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Characterisation of pre-weakening effect on ores by high voltage electrical pulses based on single-particle tests

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ABSTRACT

A method based on single-particle tests has been developed to characterise the pre-weakening effect of high voltage pulses on ores. A pre-weakening index, PWI, defined as the percentage change in ore breakage resistance indicator (A^*b) per unit of specific energy, is used to evaluate the energy efficiency of an electrical comminution machine, and to assess an ore's amenability to pre-weakening by high voltage pulses. A reduced JKRBT (JK Rotary Breakage Tester) testing procedure using five tests (instead of the standard 12 tests per sample) to determine the ore breakage parameters, makes characterisation by high voltage pulse pre-weakening more practical.

A gold–copper ore sample treated by high voltage pulses, based on single-particle tests with a specific energy of 1.6 kWh/t, achieved an A^*b change from 31 to 84 at a nominal particle size of 30 mm, representing a 171% pre-weakening result. X-ray tomography images show the induced cracks/microcracks in the pulses-treated rocks. The pre-weakening effect was found more pronounced for larger fragments, suggesting that the use of high voltage pulses to pre-weaken AG/SAG mill feed may result in more significant benefits in terms of energy savings or increased throughput than pre-weakening ball mill feed.

1. Introduction

In the 1950s, Russian researchers who used high voltage pulse technology to decompose water into oxygen and hydrogen found that the water shock waves generated by the pulses were powerful and suitable for crushing rocks (Yutkin, 1955). This technique utilises the electrical breakdown of water to create shock waves, and is known as electrohydraulic disintegration. Electrohydraulic disintegration has attracted significant interest as an alternative method to crushing rocks. A number of papers have discussed such applications (e.g. Curley-Macauly, 1968; Sparks et al., 1981; Touryan et al., 1989). The technique has also found applications in medical lithotripsy, bioelectrics, water treatment, nuclear material purifying, and in the metals industry.

A more efficient technique of rock breaking by high voltage pulses is called electrical disintegration, in which the energy of high voltage pulses is transferred to the rock by electrodes directly contacting the surface of the rock immersed in water. This differs from electrohydraulic disintegration, in which the energy is transferred through the surrounding water in the form of a shock wave impact (Andres, 1995).

Another term for high voltage pulse breakage is electrodynamic disintegration (including the term electrical pulse disaggregation, EPD), in which the electrodes do not contact the rock surface directly, as a small water gap exists between the electrodes and rock particles (Giese et al., 2009; Shi et al., 2012). Due to ore particle shape variation, it is difficult to distinguish whether the electrodes have direct contact with the particles or whether there is a small water gap under a specific electrode gap setting. In reality, electrical disintegration, electrodynamic disintegration and electrical pulse disaggregation may be classified under one similar group, with the distinguishing feature being that the high voltage rising time in this group is less than 500 ns. At this condition, the water breakdown strength is higher than solid breakdown strength, so the water acts as a special electrical insulator to prevent electrical discharge occurring outside the rocks.

The term "electrical comminution" is used here to cover electrohydraulic disintegration, electrical disintegration, electrodynamic disintegration, and electrical pulse disaggregation, all using high voltage pulses.

In the past half century, research on electrical comminution for the mineral industry has been focused mainly on mineral liberation. There are a number of reports demonstrating the effectiveness of mineral liberation by high voltage pulse processing (Andres, 1977, 1995, 2010; Anon, 1986; Andres et al., 2001a; Lastra et al., 2003; Cabri et al., 2008), some of them demonstrating better mineral recovery or higher concentrate grade as a result of the better mineral liberation. It is expected that if the recovery/grade performance improves on the cost of energy, the technology becomes

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economical. However, the application of high voltage pulse technology to the mineral industry was rather slow, because the benefits were not demonstrated sufficiently to justify the perceived risks. One major concern has been the amount of energy consumption used in the electrical breakage process itself. Andres et al. (2001b) reported that the consumption of energy per unit volume of the tested ores used for mineral liberation was on average 2–3 times higher than in conventional mechanical comminution.

Usov and Tsukerman (2006) pointed out that there is the possibility of electrical pulse method of destruction to reduce energy consumption, but this possibility is limited. Combined application of electrical pulse destruction, electrical discharge weakening and traditional mechanical methods of destruction may give an option of reducing energy consumption for mineral processing.

The Julius Kruttschnitt Mineral Research Centre (JKMRC) has conducted research on electrical comminution in the past five years with the objective of making a step-change in comminution energy efficiency for the mineral industry. One of the research aims is to develop a technique for pre-weakening of ore particles by high voltage pulses. Instead of using nearly 100 kWh/t specific energy to break particles from 30 mm down to micron sizes, the pre-weakening technique applies a specific energy (between 1 and 3 kWh/t) to damage or lightly break particles with minimal fines generation. In this approach, the pulse energy is not solely used for size reduction, but for creating cracks and micro-cracks in particles, leading to a reduction in energy consumption in the downstream grinding process (Wang et al., 2011).

The JKMRC work demonstrated that for a number of ores (such as gold, gold–copper, lead/zinc, platinum and industrial rocks), with specific energy levels ranging between 1 and 3 kWh/t, when treated with high voltage pulses, the product $A^{*}b$ value ($A^{*}b$ being a ore breakage resistance indicator which is discussed in more detail later in this paper) changed by 9–52%, and up to 24% in terms of the Bond work index (Wang et al., 2011). The data also showed significant variations in the pre-weakening effect for different ores, which suggests that the feasibility of electrical comminution and its potential benefits need to be investigated on a case by case basis.

Through experimental study and numerical simulations, the JKMRC researchers find that there are many factors affecting the pre-weakening results (Wang et al., 2012). 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 pre-weakening characterisation method is to decouple the ore-dependent factors from the machine-dependent factors, in order to quantify the relationship between the pre-weakening effect and high voltage energy requirement for a specific ore sample. The development of such a pre-weakening 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.

2. Single-particle characterisation test

2.1. The issues

Initially the pulse fragmentation experiments were performed in an open circuit: a batch of particles about 700 g in a narrow feed size fraction (e.g. 26.5–45 mm) was treated by selFrag, a laboratory high voltage pulse equipment (refer to Wang et al., 2011), with a number of pulse discharges to give a specific energy between 1 and 3 kWh/t. The reason to use narrow feed size fractions for testing, though the process can handle size-mixed feed, is to investigate the effect of particle size on pre-weakening, and to use the product fineness indicator t_{10} (will be defined later) for breakage modelling, which requires a narrow feed size to precisely define the t_{10} size. Fragments in the minus 26.5 mm size fractions were tested by a rotary breakage tester, JKRBT (Shi et al., 2009), to determine the ore breakage resistance indicator, $A^{*}b$, or by a Bond rod mill or Bond ball mill to determine Bond work indices.

In the open-circuit treatment, over half of the feed particles remained in the parent feed size fraction after the first cycle of treatment using 1.5 kWh/t of specific energy. To investigate the total energy requirement to break all particles to sub-parent size fractions, a close-circuit test was adopted. For ore characterisation, about 50 kg of feed in a narrow size fraction is required to be treated with selFrag to provide sufficient material for the JKRBT and Bond tests. The particles are tested with selFrag, with about 700 g per batch. All oversize particles from the first cycle tests were combined and re-split to generate 700 g for each batch test in the next cycle of treatment, using similar conditions to the first cycle. No fresh feed was added after Cycle 1. The cycles continued until the residual oversize mass was less than 700 g. The first cycle energy consumption, the number of cycles, and the total pulse energy consumption are subject to the cut size required, the selFrag operating conditions and the ore type.

In the close-circuit experiment, the ore breakage resistance indicator $A^{*}b$ of the undersize particles in the first cycle and the last cycle was measured. It was expected that the particles would become less resistant to breakage as the testing cycles proceeded, due to the accumulation of damage from the high voltage pulses in each preceding cycle. However, the investigation found that this was not the case. The data showed less than a 10% difference in $A^{*}b$ changes between the first cycle product and the last cycle product after the oversize ore particles had been recirculated back into the process vessel 7 times.

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 selFrag process vessel. Siomkin 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 selFrag instrument was not evenly distributed among all ore particles in the process vessel. The unbroken particles in each cycle treatment may not be attributable to their resistance to high voltage pulses, but rather to the fact that they did not receive pulse discharges. Although it may be argued that shock waves can agitate particles in the vessel, the system does not permit the optimal use of pulse energy for pre-weakening of ore particles. During the three-particle test, three pulses were discharged, one pulse for each particle on average. The product size distribution and the ore breakage resistance indicator $A^{*}b$ may not represent the true response of the ore subjected to high voltage