy and possible secondary breakage (described and partially quantified above), the JKRBT provides outstandingly consistent results. This consistency is both between identical samples and between the JKRBT and the DWT. The uncertainties appear to be adequately accommodated in the single calibration constant and to be overshadowed by the natural variability in rocks, and any bias appears to be sufficiently small to not be detected in the progeny size distribution that is used to measure the response of the rocks to impact.

Feedback from Anglo Research has indicated higher productivity and better repeatability of the first industrialised JKRBT unit compared with the Drop Weight Tester. This bodes well for the JKRBT as a powerful tool for rapid breakage characterisation in the mining industry.

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References


