Minerals Engineering 65 (2014) 109–114

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Benchmarking comminution energy consumption for the processing of copper and gold ores

G.R. Ballantyne *, M.S. Powell

The University of Queensland, Sustainable Minerals Institute, Julius Kruttschnitt Mineral Research Centre, 40 Isles Road, Indooroopilly, Brisbane, QLD 4068, Australia
CRC ORE: Optimised Resource Extraction, Level 7, Sir James Foots Building, The University of Queensland, St Lucia, QLD 4072, Australia

ARTICLE INFO

Article history:
Received 29 November 2013
Accepted 21 May 2014
Available online 19 June 2014

Keywords:
Comminution
Energy benchmarking
Energy efficiency
Copper and gold mining
Preconcentration

ABSTRACT

A survey of the comminution energy requirements of gold and copper producing mines has been conducted to provide reliable benchmarking data which can be used to compare comminution energy consumption across different mine sites. The total gold and copper production of the mines included in the study equated to 15% and 24% respectively of global production and all of Australian production. The comminution energy per unit metal product has been presented in a graphical form similar to a cost curve. This simple technique allows individual mines to be ranked with respect to energy consumption and clearly displays the potential energy and cost benefits of moving down the graph into more efficient operating regimes. Assuming similar specific energy requirements for other sites, comminution of gold and copper ores can be expected to consume about 0.2% of global, and 1.3% of Australia's electricity consumption. Efforts to reduce this figure should be aimed at the top third of consumers as they are responsible for 80% of the total consumption. Analysis of the contribution of circuit efficiency, ore competence, grind size and ore grade showed that ore grade was the greatest determinate of specific comminution energy. Therefore, concentrating the ore via gangue rejection or grade engineering prior to grinding is likely to achieve the largest positive effect on comminution energy efficiency.

1. Introduction

Comminution is the process by which rocks are reduced in size to liberate the valuable components for subsequent separation events. The process of rock breakage consumes a considerable quantity of energy and is a significant component of international electricity consumption. Curry et al. (2014) found that the mill (defined as crushing, grinding and separation) typically accounts for between 35% and 50% of the total mine costs. The proportion of energy consumed by comminution has been calculated by a number of researchers in an attempt to create a context for research into energy reduction (Daniel and Lewis-Gray, 2011; Tromans, 2008). The US Department of Energy (DOE) has investigated this subject through a combination of industry surveys and computer modelling, and its seminal work in 1981 is widely referenced. The DOE (1981) found that comminution processes accounted for approximately 2% of the total U.S. electricity consumption. The specific energy requirements (in kW h/t) were supplied by Battelle Columbus Laboratories (1976) through comprehensive energy audits of a number of key commodities across the U.S. Fig. 1 shows the DOE results plus a number of other reviews. Four complete energy audits of Australian copper/gold mines are publicly available and provide a good picture of energy use at specific mines. Marsden (2008) used case studies of Chilean copper mines as the basis for an energy model incorporating grade and processing route, Fig. 1 displays the result for an ore with a copper grade of 0.5% and a flowsheet incorporating SAG and ball milling, flotation and smelting.

Ballantyne et al. (2012) completed an audit of the energy consumed by comminution in Australian copper and gold producing mines. On average, 36% of the energy utilised by the mines was found to be consumed solely by comminution processes. Utilised energy was defined as the addition of electricity consumption and the mechanical energy utilised by diesel machinery. Forty-six mines were analysed in this study and the 95% confidence in the average comminution proportion was +/−10% (not representing the error in measurement, but the variation between mines). On a national scale, the energy consumed in comminuting copper and gold ores corresponded to 1.3% of Australia's electricity consumption (Ballantyne et al., 2012; Cuevas-Cubria et al., 2011).

The energy consumed through comminution is quantified using a number of different bases. It is most commonly reported as the

* Corresponding author at: CRC ORE: Optimised Resource Extraction, Level 7, Sir James Foots Building, The University of Queensland, St Lucia, QLD 4072, Australia. Tel.: +61 73365 5839; fax: +61 7 3365 5999.

E-mail address: g.ballantyne@uq.edu.au (G.R. Ballantyne).

http://dx.doi.org/10.1016/j.mineng.2014.05.017
0892-6875/

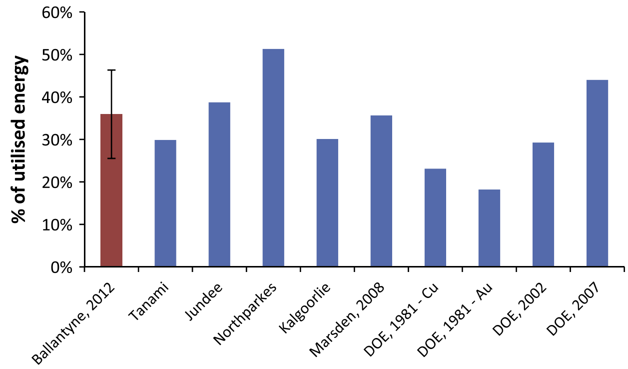

Fig. 1. Summary of calculated percentage of mine utilised energy attributable to comminution (Ballantyne et al., 2012; DOE, 1981, 2002, 2007; Dorai, 2006; Marsden, 2008; Northparkes, 2006).

specific energy per tonne of material processed (kW h/t). However it may be more useful to present the metal specific energy (MSE) in terms of final metal product as this incorporates the influence of grade. The competence of the ore and the energy can be assessed using the operating work index (Bond, 1952). Eq. (1) is the usual form of Bond's theorem of comminution in which he assumes a linear relationship between energy and crack length. The size reduction and specific energy input (kW h/t) were used to calculate the work index (WI) which is a measure of rock hardness corresponding to the energy required to reduce one tonne of in situ rock to a P_{80} of 100 μm.

$$W = 10\text{WI}\left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right) \tag{1}$$

where P_{80} and F_{80} are the 80% passing size of the product and feed respectively (μm).

Levin (1992) proposed a new method for calculating the size specific energy (SSE) requirements of an ore based on the mass of fine material produced, usually defined by the proportion of material below 75 μm. The difference between the two indices is that the work index is based on P_{80} which is always fairly close to the size of the largest particle, whereas the percentage of minus 75 μm is a more variable quantity that may be close to, or far from the size of the largest particle (Levin, 1992). Bond's theory also requires the feed and product cumulative size distributions to be parallel in log/log space. The size specific energy required to generate new minus 75 μm material is based on von Rittinger's hypothesis that energy required for size reduction is proportional to the new surface area generated (Hukki, 1962; Rittinger, 1867). Musa and Morrison (2009) found that 70 to 80% of the surface area of the product of AG/SAG/ball milling circuits exists in the minus 75 μm size fraction. Although not often credited, Hukki (1979) appears to be the earliest reference correlating the surface area with percent minus 74 μm, in his seminal paper on closed circuit grinding.

The Coalition for Eco-Efficient Comminution (CEEC) roadmap proposed that clear benchmarks and standards are required to allow performance targets to be compared with industry standards (Napier-Munn et al., 2012). If a benchmark for current operations can be established, it may provide incentive for the industry to improve the efficiency of comminution processes (Napier-Munn et al., 2012). The present paper will attempt to provide a baseline for comminution energy in current gold and copper operations internationally.

2. Methodology

The focus of the current investigation was limited to gold and copper producing mines to assess the applicability of the analysis technique on commodities with the greatest availability of data. A database was constructed to calculate each mine's comminution energy requirements individually before the results were combined, and anonymity was preserved. The comminution energy requirements were obtained from JKTech surveys, published reports, energy audits and publications of installed equipment. Although a number of different sources have been used, consistency was maintained throughout the process. Historical comminution circuit survey (JKTech) reports between 1992 and 2012 were used to provide operating information on the milling circuits. These reports provided throughput, feed and product size distributions, mill power measurements and ore hardness parameters. Installed power requirements were obtained from a minerals processing survey published in AMM magazine (Asphar Survey Group, 2011). An interesting outcome of comparing these two information sources was that the mills were found to be consistently operating at an average utilisation of 96% in relation to the installed power (Ballantyne et al., 2012).

Complete power data was available for SAG and ball milling, but it was only partially available for fine grinding and crushing. The data is also heavily weighted towards Australian mines; international mines were sampled sparsely with a skew to larger mines. Comminution data was available for 68 mines, effectively accounting for all the copper and gold produced within Australia but only 24% of the copper and 15% of the gold produced internationally.

Copper and gold production data, as well as material milled, was obtained from publicly available annual reports. The most recent production data available for each mine was collected, but inconsistencies in reporting resulted in dates varying between 2007 and 2012 for different mines. The combination of this variance and the timing of the comminution circuit surveys may result in some inconsistencies in the results, but every attempt was made to minimise this effect. Total mine site energy consumption was also collected from compulsory reporting initiatives such as Australia's Energy Efficient Opportunities Act (RET, 2006). Where possible this was also separated into electrical energy and diesel consumption for consistency.

3. Results

The results have been presented in a graphical form similar to the cost curves that are generated by financial institutions. Each mine is presented as a separate bar in a bar chart, the width of which represents the annual production and the comminution energy intensity is the height (Fig. 2). The mines are ranked in ascending order based on the specific energy, and the *x*-axis becomes the cumulative annual production. The average Australian residential electricity price in 2010/11 (22.4 c/kW h – AEMC, 2011) was used to calculate the energy cost which is displayed as a secondary *y*-axis. Using a fixed cost gives a consistent basis for comparison, but it should be noted that the actual costs vary considerably between (and within) countries and methods of energy generation.

The comminution energy intensity can be expressed in a number of different ways. The most powerful unit is energy per unit metal product as it is not only influenced by unit comminution efficiency but also upgrading strategies and recovery increases. Because copper and gold are associated geologically in orebodies, to compare like-with-like, mines were classified as either copper or gold producers depending on their major production. Grasberg was the only mine that was deemed to have equal production value of copper and gold.

The gold and copper comminution curves are displayed in Figs. 3 and 4 respectively. For gold producing mines the average energy was 353 kW h/oz and for copper it was 1134 kW h/t. The Battelle Columbus Laboratories (1975) reported the comminution energy