A study of the applications and modelling of high voltage pulse comminution for mineral ores

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Julius Kruttschnitt Mineral Research Centre
Abstract

The pre-treatment of ore particles by high voltage pulses (HVP) at low specific energy has a potential to reduce the energy consumption and operation costs. Nevertheless, the influencing factors and the behavior of HVP breakage of ore particles have not yet been fully understood. The overall objective of this thesis is to study the applications and modelling of HVP breakage by understanding the behaviour of ore particles subjected to pulse discharge. The three areas investigated are:

1) The effects of mineral properties on HVP selective breakage and the application of this selective breakage in ore pre-concentration.

2) The methods to evaluate and to characterize HVP breakage results.

3) Modelling ore particle behavior in HVP breakage.

In this project, the selectivity of HVP breakage is studied using synthetic samples made of construction grout and pyrite grains. The result confirms that the breakage response of particles is dominated by the locality of electrical breakdown channel. The electrical breakdown channel locality is controlled by the grains of minerals with high conductivity/permittivity and their location in a particle. This understanding has led to the discovery of a novel technique for ore pre-concentration using high voltage electrical pulses. The technique utilises metalliferous grain-induced selective breakage, under a controlled pulse energy loading, and size-based screening to separate the feed ore into two products for splitting of ores by grade.

To evaluate HVP breakage results, a $t_{10}$-based model was developed to predict the degree of impact breakage, $t_{10}$, of pulse-treated particles from that of untreated particles. This model incorporates only one parameter, $C_{Ab}$, which is equivalent to percentage change of $A \times b$ values. The $t_{10}$-based model can be used to assess energy reduction due to the pre-weakening effect in the downstream mechanical comminution process. A Wide-size JKRBT characterisation method was created, initially for quick determination of breakage characteristics of the HVP product; ultimately for use as an express ore breakage characterisation method. In this method, particles in wide size range are tested as one size class in the JKRBT by single–particle breakage mode, significantly simplifying the feed particles preparing and product sizing procedures. A conceptual design of an on–line ore
competence measuring system based on this principle is proposed. Both the $t_{10}$-based model and the Wide-size JKRBT method utilise a size-dependent breakage model previously developed by the JKMRC.

Behaviour of ore particles in HVP breakage was investigated with a pilot scale and a laboratory scale HVP breakage devices. The effects of specific energy, pulse voltage, cumulative discharges, feed particle size and ore particle breakage pattern (body breakage or surface breakage) were investigated. Based on the data, a model structure for HVP breakage was developed, which incorporates four sub-models using the similar structure to predict four HVP breakage indices: body breakage probability, body breakage product fineness, pre-weakening degree and metal recovery. A set of $t_n$-family of curves were established to estimate the HVP product size distribution from the HVP model predicted breakage indices.

In summary, this PhD study has delivered the following major outcomes:

• A novel HVP ore pre-concentration method, which has a potential for the mining industry in making step-change improvements in energy efficiency, environment impact and operation costs.

• A $t_{10}$-based model to evaluate HVP breakage result. This method can also be applied for comparison of ore competence change, regardless of the breakage methods causing this competence change, as long as the benchmark ore breakage characteristic parameters are available.

• A Wide-size JKRBT characterisation method, which significantly simplifies the traditional ore impact characterisation methods.

• A set of HVP breakage models, which can be used for simulations of a hybrid circuit combining mechanical comminution and electrical comminution.

• 13 papers generated during the course of this PhD study, being the first-named author for seven of them.
Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Contributions by others to the thesis

Dr. Fengnian Shi and Prof. Emmy Manlapig were responsible for setting up this thesis project, organising funding and establishing the initial project goals. They provided the initial idea of investigating the application and modelling of high voltage pulses comminution for mineral ores. They also made great contributions to the interpretation of experimental data.

Dr. Fengnian Shi assisted in preparing the thesis and critically reviewed the draft of the thesis.

Dr. Alexander Weh and Dr. Klaas Peter van der Wielen from SELFRAG AG organized the joint pilot scale high voltage pulse comminution in the Pre-weakening Test Station at SELFRAG AG and provided assistance in conducting the experimental work presented in Chapter 7.

Mr. Tyson Keegan conducted part of lab scale high voltage pulse breakage tests and JK Rotary Breakage tests presented in Chapter 6 during his vacation work in June 2012.

Mr. Lei Wang, Chao Li, Jeffrey Parkes and Dan Mitchell conducted part of JK Rotary Breakage tests presented in this thesis.

Statement of parts of the thesis submitted to qualify for the award of another degree

None.
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High voltage pulse, pre-concentration, pre-weakening, breakage model, wide size JKRBT test

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# Table of Contents

## Chapter 1  Introduction

1.1 Problem statement ........................................................................................................... 1  
1.2 Scope of this thesis ........................................................................................................ 2  
1.3 Research objectives ....................................................................................................... 3  
1.4 Thesis outline ................................................................................................................ 4  

## Chapter 2  Literature Review

2.1 Introduction .................................................................................................................... 8  
2.1.1 Pulsed Power Technology and Theory of Electrical Breakdown .............................. 8  
2.1.1 The Essence of Pulsed Power .................................................................................. 9  
2.1.2 Pulse Generator ....................................................................................................... 12  
2.1.3 General Structure of Electric Disintegrator ............................................................. 13  
2.1.4 Budenstein’s electrical breakdown Theory ............................................................... 14  
2.1.5 Role of Gas-filled Pores in the Electrical Disintegration of Dielectric Solid ............ 19  
2.2 Electrical Breakdown Channel Paths ........................................................................... 20  
2.2.1 Electric Discharge Paths in liquid-solid System ..................................................... 20  
2.2.2 Electric Discharge Paths inside Composite Solids ................................................... 25  
2.3 Mechanism of the disintegration and selective liberation of composite dielectrics in HVP breakage ............................................................................................................... 27  
2.3.1 Mechanism of disintegration of composite dielectrics in HVP breakage .................... 27  
2.3.2 Mechanism of selective liberation of composite dielectrics in HVP breakage ............ 28  
2.4 Energy Efficiency of Electrical Disintegration .............................................................. 30  
2.5 Effect of Machine Setting on HVP breakage ................................................................. 31  
2.5.1 Effect of Voltage and Energy Input on Electrical Breakdown and Electrical Disintegration ................................................................. 31  
2.5.2 Optimization of Machine Setting in Electrical Comminution ................................ 34  
2.6 Pre-weakening by High Voltage Pulse .......................................................................... 36  
2.6.1 The Application of Pre-weakening by High Voltage Pulse ...................................... 36  
2.6.2 Influence of Mineral Properties on the Pre-weakening Effect of Electrical Comminution .................................................................................................................... 37  
2.7 Research gaps and hypotheses ....................................................................................... 39  

## Chapter 3  Experimental Details

3.1 Single-particle single-pulse testing method for HVP breakage ....................................... 41  
3.2 Use of synthetic samples to investigate the selectivity of HVP breakage ......................... 43  
3.2.1 Selection of concrete grout to make synthetic sample .............................................. 43  
3.2.2 Properties of the selected construction grout ......................................................... 44  
3.3 Natural ore samples ....................................................................................................... 44  
3.4 Ore sample preparation ................................................................................................. 45
3.5 Equipment and instrument

3.5.1 Lab scale HVP breakage device (selFrag Lab)

3.5.2 Pilot scale HVP breakage device (PWTS)

3.5.3 Single particle impact breakage characterization-JKRBT

Chapter 4 The Effect of Electrical Breakdown Channel Locality on Particle Breakage Behaviour

4.1 Introduction

4.2 Contributions

Chapter 5 Development of an Ore Pre-concentration Method using High Voltage Pulses

5.1 Introduction

5.2 Contributions

Chapter 6 Characterization of Ore Pre-weakening Effect

6.1 Introduction

6.2 Contributions

Chapter 7 Experimental Study of Ore Breakage Behaviour in a Pilot Scale HVP Machine

7.1 Introduction

7.2 Contributions

Chapter 8 Modelling of High Voltage Pulse Breakage of Ores

8.1 Introduction

8.2 Contributions

Chapter 9 Conclusions and Future Work

9.1 Conclusions

9.2 Recommendations for future work

Reference
List of Figures

Figure 1-1 Schematic diagram of the main topics addressed in the scope of this thesis .................3
Figure 1-2 The overall structure of the thesis ..................................................................................5
Figure 2-1 Pulse shape parameters (Bluhm, 2006) ........................................................................10
Figure 2-2 General scheme of a pulsed-power generator (Bluhm, 2006) ......................................10
Figure 2-3 Marx generator circuit with unipolar charging through the resistors (RL) (cited from Bluhm, 2006, with minor revision) ..................................................................................13
Figure 2-4 Schematic illustration of a set-up to induce an electric discharge through a solid dielectric material (Bluhm, 2006) ..................................................................................................13
Figure 2-5 Schematic of the electrodes setup at the same side (Inoue et al., 1999) .......................14
Figure 2-6 Formative phase of polarization (Le Sueur, 1995) .......................................................15
Figure 2-7 Field enhancements during initiation phase (Le Sueur, 1995) ....................................15
Figure 2-8 Treeing and luminance produced (Le Sueur, 1995) .....................................................16
Figure 2-9 Channel enlargement and current flow (Le Sueur, 1995) ....... ...............................17
Figure 2-10 Expanding plasma and destruction (Le Sueur, 1995) .............................................17
Figure 2-11 Electric discharge paths through water (left) and solid (right) (Ilgnor, 2006) ........21
Figure 2-12 Dynamic breakdown strength of liquid, solid and air dielectrics as a function of the voltage (V) and its rise time (t) (Andres et al., 2001b) .................................................................22
Figure 2-13 Field distribution for spherical particle in a continuous medium (\(\varepsilon_p, \sigma_p >> \varepsilon_m, \sigma_m\)); \(E_o\) is applied field (Andres and Timoshkin, 1998) .................................................................24
Figure 2-14 Field distribution for spherical particle in a continuous medium for the case \(\varepsilon_p, \sigma_p << \varepsilon_m, \sigma_m\) (Andres and Timoshkin, 1998) .................................................................24
Figure 2-15 Possible paths of breakdown in the liquid-solids system (bottom curve shows the purely surface type of breakdown) (Andres and Timoshkin, 1998) .............................................25
Figure 2-16 Polarisation process in complex mineral particle in water (Andres et al., 2001a) ....26
Figure 2-17 Tree growing (A) and disintegration of mineral particle (B) (Andres et al., 2001a) ....26
Figure 2-18 Photographs of electrically disintegrated samples of kimberlitic and granite rock (Andres, 1995) ..........................................................................................................................28
Figure 2-19 Mechanisms by which components in a composite material can be liberated .......28
Figure 2-20 Plasma streamers generated around inclusions in rock (Andres et al., 2001b) .......30
Figure 2-21 Energy of pulses per cm of conductive path versus electrical field, generated in samples of granite (Andres, 1989) ........................................................................................................33
Figure 2-22 photograph of the cavities in the sandstone sample resulted from electrical disintegration (Andres, 1995) .................................................................................................................. 34
Figure 2-23 Two ore particle showing extensive cracking (Wang et al., 2011) ..................... 37
Figure 2-24 Product ore softness in relation to size of fragments produced by selFrag in comparison with the conventional crushing for samples collected from the four different mines, error bars indicating 95% confidence intervals (Wang et al., 2011) .......................................................................................................................... 38
Figure 3-1 The large rotary Divider on the left, and Gilson screens on the right used to generate representative test feed samples (Wang, 2012) ............................................................................................................ 45
Figure 3-2 Laboratory jaw crusher, large (left) and small (right) (Wang, 2012) ......................... 46
Figure 3-3 Lab scale HVP device selFrag Lab installed at the JKMRC and used in this project .... 47
Figure 3-4 Schematic drawing of selFrag lab device (van der Wielen et al., 2013) ..................... 48
Figure 3-5 Industrial JKRBT Unit (Shi et al., 2009) .................................................................... 49
Figure 4-1 Tree growing (A) and disintegration of mineral particle (B) (Andres et al., 2001a) ..... 54
Figure 4-2 Configuration of Group 2 samples ...................................................................... 57
Figure 4-3 Configuration of Group 3 samples ...................................................................... 58
Figure 4-4 Responses of single particle to pulse discharge .................................................... 60
Figure 4-5 Burning traces caused by electrical breakdown .................................................... 61
Figure 4-6 Product size distribution curves of Group 2 samples generated by electrical breakage (the legends are referred to Figure 4-2) ...................................................................................................................... 64
Figure 4-7 Product size distribution of Group 3 sample in electrical comminution (the legends are referred to Figure 4-3) ...................................................................................................................... 65
Figure 4-8 Comparison of product size distribution between Syn-7 (single column of pyrite powders along the particle axis) and Syn-17 (single coarse pyrite grain embedded in the centre of particle) ........................................................................................................................... 66
Figure 4-9 Cracks appeared on the fragment surface of samples Syn-7 (breakdown channel along the cylindrical axis of particle) and Syn-13 (breakdown channel away from the cylindrical axis of particle) ........................................................................................................................ 67
Figure 5-1 Comparison of product size distributions between Syn-15 and Syn-24 samples subjected to one pulse discharge .................................................................................................................. 76
Figure 5-2 Process of ore pre-concentration by high voltage pulse breakage. ......................... 77
Figure 5-3 Size distributions of the body breakage and surface breakage products treated by high voltage electrical pulses ........................................................................................................... 81
Figure 5-4 The newly exposed particle surface from body breakage and surface breakage in Test 4 for Sample B SAG mill pebbles ........................................................................................................... 84
Figure 5-5 Mass yield of body breakage product in relation to pulse specific energy of the six pre-concentration tests .................................................................................................................................................. 87
Figure 5-6 Copper deportment in relation to mass yield of body breakage product in the six pre-concentration tests (the kWh t-1 data indicating the pulse specific energy) .................................................................................................................. 88
Figure 5-7 Relation between energy transfer efficiency $C_{ET}$ and copper grade in Tests 1 to 5........... 93
Figure 6-1 JKRBT product $t_{10}$ values of the pulse-treated ($t_{10p}$) and untreated ($t_{10u}$) particles at same size/energy levels .................................................................................................................................................. 102
Figure 6-2 The linear relationship between the calculated $R_{10}(t)$ (Eq. (6-5)) and the smoothed $t_{10u}$ using Eqs. (6-2) and (6-3) .................................................................................................................................................. 103
Figure 6-3 Comparison of the experimental values of $t_{10p}$ with that predicted by the size-dependent breakage model (a) and the $t_{10}$-based method (b) ................................................................. 105
Figure 6-4 Comparison of the $A\times b$ values of the pulse-treated particles (a) and degree of pre-weakening (b) calculated by the size-dependent model (Eqs. (6-2) and (6-3)) and the $t_{10}$-based method respectively .................................................................................................................................................. 108
Figure 6-5 Relation between energy reduction $\Delta E$ and the target product fineness $t_{10T}$, calculated by Eq. (21) .................................................................................................................................................. 111
Figure 6-6 Procedures to determine ore breakage characteristic parameters by single particle impact tests .................................................................................................................................................. 116
Figure 6-7 $t_{n}$-family curves of ore breakage in JKRBT ........................................................................... 119
Figure 6-8 Mechanism of ore breakage characterization by express RBT test ..................................... 121
Figure 6-9 Size distributions of Dataset 1 before and after breakage with various JKRBT impact energies (Markers: experimental values; Lines: Fitted values) ................................................................. 126
Figure 6-10 Ore competence indicator $A\times b$ values determined by the Wide–size JKRBT tests using the size–dependent model in comparison with that determined by the traditional narrow–size JKRBT tests, the error bars representing ± one SD .................................................................................................................................................. 127
Figure 6-11 Ore competence indicator $A\times b$ values determined by the Wide–size JKRBT tests using the $t_{10}$–based model in comparison with that determined by the traditional narrow–size JKRBT tests, the error bars representing ± one SD .................................................................................................................................................. 129
Figure 7-1 Illustration of the pilot scale PWTS installed at Kerzers, Switzerland ......................... 136
Figure 7-2 Process zone of PWTS ........................................................................................................... 137
Figure 7-3 Testing procedures using hand sieving and mechanical sieving .................................... 142
Figure 7-4 Comparison the size analysis results between the hand sieving and the mechanical sieving .................................................................................................................................................. 143
Figure 7-5 The effect of particle size and specific energy on the body breakage probability at the first pulse discharge (Points: measured; Lines: regressed) ................................................................. 147
Figure 7-6 The effect of particle size and specific energy on the PWTS product fineness indicator $t_{10}$ at the first pulse discharge (Points: measured; Lines: regressed) .................................................. 149
Figure 7-7 The effect of particle size and specific energy on the degree of pre-weakening of the HVP product at the first pulse discharge (Points: measured; Lines: regressed) ................. 151
Figure 7-8 Porous surface of Ore C particle ................................................................. 152
Figure 7-9 Comparison of HVP breakage product fineness and the degree of pre-weakening generated by the first and second pulse discharges on Ore A samples ............................................. 155
Figure 7-10 Comparison of pre-weakening degrees between body and surface breakage products of Ore A samples under the same testing conditions ................................................................. 156
Figure 8-1 The HVP $D_1$-model fitted to the pilot scale testing data of three ore samples ........ 168
Figure 8-2 The HVP $D_2$-model fitted to the pilot scale testing data of three ore samples .......... 168
Figure 8-3 The HVP $D_3$-model fitted to the pilot scale testing data of three ore samples .......... 169
Figure 8-4 The high voltage pulse pre-concentration characterisation curves proposed by Shi et al. (2015b) .............................................................................................................. 170
Figure 8-5 The HVP breakage model fitted to Cu recovery data published in Shi et al. (2015b) ... 171
Figure 8-6 The plots of $t_n$-family of curves using the HVP breakage data for Ores A, B and C .... 173
Figure 8-7 The $t_n$-family of curves used for HVP breakage modelling .................................. 173
List of Tables

Table 2-1 Classification of pulsed-power applications................................................................. 11
Table 3-1 Symbols of the natural ore samples used in this project............................................... 44
Table 4-1 Electrical properties of pyrite and cement................................................................. 63
Table 4-2 The A×b values of the synthetic samples determined by the JKRBT tests...................... 68
Table 5-1 Testing conditions of pre-concentration by high voltage pulses...................................... 79
Table 5-2 Mass yield and copper grade-splitting in Tests 1 to 6...................................................... 83
Table 5-3 Comparison of mass yield and copper grade-splitting for ore sample A between electrical comminution (Average Tests 1 and 2) and mechanical comminution.............................................. 87
Table 5-4 Comparison of grade-splitting results according to breakage mode-based and screen-based separations for Sample A (Feed 31.5-37.5 mm)............................................................... 89
Table 5-5 Major elements/minerals in Test 1 products determined by XRF15 after treated with 3.7 kWh t⁻¹ pulse specific energy......................................................................................... 90
Table 5-6 Average spark energy and energy transfer efficiency of body and surface breakage in Tests 1 to 6....................................................................................................................... 92
Table 6-1 Summary of the data range used to develop the t₁₀-based method................................. 100
Table 6-2 Summary of the narrow–size JKRBT testing conditions ............................................. 124
Table 6-3 Summary of data range used to validate present characterization method..................... 125
Table 6-4 The A×b values and the size–dependent model parameters determined by the Wide–size JKRBT tests in comparison with the narrow–size JKRBT tests............................................. 127
Table 7-1 The adjustable range of the PWTS operation parameters.......................................... 138
Table 7-2 Test conditions for Ore A samples .............................................................................. 140
Table 7-3 Paired comparison of HVP breakage behaviour tested with the similar pulse energy but at different pulse voltages for Ore A............................................................................. 153
Table 7-4 Summary of t-tests on paired comparisons of HVP breakage behaviour between tests at different voltages for Ore A..................................................................................... 153
Table 7-5 Comparison of HVP breakage behaviour of ores between the PWTS and the selFrag Lab ..................................................................................................................................... 157
### List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>BRWI</td>
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<td>CBT</td>
<td>Cone Beam Tomography</td>
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<tr>
<td>DWT</td>
<td>Drop Weight Test</td>
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<tr>
<td>ED</td>
<td>Electro-dynamic disintegration</td>
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<tr>
<td>EHD</td>
<td>Electro-hydraulic Disintegration</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
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<tr>
<td>HVP</td>
<td>High Voltage Pulse</td>
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<tr>
<td>JKRBT</td>
<td>JK Rotary Breakage Test</td>
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<tr>
<td>PWTS</td>
<td>Pre-weakening Test Station</td>
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<tr>
<td>XCT</td>
<td>X-Ray Computational Tomography</td>
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Chapter 1  Introduction

1.1  Problem statement

Comminution is the most energy intensive process in the mining industry. It has been reported that comminution consumes, on average, 36% of the energy utilized by the industry (Ballantyne et al., 2012). This is compounded by the fact that comminution is an inherently inefficient process in light of the ratio of mechanical strain energy input to the fracture surface area generated (Fuerstenau and Abouzeid, 2002). Energy efficiency of traditional mechanical comminution is of the order of 0.002-1%, depending on the degree of fragmentation (Bluhm, 2006). The high energy intensity and low efficiency mean that any marginal improvement in comminution efficiency will be of enormous profit to mining industry. The large tonnages of mineral raw materials comminuted annually and the depletion of high-grade, coarse-grained ores over the years add further urgency to the improving the overall performance of comminution circuit.

Novel methods of comminution are continually being sought which offer the prospect of achieving the required outcomes (size reduction and mineral liberation) at lower energy consumption. These methods have included optimization of comminution circuit with modelling and simulation packages such as JKSimMet being developed from research works over the past few decades and the development of novel comminution devices such as high pressure grinding rolls (Schönert, 1988), microwave treatment (Walkiewicz et al., 1991), ultrasonic comminution (Bar-Cohen and Zacny, 2009), Instant drop of hydrostatical pressure (Yellott, 1950; Snyder, 1966), electrohydraulic fragmentation (Touryan et al., 1989) and electrical comminution (Andres, 1995). However, most of above methods has not been widely applied in mining industry due to different technical restrictions.

The interest in electrical comminution has increased significantly in recent years. The potential of electrical comminution as a mineral processing technology has been demonstrated by different researchers. Andres et al. (2001a, b) and Wang et al. (2012c) focus on using electrical comminution technology for fully fragmentation, from which the attractive merits of electrical comminution were established, including significant coarser products with
better liberation, improvements in the subsequent floatation and leaching performance, less contamination from grinding medium and large size reduction ratio. However, the abovementioned advantages are offset by the fact that the electrical comminution consumed nearly two times of energy as high as that for conventional comminution of the same ore (90 and 50 kWh/t respectively in a case study conducted by Andres et al. (2001b)). On the other hand, Wang et al. (2011) explored the potential to pre-weaken rocks by applying electrical comminution at relative low specific energy. It was found that a reduction of 9-52% for ore competence indicator $A \times b$ and a decrease of Bond Work Index up to 24% can be achieved. The positive energy balance of the pre-weakening approach has made it the preferred route for using electrical comminution technology.

Nevertheless, there are still great barriers to implement the HVP comminution technology in the mining industry. Firstly, the effect of ore properties on HVP breakage has not yet been well understood. Secondly, the measurement of pre-weakening degree needs to be improved and the corresponding energy reduction for a given pre-weakening degree needs to be predicted. Finally, the relation between HVP breakage behaviour of ore and machine setting has not yet been well profiled. All these problems have to be resolved before applying the HVP breakage technology in the mineral industry.

1.2 Scope of this thesis

A schematic diagram of the main topics addressed in the scope of this thesis, and equally importantly those which are outside its scope, are shown in Figure 1-1. The operation conditions and product characteristics of HVP breakage are summarized in the diagram. The factors considered will include the mineral properties (ore type and particle size) and the machine operation (voltage, pulse energy). Their effect on the HVP breakage product characteristics will be studied by mainly considering the selectivity of breakage, product size distribution and change of ore competence. Although surface chemical properties of breakage product are acknowledged to have a significant influence on the flotation performance, it is out of the scope of this thesis. The reason is that it is expected that the HVP breakage product will be subjected to downstream mechanical comminution in practical application. Since the particle surface generated in HVP breakage takes up a very small proportion of that generated in downstream mechanical comminution, the influence of the surface chemistry can be
ignored. It is recognised that there are other operating factors that are important for the performance of HVP breakage, such as the generator design and the gap of electrodes. However, they are not the main focus of this thesis either, and these conditions will be fixed in all of the experimental work.

![Schematic diagram of the main topics addressed in the scope of this thesis](image)

**Figure 1-1 Schematic diagram of the main topics addressed in the scope of this thesis**

### 1.3 Research objectives

This project is supported by Newcrest Mining Limited with an objective of providing fundamental studies to explore the potential applications, develop breakage characterization method for the HVP product, and modelling HVP breakage. As a result, this study will mainly focus on the following three aspects:

1. Investigating the effect of mineral properties on the selectivity of HVP breakage and understanding the selective breakage responses. Based on the achievement of this investigation, new application of HVP breakage will be pursued.
2. Developing a model to predict pre-weakening degree and developing a simplified JKRBT test to characterize ore pre-weakening degree.
3. Investigating ore particle breakage behaviour in a pilot scale HVP breakage device and developing a model to describe ore particle behaviour in HVP breakage in relation to specific energy.
Although this study was designed to provide a guideline for Newcrest to evaluate the potential of HVP breakage in industrial application, samples from various sources will be investigated so that this project has general implications for the mineral industry. The achievement of this project will be used to guide the circuit design of HVP breakage technology.

1.4 Thesis outline

This thesis is divided into nine chapters to systemically investigate the ore particle behaviour in HVP breakage. Since seven papers of the first-named author have been produced in this study, the thesis takes a format of “Thesis by papers”. In each of the main chapters (4, 5, 6, 7 and 8), a brief Introduction is given, then a section of Contributions summarises the major contributions of the research outcomes, followed by the paper(s) in detail. Figure 1-2 shows the structure of this thesis and the summary of research outcomes obtained by addressing specific research problems.

In the light of research objectives and work scope described in Section 1.3, the thesis is organized in the following chapters:

Chapter 1 introduces reader the intended research work and includes an overview of the topic providing a background and a justification to the study, the scope and the objectives of the thesis.

Chapter 2 reviews the literature available on the pulsed power technology and theory of electrical breakdown, electrical breakdown channel paths, mechanism of disintegration and selective liberation of composite dielectrics, effect of machine setting on HVP breakage and pre-weakening by high voltage pulse.

In Chapter 3 the experimental details about the testing procedure, synthetic and natural sample, and the equipment used in this project are introduced.
Chapter 4 describes an investigation for the effect of mineral properties on the selectivity of HVP breakage and the understanding the ore particle behaviour in selective breakage. An experimental study was conducted, in which synthetic samples made of construction grout and pyrite grains were subjected to high voltage pulses in a single-particle and single-pulse mode, in order to investigate the effect of electrical breakdown channel locality on particle breakage behaviour. The data confirm that the locality of electrical breakdown channel dominates the breakage response of particles. When a breakdown channel passes along the
axis of a particle, it generates a finer product and produces more cracks/microcracks on the
fragments. The electrical breakdown channel locality is controlled by the grains of minerals
with high conductivity/permittivity and their location in a particle under the identical machine
settings. The outcomes using the synthetic samples are helpful in understanding the breakage
behaviour of natural ore particles in electrical comminution. The research described in this
chapter was published in the *Mineral Engineering* in 2014 (Zuo et al., 2014b).

Chapter 5 proposes the development of a novel ore pre-concentration technique using high
voltage pulses. The technique utilises metalliferous grain-induced selective breakage, under a
controlled pulse energy loading, and size-based screening to separate the feed ore into body
breakage and surface breakage products for splitting of ores by grade. Four copper ore
samples were tested to demonstrate the viability of this technique. The research described in
this chapter was published in the *Mineral Engineering* in 2015 (Zuo et al., 2015b).

Chapter 6 establishes a model to predict impact breakage behaviour of HVP breakage product
according to its pre-weakening degree. The model can be used to calculate the energy
reduction in the subsequent impact breakage process due to the pre-weakening effect, and
indicates that the energy reduction by pre-weakening increases with an increase in the target
product fineness and the degree of pre-weakening, and with the decrease in feed particle size.
This part of research was published in the *Mineral Engineering* in 2015 (Zuo and Shi, 2015c).

This chapter also introduces an impact breakage characterization method using JK Rotary
Breakage Tester (JKRBT) to treat particles in wide size class. This method is capable of
giving ore breakage characteristic parameters similar to that obtained using the standard
JKRBT test, but with reduced time in feed preparation and product sizing. With the support
of the \( t_{10} \)-based model, this method can be used as an express method to determine ore
competence indicator \( A \times b \) value. Based on the wide-size JKRBT method, an online
automatic ore breakage characterization system was proposed. A paper presenting this part of
research was submitted to the *Mineral Engineering* (Zuo and Shi, 2015b).

Chapter 7 describes the investigation of ore particle breakage behaviour in a pilot scale HVP
breakage device. Three ores were tested using a single particle test method, by which the
behaviour of ore particle in HVP breakage was studied with regards to the probability of
breakage, product fineness and pre-weakening degree. The sample analysis method of pulse-
treated particles were reviewed and optimized. Effect of specific energy, particle size, pulse voltage, pulse discharge number, breakage response and device type on ore breakage behaviour in HVP breakage were investigated. A joint paper with SALFRAG manufacturer summarising the research outcomes described in this chapter has been submitted to the *Mineral Engineering* (Zuo et al., 2015c).

Chapter 8 presents the development of a model to describe the ore particle breakage behaviour in relation to specific energy. The model incorporates four sub-models of the same structure to predict four HVP breakage indicators, namely body breakage probability, body breakage product fineness, pre-weakening degree and metal recovery to screen undersize. A set of $t_n$-family of curves have been established for HVP breakage product. It was found that the data of various ore type and particle sizes obtained from HVP breakage tests of different testing conditions all fall on similar $t_n$-curve trend lines. These $t_n$-family curves can be employed to estimate the product size distribution from the predicted $t_{10}$ values by the HVP breakage model. A paper showing the research outcomes described in this chapter has been submitted to the Mineral Engineering (Zuo and Shi, 2015a).

Finally in Chapter 9 conclusions on the major research outcomes of this project are presented. The areas for further study and the major challenges to this novel technology are discussed.
Chapter 2   Literature Review

2.1 Introduction

In order to provide a starting point in the investigation of HVP breakage, the available literature on this area has been reviewed. The review begins with a summary of the pulse power technology and the theory of electrical breakdown. It was identified that there existed pronounced ore dependent variations that affect mineral liberation and pre-weakening by HVP breakage. Previous studies indicated that the locality of electrical breakdown channel have significant effect on the breakage response of particles. Therefore determinants of the path of electrical breakdown channel are reviewed. Pre-weakening and liberation are the two applications of HVP breakage technology. Hence the mechanism of disintegration and selective liberation of composite dielectrics are presented.

The literature also indicates that machine settings such as pulse voltage and energy have significant effect on the efficiency of HVP breakage. The effect of voltage and energy input on electrical breakdown and electrical disintegration are reviewed, as well as the efforts to optimize machine setting in electrical comminution. According to the work scope of this project, pre-weakening effect of HVP breakage is a main focus in this thesis. Correspondingly the concept of pre-weakening by HVP breakage is introduced and the ore-dependent variation of pre-weakening effect is summarized.

2.1 Pulsed Power Technology and Theory of Electrical Breakdown

In the past, dielectric breakdown occurred only as a result of gradual ageing of large isolator components in the power distribution industry. During service, a process known as “treeing” developed slowly along preferential paths between the electrical contacts. Only when the treeing process was completed between the electrodes did an unwanted discharge take place, resulting in an unwanted sudden explosion of the dielectric material.

In recent years, the appearance of pulse generator enabled electrical disintegration experiments to be conducted, in which rock is crushed through dielectric breakdown induced by high voltage pulses with the aim of creating preferential discharge path through the dielectric rock.
The method of HVP breakage was firstly proposed by the researchers of former Soviet Union (Vorobiev, 1958, 1961). The priority and significant contribution of the Russian researchers into the development of the scientific principles of electric pulse disintegration of materials has been recognized by the Russian Academy of Sciences and the authors of a monograph composed of a number of studies were awarded the P.N.Yablochkov Prize: “The transitional processes in the electric pulse technologies plants” (Usov et al., 1987).

Despite of the long history of this method, according to relevant publications, the commonly accepted understanding of electrical breakdown of solid dielectrics had not yet been provided (Andres, 2010). The result of electrical breakdown is decided by the characteristics of both high voltage pulses and composite solids. Understanding of this process required knowledge from multi-disciplines and is a complex case. (Andres, 2010).

2.1.1 The Essence of Pulsed Power

Pulsed power is a scheme where stored energy is discharged as electrical energy into a load in a single short pulse or as short pulses with a controllable repetition rate. Pulsed power is pertinent to applications where the load must be pulsed or performs better if pulsed.

Generally, the electrical power of the pulses is around one gigawatt \( (10^9 \text{ W}) \) and their energy content is of the order of one kilojoule or greater (Bluhm, 2006). The highest energy and power that can be reached in a single pulse are at present of the order of 100MJ \( (10^8 \text{ J}) \) and a few hundred terawatts \( (10^{14} \text{ W}) \) respectively (Bluhm, 2006). The corresponding voltage and current amplitudes are between 10 kV and 50 MV and between 1 kA and 10 MA, respectively (Bluhm, 2006).

In addition to its power and energy, a pulse is characterized by its shape, i.e., by its rise and fall times and by the duration and flatness of its plateau region. Typically, the overall duration of the high-power pulses lies between a few nanoseconds \( (10^{-9} \text{ s}) \) and a few microseconds \( (10^{-6} \text{ s}) \) (Bluhm, 2006). Some important pulse shape parameters are shown in Figure 2-1.

The pulse rise time is defined as the time it takes the voltage to rise from 10% to 90%. The fall, or decay, time can be defined in a similar way. Both the fall and the rise time of a pulse depend on the evolution of the load impedance, which is in most case varies with time. There is no unique definition of the pulse duration in the literature. Sometimes it is understood as the full width at half maximum (FWHM) of the pulse. However, for some applications, it is better to define it as the
duration at 90% of the peak amplitude. Flatness of the plateau region is an important requirement for driving some loads, for example Pockels cells.

A generator scheme for the production of high-power electrical pulses is always based on an energy store that is charged slowly at a relatively low charging power and, by activating a switch, is discharged rapidly. By this procedure, a large power multiplication can always be obtained. To achieve the desired power multiplication factor, this process can be repeated several times if necessary.

In addition to power multiplication, this scheme can simultaneously be applied to shape the pulse, i.e., to create the desired rise time and pulse duration. To optimize the energy transfer to a load, an impedance transformation may also become necessary. The components of a high-power pulse generator are sketched schematically in Figure 2-2.

It is obvious that pulsed-power techniques can be successful in those fields of application where they can improve efficiency or realize new function. What are the unique advantages of pulses
power? Its main characteristic is the very high peak-to-average power ratio. Therefore it can exceed critical value and nonlinear effects. For example, strong pulsed electric fields can irreversibly open the membranes of biological cells or lead to explosive electron field emission from metallic surfaces. The high peak-to-average power ratio can also suppress competing heating processes. Another set of benefits can result from the short pulse duration, which allows one to exploit the time domain (e.g., in radar and flash X-ray radiography) or to avoid competing processes (e.g., electric breakdown or heat losses).

Since World War II, the development of pulsed power has mainly been driven by military requirements, both for the advancement of pulsed-power-based weapons and for the evolution of new simulation and diagnostic tools.

Recent progress in the development of reliable and affordable components for pulsed-power systems such as long-lived high-voltage capacitors and new types of high-power semiconductor switches has created new interest in utilizing pulsed-power techniques for commercial and industrial purposes. In contrast to some military applications, economic considerations have the strongest impact on commercialization.

The various categories of pulsed-power applications are summarized in Table 2-1. These applications are based on either the production of strong pulsed electric or magnetic fields, the formation of intense radiation sources (electrons, ions, X-rays, etc.), or the creation of electric discharges. Some of the applications which are already successful are the defibrillator and the lithotripter in medicine, and the sterilization of food by intense X-ray pulses. The defibrillator and the lithotripter are based on pulsed electric fields and on pressure pulses produced by electric discharges, respectively.

<table>
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<tr>
<th>Pulsed-power driver</th>
<th>1 GW-100 TW</th>
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<tr>
<td></td>
<td>1 kJ-100 MJ</td>
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<td>10 kV-50 MV</td>
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<table>
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<tr>
<th>Foundation of applications</th>
<th>Pulsed electric and magnetic fields</th>
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<tr>
<td></td>
<td>Intense radiation sources (electrons, ions, X-rays, light, microwaves)</td>
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<tr>
<td></td>
<td>Electric (plasma) discharges</td>
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2.1.2  Pulse Generator

2.1.2.1  Energy Storage of Pulse Generator

There are two means to store electrical energy: capacitive method and inductive method. In the first case the maximum stored energy density can be estimated as 80 kJ/m$^3$ for a dielectric with $\varepsilon = 6$ and a breakdown strength of $0.78 \times 10^8$ V/m (oil impregnated paper). In the second case, take a thick ($r_o = 2r_i$, where $r_o$ is the outer radius of the cylindrical containment, and $r_i$ is the inner radius) copper-beryllium (yield strength of the containment material $\sum y = 1000$ N/mm$^2$) as example, the average energy density in the containment within the radius $r_o$ amounts to 39000 kJ/m$^3$. It can be seen that the energy density stored in a magnetic field can be about two orders of magnitude higher than that storable in an electric field.

The main components of generators with capacitive storage and inductive storage are different. The capacitive generator requires one or more closing switches which remain open during charging and hold the charging voltage. When the switches are closed, this generator achieves its power multiplication by current amplification. On the other hand, the inductive generator requires an opening switch, which is closed during charge-up, carrying a large current at this stage. When the charging is finished, the switch should open instantaneously and be capable of insulating the high voltage that is created. An inductive generator achieves power multiplication by voltage amplification. To keep the losses during charge-up small an inductive generator needs a high-current power supply. Due to the difficulty to produce reliable opening switches, capacitive storage is employed by most pulse generators even though the energy density of inductive storage is much higher.

The generators reported in literatures usually adopt capacitive storage. The energy density of capacitive storage can be calculated by equation (2-1):

$$\omega_e = \varepsilon \varepsilon_0 E^2 / 2$$  \hspace{1cm} (2-1)

here, $\omega_e$ is the electrical energy density; $\varepsilon$ is relative permittivity; $\varepsilon_0$ is vacuum permittivity while $E$ the electric field strength.
2.1.2.2 Marx Generator

In general, to produce pulses with larger amplitudes, Marx generator circuits can be applied. The basic circuit was developed by Erwin Marx in 1923. The fundamental principle of Marx generator is to charge several capacitors connected in parallel then to discharge them in a series configuration. Thus the output voltage becomes the charging voltage multiplied by the number of capacitors in the whole circuit. Figure 2-3 illustrates a simple Marx generator with unipolar charging and discharging capacitances. If the first switch is triggered or closed, the voltage at point $C$ is driven to the charging voltage $U_0$. Therefore, the voltage at point $D$ eventually becomes $2U_0$. At this instant, the second gap has a voltage potential of $2U_0$ across it. This process will proceed until all gaps have fired sequentially. At this time, the Marx generator is said to have erected. The time for such process is normally of the order of microsecond, or even of a smaller order.

![Figure 2-3 Marx generator circuit with unipolar charging through the resistors (RL)](cited from Bluhm, 2006, with minor revision)

2.1.3 General Structure of Electric Disintegrator

To initiate the discharge, the arrangement drawn schematically in Figure 2-4 is used. A capacitive energy storage device delivers a fast-rising voltage pulse of a few hundred kilovolts to a rod electrode touching the solid, which rests on a grounded plate electrode.

![Figure 2-4 Schematic illustration of a set-up to induce an electric discharge through a solid dielectric material (Bluhm, 2006)](cited from Bluhm, 2006)
Another kind of electrodes configuration is realized by setting both the high voltage electrode and the grounded electrode contact the solid at the same side (Figure 2-5). In this case the discharge can be carried through the solid and blow off pieces from its surface. By scanning across the surface with this pair of electrodes, one can remove material layers from large areas. The basic requirement of this configuration is that the high voltage breakdown strength between the electrodes is larger outside the body than inside. Application of this configuration includes scrape-off of concrete and drilling of rock.

![Schematic of the electrodes setup at the same side (Inoue et al., 1999)](image)

Ionization of gas in spark gaps, insulating the charged capacitors (cause a surge of conductivity in the switching devices of the pulse generator), is the usual method of the producing the pulses of electrical energy.

### 2.1.4 Budenstein’s electrical breakdown Theory

The early electron multiplication theories about the dielectric breakdown of solids, which were developed by Von Hippel and Fröhlich, were replaced by the Gaseous Model developed by Budenstein. Budenstein in his paper "On mechanism of dielectric breakdown of solids" (Budenstein, 1980) and in his other works (Smith et al., 1973; Budenstein, 1982) gave a very detailed description of the occurrence of electrical breakdown in solid dielectrics. He asserts that the breakdown of solids does not depend on the same electron multiplication mechanism that takes place in discharge tubes, but instead involves the development of capillary gaseous channels in dielectrics. These channels have a form of a tree and ”feed” off the solids. The channels are conductive and carry electrical current.

According to Budenstein (1980), the electrical breakdown process can be divided into four phases: Formative, Tree Initiation, Tree Growth and Return Streamer.
Chapter 2 Literature Review

The following sequence illustrates the whole process of dielectric breakdown of solids. Assuming good electrical contact between the electrodes and the rock specimen, free charges within the rock will polarize according to the electrical field applied. The rock (or dielectric) is intact and its insulation properties are undisturbed.

In formative phase, local excited states are produced in the polarized dielectric, as illustrated in Figure 2-6:

Figure 2-6 Formative phase of polarization (Le Sueur, 1995)

In the following Tree Initiation phase (Figure 2-7), local field enhancement are created at bond defects at the anode, and breaks intra-molecular bonds, results in vaporization of the solid and generation of a pattern of thin (~1μm) capillaries (treeing starts).

Figure 2-7 Field enhancements during initiation phase (Le Sueur, 1995)
The trunks of the tree formation are charged with ionized material which will later grow into the plasma channel.

The next phase is Treeing (or Tree Growth phase, see Figure 2-8), in which capillaries develop in the direction from anode to cathode with supersonic velocity \((10^6 \text{ ms}^{-1})\). In these capillary channels the energy of the pulse does not dissipate by heat conduction, sound waves or fracturing solids during the propagation of channels. The small loss of energy takes place because of luminosity of channels.

![Figure 2-8 Treeing and luminance produced (Le Sueur, 1995)](image)

Luminescence in this phase is starting due to treeing into the dielectric material from anode defects. The insulation properties are still dominant, but the physical properties of the solid matter (i.e. the particles) are changing.

The last phase (Figure 2-9) of dielectric breakdown is signalled by “return streamer”. In this phase, as one of the branches of this tree reaches the opposite surface of dielectric, this branch will undergo a rapid rise of conductance and develop into a plasma channel with very high conductivity. Other branches that fail to pass across the solid will terminate and have no effect in this phase. During this process the diameter of the complete conductive channel increases from a few micrometres to hundreds of micrometres. As soon as a conductive channel with ionized material is created between the anode and cathode on opposite sides of the test material, the insulating (dielectric) properties fail. The plasma channel expands rapidly with increase in diameter of 50 fold and of conductivity by a factor of \(10^4\), leading to a drop of resistance by a factor of \(2.5 \times 10^7\). As a
result a streamer surge of negative electricity from cathode to anode (the so called return streamer) is created in which current starts to flow. The current creates joule heating in the plasma, which creates pressure inside the return streamer and results in the complete electrical breakdown of solids. The temperature of plasma rises up to $4.5 \times 10^4$ °K. Due to mechanical confinement, the pressure creates tensile fracturing. The strength of the grain (particle) boundaries, as well as the material’s micro-structure with regard to conductive paths and resistivity, will determine where the discharge takes place.

The amount of charge available and its rapid release from the energy store will determine the extent of plasma heating and damage. Also, the larger the contact area, the more channels can be created simultaneously.
As a consequence of above four stages of dielectric breakdown, the dielectric solid breaks under the high mechanical forces generated by expanding plasma (Destruction Phase, Figure 2-10). As the dielectric (rock) expands, the contact area between the electrodes and the rock changes and this may limit the time available for the transfer of energy into the plasma channel.

The velocity of the growth and radial expansion of the plasma channel is faster than the velocity of sound. The density of plasma in the tree channels during this period is that of solids. Andres (1995) pointed out that the physical effect of the fast and massive increase of temperature in the plasma channel is not the collisional Joule heating implied by the Budenstein's description. The most probable cause of sudden release of energy is the acquired mobility of positive ions in the channel completed by the penetration of the smaller in size electrons. The surge of heat, sound and light at this stage of electrical breakdown is the result of recombination of charges.

Works of Budenstein and his group provide a good understanding of the phenomenology of electrical breakdown in solids. However, in the technique of explosive disintegration of rock and other brittle solids the event of electrical breakdown initiates only the initial stage of the process and does not necessarily result in fragmentation.

Using the chronograph based on electro-optical transducer, the Russian researchers get quality spatial-temporal images of pulse breakdown in optically transparent solids dielectrics (Vershinin, 2000). But literature reviews indicated that present understanding of dielectric electrical breakdown is not sufficient to explain the mechanism of mineral ores liberation in electrical comminution (Andres, 2010). Further physical research is required to reveal the process of electrical breakdown of composite solids and minerals (Andres, 2010). Up to now the understanding of electrical breakdown of solid matter is still limited to a narrow range of dielectric types, such as homogeneous plastic insulation in particular, of which the damage was accumulated in a relatively long period. This is distinct from the single electrical discharge caused breakage of composite mineral ores in electrical comminution (Andres, 2010).

In this respect there is a similarity between states of knowledge of mechanical and of electrical disintegration. In both techniques understanding of the mechanical and electrical failure of solids is still not matched by sufficient knowledge of the following process of the fragmentation of material.
2.1.5 Role of Gas-filled Pores in the Electrical Disintegration of Dielectric Solid

The mechanism that electrical breakdown of the heterogeneous dielectrics is initiated by the enhancement of electrical field along the boundaries of inclusions and matrix was questioned by Lisitsyn et al. (1998), who suggested and experimentally demonstrated the important role of the breakdown of gas-filled pores inside the solid in the process of electrical disintegration (all natural rocks are porous).

They argued that due to the high electrical strength of solid, very high electrical field strength is required to initiate breakdown, which is much higher than electrical field inside the solid in electrical comminution, even it has been enhanced by two or three times by polarization. Inexplicably, electrical breakdown occurs in the order of $10^2$-$10^3$ ns in electrical comminution at relatively low electrical field strength (Lisitsyn et al., 1998). This cannot be solely explained by the existing breakdown theory of either solid or liquid (Lisitsyn et al., 1999a). Comparative experimental results shown that while all dry granite or tuff samples were broken down by electrical disintegrator, there was no destruction events in water-saturated sample in which the air in the voids was replaced by water.

From this point of view, the sequence of events during the development of the breakdown channel into the solid dielectric in the applied field is described below (Lisitsyn et al., 1999a).

All the natural rocks are non-uniform composite consisting of grains, and include gas voids and solid inclusions with low electrical strength. When the potential applied on an electrode with a diameter of several mm is in the order of $10^2$ kV, the electrical field strength at the tip of the electrode is about hundred to several hundreds of kV/cm, which is enough to breakdown the air voids of the dielectric solid near the electrode (Lisitsyn et al., 1998). This process is similar to the accumulated partial breakdown at the defects of insulators (Lisitsyn et al., 1998).

The hypothesis that electrical breakdown of dielectric solid is initiated by the breakdown of air voids is described below:

“*The flashover channels are similar to the streamers in air breakdown and propagate along the surface of the solid dielectric. Since they have low diameter (several mm according to framing photographs) the electric field strength at the tips of streamers remains high until the low-voltage*
arc build-up. This electric field is surely comparable to the initial electric field near metal electrode.

After high electric field causes the breakdown of the inclusions, displacement current flowing through the breakdown plasma heats the latter. Very fast heating of the medium in the inclusion results in the increase of its internal pressure. Since the process is very fast and its time scale is comparable with voltage rise time (usually tens to hundreds ns) this is like micro-explosion in the bulk of a solid dielectric. This micro-explosion generates the pressure pulse that destroys the dielectric. However, estimation of the local displacement currents for real rocks seems to be impossible because their structure is irregular. Displacement current is determined by the ratio of capacitances, which is dependent on the location and size of a void. In the case of a crack-like void its orientation becomes important, but it is an uncontrollable parameter in experiment.

Another mechanism of the destruction (and probably the most important) can be the breakdown of gas voids having contact with the surface as cracks. The total breakdown current can flow through these voids after an arc build-up. In the case of the closed void only displacement current can flow through it, and the charging process of the void limits current amplitude.” (Lisitsyn et al., 1999a).

2.2 Electrical Breakdown Channel Paths

2.2.1 Electric Discharge Paths in liquid-solid System

In electrical comminution the composite solids are always immersed into liquid medium with high electrical breakdown strength such as transformer oil and water, in order to ensure the preferred discharge path through the solid rather than through the electrical weak medium air (Andres and Bialecki, 1986). Figure 2-11 below shows two options for the discharge path. If the discharge passes through the water instead of through the rock, inefficient comminution takes place as only an external shock wave is sent towards the rock (Electro-hydraulic disintegration, EHD).

If, however, at a sufficient high voltage (depending on the type of the dielectric) and very steep rise rate of the high-energy pulse, and the electrodes are located favourably close to the rock, the dynamic breakthrough strength of the rock becomes lower than that of the water (Andres and Bialecki, 1986). For this reason, the preferred discharge path would be through the rock and not through the water. This is referred to as Electro-dynamic disintegration (ED). In this thesis, electrical comminution refers to ED only.
2.2.1.1 Role of water in electro-dynamic disintegration

A discharge through the solid will occur if its breakdown voltage is smaller than the applied voltage and if the breakdown strength of any other path outside the solid is larger. A necessary condition for this is that the local electric field inside the solid body exceeds the breakdown field, while it does not in the dielectric surrounding it. This can always be accomplished if the solid body is embedded in a dielectric liquid whose breakdown strength is larger. A further possibility is to concentrate the electric field in the solid and to lower it outside. This requires a liquid with much larger dielectric constant than that of the solid. Finally, the path length between the electrodes through the liquid could be made much larger than the path length in the body. For example, if the solid body is spherically shaped, the shortest path-length outside the body is $\pi/2$ times larger (Bluhm, 2006).

A suitable dielectric liquid is water, whose breakdown strength increases strongly if the rise time of the voltage pulse is reduced (Andres et al., 2001b). This is shown schematically in Figure 2-12, where the breakdown field strength of water is compared with that of a solid material, and of air.
It can be seen that at short voltage rise times (line 1), the breakdown strength of water becomes larger than that of the solid material ($V_w > V_s > V_a$). The intersection (line 3) point of field-time characteristics for water and solids corresponds to the time interval of 500 nanoseconds, so the nanosecond rise of the field is necessary for penetration of electrical charge in the solid. As the voltage rise time increases (line 2) the breakdown strength of solid becomes larger than that of the water ($V_s > V_w > V_a$). Hence, breakdown would occur in water prior to the solid. The breakdown curve for air is presented as well for comparison purpose. The breakdown field of air is considerably lower than that for water or solids (about 3000 kV/m at standard atmospheric pressure) (Tipler and Meyer-Arendt, 1987). Therefore electro-dynamic process is impossible to take place in air.

It is well known that the ‘intrinsic’ breakdown field strength of solid dielectrics is higher; therefore it is difficult to understand why the breakdown strength of a liquid can be larger than that of a solid material and this “could not be satisfactorily explained solely on the basis of the difference in the ionic and electronic types of conductivity of those matters” (Andres, 2010, p33).

Water not only has good insulation strength if it is stressed for a short period of time, but also has a very high dielectric constant and thus pushes the electric-field lines into the solid material, which, in general, has a much lower dielectric constant. Of course, this effect occurs only if liquid and solid
materials between the electrodes distributed as a layer. However, this is the most frequent situation in an operating discharge vessel filled with pieces of material to be fragmented.

In conclusion, water is deemed the most commercially viable medium in electric disintegration. Transformer oil and other liquid insulators have very high resistivity and are more efficient medium for electrical comminution; however, they are obviously not appropriate for many technological applications, especially for recycling and mineral processing.

2.2.1.2 Electric Discharge Paths in liquid-solids System

The position of the electrical field concentration in electrical comminution processing chamber depends on the interaction of electrical properties of liquid medium and the disintegrating solid (permittivity and electrical conductivity). Since the breakdown channel takes place along the areas of maximum electrical field, the location of the breakdown path in electrical comminution is decided by the combination of electrical properties of liquids and solids (Andres and Timoshkin, 1998). The breakdown channel of liquid has a pattern different from that in solids. If the electrical breakdown occurs in liquid, a number of streamers with ionized gas will be initiated from a small bubble at the same time and then move toward the opposite electrode with different velocities (Andres et al., 1999). Then the plasma channel enlarges immediately and generates strong shock wave of liquid. As the front of the shock wave impact the solid, the solid suffers from fragmentation (Andres et al., 1999). In the case of field enhancement on the interface between solid and water, the disintegration is caused by external shock waves. The plasma channel only passes through this material when the maximum electrical field concentrates inside solid dielectrics.

The distribution of electrical field and the location of the breakdown path in the solid/liquid system had been investigated by Andres et al. (1999) by solving the Laplace equation for the field potential.

In Figure 2-13 and Figure 2-14 the field distribution for a spherical dielectric solid with permittivity $\varepsilon_p$ and conductivity $\sigma_p$ immersed in a liquid with permittivity $\varepsilon_m$ and conductivity $\sigma_m$ is shown.

The case of $\varepsilon_p, \sigma_p \gg \varepsilon_m, \sigma_m$, is shown in Figure 2-13. In this case the maximum electrical field strength is $E_m=3E_0$ (where $E_0$ is applied field) and the most possible path of plasma channel is through the solid-liquid interface, rather than through the dielectric solid (Andres and Timoshkin, 1998). When $\varepsilon_p, \sigma_p \ll \varepsilon_m, \sigma_m$, the electrical field will concentrate inside the dielectric solid with maximum field strength of $E_m=3/2E_0$, and the breakdown path will pass across the solid as given in
Figure 2-14 (Andres and Timoshkin, 1998). The electrical disintegration process will be most effective in such condition.

Figure 2-13 Field distribution for spherical particle in a continuous medium \((\varepsilon_p, \sigma_p >> \varepsilon_m, \sigma_m)\); \(E_o\) is applied field (Andres and Timoshkin, 1998)

Figure 2-14 Field distribution for spherical particle in a continuous medium for the case \(\varepsilon_p, \sigma_p << \varepsilon_m, \sigma_m\) (Andres and Timoshkin, 1998)

The possible breakdown path in liquid/solid system with plane-plane electrode configuration is shown in Figure 2-15.
2.2.2 Electric Discharge Paths inside Composite Solids

In electrical comminution, mineral constituents are separated from the matrix along their boundaries (Andres et al., 2001a). In anisotropic semi-conductive solids like rock, the direction of the tree trunk (the principle conductive channel, bridging the electrodes) is not as straight as in the manmade isotropic dielectric material, and is affected by the mechanical integrity of rock and by inclusions of different mineral aggregates (Andres, 1995).

Most mineral ores are anisotropic composite dielectrics, of which the location of splitting breakdown path are affected by the properties of different mineral components, including permittivity, conductivity, shape, orientation in electrical fields, the distribution and the magnitude of the electrical field (Andres et al., 1999).

In composite solids like mineral ore, electrical breakdown is initiated over the boundaries of minerals which have different permittivity and conductivity. In such boundaries, substantial enhancement of electric field will be caused by the electrostatic polarization, which will initiate and attract plasma channel. The larger the difference of electrical properties of different minerals is, the easier the happening of electrical breakdown is (Figure 2-16).
Electrical comminution is such a process. In this process, the solid is immersed in water, and placed between top electrode and ground electrode. A high voltage pulse is discharged onto this solid to initiate electrical breakdown inside ore particle, generating strong tensile force to disintegrate the particle. The diagram of this process is shown in Figure 2-17.
2.3 Mechanism of the disintegration and selective liberation of composite dielectrics in HVP breakage

2.3.1 Mechanism of disintegration of composite dielectrics in HVP breakage

Electrical disintegration of solid dielectrics is a random process that is brought about by the explosive expansion of plasma.

With sufficient energy and appropriate voltage and rise time, high voltage pulses is able to electrical break down the solid dielectric. During this process electrical current propagates through the dielectric solid and gasifies the substance of the dielectric solid (Andres, 1989). With continuous energy input the evaporated substance keeps expanding until the pressure exceeds the tensile strength of the solid and causing explosion to disintegrate it (Andres, 1995). The non-equilibrium plasma channel also contributes to this explosion possibly (Andres, 1989). Plasma is generated by the field ionization process in direct transfer of solids into ionized gas in the channels of the plasma streamers. The displacement current of charges during the ionization process and flow of charges through the breakdown channel generate ionized gas at a temperature in the order of $10^4 ^\circ$K.

Thus, an understanding of the rock behavior under tension can be beneficial in the analysis of electrical disintegration process.

In the electrical disintegration of composite dielectrics two distinct processes contribute to fragmentation of the solids (Andres et al., 2001b). One is radial expansion of plasma from the center of the channel at pressures that exceed the tensile strength of the material, compressive waves being generated over the walls of the channel by rapid (explosive) expansion of the channel of discharge. The compressive stress, produced by pulses, is usually not sufficient to crush the material but is able to produce disintegration via tensile radial cracks in the areas adjacent to the channel. The other, synergistically occurring, tensile stresses that contribute to the fragmentation process are a reflection of the pressure waves from inclusions whose acoustic impedance is different from that of the matrix material. Reflection of the pressure waves also takes place from the interface of the solids with the external medium (water), but these interfaces are usually located further from the channel of discharge and reflections from them are weak, generating only fine fissures.

Figure 2-18 shows samples of kimberlite and granite rocks electrically disintegrated by a single pulse, with characteristic radial cracks.
2.3.2 Mechanism of selective liberation of composite dielectrics in HVP breakage

Bluhm (2006) summarized three effects of selective liberation at material or grain boundaries in electrical disintegration.

The first effect of selective liberation is caused directly by the discharge channel. At inclusion whose dielectric properties are very different from those of the matrix, the electrical field strength can be maximized and attract the streamers to the inclusion, where it can continue propagate along the grain boundaries. This is presented in Figure 2-19 (a), where a conducting sphere is located inside an insulating matrix. In this scenario the separation of the inclusion from the matrix is caused directly by the breakdown channel.

Figure 2-19 Mechanisms by which components in a composite material can be liberated
(a) Metallic inclusions or inclusions with a high dielectric constant can attract the discharge track. (b) A crack propagating from the discharge channel into the solid can branch around an inclusion if the mechanical properties of the inclusion are different from those of the matrix. (c) A compression wave can be transformed into a tensile and shear wave by reflection and refraction at an inclusion and separate it from the matrix. (Bluhm, 2006)
The second effect starts from the cracks created in the immediate surroundings of the breakdown channel (Figure 2-19 (b)). The pressure generated by the expansion of shock waves always exceeds the tensile strengths of materials, which leads to the formation of cracks. If cracks have been formed in contact with the breakdown channel, channel products can penetrate into them and exert a force on the crack walls. The behavior and intensity of crack formation are determined by the rate of energy deposition in the channel and by the properties of the material. Brittle materials show a large number of cracks in the radial direction with few millimeters in size around the breakdown channel, created in the early stage of the discharge. In the later phase, a number of radially propagating cracks around the channel correlate with the rate of energy release (Semkin et al., 1995). However, the number of cracks reaching the material surface strongly depends on the total energy released from the discharge. The reason for this is the existence of increased mechanical stress at the boundary of an inclusion. Stress waves reflected from inhomogeneity or inclusion can interact with the growing crack before the inclusion is reached (Volodarskaya et al., 1971; Guz, 1974; Martynyuk and Sher, 1974; Sher, 1974). If the crack hit the inclusion they can branch, depending on the angle of incidence, as schematically indicated in Figure 2-19 (b), and separate the inclusion from the matrix.

The third effect leading to separation at the interface between an inclusion and the surrounding medium is connected with the action of an incident compressive wave launched from the discharge channel (Baron and Matthews, 1961; Pao and Mow, 1963; Achenbach et al., 1970; Kanel et al., 1996). This is illustrated in Figure 2-19 (c). Initially, due to the expansion of breakdown channel the generation of shock wave later develops into a compressive wave. It has been shown (Achenbach et al., 1970) that a compressive stresses wave is converted into a tensile wave after refraction and reflection inside an inclusion. Complete separation over the entire interface between the inclusion and the matrix was observed at sufficient high shock wave pressures.

In addition to the direct fragmentation caused by the completed breakdown channel, (Andres et al., 2001b) also introduced a kind of selective liberation caused by partial breakdown channels. The propagation of the filaments of plasma around mineral or metallic inclusions into the matrix is shown diagrammatically in Figure 2-20. These filaments are the result of partial breakdown of the solids during development of the ‘tree’. The explosive disintegration of composite dielectrics takes place when the pressure of the expanding plasma in the channel of discharge exceeds the uniaxial tensile strength of material along the radial lines in the vicinity of the channel of discharge and shatters a solid fragment. Development of the plasma streamer, bridging the high voltage and the earthed electrodes, is accompanied by development of a net of partial discharges not bridging the
earthed electrode and becoming extinguished in the bulk of solids. These partial breakdowns, localized on the interface of inclusions with different electrical parameters, induce a system of fine cracks over their boundaries. They are the main cause of the efficient liberation. During the explosive disintegration of the rock fragments the splitting takes place along these fine cracks. The velocity of propagation of the shock waves generated by the expansion of plasma exceeds that of shock waves generated by high-energy chemical explosives. A certain amount of the disintegrated particles is produced by tension resulting from the reflection of the compressive shock waves from the interface of inclusions with different acoustic impedances and from the interface with the liquid medium.

![Figure 2-20 Plasma streamers generated around inclusions in rock (Andres et al., 2001b)](image)

In highly porous and weathered rocks and slags the preferential disintegration is produced primarily by the breakdown of air and takes place at lower electrical fields and pulse energy than is the case in monolithic solid aggregates. Sandstone is an example of such highly porous materials (Andres et al., 2001b).

### 2.4 Energy Efficiency of Electrical Disintegration

The theoretical energy efficiency of electrical disintegration is presented in the monograph by Bluhm (2006).

With the notable technological progress, the efficiency of charging the capacitive energy storage device $\eta_1$ can certainly exceed 0.95. Tap water with a relatively low conductivity is chosen as the dielectric liquid for most industrial applications. For most cases, as salt from fragments dissolves in water, the conductivity would rise significantly during the process, leading to electrolytic current
losses occur before breakdown. By controlling the water quality and the filling fraction of solid, the losses can be reduced to 10% so the liquid medium efficiency $\eta_2$ reaches 0.9.

In an optimized configuration, there is a 0.8-0.9 probability ($\eta_3$) that a pulse will lead to a discharge in the solid. Only a fraction ($\eta_4$) of the available electric energy is deposited in the discharge channel while the rest is wasted in the generator in the form of ohm and dielectric losses. Experience indicated $\eta_4$ can approach 0.65-0.7. Another form of energy loss is attributed to the section of arc channel which arise in the surrounding liquid between electrodes and solid, since it is less effective than the section of arc in solid. The efficiency coefficient accounts for this energy loss approximates 0.9. Taking all the efficiency coefficients mentioned above and deducting the internal energy of the channel products, losses and the energy expended in deforming the solid, the final proportion of input energy used to create new surfaces is 0.004-0.32%. This value is in the same order of the energy efficiency for mechanical comminution equipment (0.002-1%). In conclusion, electrical disintegration is energetically comparable to mechanical fragmentation method.

The opinion and factual data used in the monograph by Bluhm (2006) are given in the thesis for the degree of Doctor of Philosophy by Tsukerman, 1970 in former Soviet Union and publications in Russian by Burkin et al. (1975) and Semkin (1989), which are summarized by, Semkin et al. (1995) and Usov and Tsukerman (2000).

2.5 Effect of Machine Setting on HVP breakage

2.5.1 Effect of Voltage and Energy Input on Electrical Breakdown and Electrical Disintegration

Electrical breakdown of gases, liquids and solids is usually associated with the surge of electrical field affecting the materials. Electrical breakdown changes the structure of matter in the affected conductive path and drastically increases its conductivity. The minimum electrical field required by the breakdown of rocks with irregular shape and fractured structures is 10 kV/cm. However, in the electrical comminution of rock and other brittle solids the event of electrical breakdown initiates only the initial stage of the process and does not necessarily result in fragmentation. At a certain level of energy, specific to the particular material, electrical breakdown is accompanied by explosive destruction of structure and by loss of cohesion in liquids and solids. The parameter characterizing the electrical breakdown is the critical electrical field.
Not all electrical breakdowns can induce plasma explosion and mechanical disintegration. Electrical breakdowns which are able to initiate plasma explosion and mechanical disintegration have a distinct dynamics from pure electrical breakdown and will be accompanied by visible traces sometimes. Studies of electrical disintegration of rock by electrical pulses showed that electrical breakdown as well as explosive disintegration of rock is characterized not only by the magnitude of critical electrical field, but also by pulse energy and by the duration of the field across the rock (Andres and Bialecki, 1986; Andres, 1989).

There could be three forms of discharge of electrical pulse through the solid dielectrics (Andres et al., 2001b). At relatively high conductivity of the disintegrating dielectrics breakdown and explosive fragmentation of the solids do not take place. The energy of the pulses is discharged by conduction through the dielectrics during slow pulses (of millisecond order). Only partial breakdown takes place when the energy is insufficient for disintegration and only thin channels (some micrometers wide) are created in the solids. Complete and explosive electrical breakdown occurs when the potential of the pulses exceeds the dielectric strength of the solids and the pulse energy is sufficient for the explosive expansion of plasma.

Extensive series of tests on the influence of the electrical field and pulse energy on electrical breakdown and electrical disintegration of black fine grained South African granite revealed the different results of electrical breakdown of solid (Andres, 1989). The experimental results are presented in a system of the iso-capacitance graphs of the specific energy versus the electrical field (Figure 2-21). The variable parameters of tests were the charging voltage, ranging from 100 to 450 kV, and the total capacitance of the Marx type pulse generator, ranging from 1.0 to $10^6$ nF. The figures of specific energy and of the electrical field are based on the charging parameters of the pulse generator while the parameters causing breakdown of solids were diminished by losses in the spark gap and were smaller than those shown in the chart. Because the real consumption of energy in the commercially operating installation will inevitably include the losses in the spark gaps of pulse generators and in other elements of circuitry, it is thus reasonable to take account of the total consumption of energy in electrical disintegration. In this series of tests the rise time of voltage was between 60-90 ns (Andres, 1995).

The responses of granite sample for electrical pulses were categorized in three types (Andres, 1989):

- Conductive transfer of energy similar to that in liner conductors,
- Pure electrical breakdown, without mechanical disintegration,
Electrical breakdown causing explosion and fracture.

In Figure 2-21 the pulses, corresponding to the points, marked by black triangles and concentrated in the area below the curve 1, represent passage of electrical current without electrical breakdown. This process is the same to electrical current transfer in linear conductors (Andres, 1989).

In the area of chart between curves 1 and 2 (the pulses marked by black circles), pure electrical breakdown was generated with very low probability of disintegration. When specific energy of pulses exceeds a critical value (30 J/cm) electrical breakdown takes place in a relatively low field of 25 kV/cm, while pulses with lower energy cause breakdown in higher fields. For instance, pulses with energy below 5 J/cm caused breakdown in fields in excess of 50 kV/cm.

![Figure 2-21 Energy of pulses per cm of conductive path versus electrical field, generated in samples of granite (Andres, 1989)](image)

In electrical breakdown a permanent damage to a rock structure is produced and a low resistive path through it is created. Mechanical strength of the whole rock is only partially affected by the presence of partial breakdown channels and a main breakdown channel. To initiate a mechanical breakage a higher mechanical stress has to be generated by an electrical breakdown and subsequent rapid discharge process.
Pulses marked by the white triangles beyond curve 2 of the chart lead to the electrical disintegration of solids with very high probability. It is important to note that the minimal consumption of energy takes place at the optimal field for this material of 68 kV/cm.

The breakage degree of electrical comminution product increases with the pulse energy. Beyond the optimum value the efficiency of disintegration does not increase with the increase of electrical field strength.

![Figure 2-22 photograph of the cavities in the sandstone sample resulted from electrical disintegration (Andres, 1995)](image)

Another expression of rock breakdown with mechanical disintegration is the production of cavities on the rock surface near positive electrode (electrodes are placed in the opposite side, rather than at the same side for drilling). In such event the even electrical breakdown is accompanied with mechanical disintegration, the discharge energy is still insufficient so that the fragmentation process failed to develop through the bulk of rock thoroughly. An example is given in Figure 2-22. But this process is not yet fully understood.

### 2.5.2 Optimization of Machine Setting in Electrical Comminution

The efficiency of electrical comminution is highly dependent on the match of parameters of pulse generator and its circuitry, with the electrical and mechanical parameters of the mineral ore to be treated (Andres, 1995). Optimization of parameters of pulses on the basis of these conditions is essential for the competence of electrical comminution.

The portion of energy, generated, stored and released by the pulse generator is characterized by its voltage and by the amount in Joules. The main parameters of the circuitry of the pulse generator
affecting the efficiency of electrical comminution are its inductance and impedance. At the
discharge of pulse generators across the rock a drop of voltage and loss of a considerable portion of
energy takes place. The breakdown of gas or liquid in the spark gaps of the switch of pulse
generator has a similar mechanism to the breakdown of rock and is accompanied by emission of
energy in the form of Joule heat, light and sound. Martin et al. (1993) suggested that the share of
energy dissipated in spark gaps is \( E = 0.25 V_{peak} I_{peak} t_r \). (Here \( V_{peak} \) and \( I_{peak} \), are peak voltage and
current in the spark gap during the resistive time \( t_r \)).

Efficiency of electrical disintegration of mineral ore is not only affected by the drop of the input
voltage and energy losses in the circuitry of pulse generator, but more important is the rate of the
buildup of the electrical field across the solid, which is dependent on the total inductance of the
circuitry of the pulse generator.

The occurrence of the electrical breakdown event in rock is possible only beyond a certain rate of
the energy delivery. For instance the so called “switching pulses” with the rise time of voltage in
order to 250 μs is impossible to generate the electrical breakdown of rock, regardless of their
voltage and energy. On the other hand, the “lightening pulses” with rise time in order of 1.0 μs are
suitable to initiate electrical disintegration.

The efficient pulses are characterized by a steep front of the voltage wave form. Electrical pulses
with rise time in the range of 20-50 ns are available from pulse generators of the Marx type, based
on low inductive capacitors, while pulses with the rise time in the range of 300-500 ps are usually
generated in pulse generators based on coaxial cables.

The significance of the steep fronted pulses for efficiency of electrical disintegration has two
aspects. Electrical breakdown of rock only takes place when the applied field exceeds the dielectric
strength of the rock. The full voltage pulse might not reach the rock because some of the charges
delivered to the electrodes may dissipate before the voltage attains this value, generating a field
exceeding the dielectric strength of a rock. And the energy, expended before the breakdown, would
be lost.

The time scale of the decay of charge due to the leakage of current during the buildup of the
electrical field depends on conductivity and permittivity of the surrounding medium and is
proportional to \( \varepsilon_r \delta_m / \delta_m \) (Culverwell, 1993). Here \( \varepsilon_r = 8.85 \times 10^{-12} \) F/m, \( \varepsilon_m \) is permittivity and \( \delta_m \) is
conductivity of the surrounding medium. In river water with \( \varepsilon_m = 80 \) and \( \delta_m = 10^{-2} \) siemens/m the
voltage rise time ensuring the breakdown of rock must be below 100 ns, while in sea water with \( \delta = 100 \) siemens/m, rise time has to be below 100 ps.

The other necessary condition on the rise time of voltage is the suitable time scale of generation of heat in the conductive channel inside the rock versus the loss of heat via thermal conduction through the walls of this conductive channel.

2.6 Pre-weakening by High Voltage Pulse

2.6.1 The Application of Pre-weakening by High Voltage Pulse

The studies of ore weakening by high voltage pulses were started in 1971 (Ignatiev et al., 1971). The basic results of these studies were presented in the Russian publication by Usov and Rakaev (1989) and in detail in the book by Rakaev (1989) and Kurets et al. (2002).

Comparison of the energy balance in electric pulse and mechanical comminution had been given by (Usov and Tsukerman, 2000), as well as in the PhD theses of former Soviet Union (Tsukerman in 1970 and Sjemkin in 1989), according to (Kurets et al., 2002).

Andres and Bialecki (1986) described “softening” of pegmatite matrix rock as a pre-conditioning for the subsequent liberation of emeralds. In this study, after the discharge of high voltage pulse, the emerald-bearing pegmatite particles became soft and plastic because of the destruction of cohesion in the area of pre-existing fractures. The product was reported to have a 400 - 500% increase in cutable emeralds.

Detailed study had been conducted by Wang et al. (2011) to evaluate the pre-weakening effect of electrical comminution on ore particles. In this study, the pre-weakening effect of high voltage pulse on ore particles was analyzed quantitatively. High voltage pulses with relative small specific energies (between 1 and 3 kWh/t) were applied to damage or lightly break particles with minimal fines generation. Apart from solely size reduction effect, cracks and micro-cracks were created in the HVP breakage product, thus the energy consumption in the downstream grinding process can be reduced. HVP breakage tests were conducted with a number of ores (such as gold, gold/copper, lead/zinc, platinum, industrial rocks, etc) at specific energy levels ranging between 1 and 3 kWh/t. The results indicated that the ore competence indicator \( A \times b \) value can be changed by electrical comminution for 9-52%. Through Bond ball work index test, the decrease of real energy
consumption was also predicted as up to 24%. The positive energy balance of the pre-weakening approach has made it an attractive alternative to existing comminution practices. X-ray tomography was performed to qualitatively assess the induced cracks and microcracks during the process. Figure 2-23 shows an example XCT scan included for ores from Mines A and D, which showed the strongest weakening (Wang et al., 2011).

![Two ore particle showing extensive cracking](image)

Figure 2-23 Two ore particle showing extensive cracking (Wang et al., 2011)

### 2.6.2 Influence of Mineral Properties on the Pre-weakening Effect of Electrical Comminution

In the work of Wang et al. (2011), comparative testing of the product residual hardness of electrical comminution and conventional crushing were conducted with four ore samples at specific energy 1-3 kWh/t. It was found that, across all fragment size ranges, almost all ore samples collected from the selFrag products of the four kinds of ore samples are weaker than the mechanical breakage product, as given in Figure 2-24.

Thus one of the keys to achieve more benefits from pre-weakening is to determine economical balance between the energy cost in electrical comminution and saved in downstream conventional comminution.

Another interesting observation from Figure 2-24 is that while the increase of $A \times b$ values decreases with increased broken product size for ore samples from Mine A, B and C, the ore samples from
Chapter 2 Literature Review

Mine D presents a contrary trend, reflecting the influence of ore type on the relation of hardness reduction to fragment size.

![Graphs of ore softness vs fragment size for different mines.](image)

Figure 2-24 Product ore softness in relation to size of fragments produced by selFrag in comparison with the conventional crushing for samples collected from the four different mines, error bars indicating 95% confidence intervals (Wang et al., 2011)

The benefit of pre-weakening on industrial comminution was evaluated through the measurement of Bond rod mill Work Index (BRWI) of product treated by electrical comminution and mechanical breakage. The pre-treatment of electrical comminution was conducted at a specific energy range 1-3 kWh/t except the ore from Mine C. Significant reductions in BRWI up to 24% was revealed by the result, though the relative reductions were much less than these shown by $A \times b$ values. In addition, Mine B ore sample exhibited marginally reduced Work Index and Mine C ore appeared slightly harder subjected to electrical comminution than to mechanical breakage.
Chapter 2 Literature Review

2.7 Research gaps and hypotheses

As indicated in the above literature review, fundamental mechanisms of solid breakdown by high voltage pulse had been well studied regarding the physical understanding of electrical breakdown and its consequential effects. But unfortunately these studies were conducted from the point view of physicist, rather than completed by mineral engineers under the framework of ore breakage characterization.

Particularly, there is a lack of understanding of the selective breakage behaviour of ore by high voltage pulse and its dependence on ore properties. Literature review suggests that there is a mechanism of selective fragmentation happening during the HVP breakage. A number of researchers had found that HVP breakage generated a higher percentage of liberated particles and a lower percentage of fine material than those obtained by mechanical comminution. Preferential breakage along the grain boundaries of minerals at high electrical field intensity has been found to be one of the major causes. However, ore particle behaviour in selective HVP breakage has not yet been well revealed, especially the difference of size reduction degree between different ore particles. Investigation on this aspect is not only helpful to better understand ore particle behaviour in pre-weakening treatment by high voltage pulse, but also offers great chances to explore more potential applications of HVP breakage.

One of the major barriers to characterize the pre-weakening effect of HVP breakage is the lack of methodologies to measure the degree of pre-weakening and to evaluate its effect. One of the most potential applications of pre-weakening by HVP breakage is as a pre-treatment operation prior to SAG milling (Shi et al., 2012). Correspondingly, single particle impact test has been adopted to characterize the breakage behaviour of pre-weakened particles. However, the pre-weakening degree (%change of $A \times b$) obtained is only a qualitative indicator of the change of ore breakage resistance and cannot be used to evaluate the reduction of energy consumption of ore particles in impact breakage. In addition, the present single particle impact testing method has not yet reached a reasonable trade-off between reliability and efficiency. Cumbersome testing work is required to obtain the reliable measurement of pre-weakening degree.

Another research gap is the ore particle behaviour in HVP breakage at different machine setting. Experimental studies of ore breakage by high voltage pulse had been conducted by different researchers using single particle testing methods (Shi et al., 2013; van der Wielen et al., 2014). Their work provides very constructive knowledge of HVP breakage characteristics, but more work
is still required. It is necessary to conduct a thorough investigation on ore particle behaviour in HVP breakage, in order to reveal the relation of specific energy to ore particle behaviour in HVP breakage.

The research gaps identified together with the research objective have led us to formulate the following hypotheses to be tested in this study:

**Hypothesis one:** Ore particles with different mineral properties respond to high voltage pulse differently in terms of size reduction, which permit the size-based separation of progeny particles with different grades.

**Hypothesis two:** There exists a mathematical relation of impact breakage degrees ($t_{10}$) between pulse-treated and untreated ore particle. This relation can be used to measure the pre-weakening degree of pulse-treated particles and to predict the energy reduction in the subsequent impact breakage process.

**Hypothesis three:** Testing on above two hypotheses will provide fundamental understanding on the interpretation of ore particle behaviour in HVP breakage, and consequently enable the description and modelling of the relation between specific energy and ore particle behaviour in HVP breakage.
Chapter 3 Experimental Details

3.1 Single-particle single-pulse testing method for HVP breakage

Through experimental study and numerical simulations, the JKMRC researchers find that there are many factors affecting the pre-weakening results (Wang et al., 2012b). These factors can be classified into two groups: machine-dependent and ore-dependent. The results of high voltage pulse applications to the mineral industry reported in the literature often show the mixed effects of these two groups of factors. Therefore a need has emerged to characterise ores based on their amenability to respond to the high voltage pulse pre-weakening technique. The objective of the HVP breakage characterisation method is to decouple the ore-dependent factors from the machine-dependent factors, in order to quantify the relationship between the HVP breakage degree ($t_{10}$) and high voltage energy requirement for a specific ore sample. The development of such a HVP breakage characterisation method using the high voltage pulse technique will help mining companies interested in this technology to better understand the amenability of their particular ores, and to assess the potential benefits of this technology to their specific operation.

To solve this problem, a method based on single-particle tests has been developed in JKMRC to characterise the HVP breakage degree of high voltage pulses on ores. As part of PhD project, the author of this thesis had taken part in the development of this HVP breakage testing method. A co-authored journal paper had been published:


In electrical comminution breakage energy is discharged to solid through electrical breakdown channels. However, the path of electrical breakdown channel in anisotropic solids such as mineral aggregates and rocks depends on the structure of these solids, pulse generator setting and electrodes configuration (Andres and Timoshkin, 1998). Figure 2-15 demonstrates the possible paths of breakdown channels in the situation of disintegration of solids, immersed in water in the plane-plane electrode configuration. In this figure the two top curves represent electrical breakdown channels passing through both liquid and solids, while the middle curve indicates that the electrical breakdown channel is developed inside solids only. The bottom curve shows an electrical breakdown channel grows purely in liquid.
Chapter 3 Experimental Details

This suggests that when pulse energy is discharged to particles bed, the energy discharge was not evenly distributed among all ore particles in the processing zone.

In order to verify the unevenly distribution of pulse discharge in particles in Figure 3-1, A number of experiments were conducted to investigate the possible reasons for this anomaly. Three particles of 26.5–45 mm were placed in the process vessel; one directly under the electrode and the other two on each side of the centre particle. After three pulses were discharged, the process vessel was inspected. The centre particle was broken and formed a number of fragments. The other two particles furthest from the electrode only lost a couple of chips from the edges, while their whole bodies remained intact. X-ray Cone Beam Tomography (CBT) was performed on the unbroken ore particles and found that no cracks or micro-cracks were generated in this process. This indicated that ore particles further from the electrodes did not receive the same pulse discharge energy as the particles under the electrode in the existing design of the selfFrag process vessel (Shi et al., 2013).

This indicated that ore particles further from the electrodes did not receive the same pulse discharge energy as the particles under the electrode in the existing design of the selfFrag process vessel. Semkin et al. (1995) showed that in a high voltage pulse device, the discharges develop in an array around the electrode axis. To achieve the best fragmentation or pre-weakening results, the material immersed in water needs to get closer to the electrodes.

The investigation confirmed that the energy consumption recorded by the selfFrag instrument was not evenly distributed among all ore particles in the process vessel. When HVP breakage test is conducted with multi-particles treated simultaneously, the breakage behaviour may not represent the true response of the ore subjected to high voltage pulses, since the pulse energy is not distributed evenly between different particles. Investigation of ore behaviour in HVP breakage may be biased if using the multi-particle characterisation batch test.

To overcome the limitations associated with the previous selfFrag batch tests, a single-particle characterisation method has been developed. In this method, only a single particle is placed each time inside the processing vessel, directly under the electrode and immersed in water. One single pulse was discharged to the particle sitting directly under the positive electrode. The pulse-treated particles were classified into two groups according to the breakage response: body breakage and surface breakage. After the pulse loading, the process vessel was inspected. If the mass of the largest progeny particle is less than 90% of the parent particle mass, the breakage is classified as body breakage. Then the whole vessel contents are removed, and another particle is treated with
new water. Otherwise, if the particle remains intact, or shows only minor surface breakage with a couple of chips being generated (less than 10% of the parent particle mass), the breakage response is considered as surface breakage and a further single-pulse is discharged. The procedure continues until the body breakage event occurs or a desired pulse discharges number is reached. Finally, the product of body or surface breakage is collected separately for analysis.

3.2 **Use of synthetic samples to investigate the selectivity of HVP breakage**

To investigate the selectivity of HVP breakage, the influence of variations in shape, mineralogy and texture of natural rocks has to be removed. This can be achieved by employing homogenous synthetic samples. The exact configurations of the synthetic samples that were used in the study in Chapter 4 and the reason to select concrete grout to make the synthetic samples are introduced in this section.

3.2.1 **Selection of concrete grout to make synthetic sample**

In a review by Michaux (2006), it was summarized that there was a long history to use concrete grout and mortar as a medium to model rock like behaviour in an explosive detonation. Michaux (2006) also affirmed that concrete grout without aggregate is the optimum material to make synthetic sample to model natural rock for blasting study in a detailed review, because concrete grout is not only cheap and easy to be fabricated, but also is similar in character to natural rock (grain size, density, and most importantly the structure of granular with matrix, etc.), and has adjustable mechanical properties.

On the other hand, Andres and Bialecki (1986) indicated that the mechanism of disintegration in electrical comminution is similar to that in blasting, since the disintegration of solid dielectrics in electrical comminution is achieved by the electrical breakdown-caused mechanical explosion. In both of these two comminution methods, tensile stress is the component predominating in the disintegration process. As a result concrete grout can also be used to model rock like behaviour in electrical comminution.

The applicability to disintegrate concrete particles with electrical comminution had also been confirmed by a series of studies which aims to investigate the feasibility to liberate concrete with electrical comminution for recycling purpose (Bluhm et al., 1997; Bluhm et al., 2000; Fujita et al.,
3.2.2 Properties of the selected construction grout

The grout selected to produce synthetic sample in this project is Dunlop® construction grout, of which the technical datasheet introduces it as “a general purpose high strength grout that can be mixed to a non-slump or flowable mix suitable for a wide range of projects”. The cement based formulation is suitable for applications where shrinkage is not tolerated and high compressive and flexural strength is required. Compressive strength of 45 MPa is achieved after 7 days and 65 MPa after 28 days”.

The size distribution of DUNLOP® construction grout was analysed by dry sieving. The grout mix is made up for quartz sand particles in a narrow size fraction around 300 μm. The cement (with additives to compensate the shrinkage during curing) which forms the matrix of synthetic sample is very fine and has a particle size below 38 μm. Such grout can be used to produce synthetic sample to simulate very weak and weathered sandstone (Michaux, 2006), with a grain size of around 300 μm.

3.3 Natural ore samples

Totally seven kinds of ore samples are tested in this project. The type of material, valuable element and referred chapters are listed in Table 3-1.

For each ore sample tested, 50 to 1000 kg raw material with top sizes from 53 to 100 mm was received. The symbols of the seven natural ore samples in Chapter 4 to 8 are summarized in Table 3-1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Valuable element</th>
<th>Chapter 4/5</th>
<th>Chapter 6 (Paper 1)</th>
<th>Chapter 6 (Paper 2)</th>
<th>Chapter 7/8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadia East Ore</td>
<td>Cu/Au</td>
<td>Sample A</td>
<td>Ore 1</td>
<td>Ore 1</td>
<td></td>
</tr>
<tr>
<td>Cadia Low Grade Plant SAG Pebble</td>
<td>Cu/Au</td>
<td>Sample B</td>
<td>Ore 2</td>
<td></td>
<td>Ore A</td>
</tr>
<tr>
<td>Ridgeway SAG Pebble</td>
<td>Cu/Au</td>
<td>Sample C</td>
<td>Ore 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sossego Ore</td>
<td>Cu</td>
<td></td>
<td>Ore 4</td>
<td>Ore 2</td>
<td></td>
</tr>
<tr>
<td>Prominent Hill Ore</td>
<td>Cu/Ag</td>
<td></td>
<td></td>
<td></td>
<td>Ore B</td>
</tr>
<tr>
<td>Rio Tinto Ore</td>
<td>Fe</td>
<td></td>
<td></td>
<td></td>
<td>Ore C</td>
</tr>
<tr>
<td>Telfer Ore</td>
<td>Cu/Au</td>
<td>Sample D</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 3 Experimental Details

In addition, historical data of four ore samples are used in Chapter 6, with symbols of Ore 5 to 8. The names of these four samples are North park Ore, Mt Isa Ore, Ernest Henry Ore and Ridgeway Ore. Geological information of the natural ore samples are introduced in the corresponding chapters.

3.4 Ore sample preparation

The ore samples received from the mines were assumed to be hand-picked or shelved into the 220 litres drums. The content of each individual drum was combined, dried, and hand-picked and screened by the JKMRC Gilson screen (Figure 3-1, left). Each individual size fraction was then homogenized by splitting using a 16-segment rotary divider (Figure 3-1, right). When necessary, coarse particles would then be crushed using jaw crusher and smaller particles with a small jaw crusher (Figure 3-2). The whole sample from one site was then combined and screened to obtain the required size fractions according to the testing scopes that followed.

The prepared samples were subjected to various high voltage pulse and mechanical breakage. It was considered that the feed represented a homogeneous mixture.

Figure 3-1 The large rotary Divider on the left, and Gilson screens on the right used to generate representative test feed samples (Wang, 2012)
3.5 **Equipment and instrument**

3.5.1 **Lab scale HVP breakage device (selFrag Lab)**

A lab scale HVP breakage device, selFrag Lab, was used in the studies described in Chapter 4 to 6.

The selFrag Lab is manufactured by SELFFRAG AG, Switzerland (Figure 3-3). The device relies on a transformer feeding a Marx generator to generate pulses and discharge them into a processing vessel. This processing vessel sits on a lifting table that moves it into a shielded processing area. The equipment consists of a High Voltage (HV) power supply, an HV pulse generator, and a processing vessel. The processing chamber is enveloped by an outer shell specially designed to guard against acoustic and electromagnetic emissions. The HV components are insulated with oil and gas walled with a steel shielding to ensure safe interlocks.
In the SELFRAG Lab machine, the voltage (92-200 kV), electrode gap (10-40 mm), pulse repetition rate (1-5 Hz) and number of electrical pulses (1-1000) can be varied.

The processing vessel is filled with de-ionized water. It is believed that the process is much efficient with deionized water as the medium since the ions in tap water may affect the behaviour of electric discharge. The bottom of the processing vessel works as bottom electrode during the pulse discharge. The processing vessel bottom can be either closed or with apertures. Closed processing vessel bottom is used in this project.

After setting the desired experiment parameters, the operator can start the automatic sequence, where the processing vessel is lifted into position inside the processing chamber and fragmentation process starts.

When the predetermined voltage is reached, the energy of the pulse generator is discharge from the electrode through the solid sample to the ground bottom (counter electrode) of the processing vessel.
This charging and discharging cycle repeat itself at a selected frequency until the selected number of pulses has been reached. After the breakage is completed, the lifting table lowers the processing vessel and the interlocks are free, so that the door can be opened to retrieve the vessel. The retrieved products are then emptied into a tray by tilting the vessel sideways and rinsing the remaining of the samples inside the vessel. The tray is then tilted in an angle to release excess water followed by drying in a 40°C oven. When dried, the products are weighted and bagged for sieving and other analysis.

3.5.2 Pilot scale HVP breakage device (PWTS)

A pilot scale HVP breakage device, Pre-Weakening Test Station (PWTS), was used in the studies described in Chapters 7 and 8. PWTS is a purpose-built R&D machine at the SELFRAG pilot plant.

The detailed configuration and pictures of PWTS are presented in Chapter 7.

3.5.3 Single particle impact breakage characterization-JKRBT

The industrialized JKRBT (Figure 3-5) employs a rotor of 450 mm in diameter. The operating system consists of a vibrating feed, a rotor-stator impacting device with its drive system and an operation control unit. In the rotor there are three 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 circumference and radial velocity components.

Figure 3-5 Industrial JKRBT Unit (Shi et al., 2009)
Chapter 4  The Effect of Electrical Breakdown Channel Locality on Particle Breakage Behaviour

4.1 Introduction

It was found that there existed pronounced ore-dependent variations that affect mineral liberation and pre-weakening by electrical comminution. For a particle with given mechanical properties and an applied mechanical stress, the result of the subsequent breakage event is determined by the locality of the stress. In the case of electrical breakdown, induced by high voltage electrical pulses, the locality of stress is determined by the passage of the channel of plasma (electrical breakdown channel), which explodes at the point of achieving critical pressure. The ore dependent variation of mineral response to electrical breakage is caused by the effect of ore aggregate structure and ore particle internal electrical field distribution on the locality of the electrical breakdown channel. However, the physical research of the electrical breakdown of composite solids and minerals has not yet been carried out. In this chapter, the effect of electrical breakdown channel locality on solid breakage behaviour in electrical comminution is explored, as well as the effect of metalliferous grains on the locality of electrical breakdown channel and breakage behaviour.

4.2 Contributions

Through the detailed experimental work as presented in Sections 3.1 and 3.2, the study using the synthetic samples has provided unambiguous evidence of how pyrite grains in a particle affect the electrical breakdown channel locality, and how the electrical breakdown channel locality affect ore particle residual competence (the $A \times b$ changes). The major contributions of this research work include:

- Evidence of the high conductivity/permittivity grains-induced breakdown channels, which can be used for numerical simulations in the future.
• The concept of using body breakage and surface breakage to classify particle breakage mode subjected to HVP treatment, which directly links with the electrical breakdown channel locality. The concept of body and surface breakage will be used in Chapter 7 for HVP breakage analysis and in Chapter 8 for modelling HVP breakage of ores.

• Fundamental understanding how the high conductivity/permittivity mineral grains-induced breakdown channels affect ore pre-weakening results.

• Discovery of the potential application of the HVP technology for ore pre-concentration presented in Chapter 5, the first time in literature.

• One journal paper (Minerals Engineering, 69 (2014), 196-204) and one peer-reviewed conference paper (27th International Mineral Processing Congress) published from this study. The journal paper is presented in this Chapter.
Electrical breakdown channel locality in high voltage pulse breakage

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ABSTRACT

An experimental study was conducted, in which synthetic samples made of construction grout and pyrite grains were subjected to high voltage pulses in a single-particle and single-pulse mode, in order to investigate the effect of electrical breakdown channel locality on particle breakage behaviour. The data confirm that the locality of electrical breakdown channel dominates the breakage response of particles. When a breakdown channel passes along the axis of a particle, it generates a finer product and produces more cracks/microcracks on the fragments. The electrical breakdown channel locality is controlled by the grains of minerals with high conductivity/permittivity and their location in a particle under the identical machine settings. The outcomes using the synthetic samples are helpful in understanding the breakage behaviour of natural ore particles in electrical comminution.

Keywords: High voltage pulse breakage; Electrical breakdown channel; Comminution.

1. Introduction

The increasing demand for natural resources has driven the minerals industry to rapidly expand into new ore bodies which are harder, deeper and of markedly lower grades. These previously uneconomic ore bodies are forcing the industry to seek innovative approaches to improve the efficiency of the comminution circuit.

In this context, the technology to break rocks using high voltage pulses has been discussed as a potential route for comminution (Usov and Tsukerman, 2000; Usov and Borodulin, 2008; Shi et al.,
In this technology a high voltage electrical pulse is transferred to the solid dielectric immersed in water, causing electrical breakdown and disintegration (Andres, 1995). Two different applications for the mineral industry were investigated. The first methodology aims to improve mineral liberation and recovery by discharging electrical pulses to diminish the cohesion between mineral constituents and ore matrices. This methodology is considered as the most feasible way to achieve intergranular breakage (the ideal method for liberation) and had been the main focus of electrical breakage study in the past half century. A number of research outcomes have been reported (Andres, 1977, 1995; Andres et al., 2001a; Lastra and Carbri, 2003; Ito et al., 2006; Cabri et al., 2008). In most cases the liberation of minerals was found to be improved by electrical breakage in comparison with mechanical comminution, but at the cost of increased energy consumption.

The second methodology to exploit electrical breakage is pre-weakening. It was found that the ore particles can be weakened after electrical breakage treatment (Usov and Tsukerman, 2006). Work carried out at the Julius Kruttschnitt Mineral Research Centre (JKMRC) demonstrated that the breakage resistance of a number of ores can be reduced significantly by high voltage electrical pulses at a low specific energy, so that the energy consumption of the downstream grinding process can be decreased (Wang et al., 2011). In recent years this methodology has attracted more and more attention.

However, it was found that there existed pronounced ore-dependent variations that affect mineral liberation and pre-weakening by electrical comminution. Wang et al. (2012a) found that while the liberation of some high conductive minerals was improved by electrical comminution, there was no significant difference in the liberation of other low conductive minerals between the two comminution methods. The competence of the electrical breakage product can be reduced significantly by using a small energy input for some ore particles, however, other ore particles did not behave similarly (Wang et al., 2011). By comparing the experimental results and numerical simulations, the reason why ores respond differently to electrical pulses was attributed to the effect of ore particle internal electrical field distribution on the locality of electrical breakdown (Wang et al., 2012a, b).

This effect can be explained by referring to the mechanism of solid electrical breakdown provided by Budenstein (1980). When the external electrical field intensity exceeds the electrical strength of a solid particle, electrical breakdown will take place in the solid, accompanied by the direct transfer of it into gas and the generation of high temperature plasma streamers. The plasma streamers
develop in a tree-like pattern. The main trunk of the tree-like plasma streamers bridges the electrodes with a diameter of several tens of microns, while the system of branches grows up to some length along the points of higher electrical field intensity but becomes extinguished inside the solids or in the water medium before bridging the ground electrode.

![Image of plasma tree and mineral particle](image.png)

**Figure 4-1 Tree growing (A) and disintegration of mineral particle (B) (Andres et al., 2001a)**

After bridging the electrodes, the main trunk of plasma streamers expands as a result of joule heating. As the joule heating increases, the diameter of the main trunk increases from microns to hundreds of microns, generating excessive tensile stresses and causing disintegration of the solid. The tree growing and solid disintegration processes of the mineral particle have been illustrated by Andres et al. (2001a), as given in Figure 4-1.

For a particle with given mechanical properties and an applied mechanical stress, the result of the subsequent breakage event is determined by the locality of the stress. In the case of electrical breakdown, induced by high voltage electrical pulses, the locality of stress is determined by the passage of the channel of plasma (electrical breakdown channel), which explodes at the point of achieving critical pressure.
Andres et al. (2001a) indicated that the electrical field on the interfaces between minerals with different electrical properties can be increased substantially by the electrostatic polarization of the composite mineral fragments. The higher the difference in electrical properties, the higher the enhancement of the electrical field along mineral boundaries. Since the channel of electrical breakdown grows preferentially along the maximal electrical field in solid, the resulting breakage of the ore particle depends on the structure of ore aggregates and on the configuration of the pulses. In other words, the ore dependent variation of mineral response to electrical breakage is caused by the effect of ore aggregate structure and ore particle internal electrical field distribution on the locality of the electrical breakdown channel.

The simulation studies of Andres et al. (2001a) and Wang et al. (2012a) provide a good understanding of the locality of the electrical breakdown channel in the electrical breakage of ore particles. However, electrical breakdown is only the initial stage of solid breakage by high voltage pulses. Andres (2010) pointed out that the physical research of the electrical breakdown of composite solids and minerals has not yet been carried out. The limited information, available in the literature, regarding the factors affecting the occurrence of electrical breakdown of solid matter (Lisitsyn et al., 1998) and the dynamics of electrical parameter wave form during breakdown (Lisitsyn et al., 1999b; Fujita et al., 2001b; Frey et al., 2002), has not provided enough information regarding the effect of electrical breakdown channel locality on ore particle breakage behaviour.

One of the reasons is attributed to the interactions between material properties and pulse discharge conditions. van der Wielen et al. (2013) conducted pulse breakage tests on 20 rock types using a SELFRAG Lab device to determine the influence of equipment parameters on breakage. They found that the number of discharges and voltage are the two major influences on the resultant product size, and this influence is compounded with mineral composition and particle properties. To decouple the influences of equipment setting and the variation in particle properties, this paper reports the results of an investigation using synthetic samples with the well-controlled particle properties subjected to a single-particle and single-pulse breakage at the identical pulse discharge setting conditions. The similar study with cement paste samples was recently reported (Cho et al., 2014), with a focus on examining crack generation and minerals liberation using an X-ray CT scanner. In the current paper, the effect of electrical breakdown channel locality on solid breakage behaviour in electrical comminution is explored, as well as the effect of metalliferous grains on the locality of electrical breakdown channel and breakage behaviour.
2. Experiment

2.1 Synthetic samples

Many factors associated with ore particles affect electrical breakage results, such as mineral composition, particle size, shape, texture and orientation (Wang et al., 2012b). Natural rock samples are not suitable for studying the effect of electrical breakdown channel locality on electrical breakage, since the breakage product is a combined result of many factors. To deliver unambiguous conclusions synthetic samples, with well controlled identical particle size, shape, texture, orientation and composition, were fabricated for the experimental investigation.

Michaux (2006) describes the long history associated with the use of concrete grout and mortar as a medium to model rock-like behaviour in an explosive detonation. Michaux (2006) also affirmed that, for blasting studies, concrete grout without aggregate is the optimal material with which to make a synthetic sample that models natural rock. This is because concrete grout is not only cheap and easy to make, but also similar in character to natural rock (grain size, density, and most importantly the structure of granular with matrix, etc.). It also has adjustable mechanical properties.

Andres and Bialecki (1986) indicated that the mechanism of disintegration in electrical comminution is similar to that in blasting, since the disintegration of solid dielectrics in electrical comminution is achieved by the electrical breakdown-caused mechanical explosion. The similarity in electrical breakdown and mechanical blasting makes the synthetic samples made of concrete grout a perfect sample for the electrical comminution study.

It is not new to break concrete by high voltage electrical pulses. A number of studies which investigated the feasibility of liberating concrete with electrical comminution for the recycling purposes have been reported ((Bluhm et al., 1997; Bluhm et al., 2000; Fujita et al., 2001a; Frey et al., 2002; Aoki et al., 2009; Araki et al., 2009; Inoue et al., 2009; Wang et al., 2009; Menard et al., 2011). This paper applies the same technique for a different purpose - to study the effect of electrical breakdown channel locality.

The synthetic samples were made of a general construction grout and water, with the addition of high conductive metalliferous grains. The synthetic sample used Dunlop® construction grout, which is a general purpose high strength grout made of quartz sand in a narrow size fraction around 300 μm and cement powder. The cement based formulation is suitable for applications where shrinkage is not tolerated and high compressive and flexural strength is required. Like other cement
based material, the Dunlop® grout sets when mixed with water to form a plastic paste which develops rigidity and then steadily increases in compressive strength (hardens) by chemical reaction with the water (hydration). The technical datasheet of Dunlop® grout claims that compressive strength of 45 MPa is achieved after seven days and 65 MPa after 28 days.

In this study, three groups of synthetic samples were prepared:

The Group 1 sample was made of pure grout and water, without the addition of high conductive metalliferous grains. The ratio of water to grout was controlled between 0.2 and 0.15. According to the standard procedures described in the technical datasheet of Dunlop® grout, the grout powder was always added to water before mixing with an electrical type mixer. The mixed grout was packed into a mould within 30-45 minutes. After curing in the sealed mould for one day the samples were removed and cured in water for six days. The samples were then dried in an oven for 48 hours at 105 °C and sealed in plastic bags to prevent the samples from reacting with water in the air. All samples had a cylindrical shape with a diameter of 38 mm and a height of 30 mm. In addition, some spare particles without the oven drying treatment were also prepared for comparison.

Group 2 samples were made of water and grout mixed at a ratio of 0.25, with the addition of high conductive metalliferous grains. Pyrite powder of the same size as the quartz sand was used as the high conductive metalliferous grains. A pyrite grain column was formed along a desired route inside the sample by injection. The diameter of the pyrite column was 4.73 mm and the length was 30 mm, which gives a mass content of 0.86% of pyrite in each synthetic particle with a single pyrite column. The sample number and the location of the high conductive pyrite column(s) of Group 2 samples used in this study are shown in Figure 4-2.

![Figure 4-2 Configuration of Group 2 samples](image-url)
Group 3 samples used the same water to grout ratio of 0.25 as Group 2. A single pyrite particle of 2.36-3.35 mm was added in each synthetic particle, immediately after the casting of paste. The locations of the coarse pyrite grains in Group 3 samples used in this study are shown in Figure 4-3.

**Figure 4-3 Configuration of Group 3 samples**

### 2.2 Single particle test

In electrical comminution, a high voltage pulse can be either discharged to a particle bed or to a single particle. To provide sufficient product material for analysis and downstream processing, almost all the published work used a particle bed of multi-layers with hundreds or thousands of continuous pulse charges in each test. The tests were completed either in batch (Ito et al., 2009) or in continuous mode (Andres, 1977). Single particle breakage had also been employed in some studies. However, these studies mainly focused on the factors influencing the occurrence of electrical breakdown (Lisitsyn et al., 1998) or highlighted the waveform of electrical parameters during electrical breakdown (Fujita et al., 2001b).

A characterization method of the pre-weakening effect on ores by electrical breakage based on single-particle tests had been developed by Shi et al. (2013). The development of this single-particle characterization method was based on the fact that, in the existing design of the pulse breakage device, the pulse energy cannot be distributed evenly to all particles in a particle bed. This was confirmed by experiments that found single-particle breakage was more efficient than particle bed breakage in ore pre-weakening characterization using high voltage pulses.
Another advantage of the single-particle test is that the response of a single particle subjected to a single pulse discharge can be inspected. In contrast to this, the batch test of a particle bed gives an average result for a number of incremental breakage events, some particles receiving more pulse energy than the other particles.

Therefore the single-particle tests were adopted to study the effect of electrical breakdown channel locality. The three groups of the synthetic samples were treated by selFrag, a laboratory high voltage pulse equipment (refer to Wang et al., 2011) installed at the JKMRC, at a nominal voltage of 180 kV and an electrodes gap of 30 mm. During the tests, only one single particle was placed at a time inside the process vessel, directly under the top electrode and immersed in water. One single pulse was discharged to treat the particle. After the single-pulse discharge, the whole vessel content was removed, and another particle was treated with fresh water.

Group 1 samples were used as a benchmark for comparison with Groups 2 and 3. Twenty repeat tests using Groups 1 samples were performed. Their fragments were combined for sizing analysis and the JKRBT test (Shi et al., 2009) was employed to compare particle competence to breakage. An additional ten repeats were conducted using Group 1 samples without the oven drying treatment. For Groups 2 and 3, ten repeats were performed for each pyrite grain position respectively. Fragments of the ten repeats were combined for sizing analysis and the JKRBT test. In total, 215 pieces of the synthetic particles were used in this study.

3. Results

3.1 Classification of breakage responses

In the preliminary tests with Group 1 samples it was found that the response of the single homogeneous (pure grout) particle to electrical comminution was random and varied from one particle to another. The breakage response of a single particle can be classified into three categories: intact, surface breakage and body breakage. For the samples without oven drying treatment, only intact response and surface breakage were found, but no body breakage occurred. For the oven dried Group 1 sample, on the other hand, the probability of body breakage increased from 0 to approximately 50%. This agrees with results in the literature reporting that replacing the water in pores with air will increase the breakage probability of the particle by high voltage pulses (Lisitsyn et al., 1998).
Chapter 4 The Effect of Electrical Breakdown Channel Locality on Particle Breakage Behaviour

Since the pulse energy discharged to each particle was kept constant, the degree of breakage for each single particle was determined by the path of the electrical breakdown channel in this study. Apparently, if the electrical breakdown channel grows through water the particle will be affected only by the external shockwave caused by electro-hydraulic breakage, which is not strong enough in this case. Therefore the particle remains intact after pulse discharge (Figure 4-4, left). When the electrical breakdown channel develops along the particle surface, the explosion of the expanding evaporated substance in the channel will result in a groove on the particle surface (Figure 4-4, middle). Body breakage, which is the desired response to electrical breakage for mineral processing purposes, can only be caused by the electrical breakdown channel passing across the main body of the particle (Figure 4-4, right).

![Figure 4-4 Responses of single particle to pulse discharge](image)

3.2 Breakage response of Group 2 samples

In almost all the electrical breakage treatment of Group 2 samples, single or multiple electrical breakdown channels were induced along the high conductive columns inside the particles, causing body breakage. The body breakage probability of samples Syn-9 and Syn-11 was 90% while all other samples reached 100%.

During electrical breakdown, the plasma streamer of very high temperature inside the electrical breakdown channel created visible burning traces on the pyrite grains. The burning traces, as an indicator of the existence of an electrical breakdown channel, suggested that not all the high conductive columns in the samples with multiple high conductive columns induced electrical breakdown. For the samples with two or three high conductive columns (Syn-10 to Syn-13), about half of the body broken particles induced two or three electrical breakdown channels passing along each of its high conductive columns, while in the other half of particles only one high conductive column induced an electrical breakdown channel successfully. Although sample Syn-13 had thee high conductive columns, there was only one particle that attracted three electrical breakdown
channels to pass all of its high conductive columns. Other Syn-13 particles induced only one or two electrical breakdown channels.

It was also found that, the horizontally-placed high conductive column in sample Syn-9 did not create a horizontal electrical breakdown channel, but generated a response similar to the samples with multiple vertically-placed high conductive columns.

Another indication of breakdown intensity is the burning trace width. Since the diameter of pyrite grain columns in all Group 2 particles are identical (4.73 mm), the observed variation in the burning trace width indicates the intensity of electrical breakdown. It was found that the pulse energy was not evenly distributed between different electrical breakdown channels. Figure 4-5 (a) presents a progeny particle of sample Syn-10, of which two conductive columns were symmetrically positioned. However, the width of the right electrical breakdown channel (about 11 mm) is more than five times that of the left one (2 mm), indicating a pronounced inequality in the distribution of the pulse energy. On the other hand, if the positions of conductive columns are asymmetric, the high conductive column with highest electrical field intensity will be charged by pulse energy preferentially. The test on sample Syn-12 is an example of such a situation. Two conductive columns were positioned in each of the Syn-12 particles, one along the cylindrical body axis, another being away from the axis. It was found that the burning traces along the cylindrical body axis were always wider than that away from the axis (Figure 4-5 (b)).
3.3 Breakage response of Group 3 samples

For Group 3 samples all the pyrite grains attracted an electrical breakdown channel to pass along them successfully, which was proved by the black burning traces around the grains. For samples with a pyrite grain embedded in the centre (Syn-17) or on the bottom surface close to the ground electrode (Syn-21), the electrical breakdown channel intruded into the top surface of the particle, then passed along the pyrite grain and reached the bottom of the particle. Since the electrical breakdown channel passed the main body of the particle, samples Syn-17 and Syn-21 were broken by the radial tensile force generated along particle axis, giving a body breakage probability of 100%.

When the pyrite grains were placed on the side or on the top surface of a particle (Syn-19 and Syn-20), the induced electrical breakdown was likely to develop along a channel on the particle surface. As a result, surface breakage dominated in the response of samples Syn-19 and Syn-20 to high voltage pulses, with a surface breakage probability of 70%. Correspondingly, the response of body breakage for the rest 30% particles can only be attributed to a split of fragments by the explosion of the electrical breakdown channel on particle surface, rather than the radial tensile force generated in samples Syn-17 and Syn-21.

Previous studies at the JKMRC found that ore particles with high conductive grains on the surface would present high resistance to electrical comminution, which was attributed to the enhancement of electrical field on the particle surface caused by the high conductive grains (Wang et al., 2012b). The response of samples Syn-19 and Syn-20 was entirely consistent with this conclusion. However, the behaviour of sample Syn-21 indicated that these particles with high conductive grains on the surface had the opportunity to cause body breakage, if the surface with conductive grain was located close to the ground electrode.

4. Discussion

4.1 Relation between high conductive material and electrical breakdown locality

As mentioned above, pyrite (forming a column or as a single particle) is able to attract an electrical breakdown channel to pass along it in electrical breakage. This ability can be explained by the pronounced difference in electrical properties between pyrite and cement (Table 4-1), which
resulted in pronounced enhancement of the electrical field along the interface between pyrite and cement.

<table>
<thead>
<tr>
<th>Material</th>
<th>Estimated Conductivity (S.m(^{-1}))</th>
<th>Reference Source*</th>
<th>Estimated Permittivity (F.m(^{-1}))</th>
<th>Reference Source*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrite</td>
<td>0.9</td>
<td>1</td>
<td>33.7-81</td>
<td>2</td>
</tr>
<tr>
<td>Cement</td>
<td>&lt;0.1</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>


The breakage test on Group 2 samples indicates that in electrical breakage the channel of electrical breakdown always grows along a high conductive column. When there are more than one high conductive columns in a particle, it is possible to induce multiple electrical breakdown channels. But the existence of an additional high conductive column cannot guarantee the generation of an additional electrical breakdown channel. As mentioned above, the process of electrical breakage of mineral can be described with a tree-like electrical breakdown model. The breakage test result of Group 2 samples suggests that the “tree” of electrical breakdown channels can have more than one “trunk” at the same time, but in most cases a main trunk would release more explosive energy than the other trunks.

In the breakage test on Group 3 samples, the channel of electrical breakdown always passes along the pyrite grain. However, the route of the electrical breakdown channel away from pyrite grain is determined by the relative position of the pyrite grain. As expected, a particle with pyrite grain located in the centre (Syn-17) attracted the electrical breakdown channel to pass along the axis of the particle, while the pyrite grains embedded on the top or side surface of particles (Syn-19 and Syn-20) resulted in an electrical breakdown channel passing along the particle surface.

The channel of electrical breakdown in sample Syn-21 is interesting. The pyrite grains are embedded on the surface (bottom) of Syn-21 particles, but the locality of the electrical breakdown channel in sample Syn-21 is similar to sample Syn-17, rather than Syn-19 and Syn-20. The reason why the electrical breakdown channel has not grown along the particle surface of Syn-21 can be explained as such: the top electrode of the selFrag machine is positive while the ground electrode is negative. During electrical breakdown, the electrical breakdown channel grows from positive electrode to ground electrode. For a particle with high conductive grain located close to the ground electrode, the high conductive grain will attract the pulse energy generated from the positive
electrode and induce the breakdown channel into passing along the axis of the particle through the high conductive grain to the ground electrode.

4.2 Effect of electrical breakdown locality on breakage product size distribution

4.2.1 Product size distribution of Group 2 samples

Figure 4-6 presents size distribution curves of all Group 2 samples. Note that each size distribution curve was determined by combining the ten duplicate test particles. At the finer end (-19 mm) all samples have a similar product size distribution, regardless of the electrical breakdown channel locality. The size distribution curves start departing at larger than 19 mm fragment size. The breakage resulting from the electrical breakdown channel passing from the axis of particles (Syn-7 and Syn-12) generates the finest fragments at the coarser end. Size distributions of the products generated from multiple electrical breakdown channels without passing through the particle centre (Syn-9, Syn-10, Syn-11 and Syn-13) appear similar, and are coarser than that broken by a single electrical breakdown channel that also passes away from the particle centre (Syn-8).

![Figure 4-6](image)

**Figure 4-6** Product size distribution curves of Group 2 samples generated by electrical breakage (the legends are referred to Figure 4-2)

4.2.2 Product size distribution of Group 3 samples

The product size distribution curves of Group 3 samples are given in Figure 4-7. Similar to Figure 4-6, each size distribution curve was determined by combining the ten duplicate test particles.
Chapter 4 The Effect of Electrical Breakdown Channel Locality on Particle Breakage Behaviour

Figure 4-7 Product size distribution of Group 3 sample in electrical comminution (the legends are referred to Figure 4-3)

Figure 4-7 shows that the size distribution curves of the electrical breakage products can be classified into two groups according to the electrical breakdown channel locality. The fragments of Syn-17 and Syn-21 were generated by the electrical breakdown channel passing along the particle axis, while the other two samples (Syn-19 and Syn-20) were generated by the electrical breakdown channel passing along the side surface of the particle. Figure 4-7 indicates that the products broken by the electrical breakdown channel passing along the particle axis are significantly finer than the products broken along the side surface of the particle. Interestingly, each group of product size distributions is very similar, as long as their locality of electrical breakdown channels is similar. This observation confirms the dominant effect of electrical breakdown channel locality on product size distribution.

4.2.3 Comparison of electrical breakdown induced by high conductive column and single pyrite grain

The above sections have demonstrated that the electrical breakdown channel locality affects breakage product size distribution. It was expected that the same breakdown channel locality would generate the same product size distributions. A comparison was made between samples Syn-7 and Syn-17, both exhibiting the same breakdown channels through the centre of the particles. The difference is in the way of inducing the breakdown channel: Syn-7 using a column of pyrite powders through the cylindrical particle axis; Syn-17 using a single coarse grain of pyrite embedded in the centre of each particle. Figure 4-8 displays the size distribution comparison. At the fine end
(<15 mm) the two size distribution curves are identical. But at the coarse end, the one with a pyrite column (Syn-7) appears significantly finer than that with a single pyrite grain (Syn-17), despite the same breakdown channel locality.

This may be explained by the description of “tree trunk and branches structure” of the electrical breakdown channel (Andres et al., 2001a). In the pyrite column induced breakdown, the pyrite content (0.86% for a single column) is much higher than in the particle with a single pyrite grain. As a result, the pulse energy may generate denser “branches” in the breakdown channel, compared with a single pyrite grain induced breakdown channel. The higher density of cracks leads to finer fragments.

![Figure 4-8](image)

**Figure 4-8** Comparison of product size distribution between Syn-7 (single column of pyrite powders along the particle axis) and Syn-17 (single coarse pyrite grain embedded in the centre of particle)

Weise and Loeffler (1993) found that during electrical breakdown the exothermic reaction of pyrite and water provides an extra heating process, which improves the expansion of evaporated gas in the electrical breakdown channel. In the two synthetic sample tests presented in Figure 4-8, the difference in pyrite content along the electrical breakdown channel may result in a difference in the amount of generated exothermal energy and hence affect the breakage result. Nevertheless, the hypotheses will be further tested with more detailed analysis presented in the next section.
4.3 Effect of electrical breakdown locality on crack generation

It was found that the location of electrical breakdown channel not only affected the product size distribution of electrical comminution, but also dominated the generation of cracks/microcracks. In the test of Group 2 samples, particles broken by electrical breakdown channel along the cylindrical axis of particle (Syn-7 and Syn-12) present denser radial cracks extended from centre to side surface of the particle. In contrast to this, only a few cracks can be found in the particles with the electrical breakdown channel away from particle axis (Syn-8 through to Syn-11 and Syn-13). The fragments of different sizes from samples Syn-7 and Sny-13 are scanned to demonstrate this finding (Figure 4-9).

Figure 4-9 Cracks appeared on the fragment surface of samples Syn-7 (breakdown channel along the cylindrical axis of particle) and Syn-13 (breakdown channel away from the cylindrical axis of particle)

The similar trend was also found in Group 3 samples. More cracks appeared on the progeny particles of samples Syn-17 and Syn-21 (breakdown channel located along the particle axis) than on samples Syn-18 and Syn-19 (breakdown channel on the particle side surface).

The JKRBT tests were conducted on the untreated synthetic particles (Group 1 without pyrite grains) and the pulse-treated fragments of Syn-7, Syn-13, Syn-17 and Syn-20 samples to quantitatively evaluate particle residual competence associated with the cracks/microcracks generation in the electrical breakage process. The value of $A \times b$ is an indicator of particle resistance.
to breakage, the larger $A \times b$ indicating the less resistance to breakage. The typical $A \times b$ values in the JKMRC database that consists of more than 2000 standard Drop Weight Tester data for ore particles are between 20 and 300. Table 4-2 gives the $A \times b$ values of the synthetic samples determined by the JKRBT tests. The $A \times b$ values indicate that the synthetic particles ($A \times b = 190$) are classified as less competent.

Table 4-2 shows that the resistance to breakage of all four treated samples are reduced significantly by the cracks/microcracks generated in electrical comminution. The JKRBT data confirm the weakening effect on the synthetic particles using high voltage pulses. In both Groups 2 and 3, the samples broken by the electrical breakdown channel along the particle axis are weaker than the samples broken by the electrical breakdown channel along the particle side surface (Syn-7 vs Syn-13 and Syn-17 vs Syn-20). The $A \times b$ values exhibit the consistent trend with their cracks densities displayed in Figure 4-9.

<table>
<thead>
<tr>
<th>Material</th>
<th>Untreated</th>
<th>Syn-7</th>
<th>Syn-13</th>
<th>Syn-17</th>
<th>Syn-20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductive material</td>
<td>No</td>
<td>1 column, along axis</td>
<td>3 columns, off-axis</td>
<td>Single grain, embedded</td>
<td>Single grain, on top surface</td>
</tr>
<tr>
<td>Breakdown channel locality</td>
<td>Along axis</td>
<td>On surface</td>
<td>Along axis</td>
<td>On surface</td>
<td></td>
</tr>
<tr>
<td>$A \times b$</td>
<td>190</td>
<td>599</td>
<td>490</td>
<td>554</td>
<td>486</td>
</tr>
</tbody>
</table>

The $A \times b$ data in Table 4-2 also show more significant weakening effect for the breakdown channels induced by a single high conductivity column along particle axis ($A \times b = 599$ for Syn-7) than that by the single coarse pyrite grain embedded in the middle of the particles: ($A \times b = 554$ for Syn-17). This supports the hypothesis of the effect of pyrite content in a particle on the tree-like breakdown channel structure as discussed in Section 4.2.3. However, for the breakdown channel located on the particle surface, there is no difference in $A \times b$ (490 for Syn-13 vs 486 for Syn-20), regardless of the conductive material presented in column or in single grain.

### 4.4 Relevance to electrical breakage of ore particles

In this study the effect of electrical breakdown channel locality on electrical breakage was investigated using the synthetic samples. The test results are highly relevant to the electrical breakage of ore particles.
The synthetic particle tests indicate that the locality of electrical breakdown channel is the most important factor affecting the product fineness, crack density, and particle residual competence. From the material property point of view, the locality of breakdown channel is determined by the existence of high conductivity/permittivity grains in a particle and the location of these high conductivity/permittivity grains in the particle. Chao et al. (2014) found that the dielectric strength of samples with pyrite showed lower values, 20–35 kV/cm, than the sample with no mineral addition (cement paste only) of 40–72 kV/cm. Understanding this mechanism helps to explain the observed variations in pre-weakening of ores and the mineral liberation results associated with ore testing for various mining companies in the past. The position of metalliferous grains in ore particles has to be considered as one of the most crucial factors for the feasibility of electrical breakage operation. In general, the ore containing most metalliferous grains inside the particles is likely to have a good result of size reduction and pre-weakened product. On the contrary, the ore containing metalliferous grains on the particle surface is unlikely to have a good response in pre-weakening, but may be good in liberation as the electrical breakdown channel passing through the metalliferous grains on the particle surface would easily liberate these high conductivity/permittivity minerals.

Test results using the synthetic particles indicate that for particles with multiple high conductive columns or multiple high conductive grains, a single high voltage pulse may generate a major breakdown channel along one of the conductive column (or grain), but cannot guarantee the generation of the electrical breakdown channels along all of the high conductive columns (or grains). This is similar to the natural ore that may contain multiple metalliferous grains in each particle. It has been found that the high grade ore is not necessarily meant easier to break or to generate the weaker fragments in electrical comminution (Wang et al., 2011). One of the major controlled factors is the location of the metalliferous grains of minerals in the particle. The synthetic particle test results indicate that more than one high voltage pulse discharges may be required to fully liberate the valuable mineral grains in ore particles. Incremental breakage with multiple low specific energy pulses may achieve better results of pre-weakening and mineral liberation.

In the synthetic particle tests the burning traces were used to locate the breakdown channels. The burning traces were the results of the exothermal reaction of high conductive grains with water, which provides extra heating process. The exothermal reaction during the electrical breakdown may cause mineral oxidation, changes in particle surface chemistry and mineral phases. These changes may have an adverse impact on the downstream processes such as flotation. More study in this area is under way.
5. Conclusion

Electrical breakage tests on synthetic sample were conducted to investigate the effect of electrical breakdown channel locality on electrical breakage. There are three categories of breakage response to electrical breakage: remain intact, surface breakage and body breakage. The locality of electrical breakdown channel dominates the breakage response of particles in electrical breakage, including product size distribution, cracks/microcracks generation and particle residual competence using $A \times b$ value as an indicator.

The synthetic sample tests indicate that when a breakdown channel passes along the axis of a particle, it will generate a finer product size distribution at the coarse end, and produce more cracks/microcracks and hence less competent fragments. The electrical breakdown channel locality is controlled by the existence of the grains with high conductivity/permittivity and the location of these metalliferous grains in a particle, rather than the amount of the metalliferous grains (i.e. ore grade) in the particles. When the metalliferous grains are embedded in the middle of a particle or are placed close to the ground electrode, the electrical breakdown channels are likely to cause body breakage. While the metalliferous grains are located on the particle surface close to the positive electrode, the breakdown channel is likely to cause surface breakage, which leads to less pre-weakening effect. Note that the conclusions drawn here are under the machine setting conditions that can provide the sufficient electrical field strength to initiate electrical breakdown and the energy to maintain the streamer propagation through a particle.

The outcomes using the synthetic samples are helpful in understanding the breakage behaviour of natural ore particles in electrical comminution. Based on the knowledge of the effects of breakdown channel locality, models for breakage probability and breakage degree will be developed for the minerals industry.

6. Acknowledgement

The financial support from Newcrest Mining for a PhD candidate in this study is gratefully acknowledged.
Chapter 5  Development of an Ore Pre-concentration Method using High Voltage Pulses

5.1 Introduction

The effect of electrical breakdown channel locality on particle breakage behaviour is investigated in Chapter 4. It was found that the electrical breakdown channel locality is controlled by the mineral grains with high conductivity/permittivity and their location in a particle. Based on the understanding from Chapter 4, a novel ore pre-concentration technique using high voltage pulses is proposed in this chapter. In the proposed ore pre-concentration process, a single or two electrical pulses with a controlled energy are discharged to ore particles in a narrow size fraction. This causes selective breakage to the particles with high conductivity/permittivity minerals, leading to a difference in product size distributions. Screening is used to separate the pulse treated product into two components. It is hypothesized that the two components have different metal grades. An experimental study using four copper ore samples was conducted to prove the hypothesis and to confirm the findings of the HVP pre-concentration technique.

5.2 Contributions

- The first time in literature to report the novel ore pre-concentration technique by HVP. Detailed results of the mass yield, copper grade, and copper distribution in the body breakage and surface breakage products are presented in this chapter. The data provide strong evidence to support the ore pre-concentration concept using metalliferous mineral-induced selective breakage subjected to HVP loading, and size-based separation.

- Four major findings in developing the high voltage pulse pre-concentration technique are reported. These include the evaluation of pre-concentration performance, correlation between the breakage mode-based separation and the size-based separation, the interaction of multiple metalliferous minerals, and the pulse energy transfer efficiency.
Chapter 5 Development of an Ore Pre-concentration Method using High Voltage Pulses

- The novel HVP pre-concentration method has a potential to provide a technical tool for the mining industry in making step-change improvements in energy efficiency, environment impact and operation costs.
- Two journal papers on HVP pre-concentration have been published. This Chapter presents Part 1 of the paper.
Pre-concentration of copper ores by high voltage pulses Part 1:
Principle and major findings

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ABSTRACT

A novel ore pre-concentration technique using high voltage pulses is proposed in this study. The technique utilises metalliferous grain-induced selective breakage, under a controlled pulse energy loading, and size-based screening to separate the feed ore into body breakage and surface breakage products for splitting of ores by grade. Four copper ore samples were tested to demonstrate the viability of this technique. This study consists of two parts: Part 1 presents the principle, the validation and the major findings; Part 2 discusses the new opportunities and challenges for the mining and mineral industry to take up this technique.

Keywords: Ore upgrading; Pre-concentration; High voltage pulses; Electrical comminution.

1. Introduction

The mining and minerals industry is facing challenges of declining ore grades and increasing ore competence, and the associated increase in processing plant throughput rates, energy consumption and operational costs. Powell and Bye (2009) estimated that ore competence, in terms of kWh t\(^{-1}\) to treat, is increasing at about one per cent per annum and ore grade dropping at about one per cent per annum. Based on these figures, they calculated that to achieve the mining company targets of a 10-20% saving in absolute energy, specific energy usage (kWh t\(^{-1}\) of ore treated) needs to drop below 40% of the usage in 2000 by 2020 and 20% by 2050! Applying current technology will not achieve anything near this objective.
Coarse waste rejection before grinding has a potential to pre-concentrate valuable minerals. The upgraded ore can bring benefits of reduced milling throughput to achieve the required metal production, reduced energy consumption and improved comminution and recovery efficiency. This technique has a potential for the mining and minerals industry to make a step-change in reduction of the energy input per unit of final product (Bearman, 2013).

Implementation of coarse waste rejection is dependent on the geological setting and association of ore and host rock type in a deposit. In some processing plants, the Run-of-Mine (RoM) ore exhibits a size-related grade differentiation between the value hosting rock particles and barren material. Burns and Grimes (1986) reported pre-concentration of a copper ore by screening at the Bougainville copper plant operation. Based on detailed recovery-size-yield data collected from the Newcrest Telfer operation, Bowman and Bearman (2014) reported a potential application of coarse waste rejection through size-based separation for copper production.

It was found that rock strength may sometimes associate with metal grade. Modifications to the energy intensity delivered to various areas of the blast can also be implemented to induce the size-related grade differentiation for coarse waste rejection (Powell and Bye, 2009).

Despite the simplicity of a separation system using a conventional screen to achieve size-related grade splits, the success of coarse waste rejection is largely dependent on the accurate classification into a dedicated ore database. There is no doubt that ore variation will affect the waste rejection efficiency and the value loss, since the grade of the coarse waste component in the feed is not directly measured by an on-line grade measuring system before being rejected.

By contrast with the size-related waste rejection through screening, ore sorters use sensors to determine grade related physical properties. In essence, ore sorters have a better opportunity to minimise value loss during waste rejection. However, many of the currently used sensors measure particle surface properties, which are then used to infer the grade of each particle for a selection decision. It may be argued that the surface properties cannot completely represent metal grade, resulting in potential miss-classification of ore as waste or vice versa. In addition, the control and ejector system used by the sorters can be onerous in operation, as they are more complex than the simple mechanical ejector by screening.

In recent years, high voltage pulse technology has been explored for the potential application of ore pre-weakening (Wang et al., 2011; Shi et al., 2013; Shi et al., 2014b) and mineral liberation (Wang
This paper proposes a third major application: ore pre-concentration by high voltage pulses. The technique utilises metalliferous grain-induced breakdown of particles under a controlled pulse energy input, and size-based screening to separate the feed ore into body breakage and surface breakage products for splitting of ore by grade.

2. Discovery of the grade-splitting function

High voltage pulse breakage is a comminution method that uses high voltage pulses to initiate electrical breakdown inside an ore particle, generating a strong tensile force to disintegrate the particle. The mechanisms of high voltage pulse fragmentation can be found in literature, eg. Andres et al. (2001a), Bluhm (2006). It was proposed as a possible alternative to conventional breakage methods for improving mineral liberation (Andres, 1977; Anon, 1986). It was also found that high voltage pulse can be used to pre-weaken ore particles before downstream mechanical comminution, making it possible to significantly reduce the total energy consumption of the comminution process (Wang et al., 2011; Shi et al., 2014a).

Although the selective fragmentation by high voltage pulse has been known to the mineral industry for a long time, the pre-concentration application remained un-discovered until a single-particle, single-pulse test procedure for high voltage pulse breakage characterisation was proposed (Shi et al. (2013). This method was developed to replace the traditional batch test procedure, in which there was no opportunity to track the behaviour of individual ore particles subjected to electrical pulses.

The concept of pre-concentration by high voltage pulse originated from the studies of the effect of metalliferous grains on the breakage behaviour of particles (Zuo et al., 2014b, a). In these studies, natural rock particles or synthetic particles were treated by high voltage pulse using the single-particle, single-pulse test procedure. It was found that the existence and the position of metalliferous grain had a pronounced influence on the breakage behaviour of particles subjected to high voltage pulse. The natural rock particles or synthetic particles with metalliferous grains inside always produced finer progeny particles than those without.

By way of example, two groups of synthetic samples (Syn-15 and Syn-24) made of construction grout (following Zuo et al., 2014a) were tested. The synthetic samples were made using high strength grout made of quartz sand in a narrow size fraction around 300 μm and cement powder. A single pyrite grain of 2.36-3.35 mm was embedded in the centre of Syn-15 particles immediately
after the casting of paste, while Syn-24 particles were made from the grout only. The diameter and height of the synthetic particles were 38 mm and 30 mm respectively.

The two groups of synthetic samples were treated by high voltage pulse at the same machine settings. A total 30 particles for Syn-24 as the control-sample and 10 particles for Syn-15 as pyrite-bearing sample were tested to increase the statistical validity. The test result indicated that the existence of metalliferous grains dominated the breakage response of the synthetic sample to high voltage pulse. The synthetic particles with pyrite grain embedded in their centre (Syn-15) attracted electrical breakdown channel passing through the boundary of the pyrite grain, causing radial explosion from the particle centre. As a result all the Syn-15 particles were broken explosively by one high voltage pulse. By contrast, at the same pulse treatment conditions, only 43% of the synthetic particles made of pure grout (Syn-24) were broken by the first pulse under the controlled low specific energy loading.

Sample Syn-24 was found to be unsusceptible to high voltage pulse breakage compared to Syn-15, as the channel of electrical breakdown was more likely to grow along the particle surface. This resulted in only a few small fragments being stripped off the particle surface, or splitting the particle into a number of large fragments. Figure 5-1 shows the product size distributions of the synthetic samples subjected to one high voltage pulse under the same machine settings. The comparison suggests that the product of Syn-15 (82.5% passing 26.5 mm) is much finer than the product of Syn-24 (16.2% passing 26.5 mm).

![Comparison of product size distributions between Syn-15 and Syn-24 samples subjected to one pulse discharge](image)

Figure 5-1 Comparison of product size distributions between Syn-15 and Syn-24 samples subjected to one pulse discharge
Chapter 5 Development of an Ore Pre-concentration Method using High Voltage Pulses

It is worth noting that the volume of pyrite grain took up less than 0.07% of the whole synthetic particle. The difference in breakage behaviour of the synthetic particles caused by such a tiny amount of metalliferous grain reflected the significant influence of selective fragmentation mechanism in high voltage pulse breakage.

The selective fragmentation mechanism of high voltage pulse is attributed to enhancement of the electrical field intensity on the boundary of minerals with different permittivities and conductivities, as a result of the electrical polarization of the composite mineral fragments and the presented plasma streamers during the discharge of high voltage pulse (Andres et al., 2001b). In high voltage pulse breakage, disintegration of the solid is achieved by the explosive expansion of the electrical breakdown channel, which grows preferentially along the maximal electrical field in solid. Such enhancement of electrical field had been confirmed by the simulations of electrical field for particles subjected to high voltage pulse (Andres et al., 2001a; Wang et al., 2012a).

The observed difference in breakage behaviour and the product size distribution caused by metalliferous grain-induced selective breakage has led to the discovery of the ore pre-concentration technique by electrical pulses. Figure 5-2 illustrates the ore pre-concentration process, in which a single or two electrical pulses with a controlled energy are discharged to ore particles in a narrow size fraction. This causes selective breakage to the particles with high conductivity/permittivity minerals. Based on the difference in product size distributions, screening is used to separate the pulse treated product into two components. It is hypothesized that the two components have different metal grades. An experiment was conducted to prove the hypothesis and to confirm the finding of the electrical pulse pre-concentration technique.

![Figure 5-2 Process of ore pre-concentration by high voltage pulse breakage.](image-url)
3. Experiment

3.1 Material tested

Four copper ore samples were used for the experiment. Samples A, B and C were collected from a gold-copper mine operation located in New South Wales, Australia. The mining operation has one open pit and two underground mines. Sample A was SAG mill feed from Underground Mine 2 collected in 2012. Sample B was SAG mill pebbles collected in 2013 from the low grade ore concentrator when treating Underground Mine 2 ore. Mineralization in this operation can be divided into two broad overlapping zones: an upper, copper rich disseminated zone and a deeper gold-rich zone associated with sheeted veins. The upper zone mineralization is controlled within the volcaniclastic unit. The deeper zone is localized around a sheeted core characterised by quartz-calcite-bornite-chalcopyrite-molybdenite.

Sample C was another SAG mill pebble sample, collected in 2011 from the concentrator treating Underground Mine 1 ore. Mineralization occurs in dense quartz vein stockworks. The most strongly developed quartz stockwork veining and alteration, and the highest copper and gold grades, occur immediately adjacent to the monzonite in this mine. Ore minerals include bornite and chalcopyrite with lesser covellite. Gold occurs in veins and as disseminations.

Sample D was collected in 2013 from a gold-copper mine operation located in the Pilbara region of Western Australia. The host for mineralization consists of a massive to thickly bedded, metamorphosed, fine to medium grained quartzite and quartz sandstone with occasional thin interbeds of siltstone and mudstone. The sulphide mineralization is characterized by fresh sulphides, predominantly pyrite and chalcopyrite. The main copper minerals listed in order of occurrence are chalcopyrite, chalcocite and bornite with minor cobaltite and nickel-sulphide. Primary gold generally occurs as free grains, on sulphide boundaries and to a minor degree with silica grains.

The RoM ore particles to feed SAG mills (Samples A and D) were crushed and screened to obtain the required size fractions (as detailed in Section 3.2) for high voltage pulse treatment. The pebbles (Samples B and C) were screened without crushing. For each test 30 particles in the designated size fractions were randomly selected from each sample.

The ore resistance to impact breakage was characterized by the JKRBT tests (Shi et al. 2009) for the four ore samples. The $A \times b$ values (equivalent to Drop Weight Test) are 33.3 for Sample A, 31 for
Sample B, 36.6 for Sample C, and 36.6 for Sample D, respectively. The data suggest that the four samples all show very high resistance to impact breakage, particularly Samples A and B. Note that Sample B is pebble, which is more competent than the SAG mill feed (Sample A). Sample C is also pebble, which exhibits the same $A \times b$ value as the SAG mill feed of Sample D, indicating the SAG mill feed in the Sample C operation may be less competent than that in the Sample D operation.

3.2 Testing method

The samples were treated by SELFRAO Lab, a laboratory high voltage pulse unit installed at the JKMRC (Wang et al., 2011). The particles were treated using a single-particle test procedure (Shi et al., 2013). One single pulse was discharged to the particle sitting directly under the positive electrode. After the pulse loading, the process vessel was inspected. The progeny particles were classified into two groups according to breakage response: body breakage and surface breakage. If the feed particle remained intact or showed only minor surface breakage with a limited number of fragments being generated (less than 10% of the parent particle mass) after the pulse loading, it was classified as surface breakage. For particles that exhibited >10% mass loss, body breakage was deemed to have occurred. The progenies were collected separately. Each particle was treated with new de-ionised water.

A total of six tests were conducted with the four samples. Details of the tests are given in Table 5-1. The first three tests were conducted using Sample A. Tests 1 and 2 were duplicate tests to assess the variability. Test 3 was an incremental breakage test, in which the unbroken (surface breakage) particles from the first pulse were subjected to the second pulse treatment. Test 4 treated SAG mill pebbles from Sample B. Test 5 treated SAG mill pebbles from Sample C with single pulse breakage. Test 6 processed SAG mill feed from Sample D with single pulse breakage.

### Table 5-1 Testing conditions of pre-concentration by high voltage pulses

<table>
<thead>
<tr>
<th>Test number</th>
<th>Sample</th>
<th>Feed size (mm)</th>
<th>Pulse voltage (kV)</th>
<th>Electrodes gap (mm)</th>
<th>Pulse number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sample A</td>
<td>26.5-31.5</td>
<td>160</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Sample A</td>
<td>26.5-31.5</td>
<td>160</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Sample A</td>
<td>26.5-31.5</td>
<td>180</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Sample B</td>
<td>31.5-37.5</td>
<td>180</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Sample C</td>
<td>37.5-45</td>
<td>180</td>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Sample D</td>
<td>31.5-37.5</td>
<td>120</td>
<td>30</td>
<td>1</td>
</tr>
</tbody>
</table>
The energy absorbed by the electrical breakdown process (spark energy) was recorded from the operation panel of the SELFRAG Lab machine. The mass of body and surface breakage products was determined, as well as the respective product size distributions. Subsamples from the body and surface breakage products from each test were rotary divided for XRF analysis performed by Australia Laboratory Services.

4. Results and discussion

Six tests on four copper ore samples were conducted to confirm the grade-splitting discovery and to validate its potential applications for ore pre-concentration in the mineral industry. The results are reported in terms of product size distributions and copper grade distribution in the body breakage and surface breakage products.

4.1 Product size distributions

By definition when surface breakage occurs, the particle subjected to a single pulse loading would lose less than 10% of the initial mass. The parent particle is likely to remain in the initial size fraction. In contrast, body breakage is often associated with explosive disintegration, with a good chance that the majority of the fragments report to undersize. If this is confirmed, the size-based separation will be effected. Figure 5-3 displays the size distributions of the body breakage and surface breakage products from the six tests.

In Tests 1 to 3, the vast majority of the surface breakage products (up to 98.2% on average) retained in the initial size fraction (26.5-31.5 mm), while the small chips stripped off the feed particles represented only 1.8% of the total mass of the surface breakage products. Interestingly, the surface breakage product size distributions were very similar in these three tests, despite the difference in the specific energy levels (Table 5-1).

The size distribution curves of the body breakage products were distinctly different from that of the surface breakage products. On average, 75.6% of the body breakage fragments were smaller than 26.5 mm (the bottom sieve of the initial particle size fraction) in Tests 1 and 2. The difference in the amount retained in the initial particle size fraction between the surface and body breakage decreased in the incremental breakage test. In Test 3 (the first pulse survivors re-treated), 44.8% of the body breakage products were found retained on the initial feed size fraction, though the size distribution of body breakage product of Test 3 was similar to Tests 1 and 2 at the finer end (-9.5 mm).
Figure 5-3 Size distributions of the body breakage and surface breakage products treated by high voltage electrical pulses.

The duplicate tests (Tests 1 and 2) demonstrated that the size distribution curves of these two tests were similar in both body breakage and surface breakage products, showing good repeatability in the process.

In Test 4 (SAG pebbles), the proportion of body breakage product retained in its initial particle size fraction (31.5-37.5 mm) was only 7.1%. By contrast, about 97.4% of the surface breakage product retained in the initial particle size fraction. This indicates that the product of Sample B in Test 4 can be separated by simple screening at 31.5 mm. The undersize particles represented 31.6% of the initial particle mass, in which 94.4% came from the body breakage product and only 5.6% from the surface breakage product.

Test 5 (SAG pebbles) showed 6.0% of the body breakage product and 99.2% of the surface breakage product retained in the initial particle size fraction (37.5-45 mm). When screening at 37.5
mm, the undersize particles represented 57.2% of the initial particle mass, in which 99.4% came from the body breakage product and 0.6% from the surface breakage product.

Test 6 for Sample D (SAG feed) indicated that 27.2% of body breakage product and 98.0% of the surface breakage product retained in the initial particle size (31.5-37.5 mm). The mass yield of the undersize was 20.8%, of which 92.9% was from the body breakage product and 7.1% from the surface breakage product.

The comparison confirms that the size distributions of the body and surface breakage products are very different, thereby providing a viable basis for the size-based separation. If screened at the bottom sieve of the initial particle size fraction, over 90% of the undersize component comprises the body breakage product. In contrast, the oversize component may be contaminated by the body breakage product (the tests show 3% to 29% of the oversize coming from the body breakage product in the five tests using one pulse treatment). This emphasises the importance of ore pre-concentration characterisation to achieve an optimal separation between the body and surface breakage products. The definition of body breakage (lost more than 10% of the initial mass) is arguably imported from the mechanical breakage. In electrical pulse breakage, particles retained on the initial size fraction may be counted as the “unbroken” particles rather than the surface breakage product, and the undersize as “broken” particles rather than the body breakage product. This avoids the arbitrary number of 10% used in this study to classify the body or surface breakage.

4.2 Grade-splitting

Assays were performed for the pulse treated products based on the body breakage and surface breakage classification. As the four samples were all from copper-gold mining operation, copper was used as an indicator of the grade-splitting results. Table 5-2 summarises the feed size, feed grade, SELFRAG pulse specific energy, mass yield, copper grade and copper distribution in the body breakage and surface breakage products for the six tests.

4.2.1 Sample A

Tests 1 and 2 were duplicate tests. The mass yield was very similar (61.4% versus 60.9% reported to the body breakage product) in the two tests. The surface breakage product grades were also very similar (0.109% Cu versus 0.104% Cu). The grade difference in the body breakage product (0.244% Cu versus 0.186% Cu) was larger than that in the surface breakage product. The duplicate tests
indicated that at the given pulse energy input settings and the operational conditions, the cut-off metal content (i.e. the copper grade in the “unbroken” product) and the mass split between the “broken” and “unbroken” components were consistent. The difference in the body breakage product grade is attributed to the variation in the copper content in each particle in the body breakage product, which can be mitigated by adequate sampling protocols. Interestingly, the body breakage product grade was approximately twice that of the surface breakage product on average. This implies that as long as the metal content exceeds a cut-off threshold, metalliferous grain-induced breakage occurs. These particles were placed in the body breakage product, despite the variation in their metal contents. The duplicate tests tend to prove the reliability of the process; however, more data should be gathered for further investigation.

Table 5-2 Mass yield and copper grade-splitting in Tests 1 to 6

<table>
<thead>
<tr>
<th>Test</th>
<th>Feed</th>
<th>Body breakage product</th>
<th>Surface breakage product</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Size</td>
<td>Grade</td>
<td>Ecs (kWh t-1)</td>
</tr>
<tr>
<td>1</td>
<td>26.5-31.5</td>
<td>0.192</td>
<td>3.7</td>
</tr>
<tr>
<td>2</td>
<td>26.5-31.5</td>
<td>0.154</td>
<td>3.9</td>
</tr>
<tr>
<td>3</td>
<td>26.5-31.5</td>
<td>0.232</td>
<td>5.1</td>
</tr>
<tr>
<td>4</td>
<td>31.5-37.5</td>
<td>0.221</td>
<td>2.3</td>
</tr>
<tr>
<td>5</td>
<td>37.5-45</td>
<td>0.279</td>
<td>1.4</td>
</tr>
<tr>
<td>6</td>
<td>31.5-37.5</td>
<td>0.047</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Test 3 was an incremental breakage test, with the first pulse survivors (the surface breakage product) receiving the second pulse to investigate if a “scavenger” procedure can further decrease the grade of the final surface breakage product. Table 5-2 shows that 7.5% of the feed particles remained unbroken subjected to two pulses, and their grade decreased to 0.036% Cu. This is encouraging as the unbroken component after two pulses loading represented a copper loss of only 1.2% if they were rejected as waste.

The particles in Tests 1 to 3 were all from Sample A. Despite the careful sample preparation procedure using a rotary divider, variation in the feed copper grade was obvious. The back-calculated feed grades from the two breakage products are 0.192%, 0.154% and 0.232% Cu for Tests 1, 2 and 3 respectively. This variation cannot be avoided using the number of particles (30 in each test) that was practical using the laboratory scale single-particle test. More particles may be required depending on ore variability and response, and how detailed the investigation is intended to be. However, the variation in the feed grade does not significantly affect the mass yield and the
surface breakage product grade, but does affect the body breakage product grade, as shown in the duplicate Tests 1 and 2.

4.2.2 Sample B

Sample B was the SAG mill pebbles from the same mine site as Sample A, with one year separating when the two samples were collected. Table 5-2 shows that for one pulse loading at 2.3 kWh t\(^{-1}\) in Test 4, the pebbles were split into 0.306\% Cu (body breakage product) and 0.181\% Cu (surface breakage product). In the body breakage product, one can often find the particles with newly exposed metalliferous grains along the fractured surface (as marked in red circles in Figure 5-4 (a)). In comparison, Figure 5-4 (b) shows a Sample B pebble with surface breakage resulted in Test 4. An electrical breakdown channel was developed along the surface of this particle, causing the stripping of small fragments and leaving a groove on the particle surface (as marked in red dash circle). No trace of the metalliferous grains can be found on the newly exposed surface. This observation confirms the principle of metalliferous grain-induced selective breakage by high voltage pulses. It also explains the reason why the body breakage product is often associated with a higher grade.

![Image of Sample B pebbles showing body and surface breakage](image)

**Figure 5-4** The newly exposed particle surface from body breakage and surface breakage in Test 4 for Sample B SAG mill pebbles.
Chapter 5 Development of an Ore Pre-concentration Method using High Voltage Pulses

It is noted in Table 5-2 that the copper distribution in the surface breakage product is still high (55.5%), which cannot be rejected as waste. This reflects an issue in designing the pre-concentration experiment as one cannot foresee the metal distribution in relation to the pulse energy application until the pulse treatment and assaying have been completed. Therefore the results presented in Table 5-2 are only the evidence to support the grade-splitting concept, but by no means indicate the optimal outcomes. Establishing the relationship between the pulse energy input and ore response in terms of mass yield, grade and recovery will be the major task in ore pre-concentration characterisation, which will be discussed in Part 2 of this study.

To demonstrate that the Test 4 result can be improved, a supplementary test was conducted. The surface breakage product in Test 4 comprised two distinguishable groups of particles by colour. The mass yield and grade of the two groups were determined separately and combined as one pulse surface breakage product presented in Table 5-2. The XRF data indicated that the two groups of the surface breakage product had different copper grades. A scenario was investigated to see if the higher grade group of the surface breakage product can be broken with a second pulse. Separate pebble particles in Sample B were treated by high voltage pulse with the similar specific energy as for Test 4. The surface breakage product from the first pulse was subjected to the second pulse. The supplementary test confirmed that for the second pulse body breakage product is of higher grade than surface breakage product as well. Based on this experiment, the results from Test 4 were re-calculated. If the first pulse surface breakage product were scavenged with second pulse treatment, the mass yield to the surface breakage product (67.9% as shown in Table 5-2) could decrease to 26.9%. The copper grade of the surface breakage product would be reduced to 0.07%. Increasing the pulse energy in the first pulse treatment has the similar effect.

4.2.3 Sample C

The mineralogy and composition of Sample C from Underground Mine 1 are similar to Samples A and B from Underground Mine 2, but the samples were collected in different years. In the previous JKMRC study, Sample C responded well to the high voltage pulse treatment in terms of pre-weakening and liberation (Wang et al. (2012c). In the pre-concentration experiment, Sample C (SAG mill pebbles) achieved a mass yield of 60.5% to the body breakage product, which was similar to Tests 1 and 2 (61.4 and 60.9% respectively), and a copper grade of 0.114% in the surface breakage product, which was also similar to that in Tests 1 and 2 (0.109% and 0.104% respectively). The body breakage grade was remarkably higher (0.386% Cu). It is noticed that the specific energy used in Test 5 was significantly smaller (1.4 kWh t⁻¹) to achieve these pre-
concentration results, mainly attributed to the larger particle size and hence the greater mass.

4.2.4 Sample D

Sample D in Test 6 had the lowest copper grade (0.047%) in the 31.5-37.5 mm SAG mill feed. This is abnormal comparing with the typical operational head grade of approximately 0.1% Cu. The abnormality may be attributed to the insufficient number of particles (30) being used for the electrical comminution test. With 1.3 kWh t\(^{-1}\) specific energy in the pulse treatment, Sample D achieved the smallest mass yield (26.5%) to the body breakage product among the six tests. However, the copper enrichment ratio was the highest (2.2) in the six tests. The surface breakage product grade was 0.028% Cu. Since 73.5% of the feed remained in the surface breakage product, the copper metal distribution in the surface breakage product was still high (42.9%), and could not be rejected as waste. Apparently, the surface breakage product should be scavenged by the second electrical pulse, or the first pulse specific energy should be increased, to further enhance the mass yield to the body breakage product and to decrease the copper grade of the surface breakage product. Test 6 indicates that there may be a good opportunity to reject a significant amount of SAG mill feed as waste for this ore.

5. Major findings

5.1 Performance of the pre-concentration tests

The six pre-concentration tests cover a wide range of pulse specific energy from 1.3 kWh t\(^{-1}\) to 5.1 kWh t\(^{-1}\), and a mass yield of body breakage product from 26.5% to 92.5%. Figure 5-5 presents the trend between the mass yield of body breakage product and the pulse specific energy.

Sample A and Sample B used in Tests 1 to 4 were collected from the same mine. As expected, the four tests fall on the same trend line showing that the mass yield of body breakage product increases with the pulse specific energy. Compared with the trend line for Tests 1 to 4, Sample C in Test 5 and Sample D in Test 6 were more liable to body breakage subjected to the same pulse specific energy. For example, to achieve a mass yield of body breakage product of 60.5%, Sample C in Test 5 consumed 1.4 kWh t\(^{-1}\), while Sample A in Tests 1 and 2 required 3.7 kWh t\(^{-1}\) and 3.9 kWh t\(^{-1}\) respectively. It is assumed that mineralogy and morphology of the ore play an important role to the different responses as shown in Figure 5-5. More detailed study is required, which will be further discussed in Part 2 of this study.
Figure 5-5 Mass yield of body breakage product in relation to pulse specific energy of the six pre-concentration tests

Figure 5-6 displays the copper deportment to body breakage product in relation to mass yield of body breakage product. The diagonal line Y=X represents a benchmark without enrichment (i.e. the grades of feed, body breakage and surface breakage products being identical). If pre-concentration occurs, the copper deportment to body breakage product must be higher than the mass yield of the body breakage product. Figure 5-6 shows that all data from the six tests are above the diagonal line, indicating that the increase in copper deportment to body breakage product exceeds the mass yield of body breakage product. This gives a conclusive evidence to support the electrical pulse pre-concentration concept. Also included in Figure 5-6 are the SELFRAG pulse specific energy used in each test. The data suggest that for the same ore samples (e.g. Tests 1-4), the pulse specific energy is well correlated to the mass yield and the copper deportment to body breakage product. For different ores, however, the energy trend is not clear. This indicates that both machine operating conditions in terms of specific energy loading and the ore properties affect the pre-concentration results.

Table 5-3 Comparison of mass yield and copper grade-splitting for ore sample A between electrical comminution (Average Tests 1 and 2) and mechanical comminution

<table>
<thead>
<tr>
<th>Test</th>
<th>Feed Size (mm)</th>
<th>Grade (%)</th>
<th>Body breakage product Mass (%) Grade (%) Cu Dist. (%)</th>
<th>Surface breakage product Mass (%) Grade (%) Cu Dist. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elect.</td>
<td>26.5-31.5</td>
<td>0.173</td>
<td>61.2</td>
<td>0.215</td>
</tr>
<tr>
<td>Mech.</td>
<td>22.4-26.5</td>
<td>0.181</td>
<td>53.5</td>
<td>0.170</td>
</tr>
</tbody>
</table>
In order to compare copper deportment between the electrical comminution and conventional mechanical breakage, a specially designed JKRBT test was performed. 30 particles in the size range 22.4-26.5 mm from Ore sample A were randomly selected. The JKRBT test was controlled at a specific energy 0.1 kWh t^{-1}, at which approximately half of the feed particles were broken at the first impact, and the rest showing surface breakage. A 22.4 mm sieve was utilised to separate the JKRBT product into body breakage and surface breakage products. The two products were assayed by XRF respectively. The results are given in Table 5-3. For comparison, the averaged results of Tests 1 and 2 by electrical comminution are also presented in Table 5-3. The mechanical breakage result in terms of mass yield and the copper deportment to the body breakage product is plotted in Figure 5-6 as well. Figure 5-6 shows that the mechanical breakage result is close to the Y=X benchmark line. This indicates that the mechanical breakage did not achieve preferential breakage of the copper-rich particles, and did not result in pre-concentration. The JKRBT breakage result gives a reference to assess the true value of the pre-concentration technique using high voltage pulses in comparison with the conventional mechanical breakage.

5.2 Size-based versus breakage mode-based separation

In the six tests, the products were separated based on the breakage modes, i.e. body breakage or surface breakage, and the grade and metal distribution given in Table 5-2 were all determined based
on the breakage mode. It is noted that some particles classified as body breakage product were still retained on the initial particle size fraction due to the particle shape effect, despite the fact that they lost more than 10% mass. If the pulse treated product were separated by screening, as designed in Figure 5-2, these particles would be separated into the oversize product, together with the surface breakage particles. Therefore the results given in Table 5-2 based on breakage mode may represent the optimal separation conditions for the pulse treated products, ignoring the efficiency in the size-based separation.

To evaluate the effect of size-based separation on the pre-concentration results, two supplementary tests were conducted using ore Sample A (31.5-37.5 mm). Two separation scenarios were investigated: breakage mode-based and size-based separation. The breakage mode-based separation was initially used to divide the pulse treated product into body breakage (lost more than 10% of the initial mass) and surface breakage; whilst the size-based separation was done by screening at undersize sieve of the feed. During the separation procedure, the body breakage fragments were also hand-screened by a sieve with an aperture 31.5 mm (the bottom feed size). The separation in this investigation provided three products: Body breakage -31.5 mm, body breakage +31.5 mm and surface breakage +31.5 mm. The three products were weighed and assayed separately. The feed data were back calculated from the three products. According to the three product data, the breakage mode-based and the size-based results were calculated and presented in Table 5-4.

<table>
<thead>
<tr>
<th>Product</th>
<th>Supplementary Test S1</th>
<th>Supplementary Test S2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass (%)</td>
<td>Grade (Cu%)</td>
</tr>
<tr>
<td>Back calculated feed</td>
<td>100.0</td>
<td>0.162</td>
</tr>
<tr>
<td>Screen undersize</td>
<td>51.6</td>
<td>0.200</td>
</tr>
<tr>
<td>Screen oversize</td>
<td>48.4</td>
<td>0.122</td>
</tr>
<tr>
<td>Body breakage product</td>
<td>62.8</td>
<td>0.187</td>
</tr>
<tr>
<td>Surface breakage product</td>
<td>37.2</td>
<td>0.119</td>
</tr>
</tbody>
</table>

Comparing the two separation modes (breakage mode-based and screen-based) found that the mass yield to the undersize product decreased if separated by the screen-based mode (62.8% and 60.1% for the breakage mode-based in Tests S1 and S2 respectively, versus 51.6% and 50.6% for the
screen-based). The copper grades in both undersize and oversize products increased slightly for the screen-based separation. The supplementary tests given in Table 5-4 provide the reference data if the results in Table 5-2 are required to convert from the breakage mode-based separation to the size-based separation.

Comparison of the breakage mode-based results for Test 2 (Table 5-2) and Test S1 (Table 5-4), both using ore Sample A, indicates that the results were similar. For example, the mass yield to the body breakage product, the body breakage grade and the surface breakage grade were 60.9%, 0.186% Cu and 0.104% Cu for Test 2, and 62.8%, 0.187% Cu and 0.119% Cu for Test S1 respectively. Note that Test 2 and Test S1 were conducted approximately a half year apart. This comparison confirms the consistency of the technology.

5.3 Interaction of multiple metalliferous minerals

Multiple metalliferous minerals with high conductivity/permittivity may co-exist in one particle. When subjected to an electrical pulse, the electrical field distribution in the particle will be affected by the joint interaction of these metalliferous minerals with the electrical field, which is thought to determine the particle breakage mode. Table 5-5 lists the major elements/minerals and their grades in the body breakage and surface breakage products in Test 1.

<table>
<thead>
<tr>
<th>Product</th>
<th>Cu</th>
<th>Fe</th>
<th>K₂O</th>
<th>MgO</th>
<th>Mn</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body breakage</td>
<td>0.244</td>
<td>3.64</td>
<td>2.98</td>
<td>2.77</td>
<td>0.05</td>
<td>59.6</td>
<td>0.63</td>
<td>15.5</td>
<td>4.81</td>
<td>0.37</td>
</tr>
<tr>
<td>Surface breakage</td>
<td>0.109</td>
<td>3.57</td>
<td>2.68</td>
<td>2.68</td>
<td>0.04</td>
<td>58.5</td>
<td>0.55</td>
<td>17.55</td>
<td>4.56</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Table 5-5 demonstrates that the copper content in the body breakage product is more than twice that in the surface breakage product. The other metalliferous minerals in the body breakage product are marginally greater than in the surface breakage product, except Al₂O₃. In this case the copper grains may dominate the breakage mode.

However, an abnormal trend of ore grade splitting was encountered when treating a Cu-Fe ore sample from South America. The valuable minerals of this ore consist of chalcopyrite, magnetite, minor pyrite, and trace molybdenite. Alteration minerals closely associated with chalcopyrite include amphibole, epidote, apatite, calcite, quartz, and locally biotite. It was found that the body
breakage product contained much less Cu (0.04%) than the surface breakage product (0.58%). It was also found that the surface breakage product had a much higher Fe grade (47.9%) than the body breakage product (10.3%). One can imagine that a particle containing 47.9% Fe, may behave like an electrical conductor due to the high abundance of iron oxide minerals to bypass the electrical pulse energy without causing damage to the particle. Obviously, more detailed research is required to understand the interactions of multiple metalliferous minerals under high voltage pulse loading.

The mining and mineral industry may be more interested in how their ores respond to the electrical pulse pre-concentration technique. In the abovementioned Cu-Fe ore example, if high Cu grade is consistently associated with high Fe grade, the size-based separation can function effectively to achieve the grade-splitting, regardless of whether the high grade valuable minerals reported to the oversize or undersize products. Therefore, accurate ore pre-concentration characterisation plays an important role in the success of this novel technology.

Although the results presented in this paper are all from copper ores, the electrical pulse pre-concentration technique may also be applied to other mineral ores as well. Part 2 of the study presents more detailed discussions for ore pre-concentration characterisation and fundamental study of the ore grade-splitting mechanisms.

5.4 Pulse energy efficiency associated with the breakage mode

There was an energy efficiency factor involved in the generation and transferring of high voltage pulse from pulse generator to electrical breakdown process, which can be attributed to two reasons. Firstly, it is unavoidable that part of the generator energy will be lost into the pulse generator and the liquid dielectric surrounding the particle (Bluhm, 2006). Secondly, the efficiency of the SELFRAF machine is compromised because of the safety considerations and the fact that ease of use and minimal sample loss are important (van der Wielen et al., 2013). This means that the energy consumption of the SELFRAF machine (pulse energy) is higher than the energy transferred to the electrical breakdown process (spark energy). (van der Wielen et al., 2013) used a ratio of spark energy to pulse energy as an indicator of electrical efficiency of high voltage breakage (here termed $C_{ET}$).

The pre-concentration tests found that the efficiency of energy transfer was strongly related to the particle breakage mode (i.e. body breakage or surface breakage), and was correlated to the copper grade associated with the breakage mode. Table 5-6 presents the average spark energy (recorded
from the display panel) and the energy transfer efficiency for body breakage and surface breakage in the six tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Average spark energy (J)</th>
<th>Energy transfer efficiency $C_{ET}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Body breakage</td>
<td>Surface breakage</td>
</tr>
<tr>
<td>1</td>
<td>332.2</td>
<td>241.0</td>
</tr>
<tr>
<td>2</td>
<td>343.4</td>
<td>225.8</td>
</tr>
<tr>
<td>3</td>
<td>353.7</td>
<td>260.8</td>
</tr>
<tr>
<td>4</td>
<td>486.0</td>
<td>401.0</td>
</tr>
<tr>
<td>5</td>
<td>546.8</td>
<td>431.3</td>
</tr>
<tr>
<td>6</td>
<td>245.7</td>
<td>164.7</td>
</tr>
</tbody>
</table>

Note that Test 3 was performed with two incremental pulses. To be consistent with other tests, the first pulse energy in Test 3 was used in Table 5-6. In Test 6 the display panel showed zero spark energy for a number of particles in the surface breakage product. These particles with zero energy readings were excluded in the energy calculations for the surface breakage product (otherwise the difference would be even greater).

The energy transfer efficiency ($C_{ET}$) is defined as the ratio of spark energy to pulse energy. The spark energy (J) is recorded from the SELFFRAG display panel, and the pulse energy (J) is calculated by $E_p = \frac{1}{2} CU^2$, where $C$ is the capacitance (F) and $U$ is the voltage (V) of the pulse from a generator.

In all six tests, the average spark energy levels and the energy transfer efficiencies for body breakage were significantly higher than that for surface breakage. Statistical analysis t-tests were performed on the $C_{ET}$ values listed in Table 6 and concluded that the energy transfer efficiency between the body breakage and surface breakage was different at over 95% significance.

Samples A, B and C were collected from the same mine operations. The relationship between the average $C_{ET}$ values and the copper grades of body or surface breakage products in the five tests with these three samples is showed in Figure 5-7. The average $C_{ET}$ values have a positive linear relationship with the copper grade. The body breakage product of Test 5 has the highest copper grade (0.386%). Correspondingly, up to 90% of pulse energy on average was converted to spark energy. The surface breakage product of Test 3 has the lowest copper grade (0.036%), which generated a mean energy transfer efficiency $C_{ET}$ as low as 0.43.
The similar phenomenon had also been observed in the study with synthetic samples. When the two groups of synthetic samples were tested, it was found that the existence of pyrite grains not only resulted in preferential body breakage, but was also associated with higher spark energy. On average, 14% more spark energy was recorded in processing the synthetic samples with pyrite grains inside.

The relation between energy transfer efficiency $C_{ET}$ and copper grade for Ore sample D in Test 6 is abnormal. Tests 5 and 6 have the similar energy transfer efficiencies for body breakage (0.90 versus 0.91), but their body breakage mass yields (60.5% versus 26.5%) and body breakage product grades (0.386% Cu versus 0.102% Cu) are very different. This may reflect that for the very low grade ore, pulse energy loading (Test 6 used the smallest energy 1.3 kWh t$^{-1}$ among the six tests) should be increased to enhance the body breakage rate. This example further emphasises the need for ore characterisation to establish a curve of pulse energy in relation to body breakage mass yield. The characterisation curves can be used to optimise the pre-concentration process. This will be further discussed in Part 2 of this study.

The data suggest that the $C_{ET}$ values in the electrical pulse pre-concentration may have a potential to be used as an indicator of the metal grade of a particle for on-line monitoring. This requires detailed calibration to establish a database for an ore deposit or a mine of interest.
6. Conclusion

The development of single-particle, single-pulse test and the study on metalliferous grain-induced breakdown channel using synthetic particles has led to the discovery of a novel technique for ore pre-concentration using high voltage electrical pulses. Four copper ore samples were tested to demonstrate the viability of this technique. Particle size distributions of the body breakage and surface breakage products from six tests on the four copper ore samples are presented. The mass yield, copper grade, and copper distribution in the body breakage and surface breakage products are reported. The data provide evidence to support the ore pre-concentration concept using metalliferous mineral-induced selective breakage subjected to high voltage pulse loading, and size-based separation.

Four major findings in developing the high voltage pulse pre-concentration technique are reported. These include the pre-concentration performance evaluation, correlation between the breakage mode-based separation and the size-based separation, the interaction of multiple metalliferous minerals, and the pulse energy transfer efficiency.

The technique may have a potential to be applied for other mineral ores. Part 2 of this study gives detailed discussions on the new opportunities and challenges for the mining and mineral industry to take up this technology.

7. Acknowledgement

The financial support from Newcrest Mining for a PhD candidate in this study is acknowledged. The detailed comments from the journal reviewers are gratefully appreciated.
Chapter 6  Characterization of Ore Pre-weakening Effect

6.1 Introduction

Currently the effect of the pre-weakening of ore particles by high voltage pulses is evaluated by the percentage change of $A \times b$ values between pulse–treated and untreated ore particles. However, the percentages change of $A \times b$ values is only a relative index for pre-weakening degree. In order to characterize ore pre-weakening effect, this chapter introduces a $t_{10}$-based method which can predict the degree of size reduction, $t_{10}$, of the pulse-treated particles from that of the untreated particles broken at the same size/energy level.

In the previous studies, the standard or reduced JKRBT tests (Shi et al., 2013) had been used to determine the pre-weakening degree of the pulse-treated particles. These tests require preparation of the narrowly sized particles, and sizing the JKRBT product for each feed. Not only the procedures take excessive time, but also present a burden in supplying sufficient pulse-treated particles in the desired size fractions. With the support of the $t_{10}$-based method, a Wide-size JKRBT characterisation method was developed in this chapter. A spreadsheet of the data reduction of Wide–size JKRBT breakage characterisation using $t10$-based model is given in Appendix II.

6.2 Contributions

This chapter presents two major contributions in a format of two journal papers respectively:

• A $t_{10}$-based method was developed to evaluate the degree of pre-weakening and to assess energy reduction due to the pre-weakening effect in the downstream mechanical comminution process.

• A Wide-size JKRBT breakage testing method using feed particles in a wide size class. This presents significant benefits in ore breakage characterisation, for both HVP product and mechanically broken particles. The principle of the Wide-size JKRBT method can be adopted for on-line ore competence measurement for the mining industry.
Chapter 6 Characterization of Ore Pre-weakening Effect

A $t_{10}$-based method for evaluation of ore pre-weakening and energy reduction

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ABSTRACT

Currently the effect of the pre-weakening of ore particles by high voltage pulses is evaluated by the percentage change of $A \times b$ values between pulse–treated and untreated ore particles. The values of $A \times b$, widely used as an ore breakage competence indicator in the mineral industry, are determined from the parameters of the JKMRC breakage models. In this study a $t_{10}$-based method was developed to predict the degree of size reduction, $t_{10}$, of pulse-treated particles from that of untreated particles broken at the same size/energy level. This method incorporates one parameter, $C_{Ab}$, which is equivalent to the percentage change of $A \times b$ values.

The $t_{10}$-based method was validated using nine sets of comparative JK Rotary Breakage Tester data on pulse-treated and untreated ore samples over a wide range of impact specific energies and particle sizes. The $t_{10}$-based method can be used to calculate the energy reduction due to the pre-weakening effect in the downstream comminution process. It indicates that the energy reduction by pre-weakening increases with an increase in the target product fineness and the degree of pre-weakening, and with the decrease in feed particle size.

Keywords: Pre-weakening characterization; Breakage model; High voltage pulse.

1. Introduction

Comminution is the most energy intensive process in the mining industry. It has been reported that comminution consumes, on average, 36% of the energy utilized by the industry (Ballantyne et al.,
Chapter 6 Characterization of Ore Pre-weakening Effect

As one of the potential technical means of reducing the energy consumption of comminution, pre-weakening of ore particles by high voltage pulses (HVP) has attracted the attention of researchers over the past few years (Usov and Tsukerman, 2006; Wang et al., 2011; van der Wielen et al., 2013; Razavian et al., 2014). Pre-weakening, liberation (Andres, 1977, 1995; Andres et al., 2001a; Lastra and Carbri, 2003; Ito et al., 2006; Cabri et al., 2008) and the recently reported pre-concentration (Shi et al., 2015b; Zuo et al., 2015a) are the three applications of HVP breakage technology. In breakage using HVP, a high voltage electrical pulse is transferred to the solid dielectric immersed in water, causing electrical breakdown and disintegration (Andres, 1995). Systematic research on the pre-weakening of ore particles by high voltage pulse has been conducted at the Julius Kruttschnitt Mineral Research Centre (JKMRC) since 2007 (Shi et al., 2014b). The research found that the breakage resistance of a number of ores can be reduced significantly by HVP breakage at a low specific energy (Wang et al., 2011), and thus the energy consumption of the downstream comminution process can be reduced.

In order to evaluate the effect of pre-weakening by HVP, the percentage change of $A \times b$ values between the pulse-treated and untreated ore particles has been used as an indicator of the degree of pre-weakening (Wang et al., 2011; van der Wielen et al., 2014). A pre-weakening index that is defined as the ratio of the percentage change of $A \times b$ to the specific pulse energy is introduced to assess the pre-weakening efficiency and ore pre-weakening amenability (Shi et al., 2013). In the pre-weakening index, $A$ and $b$ are the parameters of the JKMRC breakage model Eq. (6-1) (Napier-Munn et al., 1996).

$$t_{10} = A \left(1 - e^{-bE_{cs}}\right)$$  \hspace{1cm} (6-1)

where $t_{10}$ is defined as the cumulative mass percentage of the product passing $1/10$th of the initial feed size; $E_{cs}$ is the mass specific comminution energy (kWh t$^{-1}$).

The $A$ and $b$ parameters can be obtained by fitting the JKMRC breakage model to single particle impact testing data acquired from the JK Drop Weight Tester (JKDWT) (Napier-Munn et al., 1996) or the JK Rotary Breakage Tester (JKRBT) (Shi et al., 2009). The product $A \times b$ has been used as an indicator of ore resistance to breakage. A larger $A \times b$ value indicates the less competent ore, or less resistance to breakage. By taking the derivative of Eq. (1), it can be proved that $A \times b$ is the slope of the $t_{10}E_{cs}$ curve at ‘zero’ input energy (Napier-Munn et al., 1996). Many mineral processing engineers and researchers use the $A$ and $b$ parameters in their comminution circuit design,
Chapter 6 Characterization of Ore Pre-weakening Effect

Shi and Kojovic (2007) reported a model to describe the degree of breakage, which is modified from a breakage probability model published by Vogel and Peukert (2004). This model (Eq. (6-2)) takes a form similar to the JKMRC breakage model (Eq.(6-1)):

\[ t_{10} = M\{1 - exp[-f_{mat} \cdot x \cdot k(E - E_{min})]\]  \hspace{1cm} (6-2)

where \( M \) (%) represents the maximum \( t_{10} \) for a material subject to breakage, \( f_{mat} \) (kg J\(^{-1}\)m\(^{-1}\)) is the material breakage property, \( x \) (m) the initial particle size, \( k \) the successive number of impacts with the same impact energy, \( E \) (J kg\(^{-1}\)) the mass-specific impact energy, and \( E_{min} \) (J kg\(^{-1}\)) the threshold energy. In this paper, \( k \) and \( E_{min} \) are set at 1 and 0 respectively.

Shi and Kojovic (2007) found that the fitted material property parameter \( f_{mat} \) is not a constant, but is closely related to particle size. This has been confirmed with numerous JKDW and JKBBT data. They use an equation to describe the parameter \( f_{mat} \) in relation to particle size, which takes the following form (Shi et al., 2015a):

\[ f_{mat} = p \cdot d^{-q} \]  \hspace{1cm} (6-3)

Note that the unit of particle size \( d \) in Eq. (6-3) is mm. By substituting Eq. (6-3) into Eq. (6-2), three model parameters, \( M, p, q \), can be determined simultaneously from the data of one breakage test. The advantage of using parameters \( M, p, q \), instead of the parameters \( A, b \) in the JKMRC breakage model (Eq. (6-1)) is that the effect of particle size on the breakage response can be directly quantified using the test results. Eqs. (6-2) and (6-3) therefore constitute a size-dependent breakage model.

Eqs. (6-1) and (6-2) take a similar exponential form, and the parameters of the two equations are convertible. The ore breakage resistance indicator \( A \times b \) in Eq. (6-4) can be calculated from the parameters in Eqs. (6-2) and (6-3) using the following relationship (Shi and Kojovic, 2007):

\[ A \times b = 3600 \cdot M \cdot f_{mat} \cdot x = 3.6 \cdot M \cdot p \cdot d^{(1-q)} \]  \hspace{1cm} (6-4)
where $d$ takes a unit of mm, and $x$ in m, the constant 3600 or 3.6 is used for unit conversion. Eq. (6-4) gives the size-specific $A \times b$ values. In this paper, all the $A \times b$ values are calculated specifically for 32.5 mm, the mean size for the five size fractions used in a standard JKDWT test.

In a standard JKDWT test, particles in five size fractions are tested, each with three specific energy levels. At each size/energy level 30 particles are tested in a single-particle breakage mode. The testing procedures are time-consuming, taking typically two days to complete the characterisation of one sample. In a standard JKRBT test, four of the five size fractions in the JKDWT are tested, each with three energy levels. With the feature of rapid breakage operation, the time used for impact breakage in the JKRBT is reduced significantly compared to the JKDWT. However, the amount of material needed for a characterisation test, and the time required for sample preparation and product size analysis are still burdensome. Because of this, a reduced JKRBT test was developed (Shi et al., 2013), in which impact breakage treatments at five selected size/energy levels are used to achieve similar results to those using the standard 12 size/energy levels. The reduced JKRBT test provides a reliable breakage characterization method with significantly reduced material and time consumption.

The standard and the reduced JKRBT tests do not use all particles in the feed; only particles in the designated size fractions are used. In a test to characterise the pre-weakening effect, sufficient material is required in those designated size fractions. This may present a burden in the sample preparation process, such as the one using HVP in a single-particle treatment mode. An $A \times b$ Express test was sometimes adopted to quickly estimate the $A \times b$ value (Shi et al., 2013). The $A \times b$ value is estimated as the ratio of $t_{10}$ to $E_{cs}$ of the impact breakage for one size of particles tested at a single low specific energy. A large variation in the $A \times b$ values was often observed in the $A \times b$ Express test, largely due to the selection of the pulse-treated particles for the $A \times b$ Express test. In addition, the $A \times b$ Express test cannot provide breakage appearance function or a size reduction-energy map if the characterization is for a more detailed simulation study, eg. for the AG/SAG mill model or crusher model.

This paper presents a new method for evaluation of ore pre-weakening effect, using the known $t_{10}$ data of the pulse-untreated sample as a benchmark.

2. Data acquisition

Nine sets of data were collected for the development of the $t_{10}$-based method. Each set of data
consists of two JKRBT tests for pulse-treated and untreated particles respectively. The first five sets of data were collected from the current work, and the last four sets of data were from the previous work (Wang et al., 2011). Table 6-1 summarises the details of the data.

Table 6-1 Summary of the data range used to develop the $t_i$-based method

<table>
<thead>
<tr>
<th>Test</th>
<th>Ore source</th>
<th>Metal prod.</th>
<th>$A \times b_{(RBT)}$</th>
<th>HVP feed size (mm)</th>
<th>Pulse (kWh $t^{-1}$)</th>
<th>JKRBT testing size (mm)/energy (kWh $t^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ore 1</td>
<td>Au/Cu</td>
<td>42.0</td>
<td>26.5-53</td>
<td>2.0</td>
<td>26.5-31.5/2.5; 19-22.4/0.25, 1; 13.2-16/0.25, 1.0</td>
</tr>
<tr>
<td>2</td>
<td>Ore 1</td>
<td>Au/Cu</td>
<td>42.0</td>
<td>26.5-45</td>
<td>4.0</td>
<td>19-22.4/0.25, 1, 2.5; 13.2-16/0.25, 1, 2.5; 9.5-11.2/0.25, 1, 2.5; 5.6-6.7/0.25, 1, 2.5;</td>
</tr>
<tr>
<td>3</td>
<td>Ore 2</td>
<td>Au/Cu</td>
<td>42.5</td>
<td>37.5-45</td>
<td>2.0</td>
<td>37.5-45/0.1; 26.5-31.5/2.5; 19-22.4/0.25, 1; 13.2-16/1.0</td>
</tr>
<tr>
<td>4</td>
<td>Ore 3</td>
<td>Au/Cu</td>
<td>35.2</td>
<td>37.5-45</td>
<td>1.8</td>
<td>37.5-45/0.1, 2.5; 26.5-31.5/0.1, 1, 2.5; 19-22.4/0.1, 1, 2.5; 13.2-16/0.1, 1, 2.5</td>
</tr>
<tr>
<td>5</td>
<td>Ore 4</td>
<td>Cu</td>
<td>44.8</td>
<td>26.5-45</td>
<td>4.6</td>
<td>31.5-37.5/0.1, 0.25; 26.5-31.5/2.5; 19-22.4/0.25; 13.2-16/1.0</td>
</tr>
<tr>
<td>6</td>
<td>Ore 5</td>
<td>Cu/Au</td>
<td>39.0</td>
<td>37.5-45</td>
<td>2.4</td>
<td>26.5-37.5/0.17, 0.45, 0.95; 22.4-26.5/0.16, 0.44, 0.92; 16-19/0.16, 0.42, 0.89</td>
</tr>
<tr>
<td>7</td>
<td>Ore 6</td>
<td>Pb-Zn</td>
<td>56.6</td>
<td>37.5-45</td>
<td>2.0</td>
<td>26.5-37.5/0.17, 0.45, 0.95; 22.4-26.5/0.16, 0.44, 0.92; 16-19/0.16, 0.42, 0.89</td>
</tr>
<tr>
<td>8</td>
<td>Ore 7</td>
<td>Cu/Au</td>
<td>78.0</td>
<td>16-19</td>
<td>6.5</td>
<td>16-19/0.16, 0.42, 0.89; 12.5-16/0.16, 0.42, 0.88; 9.5-12.5/0.15, 0.41, 0.87; 6.7-9.5/0.15</td>
</tr>
<tr>
<td>9</td>
<td>Ore 8</td>
<td>Au/Cu</td>
<td>49.6</td>
<td>37.5-45</td>
<td>1.1</td>
<td>26.5-37.5/0.02, 0.42, 0.88; 19-26.5/0.04, 0.42, 1.36; 13.2-19/0.04, 0.43, 1.36; 9.5-13.2/0.08, 0.89, 1.85</td>
</tr>
</tbody>
</table>

The ores used for the HVP pre-weakening and JKRBT characterisation tests were collected from various mines. Ores 1, 2, 3 and 8 were collected from a gold-copper mine operation in New South Wales, Australia. Ore 4 was from an iron oxide copper-gold deposit in Brazil. Ore 5 was from a copper deposit in New South Wales, Australia. Ore 6 (lead-zinc ore) and 7 (copper-gold ore) were both from Queensland, Australia.

In the HVP treatment process a single-particle, single-pulse method was used for Tests 1-5 in an incremental breakage mode, i.e. the unbroken particles were subjected to another pulse loading until they were broken (Shi et al., 2013). Particles in narrow particle size fractions were tested in the HVP process. For example, Table 1 shows HVP feed size 26.5-53 mm for Test 1, which actually consists of 26.5-31.5 mm, 31.5-37.5 mm, 37.5-45 mm and 45-53 mm. The pulse energy listed in
Table 1 is the weighted average of the specific energy of all sizes tested.

For Tests 6-9, the traditional 700 g HVP batch tests were performed in the similar incremental breakage mode, with oversize particles accumulated and returned for another batch test. In each batch test, multiple pulses were loaded during the HVP treatment. The cumulative specific energy was recorded and presented in Table 6-1.

The JKRB characterisation tests were conducted on the pulse-treated and untreated materials respectively. According to the availability of particles in the HVP products, various size-energy combinations were selected in their JKRB tests. Details of the particle sizes and energy levels used in the JKRB tests are given in Table 6-1. Note that the number of tests for each JKRB characterisation is different.

3. Development of the $t_{10}$-based method

3.1 Observed $t_{10}$ trends of the JKRB tests between the pulse-treated and untreated particles

The trend of the JKRB product $t_{10}$ values between the pulse-treated particles ($t_{10p}$) and untreated particles ($t_{10u}$) is presented in Figure 6-1, in which each pair of $t_{10u}$ and $t_{10p}$ values are from the impact breakage at the same size/energy level. The observed trends can be summarised as follows:

- The majority of the $t_{10p}$ values are above the diagonal line ($y=x$), indicating that the pulse-treated particles achieve a larger degree of breakage when the same size of particles are subjected to the same specific energy in the subsequent mechanical breakage, compared with the untreated particles.

- The relation between each pair of $t_{10p}$ and $t_{10u}$ follows the same trend across all the feed size fractions, suggesting that the improvement in the breakage degree (represented by $t_{10}$) follows a trend independent of particle size.

- The relationship between $t_{10p}$ and $t_{10u}$ appears non-linear, suggesting that the ratio of $t_{10p}$ to $t_{10u}$ is not a constant, but varies with the value of $t_{10u}$. 
3.2 Modelling the pre-weakening effect using a \( t_{10} \)-based method

Based on the observed trends in Figure 6-1, a term, \( R_{t_{10}}(i) \), is adopted to describe the relationship between \( t_{10p} \) and \( t_{10u} \). The term \( R_{t_{10}}(i) \) is defined as the ratio of \( t_{10p} \) to \( t_{10u} \) for the same particle size and impact energy level (Eq. (6-5)). It is worth noting that the term \( R_{t_{10}}(i) \) is not a constant for one pulse-treated sample, but varies with \( t_{10u} \).

\[
R_{t_{10}}(i) = \frac{t_{10p}(i)}{t_{10u}(i)}
\]  

(6-5)

where \( t_{10p} \) and \( t_{10u} \) are obtained from the JKRBT test for the pulse-treated and untreated particles at the same size and impact energy levels.

As shown in Eq. (6-5) the untreated \( t_{10u} \) is used as the benchmark to calculate the term \( R_{t_{10}}(i) \). Any minor variation in \( t_{10u} \) will cause a large change in the calculated \( R_{t_{10}}(i) \). As each \( t_{10u} \) value was
produced using 30 different ore particles, the raw \( t_{10u} \) data were more susceptible to the ore variation. The size-dependent breakage model (Eqs. (6-2) and (6-3)) was employed to fit the raw data of each test, and the fitted model parameters \((M, p \text{ and } q)\) were used to generate the smoothed \( t_{10u} \) as the benchmarks in determining the \( R_{t10}(i) \) values. It is believed that the smoothed \( t_{10u} \) values would better represent the true breakage characteristics as they are defined using more constrained data points than the individual raw data. Figure 6-2 presents the trend of \( R_{t10}(i) \) in relation to the smoothed \( t_{10u}(i) \). Despite the data appearing scattered in some tests, a general trend that \( R_{t10}(i) \) has a negative linear relationship with \( t_{10u}(i) \) can be represented by Eq. (6-6):

\[
R_{t10}(i) = -\alpha t_{10u}(i) + \beta
\]

where \( \alpha \) and \( \beta \) are positive constants.

![Figure 6-2](image)

**Figure 6-2** The linear relationship between the calculated \( R_{t10}(i) \) (Eq. (6-5)) and the smoothed \( t_{10u} \) using Eqs. (6-2) and (6-3)

It is reasonable to assume that when \( t_{10u} \) approaches 100, \( t_{10p} \) at the same size/energy level also reaches 100 (as shown in Figure 6-1 \( t_{10p}\approx t_{10u} \)). This means a boundary point when \( t_{10u}=100\).
$R_{t_{10}}(i)=1$. Therefore, Eq. (6-6) can be rewritten as:

$$R_{t_{10}}(i) = 1 + \frac{C_{Ab}}{10,000} [100 - t_{10u}(i)] \tag{6-7}$$

where $C_{Ab}$ is a constant (%) to be determined by model fitting. Comparing Eqs. (6-6) with (6-7), one can find $\frac{C_{Ab}}{10,000} = \alpha$ and $1 + \frac{C_{Ab}}{100} = \beta$.

Thus, the values of $t_{10p}(i)$ can be predicted from $t_{10u}(i)$ at the same size/energy level by substituting Eq. (6-7) into Eq. (6-5) and rearranging the equation to give:

$$t_{10p}(i) = \left\{ 1 + \frac{C_{Ab}}{10000} [100 - t_{10u}(i)] \right\} t_{10u}(i) \tag{6-8}$$

Eq. (6-8) presents the mathematical description of the $t_{10}$-based method to evaluate the pre-weakening effect.

### 3.3 Validation of the $t_{10}$-based method

Eq. (6-8) was used to fit the JKRBT test data for pulse-treated samples. In each test, only one model parameter, $C_{Ab}$, was fitted. The smoothed $t_{10u}(i)$ values were used as the benchmarks to calculate the pulse-treated $t_{10p}(i)$ for each test. In comparison, the size-dependent breakage model (Eqs. (6-2) and (6-3)) was employed to fit the same JKRBT tests data for pulse-treated samples. Figure 6-3a shows the fitting results using the size-dependent breakage model (Eqs. (6-2) and (6-3)), and Figure 6-3b presents the fitting results using the $t_{10}$-based method (Eq. (6-8)). The coefficient of determination ($R^2$) is used to evaluate the fitting quality. The $R^2$ values of the fittings using size-dependent model and $t_{10}$-based method are 0.987 and 0.984 respectively. The $R^2$ values in both cases are very close to 1, which indicates that the $t_{10}$-based method can achieve as good a fitting quality as the size-dependent model.
4. Applications

4.1 Evaluation of pre-weakening effect

To evaluate the degree of pre-weakening by HVP, a term of percentage change of $A \times b$ has been used (Wang et al., 2011; Shi et al., 2013), which is defined as:

$$PW = \frac{(A \times b)_p - (A \times b)_u}{(A \times b)_u} \cdot 100\%$$  \hspace{1cm} (6-9)

where PW is the degree of pre-weakening (%).

The $t_{10}$-based method can provide a direct evaluation of the PW. By taking the derivative of Eq. (6-5):

$$R_{t10}(0) = \frac{dt_{10p}}{dt_{10u}}$$

Both numerator and denominator are divided by $dE_{cs}$:
When \( dE_{cs} \) approaches zero, \( dt_{10p}/dE_{cs} \) is \((A \times b)_p\) (Napier-Munn et al., 1996; Shi et al., 2013), and \( dt_{10u}/dE_{cs} \) is \((A \times b)_u\). Eq. (6-5) can be re-written:

\[
R_{t_{10}}(0) = \frac{dt_{10p}}{dt_{10u}} = \frac{dt_{10p}/dE_{cs}}{dt_{10u}/dE_{cs}} = \frac{(A \times b)_p}{(A \times b)_u}
\]

Similarly, when \( t_{10u} \) approaches zero in Eq. (6-7):

\[
R_{t_{10}}(0) = 1 + \frac{C_{Ab}}{10000}(100 - 0) = 1 + \frac{C_{Ab}}{100}
\]

Equating Eqs. (6-10) and (6-11) gives:

\[
\frac{(A \times b)_p}{(A \times b)_u} = 1 + \frac{C_{Ab}}{100}
\]

which after rearranging gives:

\[
C_{Ab} = \frac{(A \times b)_p - (A \times b)_u}{(A \times b)_u} \cdot 100
\]

By comparing Eqs. (6-9) with (6-13), it can be seen that parameter \( C_{Ab} \) in the \( t_{10} \)-based method equals the percentage change of \( A \times b \) between pulse-treated and untreated particles. Therefore the degree of pre-weakening by HVP can be directly represented by \( C_{Ab} \).

Figure 6-4 compares the \( A \times b \) values (Figure 6-4a) and the degree of pre-weakening (Figure 6-4b) of pulse-treated particles determined using the traditional method and the \( t_{10} \)-based method respectively:
Chapter 6 Characterization of Ore Pre-weakening Effect

1) In the traditional method, the size-dependent model parameters $M$, $p$, $q$ (Eqs. (6-2) and (6-3)) were fitted to the JKRBT data of the pulse-treated and untreated particles respectively, and the values of $A \times b$ were calculated using Eq. (6-4). The degree of pre-weakening was estimated using Eq. (6-9).

2) In the $t_{10}$-based method, the parameter $C_{Ab}$ in Eq. (6-8) was fitted to the measured $t_{10p}$ of pulse-treated particles and the smoothed $t_{10u}$ of untreated particles. The values of $(A \times b)_p$ were calculated from $C_{Ab}$ and the benchmark $(A \times b)_u$ using Eq. (6-12). The degree of pre-weakening was represented by the fitted $C_{Ab}$.

The error bars presented in Figure 6-4a are ±4.5% of the $A \times b$ values. This error was estimated from CoV (Coefficient of Variation, calculated as the standard deviation divided by the mean $A \times b$ value) that was determined by Shi and Kojovic (2011) in the JKRBT validation research project. On the other hand, the standard deviation of $C_{Ab}$ is estimated using Eq. (6-14) according to error propagation theory (Napier-Munn, 2011):

$$\sigma_{C_{Ab}} = \frac{(A \times b)_{pm} \text{CoV}_{(A \times b)_p}}{(A \times b)_{um}} \quad (6\text{-}14)$$

where $\sigma_{C_{Ab}}$ represents the standard deviation of $C_{Ab}$; $(A \times b)_{pm}$ and $(A \times b)_{um}$ are the average values of $A \times b$ for pulse-treated and untreated particles, while $\text{CoV}_{(A \times b)_p}$ is the $\text{CoV}$ of the $A \times b$ values of pulse-treated particles and it equals 4.5%. The $\text{CoV}$ of $C_{Ab}$ was then calculated by dividing $\sigma_{C_{Ab}}$ by the average of $C_{Ab}$, and used as error bar in Figure 6-4b.
Chapter 6 Characterization of Ore Pre-weakening Effect

Figure 6-4 Comparison of the A\times b values of the pulse-treated particles (a) and degree of pre-weakening (b) calculated by the size-dependent model (Eqs. (6-2) and (6-3)) and the t_{10p}-based method respectively

The nine sets of data show that the degrees of pre-weakening range from 16.1 to 78.1% according to the values of C_{Ab}. This reflects the ore-dependence of the pre-weakening effect, emphasising the importance of pre-weakening characterisation. The comparison also demonstrates that the t_{10p}-based method can give statistically similar results to the traditional method using the size-dependent breakage model.

4.2 Assessment of the breakage energy reduction

The relationship between t_{10p} and t_{10u} represented by Eq. (6-8) provides a useful tool to predict the impact breakage energy reduction attributed to the HVP pre-weakening effect. The procedures of the breakage energy reduction calculation are described below.

Assuming there is an untreated sample of given ore type with impact breakage characteristics described by the size-dependent breakage model as below:

\[
t_{10u} = M_u [1 - e^{x p(-f_{mat.u} \cdot x \cdot E_c)}]
\]  

(6-15)

where M_u and f_{mat.u} are model parameters specific for the untreated sample.

When the target of impact breakage is to achieve a product fineness t_{10T}, the required specific energy for the untreated particles and the pulse-treated particles are E_1 and E_2 respectively.
Using $t_{10T}$ to replace $t_{10u}$ in Eq. (6-15), it can be shown that:

$$E_1 = \frac{\ln \left( \frac{M_u}{M_u - t_{10T}} \right)}{f_{\text{mat.u}} \cdot x} \quad (6-16)$$

When $E_2$ (that is a specific energy used to break the pulse-treated particles to achieve the same target product fineness $t_{10T}$) is used to break the untreated particle, the product fineness is $t_{10T}$. Obviously, $t_{10T}$ is smaller than $t_{10T}$. In a similar manner, Eq. (6-17) can be derived:

$$E_2 = \frac{\ln \left( \frac{M_u}{M_u - t_{10T}} \right)}{f_{\text{mat.u}} \cdot x} \quad (6-17)$$

By solving Eq. (6-8), then:

$$t_{10u} = a_1 \pm \sqrt{a_1^2 - 4a_2 \cdot t_{10p}} \quad (6-18)$$

To calculate $t_{10u}$ from $t_{10p}$ the negative root should be taken:

$$t_{10u} = \frac{a_1 - \sqrt{a_1^2 - 4a_2 \cdot t_{10p}}}{2a_2}$$

where,

$$a_1 = 1 + \frac{C_{Ab}}{100}$$

$$a_2 = \frac{C_{Ab}}{10000}$$

At the specific energy of $E_2$, the values of $t_{10u}$ and $t_{10p}$ at the same size/energy level are equal to $t_{10T}$ and $t_{10T}$ respectively, hence:
Chapter 6 Characterization of Ore Pre-weakening Effect

\[
t_{10t} = \frac{a_1 - \sqrt{a_1^2 - 4a_2 \cdot t_{10T}}}{2a_2}
\]  \hspace{1cm} (6-19)

By combining Eqs. (6-16), (6-17) and (6-19), the energy reduction by pre-weakening to achieve target product fineness \(t_{10T}\) in a subsequent impact breakage process can be predicted by:

\[
\Delta E = E_1 - E_2 = \ln \left( \frac{M_u}{M_u - t_{10T}} \right) - \ln \left( \frac{M_u}{M_u - \frac{a_1 - \sqrt{a_1^2 - 4a_2 \cdot t_{10T}}}{2a_2}} \right)
\]

\[
\Delta E = \frac{\ln \left( \frac{M_u}{M_u - t_{10T}} \right) - \ln \left( \frac{M_u}{M_u - \frac{a_1 - \sqrt{a_1^2 - 4a_2 \cdot t_{10T}}}{2a_2}} \right)}{f_{mat,u} \cdot x}
\]  \hspace{1cm} (6-20)

Substituting Eq. (6-3) into Eq. (6-20),

\[
\Delta E = \frac{\ln \left( \frac{M_u}{M_u - t_{10T}} \right) - \ln \left( \frac{M_u}{M_u - \frac{a_1 - \sqrt{a_1^2 - 4a_2 \cdot t_{10T}}}{2a_2}} \right)}{3.6p_u \cdot d(1-q_u)}
\]  \hspace{1cm} (6-21)

where \(\Delta E\) is the energy reduction in kWh \(t^{-1}\), \(d\) is particle size in mm. The constants \(a_1\) and \(a_2\) are calculated by \(C_{Ab}\). The parameters \(M_u\), \(p_u\) and \(q_u\) are fitted to the JKRBT testing data on the untreated particles, using Eqs. (6-2) and (6-3).

Once the material breakage characteristic parameters \((M_u, p_u\) and \(q_u)\) are determined, and the degree of pre-weakening (percentage change of \(A \times b\), i.e. \(C_{Ab}\)) is established, Eq. (6-21) can be employed to predict the theoretical energy reduction due to the pre-weakening effect for a desired target breakage degree \((t_{10T})\) in the post HVP impact comminution process.

By way of example, the relation between energy reduction by pre-weakening and the target product fineness \(t_{10T}\) for Tests 1 and 2 is given in Figure 6-5. The two tests were conducted with the same ore (Ore 1) but achieved different degrees of pre-weakening with \(C_{Ab}\) being 62.0% and 34.9% respectively.
Test 1, $C_{Ab} = 62.0\%$

Test 2, $C_{Ab} = 34.9\%$

Figure 6-5 Relation between energy reduction $\Delta E$ and the target product fineness $t_{10T}$, calculated by Eq. (21).

Figure 6-5 shows that a more significant energy reduction benefit can be realised from the larger degree of pre-weakening $C_{Ab}$. For example, Test 1 achieved a degree of pre-weakening with 62.0% change in $A \times b$, compared with the untreated particles, leading to a 1.86 kWh t$^{-1}$ energy reduction for a 4.75-5.6 mm feed to be broken into a product containing particles of 50% passing 516 micron. In comparison; Test 2 achieved a $C_{Ab}$ of 34.9%, resulting in a 1.23 kWh t$^{-1}$ energy reduction for the same feed and the same product fineness as in Test 1.

Figure 6-5 also shows that for a given $C_{Ab}$, more energy reduction by pre-weakening can be expected when a larger target product fineness $t_{10T}$ is required. This is attributed to the fact that the energy requirements for the untreated particles to be broken or ground finer (ie. the larger $t_{10T}$) are larger. Similarly, the energy reduction calculations indicate that for a given $C_{Ab}$, the effect of pre-weakening on energy reduction is more pronounced for small particle size. This can be attributed to the fact that the energy required to mechanically break/grind smaller particles is larger than that required to break larger particles. This is the well-known particle size effect. It is worth emphasising that this is based on an assumption that all particle sizes achieve the same degree of pre-weakening using HVP technology.

This paper only demonstrates the direct comparison of energy reduction due to the pre-weakening effect resulted from HVP treatment, but it does not cover the pre-weakening effect on comminution circuit configuration. Shi et al. (2014a) have showed that taking account of both HVP and mechanical breakage energy consumptions in a hybrid circuit simulation, the pre-weakening effect on energy reduction through changes in comminution circuit configurations is significant.
5. Conclusion

A $t_{10}$-based method has been developed to evaluate the degree of pre-weakening and to assess energy reduction due to the pre-weakening effect in the downstream mechanical comminution process. From a comparison of nine sets of JKRBT data comprising HVP treated and untreated ore samples, it was found that the $t_{10}$ values of pulse-treated particles are closely related with the untreated particles. A relationship between the pulse-treated $t_{10p}$ and untreated $t_{10u}$ values was established, which forms the $t_{10}$-based method. The $t_{10}$-based method incorporates a single parameter ($C_{Ab}$). Mathematically, the value of $C_{Ab}$ equals the percentage change of $A \times b$ between pulse-treated and untreated particles, the indicator of pre-weakening degree. In the case where the untreated $t_{10u}$ values at various size/energy levels are available as benchmarks, this method provides a convenient way to determine the degree of pre-weakening by using the pulse-treated $t_{10p}$ and untreated $t_{10u}$ to fit the sole parameter $C_{Ab}$. Alternatively, in numerical simulations where the benchmark $t_{10u}$ values are known, the pulse treated $t_{10p}$ can be predicted from the desired degree of pre-weakening ($C_{Ab}$).

Since the benchmark $t_{10u}$ is linked with the size-dependent breakage model, in which particle size effect and specific energy are described by the model parameters ($M$, $p$ and $q$), the $t_{10}$-based method is able to calculate the energy reduction due to the pre-weakening effect. The study demonstrates that the energy reduction by pre-weakening increases with an increase in the target product fineness and the degree of pre-weakening, and with the decrease in feed particle size.

The $t_{10}$-based method has led to the development of a new breakage characterisation method, in which pulse-treated particles in wide size fractions are used for pre-weakening characterisation. This will be presented in a separate paper.

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Chapter 6 Characterization of Ore Pre-weakening Effect

Ore impact breakage characterisation using mixed particles in wide size range

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ABSTRACT

The Drop Weight Tester (DWT) for ore impact breakage characterisation uses particles in five narrow size fractions, and the JKMRC Rotary Breakage Tester (JKRBT) uses four size fractions, both with three impact energy levels for each size fraction. It is time consuming to prepare these narrowly sized particles and to carry out size analysis on the 15 DWT or 12 JKRBT products, so a Wide–size JKRBT characterisation method was developed. In this method, the mixed particles in 13.2–45 mm size range are tested as one size class in the JKRBT by single–particle breakage mode. The wide–size feed is then divided into several virtual narrow size fractions by simulation, based on which the impact product size distributions are calculated using a size–dependent breakage model. Four sets of measurement data, consisting of two feed samples in the 13.2-45 mm size range with different size distributions tested with two impact energy levels, are adequate to determine the three model parameters. In the case where a benchmark ore of known breakage characteristic parameters is available, one Wide–size JKRBT impact treatment can determine the ore competence change parameter using a $t_{10}$–based model.

Keywords: Breakage characterisation; Wide–size JKRBT test; Size-dependent breakage model

1. Introduction

The mining industry has long recognised that the performance of a comminution machine depends not only on its operating conditions, but also on the materials resistance to breakage (called ore
competence in this paper). As a result, ore breakage characterisation plays an essential role in the design and optimisation of comminution circuits.

The main objective of ore breakage characterisation is to quantify the product size distribution resulting from the application of energy to a selected feed size by a specific breakage mechanism. In particular it aims to establish the relationship between specific energy input and resultant product through various types of laboratory testing 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 competence 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 optimisation.

The single–particle test is one of the standard breakage characterisation methods adopted in the Drop Weight Test (DWT, Napier-Munn et al., 1996), JKMRC Rotary Breakage Test (JKRBT, Shi et al., 2009), and SMC Test® (SMC Testing website). The DWT uses particles in five narrow size fractions and the JKRBT uses four size fractions, both with three impact energy levels for each size fraction. The SMC Test uses one narrow particle size fraction tested with five impact energy levels. Where the SMC Test® is used to estimate values of A and b (the breakage model parameters A and b are described in Section 2.3) a calibration using a full DWT may be required.

Despite significantly reducing the time taken to break particles in the JKRBT test, it is still time consuming to prepare these narrowly sized particles (over 360 pieces for one characterisation test), and to carry out size analysis on the 15 DWT or 12 JKRBT products. In addition, only particles in the specified size fractions are used for breakage characterisation. In some cases the ability to supply sufficient particles in the desired size fractions, in order to complete one characterisation test, may become a problem. The limitations in the existing breakage characterisation tests restrict their applications when dealing with massive ore samples such as geo–metallurgical testing, optimisation of ore pre-weakening operation and on–line ore competence measurement for comminution circuits.

A new ore breakage characterisation method was developed at the Julius Kruttschnitt Mineral Research Centre (JKMRC) using the JKRBT to test mixed particles in a wide size range as one size class, in contrast to the narrow-size testing method used in the traditional ore breakage characterisation. This method significantly simplifies the feed particles preparation and product sizing procedures.
2. The existing single-particle ore impact breakage characterisation method used at the JKMRC

The single particle impact breakage characterisation methods used at the JKMRC consists of two steps:

- Single–particle breakage testing at the controlled input energy levels;
- Data reduction to determine ore breakage characteristic parameters from the testing results.

Modelling, simulating and optimising a comminution machine or a circuit, requires the establishment of a relationship between the product size distribution and the breakage testing conditions (for example, the existing AG/SAG model implemented in the software package JKSimMet), in addition to a single ore competence indicator.

2.1 Impact breakage testing

The single particle impact tests can be conducted using either DWT or JKRBT. The DWT consists of a steel drop weight mounted on two rails and a steel anvil bolted on a heavy frame. The tests with DWT are conducted on single rock specimens positioned manually on the anvil. The breakage energy is adjusted manually by changing the release height as well as the mass of the drop weight. In a standard DWT test, particles in five size fractions are tested (13.2-16 mm, 19-22.4 mm, 26.5-31.5 mm, 37.5-45 mm, and 53-63 mm), each with three specific energy levels. In each size–energy level 30 particles are tested by DWT one by one. The DWT testing procedures are time consuming, taking a couple of days to complete the characterisation of one ore sample.

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 specific comminution energy of JKRBT is dependent solely on the impact velocity of the feed particle, which is mainly determined by the rotation speed of the rotator and to a lesser extent by particle size (Shi et al., 2009). The breakage mechanism of the JKRBT allows the ore particles to be fed continuously and automatically if required. In a standard JKRBT test, four of the five size fractions used in the DWT are tested (excluding the coarsest size fraction), each at three energy levels (named ‘narrow–size JKRBT test’ in this paper). The improvement on breakage mechanism makes JKRBT a more rapid breakage tester compared to the DWT. A standard JKRBT test can be completed in approximately 1/8th–1/10th of the time it takes to complete a standard DWT test (Shi et al., 2009).
Despite the time saved in the JKRBT impact testing, the preparation of representative particles in narrow size fractions is time consuming. The sieving process used for the 12 JKRBT products to determine their size distributions also takes significant effort.

### 2.2 Data reduction procedures

The general data reduction procedure is illustrated in Figure 6-6. The dash rectangle box represents the single–particle impact test using a laboratory breakage tester at n feed size levels and three specific comminution energy ($E_{cs}$) levels. The rest of Figure 6-6 represents the data reduction procedures to determine ore breakage characteristic parameters of a selected breakage model from the testing results. The symbol $P_{ej}$ is the measured cumulative product size distribution matrix of size $i$ feed at specific energy $E_{cs} j$. Similarly, the symbol $P_{fij}$ is the fitted cumulative product size distribution matrix of size $i$ feed at $E_{cs} j$. With a set of initially guessed breakage model parameters, the values of $P_{fij}$ are calculated. For existing Single-particle ore impact breakage characterisation method, the symbol $P_{ej}$ and $P_{fij}$ are represented by percent passing 1/10 of the initial particle size ($t_{10}$).

![Figure 6-6 Procedures to determine ore breakage characteristic parameters by single particle impact tests](image)

The sum of squares ($SSQ$) of the weighted errors between the experimental and the fitted product.
size distribution indices of all size–energy levels is defined by Eq. (6-22):

\[
SSQ = \sum_{i=1, j=1}^{i=n, j=3} W_{tdE_{ij}} = \sum_{i=1, j=1}^{i=n, j=3} \left( \frac{p_{ij} - p_{eij}}{SD \cdot p_{eij}} \right)^2
\]

(6-22)

where \( W_{tdE_{ij}} \) represents the weighted error for size \( i \) feed at \( E_{cs \ j} \), and \( SD \) is the standard deviation of the testing result.

The values of the model parameters are adjusted iteratively until the minimum of \( SSQ \) is converged.

2.3 Breakage models

Traditionally the size reduction resulting from the DWT test was related to the specific comminution energy as follows (Napier-Munn et al., 1996):

\[
t_{10} = A(1 - e^{-bE_{cs}})
\]

(6-23)

where \( t_{10} \) is used as a product size distribution “fineness” index defined as the product cumulative percentage passing 1/10\(^{\text{th}}\) of the initial feed size; \( E_{cs} \) is the specific comminution energy (kWh/ t\(^{\text{t}}\)).

The \( A \) and \( b \) parameters can be obtained by fitting Eq. (6-23) to the single particle impact test data acquired from DWT or JKRBT tests. The product \( A \times b \) has been used as an ore competence indicator. A larger \( A \times b \) value indicates the less competent ore, or less resistance to breakage. By taking the derivative of Eq. (6-23), it can be proved that \( A \times b \) is the slope of the \( t_{10}-E_{cs} \) curve at ‘zero’ input energy. It is popular for many mineral processing engineers and researchers to use the \( A \) and \( b \) parameters in their comminution circuit design, simulation, optimisation and operation.

Shi and Kojovic (2007) reported a size–dependent model to describe the degree of breakage, which is modified from a breakage probability model published by Vogel and Peukert (2004). The size–dependent model, as shown in Eq. (6-24), takes a form similar to the prior–art JKMRC breakage model given in Eq.(6-23):

\[
t_{10} = M\{1 - \exp[-f_{\text{mat.}} \cdot x \cdot k(E - E_{\text{min}})]\}
\]

(6-24)
where $M$ (%) is the maximum $t_{10}$ for a material subject to breakage, $f_{\text{mat.}}$ (kg J$^{-1}$ m$^{-1}$) is the material breakage property, $x$ (m) the initial particle size, $k$ the successive number of impacts with the single impact energy, $E$ (J kg$^{-1}$) the mass–specific impact energy, and $E_{\text{min}}$ (J kg$^{-1}$) the threshold energy. In this study, $k$ and $E_{\text{min}}$ are set as 1 and 0 respectively.

Shi and Kojovic (2007) found that the fitted material property parameter $f_{\text{mat.}}$ is closely related to particle size. This has been confirmed with numerous DWT and JKRBT data. A sub–model to describe the parameter $f_{\text{mat.}}$ in relation to particle size was developed in 2007, and published recently (Shi et al., 2014). The equation takes the following form:

$$f_{\text{mat.}} = p \cdot d^{-q}$$  \hspace{1cm} (6-25)

where $d$ (mm) is averaged particle size, $p$ and $q$ are model parameters. By substituting Eq. (6-25) into Eq. (6-24), three model parameters, $M$, $p$, $q$, can be determined simultaneously from one set of impact test data. The advantage of using parameters $M$, $p$, $q$ is that the effect of particle size on the breakage response can be directly quantified using the test results, as demonstrated in Shi and Kojovic (2007). Eqs. (6-24) and (6-25) therefore constitute a size–dependent breakage model.

Eqs. (6-23) and (6-24) take a similar exponential form, and the parameters of Eq. (6-24) can be converted to that of Eq. (6-23) (but not the other way round). The ore competence indicator $A \times b$ from Eq. (6-23) can be calculated from the parameters in Eqs. (6-24) and (6-25) using the following relationship:

$$A \times b = 3600 \cdot M \cdot f_{\text{mat.}} \cdot x = 3.6 \cdot M \cdot p \cdot d^{(1-q)}$$  \hspace{1cm} (6-26)

where $d$ takes a unit of mm, and $x$ in m, the constant 3600 or 3.6 is used for unit conversion. Eq. (6-26) gives the size–specific $A \times b$ values. In this paper, all the $A \times b$ values are calculated specifically for 32.5 mm, the nominal mean particle size for the standard DWT test. The procedures to determine the model parameters are illustrated in Figure 6-6.

Narayanan and Whiten (1988) found that the $t_{10}$ parameter is uniquely related to other points on a family of size distribution curves, $t_n$, defined as the cumulative percentage passing $1/n$ of the initial size. The $t_{10}$ can then be used to generate a size distribution from relationships between $t_{10}$ and $t_n$ family curves established from the single–particle impact testing database. Figure 6-7 depicts the $t_n$–
family of curves for a range of ore types. A spline regression analysis can be carried out to describe each of the relationships $t_{10-t_2}$, $t_{10-t_4}$, $t_{10-t_{25}}$, $t_{10-t_{50}}$ and $t_{10-t_{75}}$. Thus the whole size distribution of the progeny can be determined once the single index of breakage distribution $t_{10}$ is known.

![Figure 6-7 tn–family of curves of ore breakage in JKRBT](image)

**3. The Wide–size JKRBT breakage characterisation**

With the aid of the size–dependent breakage model (Eqs. (6-24) and (6-25)), the traditional narrow–size JKRBT breakage characterisation test can be simplified. The JKRBT test using mixed particles in a wide size range is called the Wide–size JKRBT test, in contrast with the traditional narrow-size JKRBT test. The same principle can be applied to the DWT; however, the time required to break the particles using the DWT would cancel any benefits in the wide–size test. For this reason, only the Wide–size JKRBT test is presented in this paper.

**3.1 Testing procedures**

In the traditional test, the raw material received is sieved and split to prepare 30 particles for each of the four nominal narrow size fractions. As three energy levels are applied to each size fraction, 120 particles are required. At each energy level the feed sample is broken by JKRBT separately. The JKRBT products (4 sizes x 3 energies) are sieved respectively.
In the new wide–size testing process, the feed sample is sieved to determine the size distribution. Particles in the typical JKRBT testing size range (13.2-45 mm) are combined, and tested with the JKRBT. The number of testing conditions should not be no less than the number of model parameters: three. A minimum of three sub–samples are tested in the JKRBT with different rotational speeds, eg. at 1453 rpm, 2689 rpm and 4038 rpm respectively. The particle feed rate to the JKRBT was controlled to warrant the single-particle breakage mode and prevent interaction between particles during breakage. The actual specific energy used for each particle size fraction can be calculated in the data reduction stage according to the JKRBT rotational speed and the particle size using an equation presented in Shi et al. (2009). The three JKRBT products are sieved separately.

The Wide–size JKRBT characterisation offers a flexibility to test particles in the wider size range, for example, from 13.2 mm to 45 mm in the standard JKRBT testing size range, or extended to 5.6-45 mm. It does not require an equal number of particles in each size fraction. It uses all particles in the desired size range. In contrast, the traditional DWT or JKRBT tests use 30 particles in the nominal size fractions. This is particularly important when the sample availability is limited, eg. using high voltage pulse to pre–weaken particles in a single–particle, single–pulse mode (Shi et al., 2013). In the high voltage pulse test the preparation of sufficient particles for the determination of particle residual strength using the traditional narrow–size JKRBT method was often a problem. Another advantage in the Wide–size JKRBT test is that more than 30 particles can be tested to combat ore variation and offer statistically more valid results.

3.2 Data reduction using the size–dependent breakage model

The size–dependent breakage model is employed in the data reduction for the Wide–size JKRBT characterisation. The advantage of using the size–dependent breakage model is that the effect of particle size on breakage results can be well described by Eqs. (6-24) and (6-25). With the aid of the size–dependent breakage model, the breakage results of particles in a virtual narrow size fraction can be back calculated from the Wide–size JKRBT testing result.

Figure 6-8 illustrates the data reduction procedures with mathematical descriptions of each step. The general approach taken in the data reduction procedure is summarised below:

- Divide the wide–size feed into several virtual narrow size fractions by simulation. The same size fraction series used in the standard JKRBT test are recommended;
Use the size–dependent breakage model (Eqs. (6-24) and (6-25)) with a set of $M, p, q$ parameters to calculate $t_{10}$ values for each virtual narrow size of the feed;

Use the calculated $t_{10}$ value and the $t_n$–family curves to calculate product size distribution matrix resulting from breakage of each narrow size fraction of the feed;

Sum up the product size distribution matrices using the feed proportion to form a combined product size distribution;

Estimate the weighted error between the calculated and the measured product size distributions;

Repeat the procedures for three products at various impact specific energy levels and calculate the total $SSQ$;

Adjust the model parameters $M, p, q$ iteratively until the $SSQ$ reaching a minimum.

![Figure 6-8 Mechanism of ore breakage characterization by express RBT test](image-url)

Note that the approach introduced above can only be performed providing the $t_n$–family of curves is available. Either the universal $t_n$–family of curves derived from a range of ore types (Figure 6-2) or
the \( t_n \)–family of curves for a specific ore determined by the traditional JKRBT test can be used. In this study the latter method was used.

3.3. Data reduction using the \( t_{10} \)–based model

In some cases the purpose of ore breakage characterisation is to find out whether or not the ore competence changes. Typical examples can be found in assessing the pre–weakening effect by different ore treatment methods, such as HPGR (Shi et al., 2006), microwave (Walkiewicz et al., 1991), blasting (Parra et al., 2014), or high voltage pulses (Wang et al., 2011). On–line measurement of ore competence change for grinding mill operation control is another example. In these applications, the measured ore breakage competence indicator \( A \times b \) is often compared with a benchmark ore of known breakage characteristic parameters. For these cases, a further simplified Wide–size JKRBT test can be conducted with one single impact energy level, and a \( t_{10} \)–based model (Zuo and Shi, 2015) can be employed for data reduction to estimate the percentage change in \( A \times b \) values for a new sample.

The \( t_{10} \)–based model was developed through detailed analysis of nine sets of the JKRBT data of high voltage pulse treated and untreated samples from eight different ores. The model incorporates a single parameter, \( C_{Ab} \), that is mathematically equal to the percentage change of \( A \times b \). The percentage change in \( A \times b \) was defined as the degree of pre–weakening (Shi et al., 2013).

In the \( t_{10} \)–based model, the relation between \( t_{10p} \) and \( t_{10u} \) is described by a ratio term, \( R_{t10}(i) \):

\[
t_{10p}(i) = R_{t10}(i) \cdot t_{10u}(i)
\]

(6-27)

where \( t_{10p}(i) \) and \( t_{10u}(i) \) are obtained by JKRBT test for the pulse–treated and untreated particles at the same size (i) and impact energy levels. The \( t_{10} \)–based model can be expressed in Eq. (6-28).

\[
R_{t10}(i) = 1 + \frac{C_{Ab}}{100} \left( 1 - \frac{t_{10u}(i)}{T} \right)
\]

(6-28)

where \( T \) represents the value of \( t_{10u}(i) \) at which \( R_{t10}(i) \) equals to unity. As the value of \( t_{10u} \) cannot exceed its top limit defined by the parameter \( M \) in Eq. (6-24), \( T \) is replaced by \( M_u \) of the untreated ore particles.
Equation (6-28) can be converted to:

$$t_{10p}(i) = \left\{ 1 + \frac{C_{AB}}{100} \left( 1 - \frac{t_{10u}(i)}{M_u} \right) \right\} t_{10u}(i) \quad (6-29)$$

The $t_{10}$–based model is implicitly linked with the size–dependent breakage model as the benchmark $t_{10u}(i)$ has to be calculated by Eqs. (6-24) and (6-25) from the known $M, p, q$ of the benchmark ore. The step–by–step data reduction using the $t_{10}$–based model is summarised below:

- Divide the wide–size feed into several virtual narrow size fractions by simulation. The same size fraction series used in the standard JKRBT test were recommended;

- Use the size–dependent breakage model with a set of $M, p, q$ parameters to calculate $t_{10u}(i)$ values for each virtual narrow size fraction (i) of the feed and a given impact specific energy;

- From the initially estimated $C_{AB}$ and the calculated $t_{10u}(i)$ values to estimate the $t_{10p}(i)$ values using Eq. (6-29);

- Use the $t_{10p}(i)$ values and the $t_n$–family curves to calculate product size distribution matrix resulting from breakage of each virtual narrow size fraction of the feed;

- Sum up the product size distribution matrices using the feed proportion in the virtual narrow size fractions to form a combined product size distribution;

- Estimate the weighted error between the calculated and the measured product size distributions and calculate the total SSQ;

- Adjust the $t_{10}$–based model parameter $C_{AB}$ value iteratively until the SSQ reaching a minimum.

4. Data acquisition

Five sets of data of two copper–gold ores were collected to validate the Wide–size JKRBT
characterisation method. Each set of data consists of a pair of the narrow–size JKRBT and the Wide–size JKRBT tests. Data details of the narrow–size JKRBT are given in Table 6-2, and the Wide–size JKRBT given in Table 6-3.

Two ore samples were tested. Ore A was the SAG mill feed collected from a gold–copper mine operation in Australia. The gold–copper mineralisation for Ore A occurs as quartz veins, sheeted quartz sulphide veins and as disseminations. The gold occurs mainly as free grains in quartz or on the margins of sulphide grains. The principal copper sulphide minerals are chalcopyrite and bornite. The major silicate minerals are quartz, orthoclase, hornblende, chlorite, anorthoclase, and the non–silicate minerals include magnetite, calcite and apatite. Ore B was collected from an iron oxide copper–gold deposit in Brazil. The ore is composed of chalcopyrite, magnetite, minor pyrite, and trace molybdenite. Alteration minerals closely associated with chalcopyrite include amphibole, epidote, apatite, calcite, quartz, and locally biotite.

Table 6-2 Summary of the narrow–size JKRBT testing conditions

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Ore</th>
<th>Ax/b</th>
<th>HVP feed size (mm)</th>
<th>HVP energy (kWh t⁻¹)</th>
<th>JKRBT size (mm)/Ecs (kWh t⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>42.0</td>
<td>–</td>
<td>–</td>
<td>19-22.4/0.25, 1.0, 2.5;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13.2-16/0.25, 1.0, 2.5;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.5-11.2/0.25, 1.0, 2.5;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.6-6.7/0.25, 1.0, 2.5;</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>52.2</td>
<td>26.5-31.5</td>
<td>4.2</td>
<td>26.5-31.5/1.0; 19-26.5/0.75, 1.25;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13.2-19/2.5; 9.5-13.2/0.75; 6.7-9.5/1.5</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>54.9</td>
<td>22.4-26.5</td>
<td>8.7</td>
<td>13.2-19/0.25, 1.0, 9.5-13.2/2.5;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.7-9.5/0.25; 3.35-4.75/1.0</td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td>52.0</td>
<td>–</td>
<td>–</td>
<td>19-22.4/0.25, 1.0, 2.5;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13.2-16/0.25, 1.0, 2.5;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.5-11.2/0.25, 1.0, 2.5;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.6-8/0.25, 1.0, 2.5;</td>
</tr>
<tr>
<td>5</td>
<td>B</td>
<td>76.0</td>
<td>26.5-45</td>
<td>13.0</td>
<td>19-22.4/0.25, 1.0, 2.5;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13.2-16/0.25, 1.0, 2.5;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.5-11.2/0.25, 1.0, 2.5;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.6-8/0.25, 1.0, 2.5;</td>
</tr>
</tbody>
</table>

The data shown in Table 6-2 were collected at an earlier stage of research using the narrow–size JKRBT method to assess the HVP pre–weakening effect. Datasets 1 and 4 are the results for the pulse–untreated particles, and the other three sets are for the pulse–treated particles.
Chapter 6 Characterization of Ore Pre-weakening Effect

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Ore</th>
<th>JKRBT size (mm)</th>
<th>JKRBT energy (kWh t⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>6.7-26.5</td>
<td>0.25, 1.0, 2.5</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>9.5-26.5</td>
<td>1.0, 2.5</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>3.35-19</td>
<td>1.0, 1.0</td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td>5.6-22.4</td>
<td>0.25, 1.0, 2.5</td>
</tr>
<tr>
<td>5</td>
<td>B</td>
<td>5.6-22.4</td>
<td>0.25, 1.0, 2.5</td>
</tr>
</tbody>
</table>

The data presented in Table 6-3 were collected using two different methods. For Dataset 1, the raw sample from Ore A was used. Three batches of 26.5-31.5 mm particles were crushed by JKRBT at 0.1 kWh t⁻¹ and then sieved. The low specific energy level used in the JKRBT crushing to prepare the Dataset 1 sample was aiming to minimise the residual damage made to the particles during the sample preparation stage. The crushed product between 6.7 mm and 26.5 mm was combined for each batch of sample as the feed for the Wide–size JKRBT tests. The prepared 6.7-26.5 mm feed samples were treated by JKRBT at specific energy levels of 0.25, 1.0 and 2.5 kWh t⁻¹ respectively. Datasets 2 and 3 were from the HVP pre–weakened Ore A products treated with different HVP energies. The HVP products were sieved. Particles in the 9.5-26.5 mm size range were combined as Dataset 2 feed, and 3.35-19 mm particles were used as Dataset 3 feed. The prepared feed particles were treated by JKRBT at 1.0 kWh t⁻¹ and 2.5 kWh t⁻¹ for Dataset 2, and at a duplicate 1.0 kWh t⁻¹ specific energy for Dataset 3 respectively.

As there is no spare Ore B sample available to carry out an experiment using the Wide–size JKRBT tests in order to compare it with the historical Datasets 4 and 5 as presented in Table 6-2, the Datasets 4 and 5 were re-constructed mathematically to generate the ‘wide–size’ JKRBT testing data. For each energy test (0.25, 1.0 and 2.5 kWh t⁻¹), the product size distributions of the four JKRBT feed sizes (19-22.4, 13.2-16, 9.5-11.2 and 5.6-8 mm) were combined, with blending ratios of 1:1:1:1. The new data will mimic the Wide–size JKRBT tests for 5.6-22.4 mm size at 0.25, 1.0 and 2.5 kWh t⁻¹ for Datasets 4 and 5 as presented in Table 6-3.

5. Results and discussion

5.1 The Wide–size JKRBT characterisation based on the size–dependent model

The testing data given in Table 6-3 were used to fit the size–dependent model and to generate the ore breakage characteristic parameters for each dataset. As described in the Data acquisition section, the feed particle size distributions for various specific energy treatments in each dataset were
identical. Parameter $q$ in the size–dependent model (Eqs. (6-24) and (6-25)) is used to describe the particle size effect on breakage result. This parameter cannot be uniquely fitted using the same feed size. Therefore parameter $q$ was fixed at a constant taking from the pulse–untreated material. This was supported by previous research which indicates that the $q$–parameter values were similar for particles before and after the pre–weakening treatment by HVP. Thus there are only two model parameters ($M$ and $p$) that needed to be fitted to the three experimental data points with different energies (Datasets 1, 4 and 5), or to the two data points (Datasets 2 and 3). Note that for Dataset 3 the impact energy levels for the two data points were duplicate, which cannot fit two model parameters uniquely. In this case, parameter $M$ was fixed constant, and only one parameter $p$ was fitted to Dataset 3.

The model parameter fitting process illustrated in Figure 6-8 was adopted. In all cases, the size–dependent model fits the data well. Figure 6-9 gives an example of the Wide–size JKRBT product size distributions fitted by the model (presenting in lines) against that measured from Dataset 1 (in dot markers). Figure 6-10 shows the $A\times b$ values determined from the Wide–size JKRBT tests in comparison with the traditional narrow–size method for all the five datasets. The error bars display ± one SD (standard deviation) of the narrow–size JKRBT tests. The SD was calculated by a CoV (Coefficient of Variation, defined as a ratio of SD to $A\times b$) value of 0.048 from a JKRBT Validation research project (Shi and Kojovic, 2011). Both graphs demonstrate that the Wide–size JKRBT characterisation method can achieve similar characterisation results as the traditional narrow–size
JKRBT method.

![Ore competence indicator A×b values determined by the Wide-size JKRBT tests using the size-dependent model in comparison with that determined by the traditional narrow-size JKRBT tests, the error bars representing ± one SD](image)

Table 6-4 The A×b values and the size-dependent model parameters determined by the Wide-size JKRBT tests in comparison with the narrow-size JKRBT tests

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Method</th>
<th>A×b</th>
<th>M</th>
<th>p</th>
<th>q</th>
<th>$R^2$ ($t_{t_0}$)</th>
<th>$R^2$ ($t_{t_3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Narrow-size</td>
<td>42.0</td>
<td>69.1</td>
<td>0.044</td>
<td>0.62</td>
<td>0.996</td>
<td>0.998</td>
</tr>
<tr>
<td></td>
<td>Wide-size</td>
<td>40.6</td>
<td>68.6</td>
<td>0.043</td>
<td>0.62</td>
<td>0.997</td>
<td>0.998</td>
</tr>
<tr>
<td>2</td>
<td>Narrow-size</td>
<td>52.2</td>
<td>70.8</td>
<td>0.054</td>
<td>0.62</td>
<td>0.998</td>
<td>0.999</td>
</tr>
<tr>
<td></td>
<td>Wide-size</td>
<td>54.4</td>
<td>67.4</td>
<td>0.059</td>
<td>0.62</td>
<td>0.996</td>
<td>0.999</td>
</tr>
<tr>
<td>3</td>
<td>Narrow-size</td>
<td>54.9</td>
<td>69.8</td>
<td>0.057</td>
<td>0.62</td>
<td>0.982</td>
<td>0.995</td>
</tr>
<tr>
<td></td>
<td>Wide-size</td>
<td>54.4</td>
<td>69.8</td>
<td>0.057</td>
<td>0.62</td>
<td>0.982</td>
<td>0.994</td>
</tr>
<tr>
<td>4</td>
<td>Narrow-size</td>
<td>52.0</td>
<td>75.0</td>
<td>0.048</td>
<td>0.60</td>
<td>0.989</td>
<td>0.995</td>
</tr>
<tr>
<td></td>
<td>Wide-size</td>
<td>52.8</td>
<td>66.0</td>
<td>0.055</td>
<td>0.60</td>
<td>0.986</td>
<td>0.994</td>
</tr>
<tr>
<td>5</td>
<td>Narrow-size</td>
<td>76.0</td>
<td>63.8</td>
<td>0.082</td>
<td>0.60</td>
<td>0.983</td>
<td>0.992</td>
</tr>
<tr>
<td></td>
<td>Wide-size</td>
<td>75.4</td>
<td>69.4</td>
<td>0.075</td>
<td>0.60</td>
<td>0.986</td>
<td>0.990</td>
</tr>
</tbody>
</table>

Table 6-4 summarises the fitted model parameters and the $A \times b$ values using the two methods for all five datasets. It is difficult to obtain unique parameters since the three model parameters can interact if they are not well defined by the experimental data. This may lead to multiple sets of parameter values, all of which can achieve a similar SSQ. As the majority of the five datasets (Table 6-2) were acquired through 12 measurements at different particle size and energy combinations, the traditional narrow-size JKRBT tests can achieve uniquely fitted model parameters. Interestingly, Table 6-4
shows that the Wide–size JKRBT tests using less than three measurement points can deliver the similar model parameter values (with q–parameter fixed). This indicates that the Wide–size JKRBT characterisation methodology is valid.

Statistical measurements of R–squares ($R^2$) for $t_{10}$ and $t_n$ are also included in Table 3. The $R^2$ is acquired when plotting the measured values against the model predicted ones, and using a linear regression with the intercept on Y-axis set to zero. Linear regression was performed on $t_{10}$ and $t_n$ respectively. The $R^2$ is the coefficient of determination, which quantifies how closely the model predicted $t_{10}$ (or $t_n$) values correspond to the experimental ones. $R^2$ value is a number from 0 to 1 (1 indicating a perfect matching). Table 6-4 demonstrates that the fitted $t_{10}$ and $t_n$ match the measured values well.

Since using the identical feed size distributions in the Wide–size JKRBT method cannot uniquely determine the q–parameter in the size–dependent model, investigation was conducted using various feed size distributions in the Wide–size JKRBT tests. Dataset 1 was re–constructed by simulation. One feed was blended using the original feed size distribution of 45.3, 31.4, 15.2, and 8.1% in the four narrow size fractions of 19-22.4, 13.2-16, 9.5-11.2, and 5.6-6.7 mm. Another feed was blended with an inversed distribution order (8.1, 15.2, 31.4 and 45.3%) for the same size fractions. The two feed samples were tested with two different breakage energies (0.25 and 2.5 kWh t$^{-1}$). Product size distributions of the four virtual narrow size fractions subjected to the two specific energy levels were combined using the blending ratios of the two feeds. A total of four product size distributions (2 feeds x 2 energies) were acquired by the simulations.

The values of $M$, $p$ and $q$ parameters were then determined by fitting the four simulated size distributions using the procedures described in Figure 6-8. The freely fitted $M$, $p$ and $q$ values are 66.2, 0.045 and 0.59 respectively, which are very close to the $M$, $p$ and $q$ values (69.1, 0.044 and 0.62) determined by the narrow–size JKRBT tests with 12 measurement points. The investigation confirms that by using different feed size distributions (or different feed sizes) and different impact energies, more than three measurement points should be adequate to uniquely fit the three size–dependent model parameters.

5.2 The Wide–size JKRBT characterisation using the $t_{10}$–based model

As shown in Eq. (6-29) the $t_{10}$–based model has only one model parameter ($C_{AB}$) to calibrate. The parameter $C_{AB}$ is mathematically equal to the percentage change of $A \times b$. Theoretically, using one
measurement point can back calculate one unknown parameter in an equation. Advantage in using the $t_{10}$-based model for the Wide–size JKRBT data reduction is the reduced measurement requirement.

The Wide–size JKRBT data shown in Table 6-3 were used to fit the $t_{10}$–based model parameters in two ways. One was to use all energy data (two or three measurement points) together to fit one parameter $C_{AB}$, and the other was to use the individual energy data to fit the $C_{AB}$ (one measurement point). The benchmark ores of Datasets 1 and 4 are deemed “pre–weakened particles” with a percentage change in $A \times b$ ($C_{AB}$) being zero, thus the $t_{10}$–based model can also be applied to the data of Datasets 1 and 4. Using the data reduction procedures described in Section 3.3, the calculated $A \times b$ values by the Wide–size JKRBT tests from the five data sets are presented in Figure 6-11. The $A \times b$ values using the traditional narrow–size JKRBT tests are also plotted in Figure 6-11 for comparison. Note that the narrow–size JKRBT tests used more measurement points than the Wide–size JKRBT tests to fit the $A \times b$ values. The error bars indicate one SD in the traditional JKRBT tests.

Figure 6-11 indicates that in most cases the $A \times b$ values determined by the Wide–size JKRBT...
Chapter 6 Characterization of Ore Pre-weakening Effect

characterisation using the $t_{10}$–based model are within the ± one SD range of the traditional narrow–size JKRBT results. It is worth noting that the differences in the $A \times b$ values using 12 measurement points (the traditional narrow–size JKRBT), three points (the Wide–size JKRBT with three energies) or one point (the Wide–size JKRBT with a single energy) are minor. The $t_{10}$–based model seems robust in determining the $A \times b$ values. This investigation proves that the Wide–size JKRBT test with one impact energy, together with the $t_{10}$–based model for data reduction, is a valid method for rapid ore breakage characterisation.

6. Summary and conclusion

A Wide–size JKRBT characterisation method has been developed. Two data reduction methods for the Wide–size JKRBT tests were investigated. When the size–dependent breakage model is used, four impact treatments on two feed sizes broken with two energies (four sets of measurement data) are recommended to determine three model parameters ($M$, $p$ and $q$). The two feed samples should have different sizes, or different size distributions, to uniquely define the $q$–parameter of the size–dependent breakage model. This method has significantly reduced the number of impact treatments from 12 to four for one characterisation sample. Compared with the Reduced JKRBT test (Shi et al., 2013), in which five impact treatments on various narrow size fractions were recommended, the Wide–size JKRBT characterisation has further reduced the number of impact treatments. More importantly, the Wide–size JKRBT characterisation uses all material in the typical testing size range (13.2–45 mm). This feature simplifies the sample preparation procedures, provides more statistically valid results by using more than 30 particles, and mitigates the burden in collecting sufficient particles for breakage characterisation. This method can be applied in the mining industry to characterise ores with detailed characteristic parameters for sizing comminution devices, equipment modelling and plant optimisation.

When using the $t_{10}$–based model for the Wide–size JKRBT characterisation, the number of impact treatments can be further decreased to one. This has largely simplified the breakage characterisation procedures, which makes the on–line ore breakage characterisation viable. This method can be applied in situations where the breakage characteristic parameters ($M$, $p$ and $q$) for the benchmark ore are available, the characterisation aims to determine the new ore competence changes in comparison with the benchmark ore, or the characterisation does not need to produce the breakage characteristic parameters ($M$, $p$ and $q$). Such applications for the mining industry include geo–metallurgical measurements to establish detailed ore competence database, assessing ore competence changes to quantitatively determine the pre–weakening effect, and on–line
measurement of ore variation in competence for grinding circuit control and optimisation.

**Acknowledgements**

The financial support from Newcrest Mining for a PhD candidate in this study is gratefully acknowledged.
Chapter 7  Experimental Study of Ore Breakage Behaviour in a Pilot Scale HVP Machine

7.1  Introduction

The SELFRAG manufacturer has built a pilot scale Pre-Weakening Testing Station (PWTS), which offers more flexibility in terms of generator setup. Voltage and capacitance of pulse generator can be adjusted independently for the PWTS, allowing testing of a larger range of pulse energy and electrical field strength combinations. This provides a unique opportunity to conduct experimental study of ore breakage behaviour in relation to machine setting conditions. The breakage behaviour of ores was evaluated in terms of three breakage indices, namely body breakage probability, body breakage product fineness and pre-weakening degree. The concept of body breakage was initially created from the synthetic particles testing described in Chapter 4 and applied in this chapter to analyse the ore breakage behaviour. The ore breakage characterization method developed in Chapter 6 was applied here to assess the PWTS pre-weakening performance.

7.2  Contributions

- The knowledge generated from laboratory testing of synthetic samples presented in Chapter 4 has been extended to pilot scale HVP testing on three different ores. The pilot scale testing results confirm that specific energy is a dominant factor affecting ore breakage behaviour. This conclusion is critical in guiding the HVP breakage modelling, as presented in Chapter 8.
- The experimental study found that ore properties also affect breakage behaviour, compounding the machine setting effects. The principle of high conductivity/permittivity grains-induced breakdown channel described in Chapter 4 and the HVP pre-concentration mechanism presented in Chapter 5 are used to analyse and explain the PWTS testing results.
- The pilot scale PWTS study provides unique datasets to develop the HVP breakage model and to validate the model, which will be presented in Chapter 8.
• A comparison of HVP performance between the pilot scale PWTS and a laboratory machine selFrag Lab indicates that there is considerable scope for optimisation of HVP performance based on processing zone design.

• One joint paper with the SELFRAG manufacturer has been prepared for journal publication (Minerals Engineering, under review), which is presented in this chapter.
Chapter 7 Experimental Study of Ore Breakage Behaviour in a Pilot Scale HVP Machine

Ore particle breakage behaviour in a pilot scale high voltage pulse machine

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ABSTRACT

SELFrag AG has developed a flexible pilot scale Pre‒Weakening Testing Station (PWTS) using high voltage pulses (HVP). This provides a unique opportunity to investigate the machine setting conditions on ore breakage behaviour. A joint campaign was undertaken by the Julius Kruttschnitt Mineral Research Centre and SELFRAG AG to investigate the breakage behaviour of two copper‒gold ores and one iron ore in the PWTS. The effects of specific energy, pulse voltage, cumulative discharges, feed particle size and ore particle breakage pattern (body breakage or surface breakage) were investigated. The investigation revealed that the mass‒specific energy of HVP was the most significant factor affecting the breakage behaviour in the PWTS. This effect was compounded with the effects of ore properties and particle size. Comparison between the PWTS and a laboratory HVP machine indicates that there is considerable scope for optimisation of HVP performance based on processing zone design.

Keywords: Breakage characterization; High voltage pulses; Electrical comminution.

1. Introduction

Comminution remains by far the largest energy consumer in the mining industry. The high energy consumption implies both a high operational cost and a greenhouse footprint. As one of the potential technical means of reducing the energy consumption of comminution, pre‒weakening of ore particles by high voltage pulse (HVP) has attracted the attention of researchers in the past few
years (Usov and Tsukerman, 2006; Wang et al., 2011; van der Wielen et al., 2013; Razavian et al., 2014).

HVP breakage is a comminution method that uses high voltage pulses to initiate electrical breakdown inside ore particles that are immersed in water, generating a strong tensile force to disintegrate the particles. The research found that particle strength of a number of ores can be reduced significantly by HVP treatment using a low specific energy (Wang et al., 2011), thus reducing the energy consumption in the downstream comminution process. A number of potential applications of HVP technology in the mineral industry have been proposed, including pre–weakening the AG/SAG feed, hard particles treatment, ball mill feed pre-treatment, etc. (Shi et al., 2012). In addition, Shi et al. (2014a) demonstrated that, taking into account both HVP and mechanical breakage energy consumptions in a hybrid circuit simulation, the pre–weakening effect on energy reduction through changes in comminution circuit configurations is significant.

The initial study of pre–weakening by HVP breakage was performed with a selFrag Lab device manufactured by SELFRAG AG based in Switzerland (Wang et al., 2011). The selFrag Lab is primarily designed for the selective fragmentation of composite materials, mineralogical and geological samples in the kilogram range, rather than for pre–weakening study purposes. In order to demonstrate the benefits of HVP pre–weakening to the mineral industry, the equipment has to be scaled up to treat larger particles with more flexibility in operation settings. SELFRAG AG has recognized the need and developed a pilot scale Pre–Weakening Test Station (PWTS), which is a purpose–built R&D machine at the SELFRAG pilot plant (van der Wielen et al., 2014). In comparison with the selFrag Lab, the advantage of the PWTS is that it offers more flexibility in terms of generator setup, as well as the possibility to process continuously. Voltage and capacitance of pulse generator can be adjusted independently for the PWTS, allowing testing of same pulse energy but different voltages. Investigation of the ore particle breakage behavior in the PWTS is helpful in further development of the HVP technology.

van der Wielen et al. (2014) conducted a detailed HVP breakage characterization on a sample of granite with the PWTS. It was found that the relation of pre–weakening degree of the granite sample to specific energy is similar to the impact breakage product fineness–specific energy relationship described by JKMRC breakage model (Napier-Munn et al., 1996). The work helped to understand rock breakage behaviour in HVP breakage, but may not well represent ore breakage behaviour. The difference in breakage behaviour under HVP treatment between rocks and ores can be exemplified in a recent study that the content and location of the minerals with high
permittivity/conductivity affect breakage behavior of ore particles (Zuo et al., 2014; 2015). In order to obtain a thorough understanding of ore particle breakage behaviour in the PWTS, a joint campaign was conducted by the Julius Kruttschnitt Mineral Research Centre (JKMRC) and the PWTS manufacturer SELFrag AG. This study investigated the breakage behaviour of three ore samples, two copper-gold ores and one iron ore, in the PWTS under different operating conditions. The major findings of ore particle breakage behaviour in the PWTS are presented in this paper.

2. Experiment

2.1 HVP treatment with PWTS

Ore particle behaviour in HVP breakage was investigated with the pilot scale PWTS machine installed in Kerzers, Switzerland. The structure of the PWTS is illustrated in Figure 7-1. The PWTS machine consists of a pulse generator, a metal plate conveyor, a water vessel and a processing zone. The top electrode is connected to the pulse generator, just above the flat bottom section of the metal plate conveyor. The flat bottom section of the metal plate conveyor is guided by insulation material and immersed in water, acting as the counter electrode during pulse discharge (Figure 7-2).
The PWTS can be operated using different polarity of the discharge. Positive polarity uses the top electrode; negative uses the bottom electrode. In the tests the PWTS was set to negative polarity. This is to avoid water gaps to initiate the streamers by direct contact of material lying on the conveyor. The processing zone can be adopted by using top electrodes of different shapes (disk, knife, etc.) and sizes. Disk–shaped top electrode was used in this study.

The processing zone of the PWTS is defined by the electrode gap and the distance from side guides made of insulation material. The volume of the processing zone can be adjusted by the electrode gap and the distance between the side guides. HVP breakage treatment can be conducted in both continuous mode (moving conveyor) and batch testing mode (stationary conveyor).

Specifications for the PWTS are listed in Table 7-1. The machine can be operated at pulse voltage from 50 kV to 200 kV. The PWTS has power supply of 20 kW. Depending on the required specific energy a range of throughputs can be adjusted, eg. at 2 kWh t\(^{-1}\) about 8-10 t h\(^{-1}\), or at 4 kWh t\(^{-1}\) about 3-5 t h\(^{-1}\). The actual throughput depends on the particle size, particle density, the pulse energy required, and PWTS energy transformation efficiency.

The results of HVP breakage tests reported in the literature often show the mixed effects of machine–related and ore–dependent factors. A single–particle characterisation test (Shi et al., 2013) has been developed to decouple the ore–dependent factors from the machine–related factors in the HVP breakage. The PWTS can run in a continuous mode with multiple particles passing through the
electrode system. In order to minimise the machine setting–related influence on the experimental results, the experiment was conducted in a single–particle, single–pulse mode to focus the investigation on ore particle breakage behaviour. During the test the metal plate conveyor remained stationary.

<table>
<thead>
<tr>
<th>Operational parameter</th>
<th>Adjustable range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (kV)</td>
<td>50-200</td>
</tr>
<tr>
<td>Pulse energy (J)</td>
<td>27.5-750</td>
</tr>
<tr>
<td>Electrode gap (mm)</td>
<td>10-80</td>
</tr>
<tr>
<td>Polarity</td>
<td>+/-</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>1-100</td>
</tr>
<tr>
<td>Feed particle size (mm)</td>
<td>0-80</td>
</tr>
<tr>
<td>Operation</td>
<td>Batch or continuous</td>
</tr>
<tr>
<td>Throughput (t h⁻¹)</td>
<td>0-10</td>
</tr>
<tr>
<td>Installed Power (kW)</td>
<td>20</td>
</tr>
</tbody>
</table>

For each HVP treatment, only one single particle was placed on the metal plate conveyor, directly under the top electrode and immersed in water. One single pulse was discharged to the particle in batch mode (i.e. one particle per treatment). The pulse-treated particles were classified into two groups according to breakage response: body breakage and surface breakage. If a particle loses more than 10% of its original mass subjected to a pulse loading, it is classified as body breakage. (Shi et al., 2013; Zuo et al., 2014b; Zuo and Shi, 2015b, c). This criterion is adopted from the mechanical breakage classification (Tavares and King, 2002). The whole process zone contents were collected carefully, and another particle was treated. If the particle remained intact or showed only minor surface breakage with a couple of chips being generated (less than 10% of the parent particle mass), the breakage response was considered as surface breakage and a further single-pulse was discharged. The procedure continued until the body breakage event occurred or a desired pulse discharge number was reached. Finally, the product of body or surface breakage was collected separately for further analysis.

2.2 Materials tested

Samples collected from three mine sites were tested, namely Ore A, Ore B and Ore C. Ore A was collected from a gold–copper mine operation located in New South Wales, Australia. The gold–copper mineralization occurs in quartz veins, sheeted quartz sulphide veins and as disseminations.
The gold occurs mainly as free grains in quartz or on the margins of sulphide grains. The principal copper sulphide minerals are chalcopyrite and bornite. The major silicate minerals are quartz, orthoclase, hornblende, chlorite, anorthoclase, and the non–silicate minerals include magnetite, calcite and apatite.

Ore B was collected from a major copper, silver and gold mine in South Australia. The deposit is an iron oxide copper gold (IOCG) style mineralization. It consists of a breccia containing host rock clasts (dolomite, sandstone, and andesite) which are intensively hematite, chlorite and sericite altered. Major sulphide minerals are pyrite, chalcopyrite, bornite and chalcocite.

Ore C is a hematite ore from a confidential project, with Fe grade of around 63.0%. It was observed that some particles were highly porous.

The ore competences of the three samples were determined with a JK Rotary Breakage Tester (JKRBT, Shi et al., 2009). The values of the ore competence indicator $A \times b$ for Ore A, B and C are 42.0, 61.7 and 127.7 respectively. The larger $A \times b$ value indicates the less resistance to breakage. This suggests that the three ore samples cover a wide range of ore breakage competence from very hard (Ore A) to soft (Ore C).

### 2.3 Test conditions

For each ore sample, particles in three narrow size fractions were tested, including 22.4-26.5 mm, 31.5-37.5 mm and 45-53 mm. In each test, 30 particles of the same size fraction were treated by HVP in the PWTS.

For Ore A samples, particles of each size fraction were tested with 3 voltage levels $\times$ 3 pulse energies. The relationship of single pulse energy, capacitance and pulse voltage can be described by Eq. (7-1):

$$E = \frac{1}{2}CU^2$$  \hspace{1cm} (7-1)

where $E$ represents pulse energy (J), $C$ is capacitance (F) and $U$ is pulse voltage (V).

Eq. (7-1) indicates that the range of pulse energy is limited by the selectable range of pulse voltage.
and capacitance. Within this limit, the voltage and pulse energy levels for Ore A were set in Table 7-2. Note that Eq. (7-1) is a general equation. The calculation of pulse energies shown in Table 7-2 are completed with the consideration of the specific setting of the pulse generator.

<table>
<thead>
<tr>
<th>Voltage, kV</th>
<th>Pulse energy, J</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>750 550 350</td>
</tr>
<tr>
<td>172</td>
<td>550 333 259</td>
</tr>
<tr>
<td>136</td>
<td>347 254 162</td>
</tr>
</tbody>
</table>

The test conditions were set to cover a wide range of pulse energy from 162 J to 750 J, and to enable a paired comparison at the similar pulse energies but with different voltage for particles of the same size. Thus the effect of pulse voltage on ore particle breakage behavior can be evaluated. Due to the availability of the selectable range of the capacitance, the pulse energies for some paired sample comparison tests were set to be as close to each other as possible, but not exactly the same.

Ore B and Ore C samples were only tested at a fixed voltage of 200 kV, with the same three pulse energy levels used for Ore A, as shown in Table 7-2.

Minimum electrode gaps were used in the tests and determined as 25, 35 and 45 mm for the three size fractions of 22.4-26.5 mm, 31.5-37.5 mm and 45-53 mm respectively. The minimum gaps were smaller than the corresponding top size limit of each size fraction, because the thickness of the particles was usually less than its nominal top size limit. The variation of voltage and gap changes the electrical field strength considerably. This will have an effect on particle breakage results at the identical voltage.

Due to the constraint of sample availability, the actual numbers of test conditions for Ore A, Ore B and Ore C were 21, 9 and 6 respectively, including five repeated tests to determine the standard error of HVP breakage test with the PWTS.

3. Sample analysis and data reduction

In this study, three criteria were used to describe and evaluate the ore particle breakage behaviour in the PWTS experiment: the body breakage probability, HVP product fineness and pre‒weakening degree. In an ore particle subjected to pulse discharge, the breakdown channel grows preferentially along the enhanced electrical field on the boundary of minerals with different permittivities and
conductivities. The body breakage and surface breakage that resulted from the HVP treatment are distinguished by the HVP breakdown channel locality in the ore particle. It was found that mineral composition played an important role in determining particle breakage behaviour (see Shi et al., 2015b; Zuo et al., 2015b for details). The body breakage is often associated with the electrical breakdown channels passing through the particle body, resulting in large amount of cracks/microcracks. In contrast, the surface breakage is associated with the electrical breakdown channels passing over the particle surface, resulting in chipping on the particle edges and minor cracks/microcracks in the main body of the particle.

The body breakage probability is calculated based on the mass proportion of body breakage product from the initial feed sample mass. The HVP product fineness is assessed by a fineness indicator, t10. The t10 is defined as the cumulative percentage of the product passing 1/10th of the initial feed size, which can be determined from the product size distribution and the feed geometry mean size. The degree of pre–weakening is defined as a percentage change of the A×b values between the HVP treated and untreated ore particles, using JKRBT.

To determine the three criteria, the HVP products were collected for weighing, sieving and pre–weakening degree measurement. As size analysis is used on the product particles to derive the breakage behaviour criteria, it is critical to perform the size analysis of the pulse–treated particles correctly and consistently. This is described in detail below.

3.1 Size analysis of the pulse-treated particles

The HVP treated particles contain cracks and microcracks. Depending on the size of the cracks/microcracks, some particles exhibit limited microcracks distributed in an intact particle matrix. Some other particles appear as discrete fragments loosely held together by their interlocking geometries. It was found that these interlocked but disconnected particles can be disintegrated even by the collisions with the sieve surface during the mechanical vibrating sieving process. In practice, these interlocking particles would be quickly degraded during transportation, and perhaps will not contribute to energy saving in the downstream comminution process. An experiment was designed to compare the size distributions of the HVP treated products by hand sieving and mechanical sieving. The testing procedures are illustrated in Figure 7-3.
The hand sieving method was carried out gently to minimize the secondary breakage of the loosely held fragments. A randomly selected sub-sample of the HVP treated particles from Ore A was selected for size analysis. The hand sieved product was combined and sieved in a Rotap® mechanical vibrating sieving machine for 10 minutes to obtain a new product size distribution. Two more mechanical sieving tests were carried out. The size distributions of the sieving tests are given in Figure 7-4.

The initial hand sieving of the PWTS product has a $P_{80}$ of 20.7 mm. The values of $P_{80}$ change to 17.7, 17.6 and 17.4 mm after 10, 20 and 30 min mechanical sieving respectively. The result suggests that the loosely held fragments of the HVP treated particles that survived in hand sieving can be disintegrated after 10 min mechanical vibrating sieving. It was estimated that the specific collision energy accumulated during the 10 min sieving on the Rotap® machine is at the level of 0.01 kWh t$^{-1}$ (Walters and Powell, 2012). However the size distributions after 20 and 30 min mechanical sieving do not change significantly from the 10 min sieving result. It is reasoned that these loosely held fragments should be classified as part of the size reduction effect of the HVP breakage. Therefore mechanical vibrating sieving for 10 min was consistently applied to determine the product size distributions of HVP breakage tests. Note that the pre-weakening degree determined by using mechanical sieving will be smaller than that determined by hand-sieving.
3.2 Measurement of pre–weakening degree

The pre–weakening degree of pulse–treated particles is defined as the percent change of $A \times b$ values based on untreated particles. Here $A$ and $b$ are the parameters of the JKMRC breakage model (Napier-Munn et al., 1996), as shown in Eq. (7-2).

$$
t_{10} = A \left(1 - e^{-bE_{cs}}\right)
$$

(7-2)

where $E_{cs}$ is the specific comminution energy (kWh t$^{-1}$), and $A$ and $b$ are model parameters. The product $A \times b$ is widely used in the mineral industry as an indicator of ore competence. A larger $A \times b$ value indicates the less competent ore, or less resistance to breakage. By taking the derivative of Eq. (7-2), it can be proved that $A \times b$ is the slope of the $t_{10}$–$E_{cs}$ curve at ‘zero’ input energy (Napier-Munn et al., 1996).

Shi and Kojovic (2007) reported a size–dependent model to describe the degree of breakage, which is modified from a breakage probability model published by Vogel and Peukert (2003). This model (Eq. (7-3)) takes a form similar to the JKMRC breakage model (Eq. (7-2)):

![Figure 7-4 Comparison the size analysis results between the hand sieving and the mechanical sieving](image)
\[ t_{10} = M \{1 - \exp[-f_{\text{mat}} \cdot x \cdot k(E - E_{\text{min}})]\} \]  

(7-3)

where \( M \) (%) represents the maximum \( t_{10} \) for a material subject to breakage, \( f_{\text{mat}} \) (kg \ m\(^{-1}\)) is the material breakage property, \( x \) (m) the initial particle size, \( k \) the successive number of impacts with the same impact energy, \( E \) (J kg\(^{-1}\)) the mass–specific impact energy, and \( E_{\text{min}} \) (J kg\(^{-1}\)) the threshold energy. In this paper, \( k \) and \( E_{\text{min}} \) are set as 1 and 0 respectively.

The parameter \( f_{\text{mat}} \) was defined by Shi et al. (2015a) as a function of particle size (Eq. (7-4)):

\[ f_{\text{mat}} = p \cdot d^{-q} \]  

(7-4)

Note that the unit of particle size \( d \) in Eq. (7-4) is mm.

Eqs. (7-2) and (7-3) take a similar exponential form, and the parameters of Eq. (7-3) can be converted to that of Eq. (7-2) (but not the other way round). The \( A \times b \) value from Eq. (7-2) can be calculated from the parameters in Eq. (7-3) and (7-4) using the following relationship:

\[ A \times b = 3600 \cdot M \cdot f_{\text{mat}} \cdot x = 3.6 \cdot M \cdot p \cdot d^{(1-q)} \]  

(7-5)

where the constant 3600 or 3.6 is used for unit conversion. Eq. (7-5) gives the size–specific \( A \times b \) values. In this paper, all the \( A \times b \) values are calculated specifically for 32.5 mm, the mean size for the five size fractions used in the standard Drop Weight Test (Napier-Munn et al., 1996).

The \( A \) and \( b \) parameters can be obtained by fitting above breakage models (Eqs. (7-2), (7-3) and (7-4)) to the ore impact breakage testing data acquired from the DWT or JKRBT. Initially, standard JKRBT test was employed to determine the \( A \times b \) values of ore particles pre-weakened by HVP breakage (Wang et al., 2011). In a standard JKRBT test, particles in four size fractions are tested, each with three specific energy levels. In each size–energy level 30 particles are tested in a single–particle breakage mode. In order to simplify the measurement of \( A \times b \) by the JKRBT, a Reduced JKRBT test was developed by Shi et al. (2013), which reduced the number of size–energy levels of the breakage treatment from twelve, for the standard JKRBT test, down to five. Both the standard and Reduced JKRBT tests use only a portion of the particles in the designated size fractions, the demand for feed material in the JKRBT tests to determine the pre–weakening effect is high. Thus,
the provision of sufficient material from the single-particle, single-pulse HVP test is difficult.

An $A\times b$ Express test was adopted in some HVP breakage studies, including the work by van der Wielen et al. (2014). In the $A\times b$ Express test, particles of one size were tested with a single low specific energy using either DWT or JKRBT, and the $A\times b$ value is estimated by dividing the $t_{10}$ value by specific energy. However, a large variation in the $A\times b$ values was often observed in the $A\times b$ Express test, largely due to the variation in the selected particles in one size fraction.

To overcome the limitations in the existing ore breakage characterisation methods for pre-weakened particles, a Wide-size JKRBT test has been developed (Zuo and Shi, 2015b). In this test, all larger than 3.35 mm particles in the PWTS product are combined as one sample after size analysis, followed by breakage treatment with JKRBT at a given rotational speed. In the data reduction process, the wide-size JKRBT feed is divided into several virtual narrow size fractions. The specific energy level for each virtual size fraction can be calculated from particle size and rotational speed using a method developed by Shi et al. (2009). A $t_{10}$–based method (Eq. (7-6)) is employed to determine the percentage of $A\times b$ changes (Zuo and Shi, 2015c). The $t_{10}$–ased method requires the pre–determined breakage characteristic parameters of the HVP untreated ore particles using a Standard JKRBT or Reduced JKRBT test as a benchmark for comparison.

$$t_{10p}(i) = \left\{1 + \frac{C_{Ab}}{100} \left(1 - \frac{t_{10u}(i)}{M_u}\right)\right\} t_{10u}(i)$$  \hspace{1cm} (7-6)

where $t_{10p}(i)$ and $t_{10u}(i)$ are obtained by JKRBT tests for the pulse–treated and untreated particles at the same size (i) and impact energy levels; $C_{Ab}$ is equal to the percentage change of $A\times b$; $M_u$ is the maximum $t_{10}$ value of HVP untreated particles.

The Wide-size JKRBT test was adopted in this study, as it provides a simplified but reliable method to characterize the breakage behaviour of pulse-treated particles. Particles in the HVP product finer than 3.35 mm were removed from the JKRBT test. The rotational speed of the JKRBT rotor was set to deliver an average specific energy of 1 kWh t$^{-1}$ for the geometric mean size of the wide-size feed. The JKRBT test product was sieved to determine the size distribution. The $t_{10}$–based method (Eq. (7-6)) was applied to determine the degree of pre–weakening effect.
Chapter 7 Experimental Study of Ore Breakage Behaviour in a Pilot Scale HVP Machine

4. Results and discussion

4.1 The effects of specific energy and particle size on HVP breakage behaviour of ore

For all the ore samples used in this study, approximately 40-100% of initial feed particles were subjected to body breakage at the first pulse discharge. The number of particles remaining for the 2nd or 3rd pulse discharges was limited. Therefore the effects of specific energy and particle size on HVP breakage behaviour of the ores are discussed based on the body breakage product of the first pulse discharge in this section. The specific energy is calculated from the total generator energy input and the total particle mass in a test.

4.1.1 Body breakage probability

As shown in Figure 7-5, the probability of body breakage ranges from approximately 40% to 100% within the test conditions of this study. For all of the three ores, the probability of generating body breakage by the first pulse discharge in the PWTS increases with the increase of specific energy. The data show that Ore A exhibits a significant size effect, by which the coarser particles present higher body breakage probability than the finer particles at the same specific energy. Similar size effect had also been found in the work of previous researchers (Wang et al., 2011; Shi et al., 2013; van der Wielen et al., 2013; van der Wielen et al., 2014). However, the size effect on body breakage probability is not significant for Ore B and Ore C with the same PWTS testing conditions.

It is worth noting that the electrical field strength for the coarser particles (associated with the larger electrode gaps) is smaller at the same voltage. The size effect which shows higher body breakage probability for the coarser particles seems not caused by the difference in electrical field strength. The size effect is therefore sought from the difference in ore properties. Ore A includes metalliferous minerals finely disseminated in veins, which is surrounded by gangue minerals with different permittivities. It is well-known that in general the coarser feed particles should include more veins. Attributed to the electrical breakdown channel locality influence as demonstrated in Zuo et al (2014, 2015), more breakdown channels passing through the body of the coarser particles may occur, leading to higher body breakage probability for the coarser particles. In comparison, Ore B includes higher Fe content as an IOCG ore that includes more conductive gangue matrix, and Ore C is an iron ore with the highest conductivities in the three ores tested. The body breakage probability for these two ores containing high Fe contents is higher than Ore A, reaching plateau at a specific energy of 2 kWh t⁻¹ and showing insignificant particle size effect.
Figure 7-5 The effect of particle size and specific energy on the body breakage probability at the first pulse discharge (Points: measured; Lines: regressed)

Figure 7-5 also indicates that the body breakage probability increases rapidly as the specific energy increases, then slows before reaching a plateau. The critical specific energy for body breakage probability to change its rate of increase is approximately 2 to 4 kWh t\(^{-1}\), depending on the ore type.
and particle size. This suggests that the majority of ore particles tested in this study can achieve body breakage at a specific energy between 2 and 4 kWh t\(^{-1}\).

4.1.2 HVP product fineness indicator \( t_{10} \)

Figure 7-6 presents the HVP product fineness indicator \( t_{10} \) in relation to specific energy for the three ore samples. All three ores demonstrate that the HVP products become finer when subjected to larger specific energy, as expected. The particle size effect on product fineness indicator \( t_{10} \) is not significant for Ore A, but is more pronounced for Ores B and C. Subjected to the same specific energy, the coarser particles produced the larger \( t_{10} \) values for Ore B and C.

 Compared to body breakage probability, the different ores show a reversed trend in \( t_{10} \). This may be explained by the HVP breakage mode based on ore composition and texture. The fineness indicator \( t_{10} \) is to quantify the percentage of new fines (smaller than 1/10\(^{th}\) of the feed size) generation, but not to reflect the coarse fragments production. Particles undergoing body breakage when subjected to HVP treatment often produce more coarse fragments but less fines. This is the case in Ore A, in which the difference in the fines produced from the three feed sizes were not pronounced. For ores B and C the HVP breakage mode was mainly through surface breakage. Discharges moved along particle surfaces and peeled or chipped finer particles. As coarse particles have more surface being removed per discharge, this resulted in larger \( t_{10} \) for coarser feed particles, leading to a more pronounced size effect for Ores B and C.

When fitting the \( t_{10} - E_{cs} \) relationship with Eq. (7-2), an \( A \times b \) for HVP breakage can be determined. The similar exercise can be found in van der Wielen et al. (2014). The \( A \times b \) values for PWTS breakage are far less than that for the impact breakage of the same ores. To give an example, the HVP breakage \( A \times b \) values for Ore A samples were 5.1, 3.4 and 2.9 for the three feed size fractions 45-53 mm, 31.5-37.5 mm and 22.4-26.5 mm respectively. In comparison, mechanical impact breakage produced \( A \times b \) values of 49.1, 42.9 and 24.4 for the same ore samples. This indicates that ore has much higher “resistance” to the HVP breakage. In other words, the HVP breakage is less energy-efficient in size reduction and fines generation than mechanical breakage. This has been reported in the literature (eg. Wang et al., 2011). The recent research has indicated that using small HVP energy, the technology has a potential for the mineral industry in ore pre–weakening (Wang et al., 2011; Shi et al., 2014b), coarse mineral liberation (Wang et al., 2012c; Parker et al., 2015), and ore pre–concentration (Shi et al., 2015b; Zuo et al., 2015b).
Figure 7-6 The effect of particle size and specific energy on the PWTS product fineness indicator $t_{50}$ at the first pulse discharge (Points: measured; Lines: regressed)
4.1.3 Degree of pre-weakening of the body breakage product

Significant pre–weakening effects were achieved using the PWTS for Ore A and Ore B with 81.7% and 131.8% change in $A \times b$ values respectively. Figure 7-7 displays the degree of pre–weakening in relation to specific energy for the three ore samples. As expected, increasing the specific energy leads to the increased degree of pre–weakening effect for Ores A and B. There is a size effect for Ore A, with the coarse particles achieving the larger pre–weakening effect at the same HVP specific energy. The size effect for Ore B is not significant.

A different phenomenon was observed from Ore C samples. As presented in Figure 7-7, Ore C samples exhibited a negative pre–weakening degree. The data possibly indicates that the HVP body breakage product of Ore C was even harder than the pulse–untreated particles. It can be found that the change in $A \times b$ value is most significant (−40.7% change) at the lowest specific energy (0.4 kWh t$^{-1}$), and then decreases along with the increase of HVP specific energy. When the specific energy reaches 5.2 kWh t$^{-1}$ for the 22.4-26.5 mm particles, the $A \times b$ value of the pulse–treated product is close to the untreated particles (−5.8% change).

The performance of Ore C can be attributed to its composition and porous texture. Figure 7-8 shows that pores and cracks are distributed on the surfaces of the untreated Ore C particles. During the HVP breakage the expansion of electrical breakdown channels, not only generated new cracks/microcracks, but also destroyed the existing pores and cracks. At small pulse energy, more pre–existing pores and cracks were destroyed than the newly generated cracks, leading to a significant increase in ore competence. As specific energy increased (eg. over 5 kWh t$^{-1}$), more cracks/microcracks were generated than the destroyed pre–existing pores/cracks. The balance may be equivalent to the pre–existing pores and cracks, leading to a similar ore competence to the untreated ore particles. In this process, over 5 kWh t$^{-1}$ specific energy was wasted. The performance of Ore C suggests that for particles with composition like Ore C, the weak components (for instance the porous texture) would be broken by HVP discharge preferentially, leaving more competent residues. The increased competence of the HVP product of Ore C is the result of the more competent residues.
Figure 7-7 The effect of particle size and specific energy on the degree of pre-weakening of the HVP product at the first pulse discharge (Points: measured; Lines: regressed)
4.2 The effect of voltage on HVP breakage behaviour

To investigate the effect of voltage on HVP breakage behaviour, the experiment for Ore A was designed to make a paired comparison for the product of first pulse discharge at the same particle size and pulse energy but with different pulse voltages. Table 7-3 lists the testing conditions including particle size, electrode gap, pulse voltage, electrical field strength (kV mm\(^{-1}\)) and single pulse energy. The breakage behaviour of the first pulse discharge product in terms of body breakage probability (\(P\%\)), product fineness index \(t_{10}\) and pre-weakening degree (%\(A \times b\) change) are also given in Table 7-3.

There were seven pairs of datasets used for the comparison. In each pair of the data the major difference in operational variables was pulse voltage, while the other variables being kept similar. The pulse energy was adjusted (refer to Table (7-3)) to be similar for each pair by capacitance settings available in the PWTS pulse generator system, according to the designated pulse voltage. Statistical \(t\)-Tests were performed on paired comparisons of the HVP breakage behaviour indicators of the seven datasets. Table 7-4 summarises the statistical test result. The null hypothesis is that there is no difference in HVP breakage behaviour indicators caused by pulse voltage, as long as the pulse energy is the same. The null hypothesis is assumed true unless proved otherwise. The \(t\)-Tests result indicates that the differences in body breakage probability and product fineness attributable to the pulse voltage effect are at the significance levels of 93 and 94\% respectively, not reaching the 95\% significance level. As for the pre-weakening degree (%change of \(A \times b\)), the difference is at a
Chapter 7 Experimental Study of Ore Breakage Behaviour in a Pilot Scale HVP Machine

significance level over 99%.

Table 7-3 Paired comparison of HVP breakage behaviour tested with the similar pulse energy but at different pulse voltages for Ore A

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Gap (mm)</th>
<th>Voltage (kV)</th>
<th>kV/mm</th>
<th>Pulse (J)</th>
<th>P (%)</th>
<th>$t_{10}$ (%)</th>
<th>$%A \times b$ change</th>
</tr>
</thead>
<tbody>
<tr>
<td>45-53</td>
<td>45</td>
<td>200</td>
<td>4.4</td>
<td>550</td>
<td>77.7</td>
<td>4.4</td>
<td>36.0</td>
</tr>
<tr>
<td>45-53</td>
<td>45</td>
<td>172</td>
<td>3.8</td>
<td>555</td>
<td>60.9</td>
<td>1.9</td>
<td>16.9</td>
</tr>
<tr>
<td>45-53</td>
<td>45</td>
<td>200</td>
<td>4.4</td>
<td>350</td>
<td>50.5</td>
<td>2.1</td>
<td>23.6</td>
</tr>
<tr>
<td>45-53</td>
<td>45</td>
<td>136</td>
<td>3.0</td>
<td>347</td>
<td>47.9</td>
<td>1.6</td>
<td>0.2</td>
</tr>
<tr>
<td>31.5-37.5</td>
<td>35</td>
<td>200</td>
<td>5.7</td>
<td>550</td>
<td>81.8</td>
<td>6.9</td>
<td>37.3</td>
</tr>
<tr>
<td>31.5-37.5</td>
<td>35</td>
<td>172</td>
<td>4.9</td>
<td>555</td>
<td>71.5</td>
<td>6.4</td>
<td>37.6</td>
</tr>
<tr>
<td>31.5-37.5</td>
<td>35</td>
<td>136</td>
<td>3.9</td>
<td>254</td>
<td>68.4</td>
<td>3.8</td>
<td>19.9</td>
</tr>
<tr>
<td>22.4-26.5</td>
<td>25</td>
<td>200</td>
<td>8.0</td>
<td>550</td>
<td>90.8</td>
<td>12.7</td>
<td>71.7</td>
</tr>
<tr>
<td>22.4-26.5</td>
<td>25</td>
<td>172</td>
<td>6.9</td>
<td>555</td>
<td>87.2</td>
<td>14.2</td>
<td>63.4</td>
</tr>
<tr>
<td>22.4-26.5</td>
<td>25</td>
<td>136</td>
<td>5.4</td>
<td>347</td>
<td>78.0</td>
<td>8.3</td>
<td>53.2</td>
</tr>
<tr>
<td>22.4-26.5</td>
<td>25</td>
<td>172</td>
<td>6.9</td>
<td>259</td>
<td>78.3</td>
<td>8.1</td>
<td>65.8</td>
</tr>
<tr>
<td>22.4-26.5</td>
<td>25</td>
<td>136</td>
<td>5.4</td>
<td>254</td>
<td>76.0</td>
<td>6.5</td>
<td>57.1</td>
</tr>
</tbody>
</table>

The results of statistical tests suggest that the effect of pulse voltage on body breakage probability and product fineness $t_{10}$ are not pronounced at 95% significance level, but very close. A larger database is required for further confirmation of the observed trends. The pulse voltage effect on pre‒weakening is confirmed, with the higher pulse voltage resulting in the larger pre‒weakening effect at the same particle size and pulse energy.

Table 7-4 Summary of t-tests on paired comparisons of HVP breakage behaviour between tests at different voltages for Ore A

<table>
<thead>
<tr>
<th>Item</th>
<th>Body breakage probability</th>
<th>Body breakage product fineness $t_{10}$</th>
<th>Degree of pre‒weakening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean difference</td>
<td>6.1</td>
<td>0.8</td>
<td>14.3</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>8.8</td>
<td>1.2</td>
<td>9.0</td>
</tr>
<tr>
<td>Degree of freedom</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>$t$</td>
<td>1.8</td>
<td>1.7</td>
<td>4.2</td>
</tr>
<tr>
<td>Distribution</td>
<td>1‒Tailed</td>
<td>1‒Tailed</td>
<td>1‒Tailed</td>
</tr>
<tr>
<td>Significance level (%)</td>
<td>94.3</td>
<td>93.1</td>
<td>99.7</td>
</tr>
</tbody>
</table>
Chapter 7 Experimental Study of Ore Breakage Behaviour in a Pilot Scale HVP Machine

The study suggests that ore particle breakage behaviour subjected to HVP treatment is mainly controlled by pulse energy, but the pulse voltage also exerts an influence on the breakage results. As the comparison was made on the same electrode gap for each pair, the change in pulse voltage was associated with a change in electrical field strength (data given in Table 7-3). It is unclear in the existing experimental design whether the enhanced particle breakage results were attributable to the pulse voltage, or the electrical field strength, or both. However, numerical simulations from the previous study have indicated that electrical field strength is a dominant factor (Wang et al., 2012a, b).

4.3 The effect of the number of cumulative discharges on HVP breakage behaviour

In the PWTS experiment, the surface breakage product of the first pulse discharge was subjected to the second pulse discharge at a similar specific energy level to the first pulse. The samples of the first and second pulse discharge products were collected and analysed separately. This data can be used to establish the effect of cumulative pulse discharge on HVP breakage behaviour. Figure 7-9 shows the comparisons of product fineness ($t_{10}$) and the degree of pre‒weakening (%change of $A \times b$) between the first and the second pulse treated products.

The comparisons illustrate that the second pulse discharge generated the finer body breakage product (larger $t_{10}$) and the larger pre‒weakening degree than the first pulse discharge. This is expected since the particles subjected to the second pulse discharge received twice the pulse energy than that of the first pulse product. The surface breakage caused by the first pulse reduced the electrical strength of particle (Bluhm, 2006). Although the surface breakage by the first pulse did not cause body breakage, the surface discharge injected a certain amount of damage, producing cracks/microcracks. This opened easier pathways for streamers to enter the material and to be more efficient to create breakdown channels, as less energy would be wasted in the initial introduction into the solid. As a result, the second pulse resulted in the finer product with the larger pre‒weakening degree.
4.4 Comparison of HVP breakage behaviour between body and surface breakage products

In order to compare the pre–weakening degrees between body and surface breakage products, the surface breakage products of the first pulse discharge from seven tests (Ore A, 31.5-37.5 mm) were reserved for pre–weakening degree measurement. Figure 7-10 shows a comparison of the pre–weakening degrees for the surface breakage products and the body breakage products at the same testing conditions.
The data indicates that all body breakage products achieved a significant pre–weakening effect with a percentage change of $A \times b$ varying between 19.9 and 48.8. In comparison, the pre-weakening data of surface breakage product varied significantly. In four out of the seven tests, the surface breakage products showed little change (±10%) of $A \times b$ values. The negative change of $A \times b$ reflected that some weaker components of the feed particles were removed by surface discharge as the chips or fines that were not included in the JKRBT characterisation (outside the testing size range). The more competent components in the remaining particles were used as the surface breakage product for the JKRBT tests. As a result, these surface breakage products appeared “harder” than the untreated particles. However, the other three tests showed that the surface breakage products also achieved significant pre–weakening results. In general, the pre–weakening effect caused by the surface breakage is less than the body breakage at the same HVP treatment conditions.

The large variation in the pre-weakening result of the surface breakage product may be attributed to the mineral composition and texture of individual particle. If the veins containing metalliferous minerals occur on a particle surface or near the surface, they can misguide the discharge through the particle surface and restrict the energy transfer. A part of the pulse energy is lost in the water. If the metalliferous minerals occur not only on particle surface, but also inside a particle, the induced breakdown channels will create cracks/microcracks, resulting in a higher degree of pre-weakening effect. It needs to point out that the surface breakage particles can be broken by the second pulse application (refer to Section 4.3).
4.5 Comparison of ore breakage behaviour between PWTS and selFrag Lab

The experiment was designed to use PWTS and selFrag Lab to treat the same ore samples under the same HVP settings. The selFrag Lab used for the comparison is a laboratory scale HVP device installed at the JKMRC (Wang et al., 2011). Three ore samples were used for the comparison. The single-particle, single-pulse breakage method was adopted in the selFrag Lab tests, similar to the tests using the PWTS. Table 7-5 lists the three ore breakage behaviour indicators: body breakage probability (P%), body breakage product $t_{10}$ and body breakage product pre-weakening degree (% $A \times b$ Change), of four pairs of comparative tests conducted with the PWTS and the selFrag Lab.

<table>
<thead>
<tr>
<th>Ore</th>
<th>Ore A (31.5-37.5 mm)</th>
<th>Ore B (22.4-26.5 mm)</th>
<th>Ore C (31.5-37.5 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device</td>
<td>PWTS</td>
<td>Lab</td>
<td>PWTS</td>
</tr>
<tr>
<td>Voltage (kV)</td>
<td>200</td>
<td>200</td>
<td>172</td>
</tr>
<tr>
<td>Pulse energy (J)</td>
<td>750</td>
<td>750</td>
<td>550</td>
</tr>
<tr>
<td>P (%)</td>
<td>90.0</td>
<td>36.6</td>
<td>71.5</td>
</tr>
<tr>
<td>$t_{10}$ (%)</td>
<td>8.4</td>
<td>3.2</td>
<td>6.4</td>
</tr>
<tr>
<td>$A \times b$ change (%)</td>
<td>51.8</td>
<td>51.7</td>
<td>37.6</td>
</tr>
</tbody>
</table>

For the two pairs of Ore A samples, performance of the PWTS is significantly better than the selFrag Lab, in terms of body breakage probability and product fineness; but there is no significant difference for the pre-weakening degree of body breakage product.

A similar phenomenon was also found for Ore B samples. Tests in both devices resulted in body breakage probability reaching or being very close to 100%, but the PWTS generated finer body breakage product than the selFrag Lab. The pre-weakening degrees of body breakage products generated by the two devices are similar (134 vs 132 in percentage change of $A \times b$).

For Ore C, however, the selFrag Lab outperformed the PWTS in all of the three HVP breakage behaviour indicators. This may be associated with the porous texture of Ore C. Further research is required to understand the effect of Ore C properties on HVP breakage.

The differences in the breakage behaviour may be caused by the inherent processing zone differences between the two units. The PWTS uses a disk-shape top electrode, while the selFrag Lab uses a tip electrode. The PWTS has a far more homogenous electrical field on account of the plate-plate configuration. This leads to less focused streamer initiation and a larger but less intense
electrical field. Compared with the Lab machine, the tip-plate configuration is more focused and energy transfer is more localised. The chance of a particle being the initiation point or at least being part of the discharge channels in the PWTS is larger. Hence the probability of body breakage should be larger. In addition, the polarity change of the electrode system would also contribute to the particle breakage behaviour. As described in Section 2.1, PWTS uses negative polarity electrode system. This can extend the time available for streamer growth to create more ignition points for streamers that affect the energy transfer efficiency.

The initial work comparing the PWTS and the selFrag Lab performance indicates that there is considerable scope for optimisation of HVP performance based on process zone design.

5 Conclusion

Investigation of particle breakage behaviour of three ore samples treated with HVP in a pilot scale PWTS was conducted. The investigation reveals that the mass–specific energy of HVP is one of the most significant factors affecting the breakage behaviour in the PWTS, with the larger specific energy producing the higher body breakage probability, the finer product size distribution and the more significant pre-weakening effect. The effect of particle size on HVP breakage behaviour is ore-dependent. For a copper-gold ore with finely disseminated metalliferous minerals in veins, the larger particle size produces the higher body breakage probability and the larger change in $A \times b$ values, but its effect on product fineness ($t_{10}$) is insignificant. For an iron oxide copper-gold (IOCG) ore, the body breakage probability and the %change in $A \times b$ are higher than the copper-gold ore at the same specific energy (at lower specific energy in particular), but the size effect is not obvious. For a highly porous hematite ore, the body breakage probability is high (similar to the IOCG) and without the size effect. However, the HVP product appears even ‘harder’ than before the HVP treatment. These results confirm the influence of ore properties such as mineral composition, texture and particle size on the HVP breakage.

Comparison between the PWTS and the selFrag Lab treating the same ores with the similar pulse energy indicates that there is considerable scope for optimisation of HVP performance based on processing zone design.

Acknowledgements

The financial support from Newcrest Mining for a PhD candidate in this study is gratefully acknowledged.
8.1 Introduction

The simulation software package, JKSimMet, can predict the performance of a comminution circuit through simulations. For this purpose, a model predicting the HVP breakage of ore particles is required to simulate and optimize the performance of the comminution circuit which incorporates HVP breakage to pre-condition the material for downstream mechanical comminution. Based on the investigation of ore particle breakage behaviour in HVP breakage introduced in Chapter 7, an HVP breakage model was developed to predict the body breakage probability, product size distribution and pre-weakening degree of ore in HVP breakage. With the data from the study of pre-concentration by HVP breakage, the HVP breakage model is extended to predict the metal recovery of body breakage product. The development of this HVP breakage model is introduced in this chapter.

8.2 Contributions

- For the first time in literature an HVP breakage model structure was developed with three sub-models to represent the three HVP breakage indices: the body breakage probability (the \(D_1\)-model), body breakage product fineness (the \(D_2\)-model), and body breakage product pre-weakening degree (the \(D_3\)-model). These sub-models can be used separately for different HVP applications in a hybrid comminution circuit.

- Relations between the HVP breakage indices and HVP pre-concentration characterisation curves were established (the \(D_f\)-model). The preliminary result indicated that the HVP breakage model has a potential to predict the recovery of valuable metals from the calibrated model parameters.

- A set of \(t_n\)-family of curves were established for the HVP breakage product. It was found that the data of various ore types and particle sizes obtained from the HVP breakage tests at different testing conditions all fall on similar \(t_n\)-curve trend lines. The \(t_n\)-family of curves
can be employed to estimate the product size distribution from the predicted $t_{10}$ values by the $D_2$-model.

- A journal paper has been prepared (Minerals Engineering, under review), which is presented in this Chapter.
Modelling of high voltage pulse breakage of ores

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ABSTRACT

A high voltage pulse (HVP) breakage model was developed as a general modelling structure to represent the three HVP breakage indices: body breakage probability (the $D_1$-model), body breakage product fineness (the $D_2$-model), and body breakage product pre-weakening degree (the $D_3$-model). Relations between the HVP breakage indices and HVP pre-concentration characterisation curves were established. The preliminary result indicated that the HVP breakage model has the potential to predict the recovery of valuable metals from the calibrated model parameters. A $t_n$-family of curves ($t_n$ is defined as cumulative percentage of product passing $1/n$ of the initial size) was used to describe the HVP breakage product size distribution. The $t_n$-family of curves can be employed to estimate the product size distribution from the predicted $t_{10}$ values by the $D_2$-model.

Keywords: Breakage characterization; High voltage pulse breakage; Breakage model.

1. Introduction

The mineral industry is facing increasing challenges in improving comminution energy efficiency and reducing operation costs. Much has been done in the past to improve the existing comminution processes and various novel methods that will transform current comminution practices have been sought. One of these novel methods is high voltage pulse (HVP) breakage, a comminution method that uses high voltage pulses to initiate electrical breakdown inside ore particles which are immersed in water, generating a strong tensile force to disintegrate the particles.
Initially, HVP breakage had been investigated as a selective liberation method characterised by the intergranular breakage of ore particles (Andres, 1977). In the past few years, the application of HVP breakage for ore pre-weakening has attracted more attention from researchers and mining companies (Shi et al., 2014b). In this application, a small specific energy (e.g. 1-3 kWh/t) is discharged to ore particles in order to reduce ore strength by generating cracks and micro-cracks, leading to significant potential energy saving in downstream comminution processes (Wang et al., 2011).

In addition to selective liberation and pre-weakening, ore pre-concentration was reported as the third potential application of HVP breakage (Shi et al., 2015b; Zuo et al., 2015b). The technique utilises metalliferous grain-induced selective breakage under a controlled pulse energy input, and size-based screening to separate the feed ore into body breakage and surface breakage components, leading to ore grade splitting. This technique offers potential opportunities for barren pebbles rejection from the AG/SAG mill pebble stream and coarse waste rejection at mine site to reduce the RoM. As the product of pre-concentration is also pre-weakened during the HVP breakage treatment, the combined advantages of both pre-concentration and pre-weakening may be realised.

Mining companies are often interested in knowing the pre-weakening effect on their ores by HVP, as well as how the pre-weakened ore responds in a grinding mill in terms of mill throughput and energy consumption. The simulation software package, JKSimMet, can predict the performance of a comminution circuit through simulations. For this purpose, a model predicting the HVP breakage behaviour of ore particles is required to simulate and optimise the performance of the comminution circuit which incorporates HVP breakage to pre-condition the material for downstream mechanical comminution.

The development of an HVP breakage model requires a detailed investigation of ore particle behaviour in HVP breakage. A joint experimental study of HVP breakage of ores was conducted by the Julius Kruttschnitt Mineral Research Centre (JKMRC) and the SELFRAG AG Company in 2014, using a pilot scale HVP breakage device to treat three ores (Zuo et al., 2015c). With the data collected from the joint experimental study, a model was developed at the JKMRC to predict the breakage probability, product size distribution and pre-weakening degree of ores in HVP breakage. Methods to incorporate the HVP model in HVP pre-concentration characterisation and in modelling HVP product size distributions are also included in this paper.
Chapter 8 Modelling of High Voltage Pulse Breakage of Ores

2. HVP breakage modelling

2.1 The three HVP breakage indices

In the experimental study of ore particle breakage behaviour subjected to HVP treatment using pilot scale machine, the effects of specific energy, pulse voltage, cumulative discharges, feed particle size and particle breakage pattern (body breakage or surface breakage) were investigated in detail (Zuo et al., 2015c). Three breakage indices were adopted to describe HVP breakage behaviour of ores, namely body breakage probability \(D_1\), body breakage product fineness \(D_2\) and body breakage product pre-weakening degree \(D_3\).

There are two distinct breakage modes when a particle is subjected to a single pulse discharge (Zuo et al., 2014b). If an electrical breakdown channel passes through the particle body and splits the particle into several fragments, this is called body breakage. On the other hand, when the electrical breakdown channel, caused by the pulse discharge, develops along the particle surface and generates a few chips, while the main body of the particle is unbroken and retains at the parent size fraction, this breakage mode is called surface breakage. The threshold used in the experimental study to classify a particle into body breakage or surface breakage was that if more than 90% of the parent particle mass was retained in the largest progeny particle, the breakage response was classified as surface breakage. Previous research has indicated that the size reduction effect of surface breakage is negligible, with the vast majority of surface breakage product mass (from 97.4% to 99.2% in six tests) retained in the initial size fraction (Zuo et al., 2015b). In addition, the pre-weakening effect on surface breakage product is either insignificant or much less than that on body breakage (Zuo et al., 2015c). Due to these two reasons, the three HVP breakage indices discussed in this section only refer to the characteristics of body breakage product.

The first HVP breakage index, the body breakage probability is adopted to describe the probability of an ore particle reported to the body breakage class. The body breakage probability is defined by Eq.(8-1):

\[
D_1 = \frac{m_p}{m_f} \cdot 100\%
\]  

(8-1)

where \(D_1 (%)\) refers to the body breakage probability, \(m_p\) is the mass of body breakage product; \(m_f\) is the mass of initial feed in the HVP treatment. It has been demonstrated that body breakage of
particles is often caused by metalliferous grain-induced breakdown, and the index of body breakage probability is closely related to metal grade (Zuo et al., 2015b).

The second breakage index \( D_2 \) evaluates the size reduction effect of HVP breakage, and is defined by Eq. (8-2):

\[
D_2 = t_{10}
\]

(8-2)

where \( t_{10} (%) \) is the mass percentage of the body breakage product passing one tenth of the initial mean particle size. \( t_{10} \) is widely used in comminution engineering to represent breakage product fineness.

The third breakage index for the HVP breakage model is the pre-weakening degree of body breakage product. The pre-weakening degree of body breakage product is defined as the percentage change of ore competence indicator \( A \times b \) (Shi et al., 2013). Thus, the third HVP breakage index \( D_3 \) can be represented by:

\[
D_3 = \frac{A_{b_p} - A_{b_u}}{A_{b_u}} \cdot 100\%
\]

(8-3)

where \( A_{b_u} \) is the \( A \times b \) value of untreated material, \( A_{b_p} \) is the \( A \times b \) value of body breakage product of pulse-treated material. The larger \( A \times b \) value indicates the less resistance to breakage. \( D_3 \) is closely related to the density of cracks/microcracks generated by high voltage pulse. It was observed that there were significantly more cracks/microcracks in the body breakage product (Zuo et al., 2014b).

2.2 Modelling approach

The experimental study of ore breakage behaviour in the pilot scale and laboratory scale HVP machines revealed that the mass-specific energy of HVP was the most significant factor affecting the breakage behaviour. This effect was compounded by the effects of ore properties and particle size. The trend lines presented in (Zuo et al., 2015c) indicate that a model with the exponential equation form is able to fit the experimental data.

A size-dependent breakage model reported by Shi and Kojovic (2007) uses an exponential equation
to describe size reduction in relation to specific energy input and particle size. Details of the size-dependent breakage model have been given in the recent publications (Shi et al., 2015a; Zuo and Shi, 2015b). The model takes the following form:

$$t_{10} = M \{1 - \exp[-f_{\text{mat}} \cdot x \cdot k(E - E_{\text{min}})]\} \quad (8-4)$$

where $t_{10}$ (%) is the body breakage product fineness index defined in Eq. (8-2), $M$ (%) represents the maximum $t_{10}$ for a material subject to breakage, $f_{\text{mat}}$ (kg J\(^{-1}\) m\(^{-1}\)) is the material breakage property that is modelled by Eq. (8-5), $x$ (m) the initial particle size, $k$ the successive number of impacts with the single impact energy, $E$ (J kg\(^{-1}\)) the mass-specific impact energy, and $E_{\text{min}}$ (J kg\(^{-1}\)) the threshold energy.

$$f_{\text{mat}} = p \cdot d^{-q} \quad (8-5)$$

where $d$ (mm) is particle size, $p$, $q$ are model parameters.

Eqs. (8-4) and (8-5) were developed to treat impact breakage data, and have been tested with hundreds of sets of Drop Weight Test and JK Rotary Breakage Test data to prove their validity. The other studies had also confirmed the applicability of Eqs. (8-4) and (8-5), eg. in modelling batch grinding using a modified Hardgrove mill (Shi, 2013), the vertical spindle mill modelling (Kojovic et al., 2015; Shi et al., 2015a) and ball mill modelling (Shi and Xie, 2015). As for HVP breakage, Eq. (8-4) has been used to predict the product fineness index $t_{10}$ of HVP breakage tests conducted in batch testing mode (Wang, 2012) or single particle testing mode (van der Wielen et al., 2014). Moreover, van der Wielen et al. (2014) found that the relation of HVP breakage product pre-weakening degree to specific energy can also be described with a model similar to Eq. (8-4).

Despite these successful applications of the size-dependent breakage model, one limitation in the previous HVP breakage modelling is that all work focused on predicting the HVP breakage product fineness index $t_{10}$ and pre-weakening degree. No attempt to predict HVP body breakage probability was reported. Thus the predicted HVP product is a mixture of body breakage and surface breakage. Since Eq. (8-4) was modified from an impact breakage probability model developed by Vogel and Peukert (2003), it was assumed that this model is applicable to fit the HVP body breakage probability data. An investigation was performed using the size-dependent breakage model (Eqs. (8-4) and (8-5)) to describe the three HVP breakage indices respectively.
2.3 HVP breakage models

To model the three HVP breakage indices, Eqs. (8-4) and (8-5) were modified as:

\[ D_n = M_n \{ 1 - \exp[-f_{mat,n} \cdot x \cdot k(E - E_{min})] \} \]  \hspace{1cm} (8-6)

where \( D_n (\%) \) represents HVP breakage indices; when the subscript \( n = 1, 2 \) and 3, \( D_n \) refers to body breakage probability (the \( D_1 \)-model), body breakage product \( t_{10} \) (the \( D_2 \)-model) and body breakage product pre-weakening degree (the \( D_3 \)-model) respectively. \( M_n (\%) \) and \( f_{mat,n} \) represent the maximum value of \( D_n \) and ore properties effect on the corresponding breakage indices. Here \( f_{mat,n} \) represents the compounded effects of mechanical and electrical properties of ore; \( x \) (m) the initial particle size; \( E \) (J kg\(^{-1}\)) the ratio of generator energy input to particle mass; the value of \( k \) and \( E_{min} \) was set as 1 and 0 in this study.

Statistical \( t \)-Tests to evaluate the effect of pulse voltage on HVP breakage indices in the pilot scale HVP tests suggest that the effect of pulse voltage is insignificant for body breakage probability and body breakage product fineness, but is significant for body breakage product pre-weakening degree (Zuo et al., 2015c). In order to reflect the pulse voltage effect, Eq. (8-6) is modified:

\[ D_n = M_n \{ 1 - \exp[-f_{mat,n} \cdot x \cdot U^{g_n}(E - E_{min})] \} \]  \hspace{1cm} (8-7)

where \( U \) (kV) means the voltage set in the pulse generator and \( g \) is a parameter of \( U \) used to describe how significant the effect of pulse voltage is on the HVP breakage indices. The value of \( g_1 \) and \( g_2 \) are set as 0 to reflect the insignificance of pulse voltage effect when \( n=1 \) and 2.

In the previous applications of Eq. (8-4) in HVP breakage modelling (Wang, 2012; van der Wielen et al., 2014), the value of \( f_{mat} \) was assumed to be independent of particle size. However, the result of the pilot scale HVP tests suggests that the significance of particle size effect on HVP breakage indices varies from case to case. With reference to Eq. (8-5), the model parameter \( f_{mat,n} \) can be described:

\[ f_{mat,n} = p_n \cdot d^{-q_n} \]  \hspace{1cm} (8-8)
where the unit of $d$ is mm.

Eqs. (8-7) and (8-8) compose the HVP breakage model. The model incorporates four parameters, $M_n$, $p_n$, $q_n$ and $g_n$, which can be calibrated by fitting the model to the measured data.

### 2.4 Model validation

The data collected from the pilot scale HVP tests on three ore samples (Zuo et al., 2015c) were used to validate the HVP breakage model. The pilot scale HVP breakage device, named Pre-Weakening Test Station (PWTS), is a purpose-built R&D machine at Kerzers, Switzerland. PWTS offers considerable flexibility in terms of generator setup, as well as the possibility to process continuously or in batch. The machine can be operated at pulse voltage from 50 kV to 200 kV, with pulse energy up to 750 J. Three ore samples were treated using the PWTS: a gold-copper ore, an iron oxide copper gold ore (IOCG), and a hematite ore. There are a nominal 27 data points for Ore A (3 sizes $\times$ 3 voltages $\times$ 3 energies) and 9 data points for Ore B and Ore C (3 sizes $\times$ 3 energies). The datasets may miss a couple of measurement points due to insufficient samples for those tests. The actual numbers of test conditions for Ore A, Ore B and Ore C were 21, 6 and 9 respectively, including five repeated tests.

Figures 8-1 to 8-3 show the fitting results of the three HVP breakage indices for the three ore samples. All of these data points represented the HVP breakage testing results of particles subjected to a single pulse discharge. The results indicated that the HVP breakage behaviour is ore-dependent, subjected to mineralogy, texture and electrical properties of ore (Zuo et al., 2015c). Since the pulse voltage in the tests for Ore B and Ore C was fixed at one level, the model parameter $g_3$ was set as 0 for Ore B and Ore C, and the number of model parameters fitted to the data presented in Figures 8-1 to 8-3 for Ores B and C reduced to three.

It was believed the scatter of the data reflected ore variation in metal grades. Ore A data appeared more scattered than the other two ores. Ore A was also used for HVP pre-concentration tests, in which copper grade variations in the feed particles have been demonstrated (Zuo et al., 2015b). Despite the scatter, the fitting results suggest that the model is robust enough to replicate the complex interaction of different influencing factors on the HVP breakage indices.
Chapter 8 Modelling of High Voltage Pulse Breakage of Ores

Figure 8-1 The HVP $D_1$-model fitted to the pilot scale testing data of three ore samples

Figure 8-2 The HVP $D_2$-model fitted to the pilot scale testing data of three ore samples
3. Incorporating the HVP breakage model in ore pre-concentration characterisation

As mentioned in Section 2.1, there was a difference in grade between the body and surface breakage products subjected to HVP treatment. This is attributed to the existence of metalliferous grains inside ore particles that initiate and attract electrical breakdown channels to pass through the solid body, leading to the increase of body breakage probability. The concept of ore pre-concentration by HVP breakage was proposed based on this phenomenon. Since the effects of pre-weakening and pre-concentration can be generated simultaneously in HVP breakage, there is a potential application to incorporate the HVP breakage model in ore pre-concentration characterisation. In this study, it is proposed to use the fourth HVP breakage index ($D_4$) to describe the recovery of valuable minerals reported to the body breakage product.

With the pre-concentration by high voltage pulse technique, the HVP breakage product was classified into body breakage or surface breakage product based on a critical mass loss (10%) from the parent particle. It was found that some particles classified as the body breakage product were
still retained on the initial particle size fraction due to the particle shape effect (Zuo et al., 2015b). It has been proposed to split the HVP product based on screening in order to apply this HVP technology in a continuous operation. Thus, $D_4$ can be calculated by:

$$D_4 = \frac{D_1 G_u}{D_1 G_u + (100 - D_1)G_o} \cdot 100$$

(8-9)

where $G_u$ is metal grade of screen undersize (%), $G_o$ is metal grade of screen oversize (%), and $D_1$ is body breakage probability defined in Eq. (8-1).

A pre-concentration characterisation graph has been proposed to present the relationships between the test output, in terms of metal-mass-size distributions, and the test input, in terms of specific energy provided by the high voltage pulse generator. By way of example, Figure 8-4 presents a pre-concentration characterisation graph for a copper ore in a given feed size (Shi et al. (2015b)). In this chart, the HVP breakage product of the copper ore is divided into two components by a critical size (bottom size of the narrow-size fraction of the feed), namely screen undersize (body breakage...
product) and screen oversize (surface breakage product).

The graph consists of four curves. Parameters required to draw these four curves include:

- \( G_u \): metal grade of screen undersize (\%)
- \( G_o \): metal grade of screen oversize (\%)
- \( R_u \): metal recovery of screen undersize (\%)
- \( R_o \): metal recovery of screen oversize (\%)
- \( m_u \): Mass yield to screen undersize (\%)
- \( E_{cs} \): Specific energy (kWh/t).

With the data determined from Figure 8-4, an attempt was made to test the applicability of the HVP breakage model for the fourth HVP breakage index (\( D_4 \)): the recovery of valuable minerals reported to the body breakage product. The values of \( D_4 \) were calculated according to Eq. (8-8) and Figure 8-4. The calculated \( D_4 \) values were used to fit the parameters in Eqs. (8-6) and (8-7). The fitting result is given in Figure 8-5, which indicates the HVP breakage model can predict the recovery of valuable minerals well.

![Figure 8-5 The HVP breakage model fitted to Cu recovery data published in Shi et al. (2015b)](image)

As there is only one size/voltage level available for the data derived from Figure 8-4, the HVP breakage model parameters \( q_4 \) and \( g_4 \) were fixed at 0, thus to reduce the number of the fitted model parameters to two in producing Figure 8-5. More testing data are required to further validate the applicability of the HVP breakage model to predict metal recovery index \( D_4 \).
Once the HVP breakage model is calibrated with experimental data for a given ore sample, the predicted breakage indices can be related to the pre-concentration characterisation parameters. The index $D_1$ is equal to $m_a$ and $D_4$ equal to $R_u$, which can be predicted by the $D_1$-model and $D_4$-model from the given specific energy $E_{cs}$ and particle size. From the predicted $D_1$ and $D_4$, the values of $G_u$ and $G_o$ can be calculated by

$$G_u = G_f \cdot \frac{D_4}{D_1} \quad \text{(8-10)}$$

$$G_o = G_f \cdot \frac{100 - D_4}{100 - D_1} \quad \text{(8-11)}$$

where, $G_f$ is the metal grade of feed.

Therefore, the pre-concentration characterisation curves (Figure 8-4) can be drawn using the calibrated HVP breakage model and the back calculated metal grade data by Eqs. (8-10) and (8-11).

4. **Modelling HVP product size distribution**

The HVP $D_2$-model predicts a single variable $t_{10}$ that represents the cumulative percentage of the product passing 1/10th of the feed size. This $t_{10}$ parameter indicates the fineness of a product when subjected to breakage with a certain input energy. In order to predict the complete product size distribution to enable circuit simulation and optimization, (Narayanan and Whiten, 1988) found that $t_{10}$ has unique relations to other points on a family of size distribution curves in mechanical impact breakage, with $t_n$, defined as the cumulative percentage passing a given fraction of the initial size, $x/n$.

It was known that the $t_n$-family of curves are dependent on breakage mechanism. An investigation was performed to validate the applicability of the $t_n$-family of curves for HVP breakage. Figure 8-6 shows the plots of $t_n$ versus $t_{10}$ using the HVP breakage data of three ore samples treated by pilot scale HVP machine (Zuo et al., 2015c). The data illustrate that the three ores fall on similar trend lines, regardless of ore type, initial particle size, pulse voltage and specific energy.
Figure 8-6 The plots of $t_n$-family of curves using the HVP breakage data for Ores A, B and C

Figure 8-7 The $t_n$-family of curves used for HVP breakage modelling

Figure 8-7 presents the regressed $t_n$-family of curves with the data displayed in Figure 8-6. These plots (together with their regression equations) can be used to determine the product size distribution of HVP breakage product with a given $t_{10}$, when there is no sizing data available, as in the case of numerical simulations. However, errors are associated with the generalized $t_n$-family of curves, as Figure 8-6 suggests that the data on each trend line are rather scattered. This is similar to
the $t_n$-family of curves plotted from the rock impact tests (Narayanan, 1985). To minimise the errors associated with product size distributions, using the sizing data to establish a set of ore-specific $t_n$-family of curves for the tested ore sample is preferred.

The HVP breakage model and the $t_n$-family of curves provide a useful tool for HVP breakage characterisation. The HVP $D_2$-model can be used to predict the HVP product fineness for a given ore sample. The corresponding $t_n$ values to the predicted body breakage product $t_{10}$ can be found from the $t_n$-family of curves (Figure 8-7), then the body breakage product size distribution can be converted from the $t_n$ values.

![Figure 8](image.png)

**Figure 8 – Comparison of Ore B body breakage product size distributions between the experimental and predicted values (Markers: experimental values; Lines: predicted values)**

The use of $D_2$-model and $t_n$-family of curves to predict HVP body breakage product size distribution is demonstrated in Figure 8. In Figure 8, the body breakage product size distributions of the six tests with Ore B were predicted and compared with the experimental data. The comparison indicates that the body breakage product can be predicted using the $D_2$-model and $t_n$-family of curves.

### 5. Conclusion

The size-dependent breakage model was modified as a general modelling structure to represent the three HVP breakage indices: body breakage probability (the $D_1$-model), body breakage product fineness $t_{10}$ (the $D_2$-model), and body breakage product pre-weakening degree (the $D_3$-model). Each of the HVP breakage sub-models incorporates particle size, specific energy of pulse generator and
pulse voltage as model input variables. Four model parameters are introduced to describe ore properties and machine setting conditions on the HVP breakage results. The data of three ores treated with a pilot scale HVP machine were used to fit the model parameters. Despite the large variations in ore properties, the model fits the data reasonably well, confirming the robustness of the model.

The HVP breakage model was applied to represent the ore pre-concentration characterisation data published by the same authors. Relations between the HVP breakage indices and ore pre-concentration grade-recovery characterisation curves were established. The preliminary exercise indicated that the HVP breakage model structure has a potential to predict the recovery of valuable metals reported to the screen undersize, once the model is calibrated. More data are required for further validation.

A set of $t_n$-family of curves have been established for HVP breakage product. It was found that the data of various ore types and particle sizes obtained from HVP breakage tests at different conditions all fall on similar $t_n$-curve trend lines. These $t_n$-family of curves can be employed to estimate the product size distribution from the predicted $t_{10}$ values by the $D_2$-model.

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Chapter 9  Conclusions and Future Work

9.1 Conclusions

The overall objective of this thesis is to explore the potential applications using HVP electrical comminution at low specific energy for the mining industry. The motivation underlying this work was that the pre-treatment of ore particles by high voltage pulses at low specific energy has a potential to reduce the energy consumption and operation costs. A comprehensive literature review was conducted to evaluate the existing knowledge related to this study. Based on the research questions and the gaps identified in the literature review, three hypotheses were set for this study (Section 2.7). This Chapter summarises the conclusions focusing on testing the three hypotheses.

The first hypothesis tested is that: Ore particles with different mineral properties respond to high voltage pulse differently in terms of size reduction, which permit the size-based separation of progeny particles with different grades. The selectivity of HVP breakage on ore particle size reduction is assessed by an experimental study with the synthetic samples made of construction grout and pyrite grains. The results in Chapter 4 confirm that the breakage response of particles is dominated by the locality of electrical breakdown channel. When a breakdown channel passes along the axis of a particle, it generates a finer product and produces more cracks/microcracks on the fragments. The electrical breakdown channel locality is controlled by the grains of minerals with high conductivity/permittivity and their location in a particle when subjected to HVP treatment under the identical machine settings.

It is presented in Chapter 5 that the study on metalliferous grain-induced breakdown channel using synthetic particles has led to the discovery of a novel technique for ore pre-concentration using high voltage electrical pulses. The technique utilises metalliferous grain-induced selective breakage, under a controlled pulse energy loading, and size-based screening to separate the feed ore into body breakage and surface breakage products for splitting of ores by grade. Four copper ore samples were tested to demonstrate the viability of this technique.

The second hypothesis tested was that: There exists a mathematical relation of impact breakage degrees ($t_{10}$) between pulse-treated and untreated ore particle. This relation can be used to measure...
the pre-weakening degree of pulse-treated particles and to predict the energy reduction in the subsequent impact breakage process. In the first paper of Chapter 6 a $t_{10}$-based model was developed to predict the degree of impact breakage, $t_{10}$, of pulse-treated particles from that of untreated particles broken at the same size/energy level. This model incorporates only one parameter, $C_{Ab}$, which is equivalent to the percentage change of $A\times b$ values. The $t_{10}$-based model was validated using nine sets of comparative JK Rotary Breakage Test data on untreated and pulse-treated ore samples over a wide range of impact specific energies and particle sizes. The validation revealed that the $t_{10}$-based model fits all the data sets well with only one model parameter. The $t_{10}$-based model can be used to calculate the energy reduction in impact breakage due to the pre-weakening effect, and indicates that the energy reduction by pre-weakening increases with an increase in the target product fineness and the degree of pre-weakening, and with the decrease in feed particle size.

In the second paper of Chapter 6 a Wide-size JKRBT breakage characterization method was developed. In this method the use of feed particles in wide size class replaces the traditional narrow size fraction feed for single particle impact test. Hence the procedures of sample preparation and product sizing can be simplified significantly. The number of testing conditions to determine the breakage characteristic parameters can be reduced from the standard 12 down to 1 or 4. The $t_{10}$-based model developed in the first paper of Chapter 6 is used in the data reduction of the Wide-size JKRBT characterization method. Furthermore, an on-line automatic ore breakage characterization system was proposed based on the Wide-size JKRBT characterization method. The automatic characterization system enables automatic, express, low-cost, on-line and real time ore breakage characterization for the mining operation.

The last hypothesis tested was that: Testing on above two hypotheses will provide fundamental understanding on the interpretation of ore particle behaviour in HVP breakage, and consequently enable the description and modelling of the relation between specific energy and ore particle behaviour in HVP breakage. With the understanding from the investigation of the first two hypotheses, behaviour of ore particles in HVP breakage was investigated with a pilot scale HVP breakage device (Chapter 7). The tests were conducted for three ores (a gold-copper ore, an IOCG ore and a hematite ore) using a single particle test method. Ore breakage behaviour in terms of body breakage probability, product fineness and pre-weakening degree was studied. The effects of specific energy, particle size, pulse voltage, pulse incremental discharge on ore breakage response were established. Comparison between the pilot scale and the laboratory scale HVP machines treating the same ores was presented to show the potential in optimising the processing zone design.
Chapter 9 Conclusions and Future Work

In Chapter 8, a general modelling structure was developed, which consists of three sub-models to represent the three HVP breakage indices: the body breakage probability (the $D_1$-model), body breakage product fineness (the $D_2$-model), and body breakage product pre-weakening degree (the $D_3$-model). Relations between the HVP breakage indices and HVP pre-concentration characterisation curves were established. The preliminary result indicated that the HVP breakage model has a potential to predict the recovery of valuable metals from the calibrated model parameters. A set of $t_n$-family of curves were established for the HVP breakage product. The $t_n$-family of curves can be employed to estimate the product size distribution from the predicted $t_{10}$ values by the $D_2$-model.

9.2 Recommendations for future work

For the future work, the following recommendations are made:

1) Investigate ore particles behaviour in HVP breakage using multiple particles testing method

The single-particle testing method can provide a benchmark of HVP breakage characteristics of ore which decouples the ore-dependent factors from the machine-dependent factors for HVP breakage. However, when a single pulse is discharge into a group of particles, multiple electrical breakdown channels are like to be generated among these particles. In a preliminary investigation conducted in JKMRC, it was found that the energy efficiency of HVP breakage is affected by the number of particles subjected to the same pulse discharge. Therefore, it is necessary to investigate ore particle behaviour in HVP breakage using multiple particles testing method, in order to optimize the energy efficiency of HVP in practical operation.

2) Characterization of pre-concentration

For industrial application of the HVP pre-concentration technology, the first step is to establish the HVP pre-concentration characteristics for a given ore. It is necessary to establish the relationships between the metal-mass-size distributions and the operation conditions of the HVP facility. The characterization will provide essential information for a feasibility study and circuit simulation. The effects of minerals and their grade, texture and locality on HVP pre-concentration performance needs to be studied using advanced technical tools.
3) Design and simulation of hybrid comminution circuit incorporating HVP technology

This thesis explores the potential applications of HVP pre-concentration technique, establishes a characterization methodology, and develops a number of models. These research outcomes need to be validated using more ore samples. Once validated, these outcomes can be used for design and simulation of a hybrid comminution circuit incorporating the HVP technology for ore pre-concentration and pre-weakening for the mining industry.
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